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On Thermal Radiation in Absolute Measure

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XIV. *On Thermal Radiation in Absolute Measure.*

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Communicated by Sir W. Thomson, *Knt., LL.D., F.R.S.*

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[Plates 24–26.]

In June, 1884, I had the honour of laying before the Royal Society a communication "On the Permanent Temperature of Conductors through which an Electric Current is passing, and on Surface Emissivity."* In carrying out the experiments described in that communication, it became evident that the method then adopted would lend itself readily to the determination in absolute measure of the loss of heat, under various circumstances, from the surface of electrically conducting wires; from metallic wires, for example, and from carbon filaments, such as those used in incandescent electric lamps. Accordingly, at the conclusion of the paper just referred to, the results were given of some preliminary experiments on radiation from metallic wires in high vacuums; and I desire in the present communication to give an account of a more extended investigation in the same direction.

Although loss of heat by radiation and convection has been studied by various experimenters, few determinations in absolute measure of the loss under definite circumstances have been made; and, with the exception of those of Schleiermacher, to be mentioned immediately, no determinations, so far as I am aware, have been made through any considerable range of temperatures, or with a difference of temperatures between cooling body and surroundings of considerably more than 100° C.

Probably the best known results are those of D. Macfarlane,† who experimented on the cooling of polished and blackened copper globes in air, at ordinary pressure and saturated with moisture. Professor Tait has also published‡ the results of observations by J. P. Nicol on loss of heat from polished and blackened copper at three different pressures, viz., 760 mm. of mercury, 102 mm., and 10 mm. Recently

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* 'Roy. Soc. Proc.,' vol. 37 (No. 232), 1884, p. 177.

† 'Roy. Soc. Proc.,' vol. 20, 1872.

‡ 'Edinburgh, Roy. Soc. Proc.,' 1869–70.

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A. Schleiermacher,* using a method precisely similar to one of two which I described in the preliminary paper already referred to, has experimented in high vacuum through wide ranges of temperature. The object of these experiments was to test the supposed law of Stefan, viz., that radiation of heat is in proportion to the fourth power of the absolute temperature of the radiating surface. Schleiermacher's results are not stated in absolute measure; but, from the data given in his paper, I have been able to make the calculations, and to compare his results with my own.

Of other recent experimenters it is only necessary to mention Kundt and Warburg, who in 1875 published an important research on friction and heat conduction in rarified gases;† and Mr. Crookes,‡ who has given a very valuable comparative determination of the loss of heat from the same surface, the bulb of a mercury in glass thermometer, at different pressures from full atmospheric pressure down to a pressure of two millionths of an atmosphere.

In order to make this paper complete, it seems advisable that I should here explain fully the method of experimenting, and the apparatus used; even though this has already been partially done in my preliminary paper.

The general principle of my method of experimenting may be thus described: the wire for which it is desired to measure the surface loss of heat is stretched in the air or so-called vacuum, and an electric current is passed through it. The wire becomes heated; but very shortly the temperature becomes steady, a balance having been established between the energy supplied by the current and that lost by emission from the surface and by conduction to the fixed supports at the extremities. The latter part is of but small importance in the fine wires, one metre long, which I have been using, and it is allowed for in accordance with a calculation given by Sir William Thomson in a note appended to my first paper.§

When a permanent temperature has been attained by the wire, the current passing is determined in absolute measure. Simultaneously the resistance of the wire is measured; and from these measurements the energy is calculated which is expended in maintaining the temperature of the wire—that is, as has been said, the energy lost at the surface of the wire. The measurement of the electric resistance of the wire also enables me to calculate the temperature of the wire, by means of the results of a separate determination of the electric resistance at different temperatures of the particular wire in use. Lastly, the dimensions of the wire are measured, so that the loss of heat per square centimetre may be calculated; and the circumstances of the experiment and condition of the surroundings are noted.

Fig. 1, Plate 24, shows the electric connections of the apparatus chiefly used for

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* 'Wiedemann, Annalen,' vol. 26, 1885, p. 287.

† 'Poggendorff, Annalen,' vols. 155 and 156, 1875.

‡ 'Roy. Soc. Proc.,' vol. 21, 1881, p. 239.

§ 'Roy. Soc. Proc.,' vol. 37, 1884, p. 187.

sending a known current through the radiation wire, and simultaneously measuring the current and the electric resistance of the wire. This arrangement is one of two described in my first paper on this subject. It has proved entirely satisfactory; and I have used the other method but little, except in some experiments on incandescent lamps, and in a special experiment described at the end of this paper.*

The arrangement shown in fig. 1 is a WHEATSTONE'S bridge adapted to suit the purpose in hand. The wire *w* under experiment is represented in this diagram as stretched between the points *c* and *d*. In reality it is surrounded with a tube which is immersed in a water-jacket, as will be described presently. *ab* is a frame in which there are stretched a large number of somewhat fine copper wires, sometimes 12 or 15, or more. These wires are stretched between two very stout copper bars, shown cross-hatched at *a* and *b*. The multiple copper wires offer but little resistance to the battery currents, and present so large a surface to the air that the heating due to any current they are called upon to carry is absolutely insensible. At G is shown the THOMSON'S current galvanometer (of extremely small resistance, $\frac{1}{500}$ ohm) which measures the current flowing in the branch *abcd* of the WHEATSTONE'S bridge—that is, the current passing though the wire *w*.

The other branch of the WHEATSTONE'S bridge is a long fine platinum wire, specially drawn, and excellent as to uniformity. It is so long and fine that the minute proportion of current passing through it is quite insufficient to warm it sensibly. It is stretched backwards and forwards on a board of polished pine; and a sliding contact piece *e*, guided by a V-groove, runs along one length of the wire, the position of the slider being read off on the scale *ss*. One electrode from the testing galvanometer T of the bridge is attached to the slider, while the other is attached at *c* in the other branch of the bridge. The battery consists of six large secondary cells arranged in series; and a THOMSON'S rheostat wound with thick platinoid wire is used to control the current.

It will be seen that the arrangement here described gives a WHEATSTONE'S bridge in which the only part sensibly heated is the radiation wire *w*; and that its resistance at any temperature can be measured in terms of the other three parts of the bridge. Every connection in the four branches of the bridge is soldered.

The current galvanometer used during my earlier experiments was one of Sir W. THOMSON'S graded current galvanometers with a magnet of low power to give sufficient sensitiveness. More recently I have substituted for the graded galvanometer one of a different pattern, called by Sir W. THOMSON a 'lamp-counter,' and designed for finding the number of lamps in use on an electric light circuit. To keep

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* The alternative method referred to in the text consists in measuring the current passing through the radiation wire, and, simultaneously, the difference of potentials between two points at known distance apart. (See figs. 5A, 5B, Plate 24.) It possesses one great advantage, viz., the avoidance of the disturbance by conduction of heat from the ends, but it would be difficult or impossible to use this method with a vacuum, except in an envelope of glass.

a check on the current galvanometers, the absolute values of their readings were frequently determined by electrolysis; and this was done specially after the chief series of experiments, and before calculation of the several portions of the results tabulated and shown in the curves given with this Paper. In such determinations the galvanometer was not removed from its place, nor was any alteration made in the soldered connections, with the exception of opening the main branch of the bridge at the point *c* to admit the electrolytic cell. By this means local disturbance (if any) of the current galvanometer due to electrodes was taken into account; and this method of ascertaining the absolute value of the indications of the current galvanometer was satisfactory because of the complicated nature of the circuits. Influence from the electrodes was done away with as far as possible by laying side by side, insulated with paraffined paper, the electrodes coming to and going from any particular point; but a certain amount of complication was unavoidable, due regard being given to convenience of working, on account of the great number and variety of the pieces of apparatus used in these experiments, and on account of the necessity of placing the tube which contained the radiation wire, and which was attached to the SPRENGEL pump, at some little distance from the testing parts of the WHEATSTONE'S bridge.

The radiation wire, in the present experiments of platinum, was stretched from end to end of a long straight tube, and this tube was kept permanently connected to a five-fall SPRENGEL pump. In my earlier experiments, including in particular one long and very complete series of measurements,* the platinum wire was contained in a glass tube, being sealed into the glass at the ends. I also tried platinum spirals in glass globes similar to the globes of incandescent electric lamps, although these spirals had the disadvantage of having the sides of the turns radiating towards each other. A glass envelope surrounding the radiation wire is, however, extremely unsatisfactory. It is impossible to tell with a material like glass, of low thermal conductivity and nearly opaque to heat radiations of low refrangibility, at what temperature the inner skin may be of a tube half an inch in internal diameter, with walls $\frac{1}{16}$-inch thick, and containing a red-hot wire stretched at its centre from end to end. And it is still more difficult to form an opinion as to the amount of heat that may be returned by reflection and radiation together to the radiation wire. I shall have occasion to refer to this matter somewhat later.

My reason for using glass envelopes in my earlier experiments was simply that I was unable to find a method of stretching a wire in a metal tube with one end at least of the wire insulated, and connecting such a tube in a satisfactory manner with the glass exhausting tube of the SPRENGEL pump. Very moderate experience in the production of high vacuums shows the futility of attempting to work with connections of india-rubber, vulcanite, or the ordinary cements and varnishes.

I have, however, been fortunate enough to find a cement which, when properly

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* 'British Association Report,' 1885, and 'Nature,' 1885.

used, does act perfectly in keeping as good a vacuum, I believe, as can be made, and which does not give off at common temperatures any vapour which can be detected by the tests known at present. This invaluable material is "Siegelwachs,"* a small piece of which was given to me by Professor QUINCKE, with the remark that it would "hold a vacuum"; and with it I construct my vacuum-tube with a wire stretched in it in the following way. *ab* (figs. 2A and 2B) is a copper tube one metre long. The bottom is closed with a metal plate, which is soldered on: but in the centre of the plate there is a small hole through which is brought out the extremity of the hard-drawn copper spiral shown in the diagram. At the top of the copper tube there is soldered in a short piece of re-entrant tube of a nearly conical shape; *e* is a glass tube which is prepared to fit the mouth of the tube *ab*. To do this, the glass tube, closed for the time at *o*, is heated to softening round about, and is blown into the tube *aa′* as into a mould. It is then quickly withdrawn and carefully annealed. Lastly, two or three stout platinum wires are sealed into the glass piece at *d*, and these, after the glass splint at *o* has been cut off, are brought out to a point to which one end of the radiation wire is silver-soldered. The other extremity of the radiation wire is attached to the spiral spring already inside the copper tube, but which for the purpose of silver-soldering is brought to the top *a* of that tube. When the soldering has been effected the tail-piece of the spiral is pulled down and out through the hole at *b*, and when all other arrangements are completed is soldered in its place. Previously to this, however, the glass piece *e* is put into its place with an extremely minute quantity of "siegelwachs"; and then, with the help of a pointed glass rod, heated in a spirit lamp, the cement is put in drops round the junction of copper and glass, and carefully worked in so as to fill up every re-entrant corner, and make a coating everywhere convex outward except just where it joins the vertical part of the glass tube. Here the wax is thinned away very gradually, the greatest care being taken to make sure that all round the edges the cement is adhering perfectly to the glass. With a joint made as described I have maintained a high vacuum for weeks together; and, in fact, I have no reason for thinking that such a joint is not quite as good at atmospheric temperature as the usual joint made by fusion of glass on to the exhausting tube of the SPRENGEL pump.

It is unnecessary for me to enter into details as to the production of high vacuums by means of the SPRENGEL pump. In this matter the splendid researches of Mr. CROOKES have, in every detail, pointed the way for obtaining the best results; and the five-fall SPRENGEL pump of Mr. GIMINGHAM[†] is admirably convenient for exhausting vessels of moderate capacity. In measuring the vacuums produced, I use

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[*] "Siegelwachs" is not similar to English sealing-wax ("Siegellac"). It is a soft wax easy to manipulate and not liable to crack, and it shows no tendency to contract and draw away from the glass or metal to which it has been made to adhere. I obtain it from the firm of J. GAUTSCH, Königliche Hof-Wachswaaren-Fabrik, Munich, whose name was given me by Professor QUINCKE.

[†] 'Roy. Soc. Proc.,' vol. 25, 1877.

the McLeod gauge as modified by Mr. C. H. Gimingham,[*] and shown in figs. 3a and 3b. The modification consists in supplying at the top of the volume-tube, as commonly constructed, a short piece (3 centims.) of fine thermometer tubing carefully calibrated. For the lower exhaustions the air is compressed into the wider portion of the volume-tube; but for the higher exhaustions it is compressed into the divisions of the thermometer tube. To avoid errors from capillarity, there are two pressure tubes: that shown on the left in the diagram being a portion of the same tube as the wide part of the volume-tube, while the tube on the right in the diagram is made of a piece of the same thermometer-tube as is used for the finer part of the volume-tube. The mercury rises, of course, simultaneously in both pressure-tubes. It is usual, I think, to work the McLeod gauge by means of mercury from the main reservoir; but it will be found far more convenient to have an independent mercury reservoir as shown in the diagram, and, indeed, as it was originally described by the inventor.

In my experiments up to the present time I have not introduced the iodine-sulphur-silver tube proposed and used by Crookes[†] as a stopper against the mercury vapour of the pump; and, as the McLeod gauge measures only the pressure of that which is not collapsible in the vacuum space, its results are rendered imperfect for my purposes by the existence of mercury vapour. I must confess, however, that I cannot feel confidence in the power of finely divided silver or copper for stopping the vapour of sulphur out of the vacuum space, and unfortunately the testing spectroscopically, or otherwise, for vapour of sulphur is not so easy as for vapour of mercury. In experiments on radiation of heat the presence of any vapour whatever vitiates the results just to the extent to which it is present. In this connection I must also call attention to the difficulty of avoiding vapour from the material used in the drying tubes of the pump. It is now usual to employ drying tubes of phosphorus pentoxide; but it is extremely difficult to prepare this material perfectly free from small unburnt particles of phosphorus, and these will undoubtedly give rise to vapour of phosphorus. It may, I think, be doubted whether, after all, sulphuric acid is not in this respect a better drying material than phosphoric anhydride. I propose, however, shortly to make a series of experiments in which all vapours shall as far as possible be removed from the vacuum space, and afterwards stopped out of it by the interposition of a freezing chamber.

Another reason, however, prevented my using Mr. Crookes' mercury stopper, and, as it has also thrown great difficulty in the way of my measurements of the vacuum, I desire to mention it here. In determining the radiation, as will be seen presently, it is necessary to record *simultaneously* the energy lost and the pressure. But, unfortunately, I have been unable to find a platinum wire which does not incessantly give off small quantities of gas at high temperatures. This would be of no consequence at moderate pressures ($\frac{1}{100}$ mm., for example): but in extreme vacuums the effect is very

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[*] 'Journal of the Society of Chemical Industry,' 1884.

[†] 'Phil. Trans.,' 1885, p. 693.

great indeed. Now it is, perhaps, scarcely realised that the time taken for a high vacuum ($\frac{1}{10}$ M, one-tenth of one-millionth of an atmosphere, for example) to equalise itself throughout the narrow glass-tubes used for connections with the Sprengel pump is very considerable, and may amount to 20 minutes, half-an-hour, an hour, or two, according to circumstances. It follows from this that the indications of the McLeod gauge are certain to be behind time in the case of a high, but variable, vacuum; and the introduction of any considerable length of tubing that can possibly be avoided is very disadvantageous. The difficulty here referred to has proved a more fruitful source of trouble, and seems to me less likely to be successfully dealt with, than any other connected with these experiments; though it is just possible that the use of platinum-iridium wire or platinum-silver may prove of considerable advantage.

It has been already explained that the temperature at which the radiation is taking place is determined in these experiments by finding the resistance of the wire at the moment, and by knowing from separate experiments the resistance of the wire at different temperatures. The variation of electric resistance of platinum wire with temperature is very different in different specimens. It seems likely that small impurities in the platinum, in the way of admixture with it of minute quantities of the iridium class of metals, may be the cause of this variation. I, myself, have found that a very minute quantity of tungsten combined with German silver makes a vast difference as to the variation of resistance with temperature of that alloy.* The great variableness as to this quality in platinum wires is abundantly attested by many experimenters,† and my own experiments fully confirm those of others. I have, therefore, in every case taken a portion of the radiation wire itself, and determined its resistance through as wide a range of temperature as was attainable in the way to be described presently. The results of these experiments are laid down in the form of a curve having temperatures as abscissas and resistances as ordinates; and from this curve, which turns out to be almost a straight line with different inclinations in different specimens, the temperature of the wire in any experiment is taken off, its resistance being known.

The apparatus used in determining the resistance of platinum wires at high temperatures is shown in fig. 4, *a*, *b*, *c*. In my earlier experiments, and at lower temperatures, I employed the vapours of liquids with high boiling points as first proposed by Andrews,‡ some of the liquids suggested by Drs. Ramsay and Young § proving convenient. The boiling points of liquids, however, would not give temperatures nearly high enough for the purpose in hand, and I was about to construct a

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* "On the Electric Resistance of a new Alloy named Platinoid," 'Roy. Soc. Proc.,' vol. 38, 1885, p. 340.

† Siemens: Bakerian Lecture for 1871, but first published in the 'Transactions of the Society of Telegraph Engineers' for 1874. Schleiermacher: 'Wiedemann, Annalen,' vol. 26, 1885, p. 295. H. L. Callendar: 'Roy. Soc. Proc.,' vol. 41, 1887, p. 231.

‡ 'Comptes Rendus,' vol. 81, 1875, p. 279.

§ 'Chem. Soc. Journ.,' 1885.

massive copper-jacket for the purpose, when Sir WILLIAM THOMSON proposed to me to use a cylindrical jacket made up of a large number of thin co-axal copper-tubes, and pointed out to me the great advantages possessed by such a composite jacket in equalising the temperature. Accordingly, the heating jacket shown in fig. 4, *b*, is made up of eight co-axal copper tubes, each with a copper bottom, fitting closely one inside another, a few turns of the finest asbestos yarn being wrapped spirally round each of the tubes before it is pushed into the tube in which it fits. The internal diameter of the smallest tube is $3\frac{1}{2}$ centims., the outside diameter of the outermost tube is 6 centims., the length over all is 33 centims. The sheet copper used for making the tubes is $\frac{3}{4}$ mm. in thickness, and the weight of the whole is 4 kilos. I have used electrolytic copper, technically known as "conductivity copper," supposing it probable (though I have not had time to verify the supposition) that the pure copper, which shows such marked superiority to less pure copper as to electric conductivity, may also possess at least some superiority as to thermal conductivity.

The copper-jacket is closed with a stopper of woven asbestos about 5 centims. long. Holes are pierced in the stopper, through which pass two thick copper electrodes and the stem of an air-thermometer, to be described presently. The jacket is heated sometimes by two rows of six Bunsens in each row; the BUNSEN tubes in each row being screwed into holes tapped in a $\frac{1}{2}$-inch iron pipe. I find the most convenient heater, however, to be one of FLETCHER's large "solid flame" burners. This burner gives an enormous flame, enveloping the whole of the copper-jacket (which is placed inclined as shown in fig. 4, *a*), and easily raising it to a good red heat through and through. The electrical measuring apparatus which I use is amply sensitive to a change of two or three degrees of temperature; and, using the jacket and heater as just described, it is easy to maintain the internal cavity at a good red heat without any such variation of temperature for ten minutes or twenty minutes at a time, or longer if need be.

The air-thermometer used is shown separately in fig. 4, *c*. It is made from combustion tubing which remains perfectly hard and unyielding at a moderate red heat. The thermometer is formed from tubing, half-an-inch in internal diameter, by drawing off a portion *ab*, about $2\frac{1}{2}$ inches in length, and then drawing out the extremities so as to form capillary tubes *ad* and *bc*. One of these, *bc*, is for convenience bent up nearly close along the bulb of the thermometer. The other capillary tube is sufficiently long to pass through the asbestos stopper of the heating jacket, and to project down from it so far as to bring the bulb to the middle of the heating jacket.

The thermometer, as soon as it is drawn off, is attached, with both ends *c* and *d* open, to a water aspirator, and a current of air, purified and dried, is drawn through it. While the current of air is passing, the whole of the glass is raised to a good red heat two or three times by means of a powerful BUNSEN flame. In this way every trace of moisture and of condensed gas is driven off from the walls of the tube; and it appears probable from a recent investigation by BUNSEN,* and from experiments which I have myself made, that when the moisture has been thoroughly removed there is no considerable condensation of air at the surface of the glass of the kind frequently supposed to disturb the indications of the air-thermometer. It is during the last of the heatings just described that the capillary tube *bc* is turned up as shown in the figure. When the glass has thoroughly cooled, with the stream of pure dry air still flowing through it, a tap leading to the aspirator is closed, and the ends *c* and *d* are drawn out and sealed with the help of a portable blowpipe, care being taken to draw off small portions of the stems in such a way as not to allow any air from the blowpipe flame to enter the thermometer.

I may here, for convenience, describe the subsequent use of the thermometer. The bulb is passed into the coil of platinum wire whose temperature is to be determined, and the point *d* is passed through a hole in the asbestos stopper and secured there by a small brass wedge. A wrapping of thin asbestos paper is then secured with asbestos yarn round the platinum wire and thermometer bulb, and the whole is passed into the copper jacket as shown figs. 4A, 4B. A screen of thick asbestos mill-board prevents the gases from the heating flame from playing round the point of the thermometer. As soon as the heating has commenced the point *d* is opened with a sharp file: and when the temperature to be measured has been reached this point is closed up again by means of a portable blowpipe, care being taken, as before, to avoid the introduction into the thermometer of gases from the blowpipe flame. The barometric height at the time of sealing is also noted.

When the jacket and thermometer have cooled down, the latter is removed and weighed as follows. First the weight of the glass itself is taken, the air within being neglected. Next the point *c* of the thermometer is cut off under mercury or water, and the glass and its contents are weighed. Lastly, the point *d* is cut off; the glass is drawn quite full of mercury or water, and again weighed. The barometric height is noted at the time of opening the thermometer, and also the temperature of the mercury or water. The expansion of the glass envelope is approximately known; and, if water be used for filling the thermometer, the barometric height is corrected for the pressure of water-vapour. The temperature to which the thermometer was raised at sealing can be calculated from these data by well-known formulas.

When water is used for filling the thermometer the precautions pointed out by BUNSEN and others in connection with gas analysis for avoiding absorption of the air by the water are, of course, attended to; and I find water preferable to mercury for the purpose in hand, owing to the largeness of the error introduced by any slight inaccuracy as to equality of mercury levels inside and outside the vessel at the first opening of the thermometers.

Thermometers on the same principle as is described here were, I find, used by

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* 'WIEDEMANN, Annalen,' vol. 29, 1886, p. 161.

REGNAULT* in determining the boiling point of mercury. BUNSEN† has also used an air-thermometer which was closed with a stopper when the high temperature was reached. The quantity of air left in the thermometer at the high temperature was determined volumetrically instead of by weighing. The form of thermometer here described, with a capillary tube at each end, will, I think, be found an improvement in point of practical convenience.

Fig. 4, *a*, shows the electric connections used in determining the resistance of the platinum wire at various temperatures. The potential method has been chiefly employed, and has been found very convenient and satisfactory. For this purpose there are connected in series a single gravity DANIELL'S cell, a THOMSON rheostat, the platinum wire to be tested, and a standard coil of platinoid wire about double the resistance of the platinum wire. At low temperatures the difference of potentials between the two ends of the standard coil is half, or considerably less than, that between the ends of the platinum wire, and when the temperature has been raised to 500° C. or 600° C. this relation is reversed. The standard coil is silk-covered wire wound in a single layer on a brass can which is kept filled with cold water; and, being of platinoid, its variation of resistance for two or three degrees of temperature is quite unimportant. A potential galvanometer having a resistance of 5000 ohms, and with an interposed resistance of 10,000 ohms or more, was used for determining the differences of potential on the standard coil and on the platinum wire; and the rheostat enabled me to obtain convenient deflections of the potential galvanometer.

In recent experiments on this subject I have also used a WHEATSTONE'S bridge instead of the potential method; the four resistances of the bridge being two standard coils of platinoid, the platinum wire to be tested, and a calibrated rheostat. As the resistance of the platinum wire rises with temperature in one branch, increased resistance is thrown in in the rheostat branch so as to maintain the balance in the bridge.

I come now to give an account of the main results which have been obtained up to the present time.‡

Three modes of experimenting have been used.

1. A constant current was kept flowing through the wire, and the SPRENGEL pump was worked so as gradually to improve the vacuum. The resistance of the wire at different vacuums was determined, and thus the temperature which the given current would maintain in the wire at a measured vacuum was determined.

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* 'Paris, Acad. Mém.,' vol. 21, p. 230.

† 'WIEDEMANN, Annalen,' vol. 24, 1884.

‡ In doing this, I may perhaps be permitted to remark that, owing to the very limited amount of time at my disposal, these results have been obtained in the course of experiments scattered over long intervals of time. They have also been obtained with apparatus which I have incessantly altered wherever I could see a possibility of improving. Moreover, it was impossible to foresee the bearing of any one result in the long series of experiments, and few of them could even be calculated till long after they were obtained and recorded. I have, therefore, reason to be satisfied with their agreement among themselves.

This method has been but little used recently. It was convenient at first on account of the battery power at my disposal, and on account of the current galvanometer I was using. It also gave me useful preliminary information.

2. A second method, and that which I have mainly employed, is to take the wire at a definite air-pressure—a vacuum—and to maintain this with the help of the pump if need be:* then to apply a measured current, increasing step by step from the lowest to the highest attainable with the battery at my disposal, or at high vacuums safe to use with the wire, and, as before, to find the temperature of the wire. A complete series of currents having been taken at one vacuum, a higher exhaustion was produced and a new series taken, and so on. The curves appended represent this kind of experimenting.

3. Keeping the temperature of the wire constant (that is, its resistance constant), the SPRENGEL pump was gradually worked, and the current required to maintain the given temperature was measured. This method of experimenting has only become practicable to me recently. It requires a specially sensitive and readable current galvanometer. I propose to make considerable use of it in future, and meantime have employed it in the asymptotic experiment described below, p. 446.

The curves, Plate 25, show emission of heat in gramme-water-degree-Centigrade units, per square centimetre of surface of the heated wire at different temperatures. The temperature of the outer case was always within 1° of 15° C. Each curve shows the loss at the air-pressure marked on it. On the axis of abscissas the temperature is given in degrees Centigrade; while on the axis of ordinates, which shows emission, the scale unit is $\frac{1}{100}$ gramme-water-degree unit per square centimetre per second. The pressures range from 50 mm. to about 0·0000675 mm. (about 0·09 **M**, where **M** stands for a pressure equal to the one-millionth of the atmospheric pressure). I cannot, however, say whether the whole or any part of the most outlying curve on the right corresponds precisely to this pressure. It is here that the difficulty enters to which I have already referred, viz., the giving off of gas by the wire. When gas is being given off by the wire, however small the quantity, it becomes impossible to interpret the observations of the McLEOD gauge on account of the long time that is required for the pressure to equalise itself through the connecting tubes. For the same reason I have not been able to push the method of experimenting, in which a series of radiations at the same pressure but at different temperatures is determined, higher than about ·09 **M**.

In order, if possible, to get rid of this exhalation of air from the platinum wire—for such I take it to be—I have made many experiments in keeping the wire at a high temperature and under extreme vacuum for lengthened periods, but all to no purpose. Previous to the series of experiments represented by the most outlying two curves shown in Plate 25, the wire was kept for five days and nights with a current flowing through

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* This was necessary at high vacuums, when the wire became very hot, as will be explained further on, and required experience and caution.

it which maintained it at a good red heat; and each morning and evening the traces of gas that had come off were removed by working the pump. In spite of this, however, the supply was by no means exhausted, although an improvement had certainly been made, and in the course of ten minutes' heating of the wire the vacuum would become sensibly deteriorated. I was at first inclined to attribute these effects to some extremely minute leakage, such as one may get from electric perforation of a glass tube or from a *nearly* perfect sealing of a platinum wire or of a joint. The pump, however, and all the connections were absolutely faultless so long as the wire was maintained at lower temperatures, say below dull-red heat; but, on being raised perhaps to 700° C. or so, I might make a determination of the radiation, and, on making a second determination one or two minutes later, might find that a distinct cooling influence had set in. The rapidity with which the change supervenes proves at any rate that the minute quantity of gas is generated in the immediate proximity of the wire, and it is not till a considerable time later that the McLeod gauge begins to be affected.

On the other hand, with regard to pressures higher than about 50 mm., I was unable to obtain satisfactory series of results on account of the incessant disturbance of the temperature of the wire at high temperatures by the air-currents which its own temperature produces. Special experiments were, however, made at not very high temperatures (see p. 445) in order to bridge over to some extent the interval between normal air-pressures and the highest pressure to which these curves refer.

As the results of the experiments just described are shown on the curves, the actual points experimentally found being marked, it would serve no useful purpose for me to quote the long Tables of numbers from which the curves are plotted. It may, however, be of interest that I should put down a single specimen of a series observed and calculated. I therefore insert here an extract from my laboratory note-book of June 22, 1886, and show side by side with it the results obtained by calculation from the observations.

EXTRACT from Note-book, date June 22, 1886. (Pressure to be about $\frac{1}{40}$ mm.; actual pressure $\frac{1}{41}$ mm.)

Observed.						Calculated from observations.					
Hour.	Current galvanometer.	Slider.	Water-jacket.	McLEOD gauge.		(1) Current (absolute).	(2) Resistance of wire. Ohms.	(3) r/r_{15}.	(4) Temperature of wire.	(5) C^2R (absolute).	(6) C^2R/Js. Emission.
				P.	V.						
A.M. 11	Im.*	938·0	15·4°	9·6	35				°		
	1	889·5	Temperature rising to 16°.	..	..	·0174	2·590	1·068	40	$·7847\times10^{6}$	$27·99\times10^{-4}$
	2	742·5		9·6	35	·0348	3·118	1·284	118	3·773 ,,	134·6 ,,
	3	567·7		..	..	·0522	4·105	1·691	282	11·16 ,,	398·2 ,,
	4	472·0		9·8	35	·0696	4·952	2·041	430	24·52 ,,	874·6 ,,
	5	424·2		..	..	·0870	5·521	2·275	530	41·79 ,,	1490 ,,
	6	397·9		10	..	·1044	5·889	2·428	592	64·19 ,,	2290 ,,
	7	368·3		..	..	·1218	6·371	2·629	677	94·3 ,,	3362 ,,
	8	344·0		Pressu	re† low	·1392	6·826	2·817	752	105·2 ,,	3752 ,,
	9	325·0		10	10	·1566	7·231	2·980	820	177·2 ,,	6319 ,,

(1) Current calculated by knowing galvanometer constant, which was found by electrolysis. (p. 432.)
(2) Resistance of wire from observation of position of slider. (See p. 431 and fig. 1.)
(3) r/r_{15}, ratio of resistance of wire to its resistance at 15° C.
(4) Temperature found from (3). (See pp. 435, 436.)
(5) C^2R, electric energy (absolute).
(6) is (5) divided by J (JOULE's equivalent) and by s, the surface of the wire.

An examination of the emission curves shows very clearly the part taken by the air in carrying away heat from the wire; and, in the process of experimenting, the diminution in the amount of this phenomenon produced by diminution of pressure is very striking. It will be seen from the curves that but little diminution of carrying power is produced by reducing from 50 mm. to 5 mm., or even to $2\frac{1}{2}$ mm., and it is very remarkable (p. 445) how small is the effect produced by reducing from 760 mm. down to 50 mm. On reducing to 1 mm. or to $\frac{1}{2}$ mm., however, the effect produced by the smallest alterations of pressure is very striking; so much so that it would be easy to show it even as a popular or lecture-room experiment. Suppose a steady current flowing through the radiation wire, fig. 1, which is in a vacuum of $\frac{1}{4}$ mm.; and suppose that a balance has been obtained on the WHEATSTONE bridge, the testing galvanometer giving the zero or *nil* indication. Let the mercury of the SPRENGEL

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* Im., unmeasurably small. Taken at commencement of each series, partly to ascertain that electric connections are right.

† The pressure was increasing slightly; the pump was worked and pressure diminished too much. The gas coming from wire puts this to rights after a little time, or else a minute quantity of air is admitted from one of the air-traps. It has been impossible for me to describe all the minutiæ of working in this paper.

pump be started to flow. The dropping of the mercury is scarcely heard to commence before the balance is disturbed, and the index spot of the reflecting galvanometer is seen travelling along the scale in the direction which shows that the temperature of the wire has begun to rise.

The difference also as to speed of heating and cooling at common pressures and in high vacuums is often surprising during experimenting. At common pressures, from 760 mm. to 10 mm., the times which elapse on starting or stopping the current, before the wire assumes a permanent condition (that is, the times for heating and for cooling), are not strikingly different; but at very low pressures, $\frac{1}{1000}$ mm. or so, the heating on starting the current is seemingly instantaneous, while the cooling, when the current is stopped, of the fine platinum wire, weighing only a few grains, is so slow sometimes as to be almost a tedious process.

It has been pointed out by Mr. CROOKES, and it is not difficult to understand, how it is that a change of pressure between 760 mm. and 10 mm. has so small an influence on the carrying power of the air, while a slight change at a pressure of $\frac{1}{4}$ mm. or less has a great influence. In the first case, the number of molecules is great and the length of the free path small; and, although, on diminishing the density, the number of carrying molecules is reduced, yet at the lower pressure these molecules meet with correspondingly less obstruction in their movements, and have correspondingly greater facility for transferring the heat outwards which they receive from the wire. But at low pressures and in a small vessel the free paths of the molecules become comparable with the distance from the hot wire to the cool envelope, and molecules can move to and fro between the wire and the envelope, experiencing but few collisions and comparatively little obstruction from other molecules. In this case diminishing the number of molecules reduces their aggregate carrying power, but does not correspondingly increase the facility with which they can, as it were, carry their charges to the cold walls of the enclosure.

It is a matter of considerable interest to compare these experimental results with the well-known "Law" of STEFAN, in accordance with which the radiation from a given surface for any particular wave-length at different temperatures is supposed to be proportional to the fourth power of the absolute temperature; and the loss of energy, therefore, proportional to the difference between the fourth powers of the absolute temperatures of the cooling body and its surroundings. It was to test the exactness of this law that the experiments of SCHLEIERMACHER,[*] already referred to, were undertaken. To compare STEFAN'S Law with the results of my experiments (though it is to be remarked that the law as stated refers to pure radiation), I have calculated the values of $T^4 - T_0^4$ for a sufficient number of temperatures, taking $T_0 = 273 + 15$. Choosing then an experimental point on one of the curves traced with high vacuum, I laid down the curve $y = a\,(T^4 - T_0^4)$, making it pass through the point $y = 0$, $t = 15°$ C., and through the chosen experimental point. This curve is

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[*] 'WIEDEMANN, Annalen,' vol. 26, 1885, p. 287.

indicated on the diagram by the dots surrounded by dotted circles. It will be seen that, so far as they have gone, my experiments give no confirmation to this supposed law; and the results of Herr SCHLEIERMACHER lead to a precisely similar conclusion.

Comparing the results of SCHLEIERMACHER with my own, I find a satisfactory agreement between them. His results, except for what is termed, in connection with STEFAN'S Law, "the radiation constant,"* are not stated in absolute measure;† but the particulars given in his paper enable me to calculate the loss, in heat-units lost per square centimetre per second. SCHLEIERMACHER used in his experiments three wires—two of bright polished platinum, and one of platinum coated with black oxide of copper. These are called respectively Pt_1, Pt_2, and Pt_3.

The following Tables, and the corresponding curves, Plate 26, show the results of SCHLEIERMACHER reduced to absolute measure. The column headed t gives the temperature Centigrade of the radiation wire; that headed C^2R/Js is the loss of heat in gramme-water-degree units per square centimetre per second; while the column headed *Em* is the emissivity, and is found by dividing the absolute loss by the difference of temperatures of radiation wire and surroundings. The temperature of the water surrounding the envelope, which was of glass, was in each case quoted 0° C. Along with these results I give for comparison a similarly calculated set of results from one of my own series.

Pt_1, No. 1. (Enclosure at 0° C.)

t	C^2R/Js	*Em*
° 130	$28{\cdot}08 \times 10^{-4}$	$21{\cdot}6 \times 10^{-6}$
200	60·0 ,,	30·0 ,,
337	181·1 ,,	53·8 ,,
581	793 ,,	137 ,,
826	2600 ,,	315 ,,

Pt_2, No. 1. (Enclosure at 0° C.)

t	C^2R/Js	*Em*
° 65	$9{\cdot}45 \times 10^{-4}$	$14{\cdot}5 \times 10^{-6}$
110	20·53 ,,	18·7 ,,
232	74·7 ,,	32·2 ,,
383	236 ,,	61·6 ,,
740	1468 ,,	198 ,,
900	3218 ,,	358 ,,

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* The radiation constant is $C^2R/Js\,(T^4 - T_0{}^4)$.

† It is surprising to find the paucity of the experimental results as to emission of heat which are stated in absolute measure; so that, although we have many comparisons between surfaces of lampblack, black paper, white paper, oxidised metal, polished metal, &c., there is scarcely a trustworthy result to be

Pt_3. (Enclosure at 0° C.)

t	C^2R/Js	Em
°		
16	$9{\cdot}75 \times 10^{-4}$	$60{\cdot}9 \times 10^{-6}$
38	25·7 ,,	67·6 ,,
94	78·7 ,,	83·7 ,,
228	335·5 ,,	147 ,,
403	1182 ,,	293 ,,
585	3157 ,,	540 ,,

B_5, Wire experimented on by myself. (Enclosure at 15°.)

t	C^2R/Js	Em
°		
302	$186{\cdot}7 \times 10^{-4}$	$65{\cdot}05 \times 10^{-6}$
425	493·5 ,,	120·3 ,,
613	1689 ,,	282 ,,
744	3918 ,,	537 ,,
806	5163 ,,	653 ,,

From these Tables it will be seen that of the two polished platinums, Pt_1 and Pt_2, the latter has a somewhat greater emissivity; while in the case of the blackened platinum, Pt_3, the emissivity is very much greater, being at 585° C., the highest temperature to which the blackened platinum was carried in these experiments, about four times that of the polished platinums. The numbers which I have quoted from one of my own experiments for comparison give an emissivity for polished platinum, with the vacuum of July 1 and 2, 1886, much higher than that found by SCHLEIERMACHER. This may be due partly to difference in the polish of the surfaces, as I find that a very slight difference in this respect produces a very great effect. It may be, also, that the vacuum at which the determinations of SCHLEIERMACHER were made was of a higher order than mine of July 1 and 2, though I do not think this probable.* I think, however, it is most likely that the true explanation of the greater part, at least, of the difference lies in the fact that SCHLEIERMACHER surrounded the wire with a glass envelope. It is impossible to estimate with a non-diathermanous and badly conducting substance like glass how much heat may be returned to the wire from the polished walls of the tube; and it

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found, with the exception of those given by MACFARLANE, a few given by PICTET, and one or two by KUNDT and WARBURG, expressed in units of heat or units of energy emitted, under definite circumstances, per square centimetre per second.

* SCHLEIERMACHER used the BESSEL-HAGEN pump. My experience of this pump does not lead me to feel confidence in it as being capable of producing a very high vacuum. My reasons for this statement were given to the British Association, September, 1886, in a paper "On an Improved Mercury Pump."

was to avoid these uncertainties that I was led to abandon the far more manageable (for these experiments) glass envelope, and to take in its place a copper envelope blackened on the inside.

The next series of experiments which I desire to describe was undertaken for the purpose of tracing the rates of emission of heat at one fixed difference of temperatures between cooling body and surroundings, but at different pressures; commencing with ordinary atmospheric pressure, and passing to the highest vacuum I could command. The experiments, of which the results are given in the Tables, pp. 447, 448, were made with the apparatus of fig. 1. The slider was set at a particular point of the scale; and, by adjusting with the rheostat, the current was found which was required to maintain the temperature in the wire corresponding with the fixed position of the slider, while the pump was worked and the vacuum gradually produced. A complete series of readings was obtained from a common atmospheric pressure downwards for the temperature 408° C.; and a partial series for the temperature 505° C., commencing with the pressure ·094 mm. This kind of experimenting, as I have already remarked, only recently became possible, or at all events practicable. It requires a current galvanometer of great sensitiveness, and easily readable in a continuous way, qualities which have only now been supplied by the invention and perfecting of Sir W. THOMSON's current galvanometers. It is, however, an extremely convenient and satisfactory method.

An inspection of the Table shows the smallness of the falling away of the rate of loss of heat between full atmospheric pressure and pressures of 10 mm., 5 mm., or even 1 mm.; and the very rapid fall at pressures slightly lower than 1 mm. This has already been shown for temperatures below 100° C. by the experiments of KUNDT and WARBURG and of CROOKES, and is in accordance with the theory and experiments of MAXWELL, which show that heat conduction in gases is independent of the pressure so long as the density is such that the average length of free path of the molecules remains small in comparison with the dimensions of the containing vessel. The numbers given in my Tables are, as in all other cases throughout this paper, in absolute measure. The curve (see Plate 26) shows graphically the relation between pressure and energy lost at the temperature 408° C. The line of abscissas represents the pressure, while the ordinates represent the energy lost.

Carrying on the experiment as described above, I was able, as the vacuum gradually improved, to reach an interesting condition of matters in which further rarefaction of the space produced no further diminution of the rate of loss of energy from the wire. This was reached in the following way. The radiation wire was kept from the morning of March 28 till the morning of March 30 at a moderately high vacuum, and with the current incessantly flowing through it. During parts of March 28 and 29 experiments on radiation were being carried on, and during the evenings and nights of the 28th and 29th the current was raised so as to maintain the wire at a temperature very much higher than that at which I proposed to experiment. On

March 30, at 11 A.M., I commenced running the five-fall SPRENGEL pump continuously, making frequent observations on radiation and with the McLEOD gauge. Starting with a pressure of ·0071 mm. (= 10 M), the pressure was reduced in an hour and a half to 0·1 M, as indicated by the McLEOD gauge, though the actual pressure surrounding the wire may have been considerably different from this. As this point was reached the radiation of heat seemed to become steady, so that further working of the pump did not make any diminution in the amount of current required to maintain the fixed temperature of the wire. The pumping was continued for another half-hour, with a vacuum gradually improving, but with no change as to rate of loss of heat from the wire. I am therefore, I think, entitled to conclude that the limiting value of the radiation reached in this asymptotic experiment is the absolute radiation of the platinum wire for the difference of temperatures stated in a space freed from everything that the mercurial pump will remove, and that is not collapsible in the McLEOD gauge. There was no doubt vapour of mercury present, and possibly, seeing that it is so difficult to remove, some minute trace of vapour of water. There seems, however, very little doubt, from the concurrent testimony of recent experimenters, that the numbers commonly set down from REGNAULT'S observations as representing the pressure of mercury vapour at ordinary temperatures are very much in excess of the truth.

The numbers which I take, for the present at least, as representing the radiation from my particular polished platinum wire contained in a non-reflecting envelope of copper, at the temperatures 16° C. and 17° C. respectively, are as follow :—

At 408° C.	$378{\cdot}8 \times 10^{-4}$	gramme-water-degree Centigrade units per square centim. per sec.
At 505° C.	$726{\cdot}1 \times 10^{-4}$	,, ,, ,,

Two sets of experiments, made at an interval of a fortnight, gave me precisely the same number for the radiation at the lower temperature. That at the higher temperature I have only determined on one occasion. I hope, with experiments to be shortly undertaken, and with perhaps improved arrangements, to confirm or possibly modify these numbers, and to obtain radiations at other temperatures.

Asymptotic Experiments, March 22 to March 30, 1887. Slider placed at 500 of scale (see fig. 1). Barometric height, 740 mm. Temperature of wire, 408° C.

Temperature of water-jacket.	Pressure.	Current.	C²R/Js.	Total emission divided by lowest emission observed (378·8 × 10⁻⁴), which is taken as unity.
° C.	mm.	Amperes.		
16	740	2·1776	8137 × 10^{-4}	21·48
	560	2·1603	8004 ,,	21·13
	440	2·1560	7971 ,,	21·04
	340	2·1538	7956 ,,	21·00
	240	2·1517	7941 ,,	20·96
	140	2·1431	7875 ,,	20·79
	90	2·1345	7818 ,,	20·64
	64	2·1172	7686 ,,	20·29
	52	2·1129	7658 ,,	20·21
	49	2·1108	7643 ,,	20·18
	42	2·1042	7591 ,,	20·04
	34	2·0999	7563 ,,	19·96
17	24	2·0784	7408 ,,	19·56
	17·2	2·0558	7249 ,,	19·14
	13·2	2·0352	7104 ,,	18·75
	5·7	1·9880	6314 ,,	16·67
	4·0	1·8757	6036 ,,	15·93
	2·5	1·7291	5125 ,,	13·53
	1·7	1·5954	4364 ,,	11·52
	0·88	1·4264	3487 ,,	9·206
	·444	1·2505	2683 ,,	7·096
15	·141	·9357	1502 ,,	3·965
	·094	·8300	1181 ,,	3·118
	·070	·7805	1045 ,,	2·759
	·053	·7287	910·5 ,,	2·404
	·034	·6511	727·3 ,,	1·920
	·012	·5606	539·2 ,,	1·423
	·0071*	·5174	459·1 ,,	1·212
	·0051*	·5045	436·4 ,,	1·152
15	·00015*	·4786	392·7 ,,	1·037
16	·00007*	·4700	378·8† ,,	1·0

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* Pressures observed, but uncertain, owing to lagging of McLeod gauge.

† Further diminution of pressure by continued working of Sprengel pump made no diminution in the amount of radiation, which remained unaltered during more than an hour of working.

ASYMPTOTIC Experiments, March 25 to March 30, 1887. Slider at 450 of scale. Temperature of wire, 505° C.

Temperature of water-jacket.	Pressure.	Current.	C^2R/Js.	Total emission divided by lowest emission observed, ($726{\cdot}1 \times 10^{-4}$), taken as unity.
° C.		Amperes.		
17	·094	0·9400	1688×10^{-4}	2·324
	·053	·8106	1255 ,,	1·728
	·034	·7675	1126 ,,	1·551
	·019	·7201	990·3 ,,	1·363
	·013	·6942	920·4 ,,	1·267
	·011	·6899	909·0 ,,	1·242
	·0071	·6597	831·4 ,,	1·144
	·0046	·6468	798·7 ,,	1·100
	·00052	·6339	767·4 ,,	1·056
	·00019	·6252	746·4 ,,	1·028
	*	·6446	793·6 ,,	1·093
	*	·6338	767·0 ,,	1·056
	*	·6252	746·4 ,,	1·028
		·6230	741·3 ,,	1·021
	†	·6209	736·2 ,,	1·014
		·6187	731·1 ,,	1·007
		·6166	726·1 ,,	1·0

It only remains for me to give a brief account of experiments commenced on radiation from various surfaces in high vacuum. On this important subject I have, up to this time, been only able to touch very lightly by experiment; but I hope before long to be able to offer a communication on the subject. Figs. 5A, 5B, Plate 24, show an apparatus which I am using. A platinum wire, *ab*, is held, stretched between two spiral springs, in a glass tube. The outer ends of the spiral springs terminate in loops; and two pieces of glass rod, which are passed into tubes *cc*, *c′c′*, pass through the loops, so that the springs pull on these glass rods. After the rods have been passed into their places, the ends of the tubes *cc*, *c′c′*, are closed up, except one which is used for exhausting. Flexible copper electrodes are soldered to the loops, and are silver-soldered to stout multiple platinum terminals; and by means of these, which are fused with the help of some white enamel into the glass at *d*, *d*, the current is passed through the platinum wire. At *e*, *e*, *e*, platinum wires are brought through the sides of the tube and serve as potential electrodes; and it is to keep the platinum wire *ab* in the middle of the length of the tube, and to avoid pulling unduly on the potential electrodes, that the two spiral springs, one at either end of the tube, are employed.

The two halves of the platinum wire *ab* are differently treated as to surface; for example, I am at present experimenting on a wire, one half of which is brightly

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* Pressure not measured, but gradually diminishing.

† Pressure coming down; during 1½ hour radiation gradually fell to lowest figure given, and then remained unaltered.

polished, and the other half coated with lampblack. I have also tried a wire extremely thinly coated, or rather stained in appearance, with platinum black. The same measured current passes through both halves of the wire, or, when I desire it, I can vary the amounts in the two halves by means of the electrodes *e*, *e*, *e*. By means of these electrodes, also, the differences of potentials at the extremities of the two halves are taken; and thus the energy expended in each part can be found, and the temperature ascertained at the same time: and with the glass envelope I am at present using, the condition of the wire and the light given off by it, if any, can be observed.

With this apparatus, and using a platinum wire No. 22 S.W.G., 0·7 millim. in diameter, one half thinly coated with lampblack and the other half bright and polished, I find that, with a current passing through the wire which keeps the polished wire at a strong red heat approaching to whiteness, the blackened portion is scarcely rendered luminous. I find, also, that an alteration in the surface of the wire, which, so far as appearance goes is very slight indeed, may yet give a very marked alteration in the emissive power of the surface. The merest staining of the platinum wire, by washing it over with solution of ammonio-chloride of platinum and then heating with the current, is sufficient to keep the stained half non-luminous when the polished half is heated to redness.

In the 'Proceedings of the Royal Society,' No. 243, 1886, p. 207, Mr. Mortimer Evans, C.E., has given an account of some remarkable observations on the light-giving properties of polished and unpolished carbon filaments in incandescent lamps. With the help of Mr. Evans I have been enabled to repeat some of his experiments; and the result has been a complete verification of his conclusions. In repeating these experiments careful measurement was made of the vacuum used: a point which was left doubtful in the original investigation.

An Edison A-lamp was taken for the purpose of experimenting, being chosen on account of the remarkable dulness of the surface of the filaments used in the Edison lamps. The filament in these lamps has almost the appearance of a lampblacked surface. This lamp was opened and the filament re-mounted in a form more convenient for the purpose, being somewhat shortened in the process. The filament was then placed in a bulb which was exhausted with the Sprengel pump down to a point measured by the McLeod gauge; all the necessary precautions for making a good incandescent lamp being strictly attended to. The lamp was sealed off from the pump, and was tested against a suitable Swan lamp, which was kept at moderate incandescence, as it is not desirable to incandesce Edison filaments very highly. The lamps were regulated, with resistances and a rheostat, in such a way that the brightnesses of the two filaments matched and the energy (current and potential) required in each lamp was determined. The Swan lamp using a definite amount of energy was taken as the standard to which return was to be made in subsequent trials. The candle-power of each lamp was also observed.

The Edison lamp was now opened, and, the filament having been removed, it was re-"flashed" in such a way as to give it a beautiful polished metallic-looking surface. It was then placed in a fresh globe, and was exhausted down to the same point as before and sealed off from the pump; and the new lamp was re-tested against the Swan lamp and standard candle. The result of these experiments was as follows:—

Incandescent Lamp at same candle-power in two cases.

	(1.) Original Edison filament—dull lustreless surface.	(2.) Same filament re-"flashed," to have brilliant surface.
Potential (volts). . . .	77·7	58·5
Current (amperes) . . .	0·745	0·680
Watts	57·9	39·8

It thus appears that to maintain the same carbon in these two conditions, at the same candle-power, there is required 30 per cent. less energy in the second case than in the first.

On this important subject, of the influence on radiation of the nature of the surface, I hope at an early date to make a more complete investigation: and I propose, also, as soon as may be, to repeat and extend the observations of Macfarlane, to which I have already more than once referred. The increase in the rate of loss of heat due to diminution of the radiating surface demands further examination.

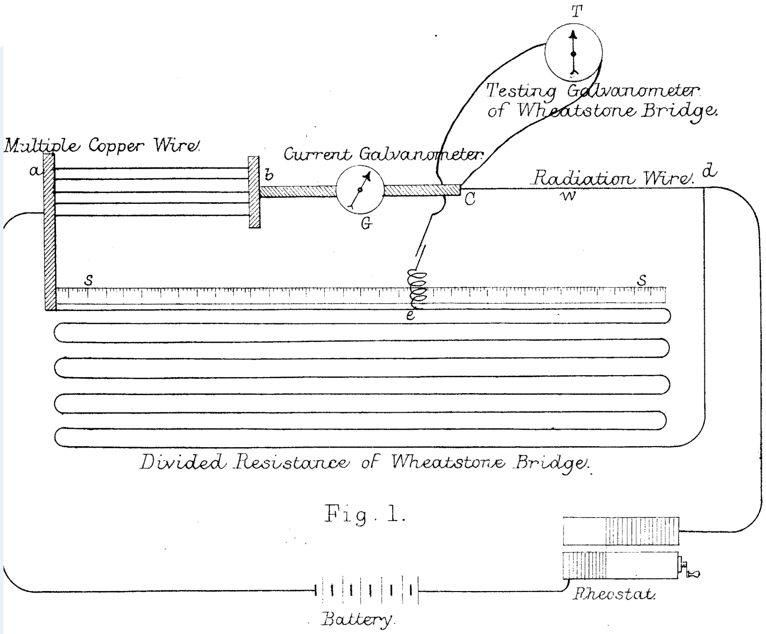


Fig. 1.

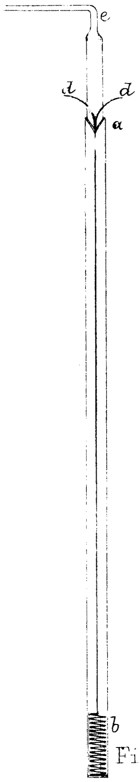


Fig. 2a.

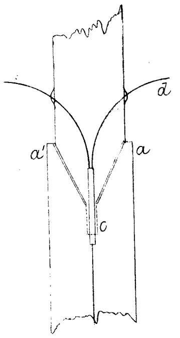


Fig. 2b.

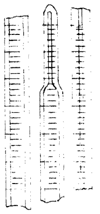


Fig. 3b.

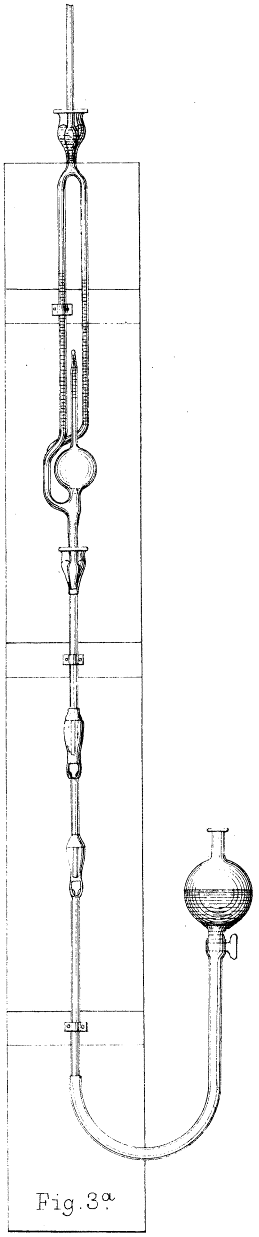


Fig. 3a.

McLeod Gauge.

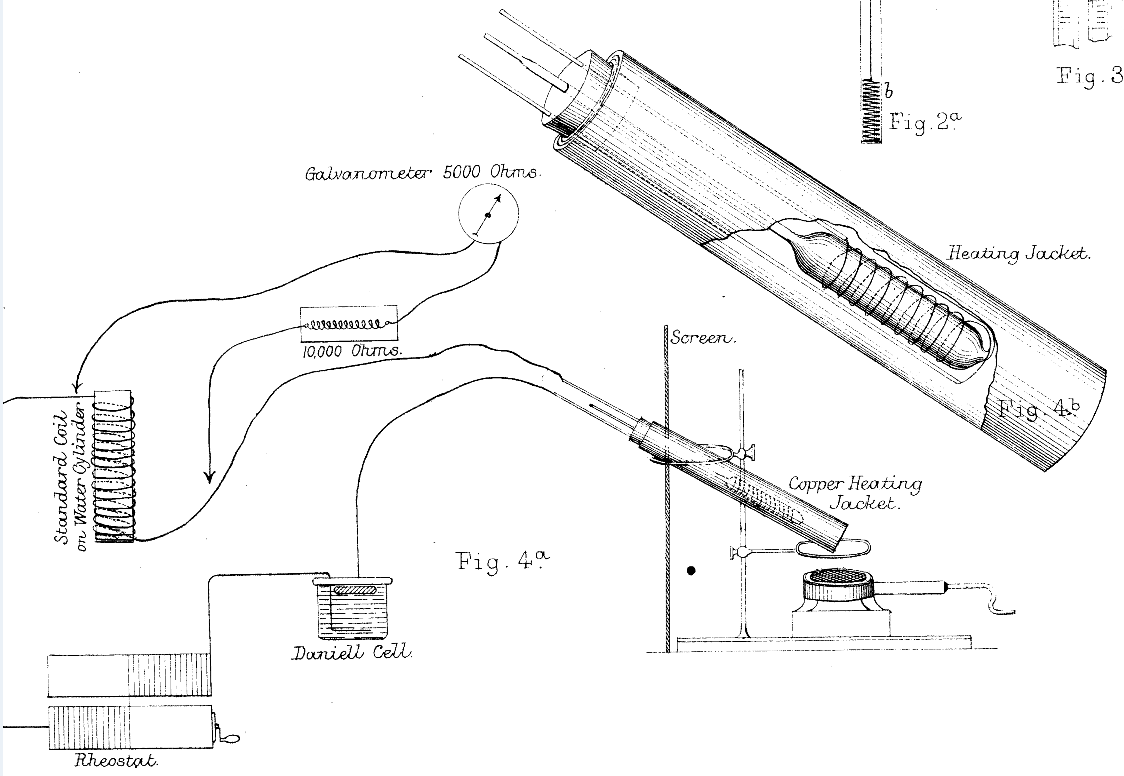


Fig. 4b.

Fig. 4a.

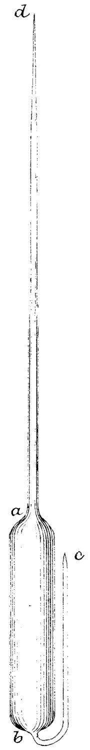


Fig. 4c.

Air Thermometer.

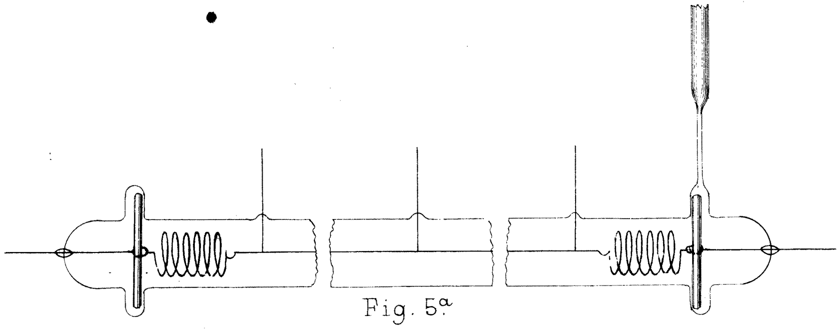


Fig. 5a.

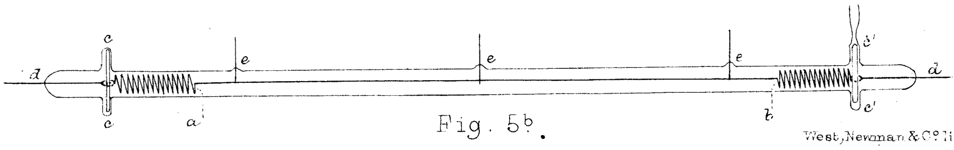
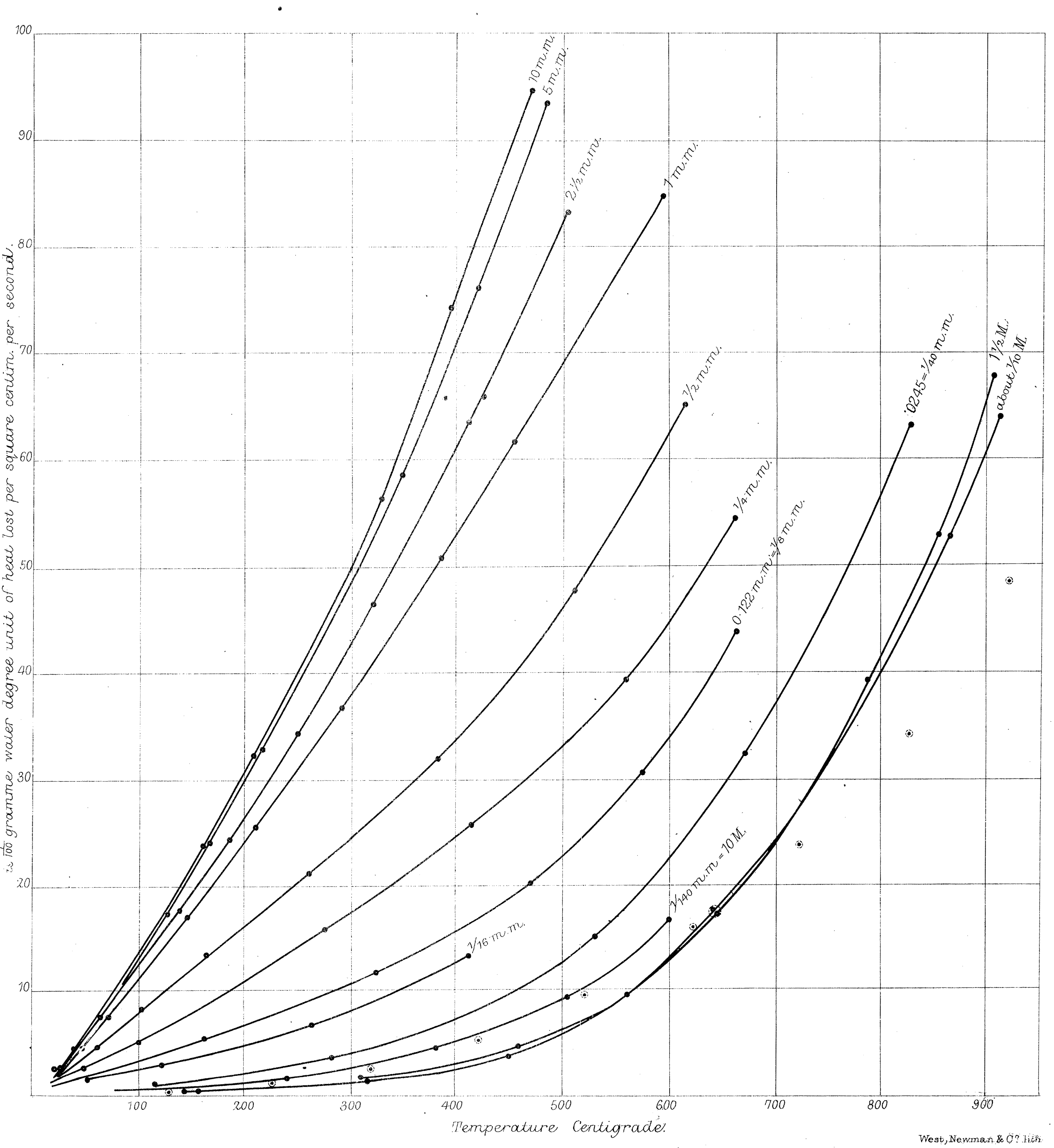


Fig. 5b.

West, Newman & Co. lith.

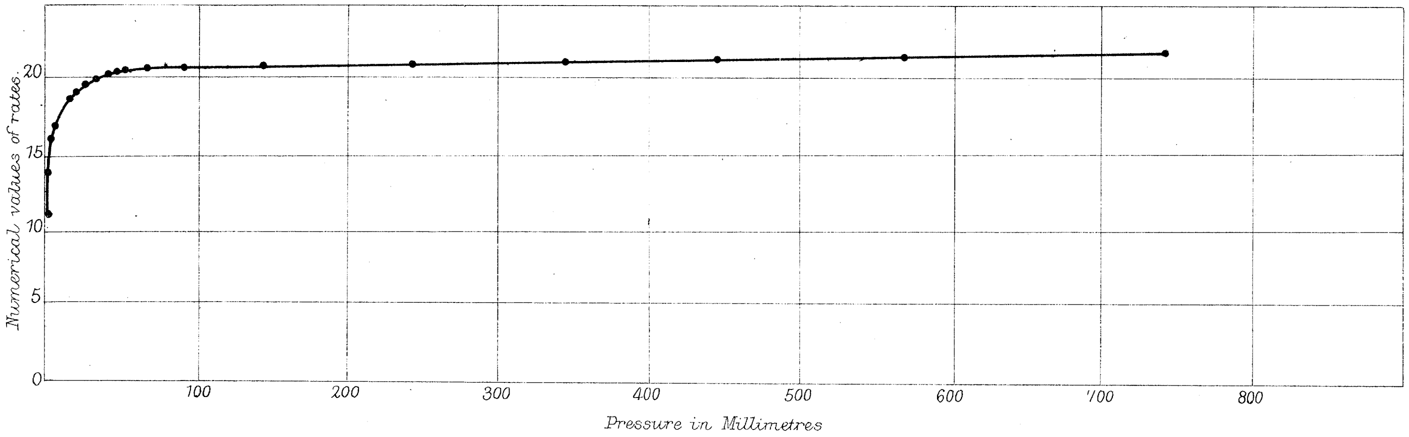
Diagram showing emission of heat at various pressures & temperatures. The Curves are drawn for the various pressures which are marked at their extremities.

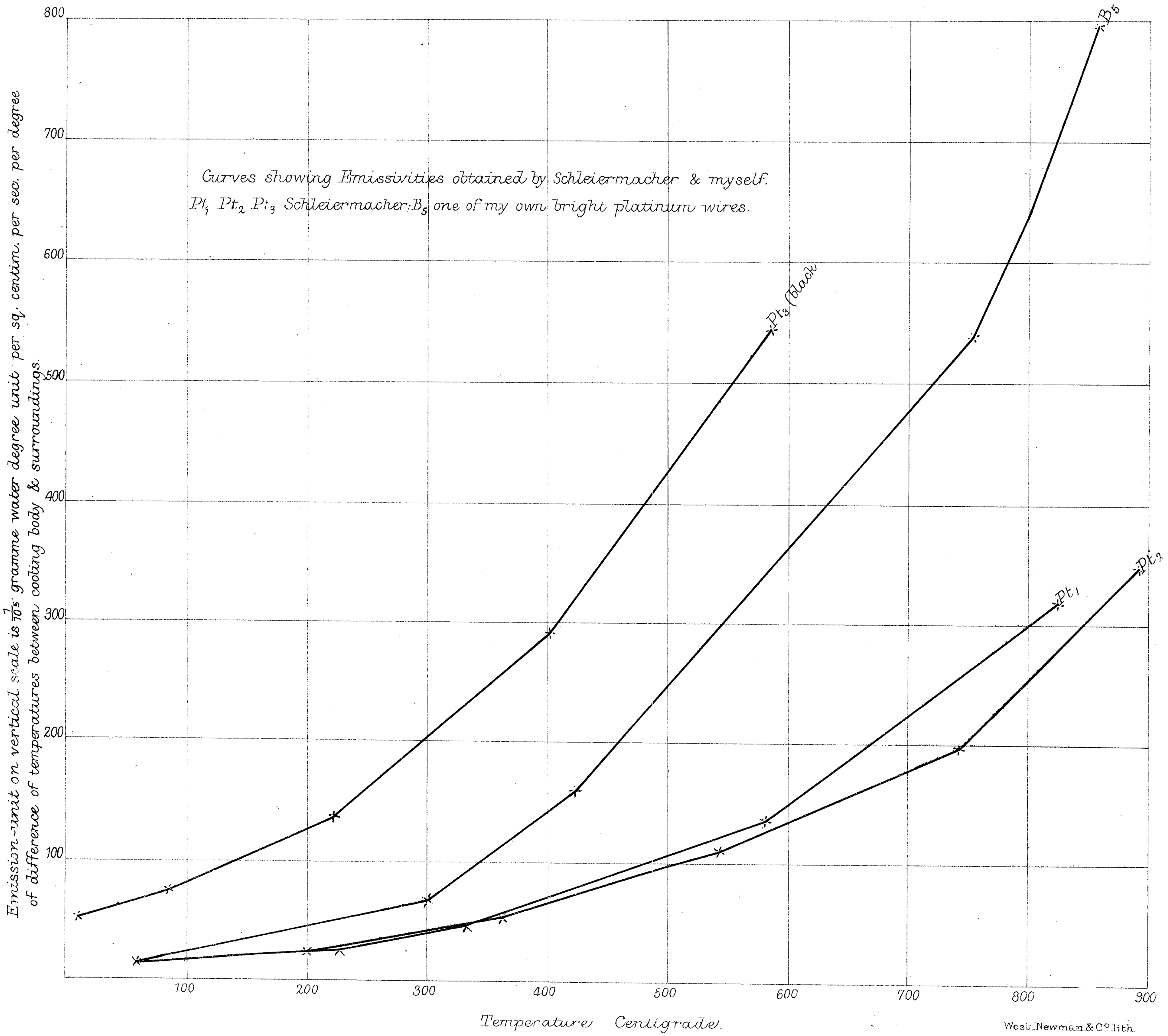
The points surrounded by dotted circles, are points on the Curve $y = a(T'^4 - T_0^4)$ (Stefan's law); a being chosen to make y = o for T = T' = 273 + 15 & to make y correspond with a second well established experimental point on my emission curves at high vacuum.



West, Newman & Co. lith.

Curve showing for Temperature 408°C. the ratio between the rate of loss of heat with air present at various pressures & the rate of loss at the highest vacuum procurable with the Sprengel Pump the rate of loss at highest vacuum being taken as unity.




Curves showing Emissivities obtained by Schleiermacher & myself. Pt_1 Pt_2 Pt_3 Schleiermacher: B_5 one of my own bright platinum wires.

West, Newman & Co lith.