EXPERIMENTAL DETERMINATIONS OF THE TEMPERATURE IN GEISSLER TUBES.

By R. W. Wood.

§ 1. The opinion that the temperature of the gas in the positive part of the discharge in Geissler tubes lay far below the red heat was first expressed by E. Wiedemann,[1] and Hittorf[2] was led to the same conclusion from simple experiments. The theoretical calculations of the temperature in the unstratified anode light by Warburg[3] yielded similar results. Hittorf[4] showed, further, that the temperature in the negative light lay at least below the melting point of platinum, for at this temperature the luminosity of the gas disappeared entirely.

Calorimetric observations have been made by Paalzow and Neesen[5] and others, which give some idea of the total heat production, but as far as I know no accurate measurements have been made of the temperature of the gas in different parts of the discharge. It is clear that such measurements must be made in the discharge of a constant battery, and not in the intermittent discharge of an induction coil.

The prime object of this investigation has been to obtain the relative temperatures in different parts of the discharge, with especial reference to the stratifications. Owing to the narrow space limits between which it was necessary to work in the stratified discharge, a bolometer, consisting of a loop or spiral of very fine platino-iridium wire, appeared to be the most suitable measuring instrument.

§ 2. The constant current for producing the discharge in the vacuum tube was furnished by a high potential accumulator bat-

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[1] E. Wiedemann, Wied. Annalen, 6, p. 298, 1879.

[2] W. Hittorf, Wied. Annalen, 7, p. 577, 1879.

[3] E. Warburg, Wied. Annalen, 54, p. 265, 1895.

[4] W. Hittorf, Wied. Annalen, 21, p. 123, 1884.

[5] H. Paalzow and F. Neesen, Wied. Annalen, 56, p. 276, 1895.

tery of 600 cells, the electromotive force being about 1250 volts. A Hittorf resistance tube, with a movable electrode filled with a solution of cadmium iodide for regulating the current strength, and a Siemens & Halske direct-reading torsion galvanometer for measuring the current, were introduced into the circuit.

§ 3. Before commencing work with the bolometer, a preliminary investigation was made on the rise of pressure within the tube due to the discharge, and from this pressure increment the corresponding temperature increment was calculated. Hittorf speaks of using one of his tubes as an air thermometer, and of the very slight expansion of the gas due to the heating, but he gives no numerical results. The change of pressure being too slight to be accurately measured by means of a mercurial manometer, sulphuric acid was used in place of the heavier fluid. The apparatus is shown in Fig. 1, and consists of a small glass flask *A*, into the neck of which is fused a vertical tube, which passes to the bottom and communicates above with the discharge tube *B*. The flask contains a little sulphuric acid, and the space above the liquid is also in communication with the discharge tube through the lateral tube, which is furnished with a stopcock. By this arrangement the pressure above the liquid can be made just sufficient to support a short column of acid in the vertical tube, the cock being opened during the process of exhaustion and closed a few minutes before the requisite vacuum is reached, the further exhaustion causing a rise of the fluid. On closing the cock between the tube and the pump, and turning on the current, a fall of the column is immediately noticed, and by measuring this the increase of pressure and consequently of temperature can be determined from the formula

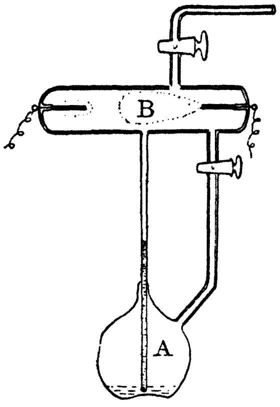

Fig. 1.

$$t - t_0 = \frac{p - p_0}{p_0}(272.5 + t_0).$$

The temperature at the start was 20° and the pressure 2 mm. The passage of a current of 0.001 ampere caused a depression of

1 mm. in the H_2SO_4 barometer, corresponding to 0.135 mm. of mercury. By the formula we find that the rise in temperature, or $t - t_0$,

$$= \frac{0.135}{2}(272.5 + 20) = 19.7.$$

The change of volume in the two vessels due to the sinking of the column is vanishingly small in comparison to their volumes, and can be neglected. This method, of course, shows only the average temperature rise, and the result cannot be strictly compared with any of those found with the bolometer, which gives local temperatures.

§ 4. Warburg has shown by his calculations that in a gas at low pressure, heated by the discharge, a stationary temperature is established within a fraction of a second, so rapid is the conduction of heat. In other words, a gas is heated to its maximum, or cools to its original temperature within a small fraction of a second, on the commencement or cessation of the discharge. With an interrupted current, providing the interruptions are not too rapid, we should then expect the temperature to rise and fall exactly in time with the interrupter. Corresponding to this rise and fall of temperature there should be a rise and fall of pressure, and this I find to be the case.

The inertia of the column of acid in the apparatus last described (Fig. 1) is too great to allow the fluid to respond to these rapid changes of pressure, but I find that with the device shown in Fig. 2 they can be shown very well. This consists of a discharge tube with a rectangular U manometer, in which are two drops of sulphuric acid. The tube is connected with the pump by means of a short piece of rubber hose, and during the process of exhaustion the acid is collected into a single drop. When the desired vacuum has been reached, the drop can be separated into two by carefully tipping the tube back and forth, forming a bubble between, in which the gas is at the same pressure as that in the discharge tube. On connecting the electrodes with a Ruhmkorff coil in action, the

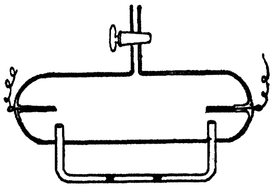

Fig. 2.

drops, which are about 3 cm. apart, alternately approach and recede, vibrating exactly in unison with the interrupter. The pressure at which this is shown to the best advantage is about 5 mm. When it is too low, the amplitude of the vibrations is too small to be observed.

§ 5. Of the measurements made with the bolometer I shall first take up those which show the relation of the rise in temperature to the current strength. In this investigation the bolometer wire was fixed in position, while in experiments to be described further on it was so arranged that it could be moved up and down within the discharge tube.

The arrangement of the apparatus is shown in Fig. 3.

In the axis of the discharge tube is mounted a spiral of very fine platino-iridium wire. The length of the wire was 2 cm., its diameter 0.035 mm., and the distance between the ends of the large wires which supported the spiral was 0.5 cm. The internal diameter of the tube was 1.5 cm., being the same as used by A. Herz in his research on the fall of potential in the anode light, which will be alluded to later, and on which Warburg based his calculations. The high potential battery *A*, the resistance tube *B*, and the

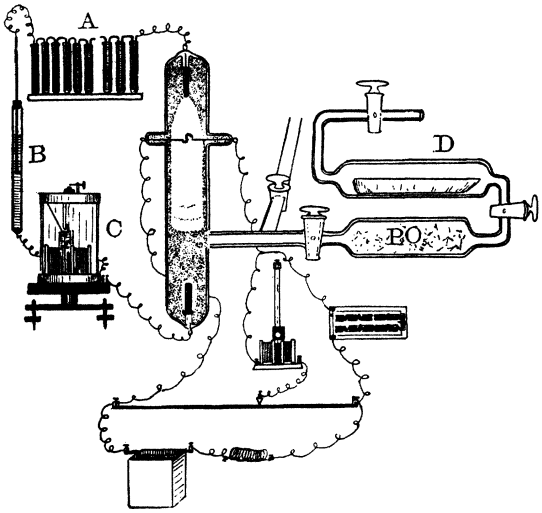

Fig. 3.

torsion galvanometer *C*, I have already alluded to. The bolometer was connected with a mirror galvanometer, resistance box, and Wheatstone bridge in the usual manner, as shown in the diagram, the current being furnished by a single accumulator, with a 20-ohm resistance coil in the circuit.

§ 6. Nitrogen made by passing air over heated phosphorus contained in a porcelain boat in the tube *D*, and then dried by means of phosphoric acid, was used in most of the experiments, the current in air not being steady enough to admit of accurate measurements being made.

§ 7. The apparatus was so arranged that within the temperature limits that were observed, the rise in temperature was proportional to the deflections of the galvanometer, as observed with a scale and telescope. The temperature increment corresponding to a deflection of one scale division was found by immersing the bolometer wire in warm oil with a normal thermometer reading to tenths of a degree, and allowing the oil to slowly cool. One degree was found to correspond to 4 mm. scale deflection.

§ 8. It is of course a question how nearly the wire takes the temperature of the gas. On account of radiation and conduction it must lag behind the gas, and to give absolutely correct values should be of infinite thinness. Some idea of the size of the error can be formed by working with wires of different thickness. The one used was 0.035 mm. in diameter, and since finer wire is hard to procure and difficult to manage, platinum leaf less than 0.001 mm. in thickness was used, which was furnished rolled together with silver. A strip 1 mm. wide and 1.5 cm. long was mounted in the tube in place of the spiral, the silver backing giving the necessary rigidity. The soldered joints were protected with asphalt varnish, and the silver removed with dilute nitric acid. Owing to the extreme tenuity of the remaining strip, great care was necessary in washing and drying out the tube. The resistance of the strip was found to be 2.8 ohms, which is almost identical with the value calculated for a strip of its size having a thickness of 0.001 mm. The tube was exhausted to a vacuum of 2 mm. and a current of 0.0012 ampere sent through it, the strip of platinum leaf being in the anode light. The scale deflection was 40 cm., about ten times as large as with the wire. This was due principally to the larger temperature coefficient of the strip, which was of pure platinum, while the wire was an alloy of platinum and iridium. The strip was now immersed in oil at 25°, and the temperature was raised until a galvanometer deflection of 40 cm. scale was produced, the temperature of the oil being found to be 43°, showing a rise of 18°. The temperature rise of the gas in the anode light, under similar conditions, as measured with the wire, was 19°, as will be seen by reference to Table IV. The platinum foil took the temperature of the gas more rapidly than the wire, and would consequently have been better adapted to the experiments, were it not for the influence that the wide strip had on the uniformity of the discharge. With the fine wire this deforming action was noticeable to a certain degree, especially in working with stratified discharges with the movable bolometer, the strata appearing as though elastic, and only yielding to the wire after slight deformation. This effect will be alluded to subsequently. The similarity of results obtained with the wire and the foil justify the assumption that the wire takes the temperature of the gas nearly enough for our purpose.

§ 9. It is also necessary to make sure that the discharge within the tube can only affect the galvanometer by changing the resistance of the wire. The current was shut off from the bolometer circuit and a discharge passed through the tube, which caused no deflection, showing the absence of thermo-currents, or currents switched from the high potential discharge.

§ 10. The first sets of measurements were made in the unstratified anode light, at different pressures and with varying current strength. The cock communicating with the air pump was left open, to eliminate as much as possible the rise of pressure due to the warming of the gas. The values are given in the following tables: i being the current strength, w the temperature rise, and $\frac{w}{i}$ the ratio between these values. To avoid complicating the tables I have omitted the galvanometer deflections and given the corresponding temperatures.

TABLE I.

PRESSURE, 0.3 mm.

i	w	$\frac{w}{i}$	i	w	$\frac{w}{i}$
0.0015	13°.0	87	0.0022	18°.0	82
0.0017	15°.0	88	0.0025	19°.5	78
0.0018	15°.7	87	0.0032	22°.5	73
0.0021	17°.7	84	0.0036	25°.7	71

TABLE II.

PRESSURE, 1.8 mm.

i	w	$\frac{w}{i}$	i	w	$\frac{w}{i}$
0.0007	11°.5	164	0.0019	26°.2	138
0.0009	14°.0	155	0.0025	34°.0	136
0.0012	17°.0	142	0.0032	42°.2	132
0.0015	21°.7	145			

TABLE III.

PRESSURE, 2 mm.

i	w	w calculated by Warburg.	$\frac{w}{i}$
0.0012	19°.0	22°.0	158
0.0020	30°.0	—	150
0.0032	45°.0	40°.6	143

TABLE IV.

PRESSURE, 3 mm.

i	w	w calculated.	$\frac{w}{i}$	i	w	w calculated.	$\frac{w}{i}$
0.0010	23°.0		230	0.0022	44°.0		200
0.0012	27°.0	30°.0 Warburg	225	0.0025	49°.7		198
0.0015	31°.0		207	0.0027	50°.7		187
0.0018	37°.0		205	0.0032	59°.5	62.7 Warburg	186
0.0020	40°.0		200	0.0046	73°.0		160

It will be seen from the values w, which show the rise in degrees above the room temperature, 25°, that the views held by Wiedemann and Hittorf regarding the comparatively low temperature in the Geissler tube are corroborated. The theoretical calculations by Warburg, to which I have previously alluded, which are based on the supposition that the electrical energy consumed in a portion of the tube, and represented by the product of the current strength and the potential fall, is practically all transformed into heat, give results which agree well with the values which I have found. These calculated temperatures for the axis of the anode light are given with the observed ones in Tables III. and IV.

The bolometer wire, not coinciding with the axis of the discharge, but occupying a space 0.5 cm. wide, gives the average temperature in this space, which is found by calculation to be about $\frac{17}{18}$ of the value in the axis.

The ratio $\frac{w}{i}$ is, according to the theory of Warburg, proportional to the potential gradient. The decrease in the values, with increasing current strength, is most probably due to the fact that, the gas being at constant pressure, its density, and therefore the gradient, diminish with rising temperature. The stop-cock leading to the pump was next closed, thus keeping the gas in the tube at a constant volume and density. In this case it was found that $\frac{w}{i}$ was nearly a constant, as shown in the following tables. According to the work of Herz on potential fall, we should expect $\frac{w}{i}$ to decrease in this case also, but this did not seem to be the case.

TABLE V.

PRESSURE, 0.3 mm.

i	w	$\frac{w}{i}$	i	w	$\frac{w}{i}$
0.0015	13°.0	87	0.0026	21°.9	84
0.0017	15°.2	89	0.0029	24°.2	83
0.0020	17°.4	87	0.0034	28°.5	84

TABLE VI.

PRESSURE, 1 mm.

i	w	$\frac{w}{i}$	i	w	$\frac{w}{i}$
0.0015	19°.0	126	0.0028	34°.0	121
0.0018	21°.0	117	0.0039	48°.0	123
0.0022	26°.0	118			

§ 11. By reversing the direction of the current the bolometer was brought into the dark space which separates the positive and negative light, and a set of values obtained in this portion of the discharge with currents of varying strength. The temperature here was found to be much lower than in the anode light, and the quotient $\frac{w}{i}$ was nearly constant, indicating that in this case the potential fall was independent of the current strength. Table VII. gives the values found in the dark space.

TABLE VII.

PRESSURE, 2 mm.

i	w	$\frac{w}{i}$	i	w	$\frac{w}{i}$
0.0009	08°.7	97	0.0038	35°.7	94
0.0010	10°.2	93	0.0040	37°.5	94
0.0012	11°.5	96	0.0048	45°.0	93
0.0021	19°.5	93			

§ 12. The measurements described thus far have been for a fixed part of the discharge. The complete investigation of the temperature fluctuations in passing along the tube from anode to cathode was next undertaken.

The chief difficulty lay in devising a method of easily and rapidly moving the bolometer back and forth in the discharge without impairing the vacuum. The apparatus is shown in Fig. 4. A vertical tube A, 1 cm. in diameter and 80 cm. long (shortened in diagram), carries on its upper end the discharge tube with its laterally placed electrodes. Through *A* passes a small tube *C*, bent in a U at the bottom and carrying on its upper end the loop *D* of platino-iridium wire which serves as the bolometer wire. Within *C* are the two insulated copper conducting wires, terminating in platinum points which are fused through the glass, and to which are soldered the terminals of the bolometer loop, which is bent into a horizontal plane by manipulation through the side tube *E*, subsequently joined to the pump.

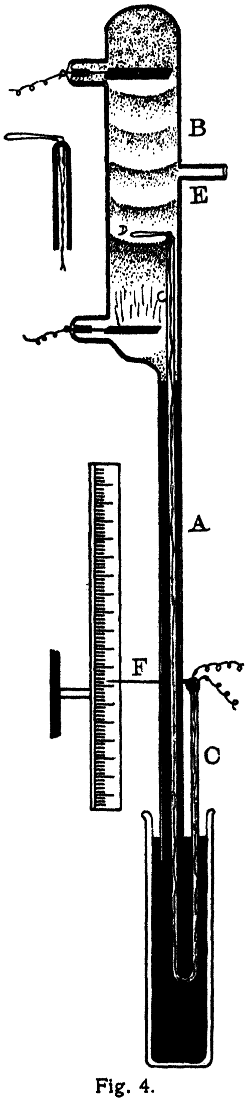

Fig. 4.

An enlarged view of the upper end of the tube carrying the bolometer is shown to the left of the discharge tube. The lower end of *A* is now introduced into a deep jar of mercury, and on exhausting the apparatus the fluid rises, forming a barometer column, through which the smaller tube, carrying the bolometer on its end, slides up and down. The arm of the U which projects from the mercury jar carries a pointer *F*, which moves along a millimeter scale and indicates the exact position of the wire loop in the discharge. All the connections were carefully soldered, otherwise changes of resistance occurred when the bolometer tube was moved. With this device it was possible to explore the entire tube from the cathode to the anode and make a complete map of the temperature changes.

§ 13. In the unstratified anode light the temperature was sometimes constant for the greater part of the column, and sometimes rose to a maximum near the middle, falling away again as the dark space was approached. This maximum was always found when the light was on the point of stratifying, and sometimes at higher pressures. The exact conditions that determined whether the temperature had a maximum in the middle of the column or was constant for the greater part, could not be determined, but the extent of the anode light appeared to have something to do with it. Under exactly the same conditions of pressure and current strength, so far as can be determined, the light will sometimes extend much further down the tube than at others, and I could find no way of remedying this trouble, which has been observed by other experimenters.

There was always a decrease of temperature on nearing the dark space. On leaving the anode light, the temperature drops very suddenly, reaching a minimum near the middle of the dark space, and then rises again very rapidly on entering the blue negative light. The results obtained with the movable bolometer are clearer when shown by curves than when expressed in tabular form. The condition where a maximum exists in the anode light is shown in Fig. 5, the abscissæ being distances from the anode, as shown by the pointer on the scale, and the ordinates temperatures as calculated from the galvanometer deflections. The room temperature (26°) is shown by the horizontal line, and the character of the discharge and its position on the scale indicated by the drawing beneath. The pressure was about 1.5 mm. and the current strength 0.001 ampere. A series showing constant temperature in the anode light is shown in the upper curve in Fig. 6, the position of the boundary between the positive light and the dark space being indicated.

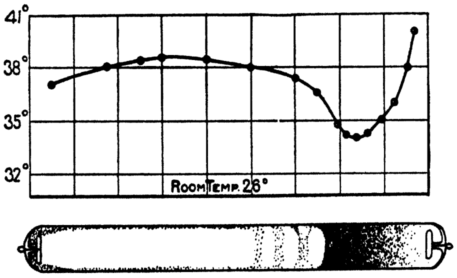

Fig. 5.

§ 14. When the pressure in the tube is sufficiently reduced to cause the appearance of stratifications in the anode light, a maximum in the middle of the column is always to be found, the temperature rising as we recede from the anode, and falling again after the middle of the column is passed. In addition to this there is a periodic rise and fall, the light disks being warmer than the dark spaces between them, although one often finds a point where there is no change of temperature on passing from a light space to a dark. The cause of this is at once apparent when the results are plotted on coördinate paper, the decrease due to the passage from light to dark being compensated by the increase due to approach to the maximum point (Fig. 7).

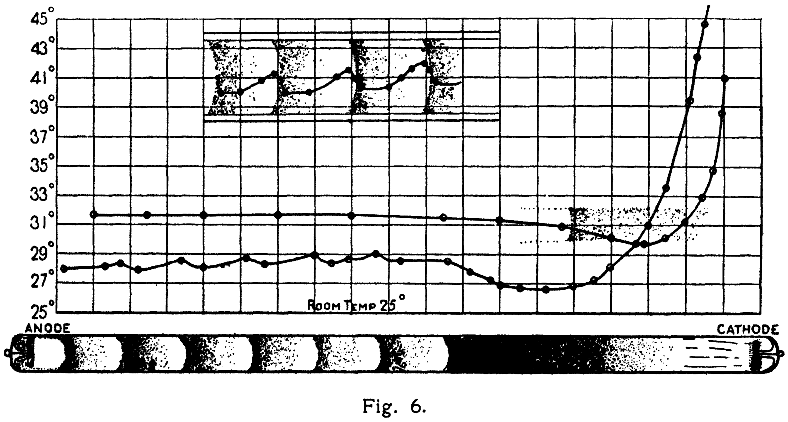

Fig. 6.

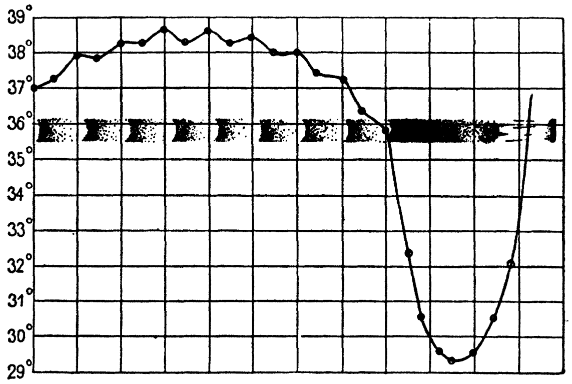

Fig. 7.

Lehmann[1] came to the conclusion that in the stratified discharge the temperature of the light spaces was higher than that of the dark. By mixing oil vapor with the gas, he observed that the car-

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[1] O. Lehmann, Zeitschrift für Electrochemie, 21 and 22, 1896.

bon particles set free glowed in the light spaces, but were invisible in the dark. If this luminosity of the carbon was true incandescence caused by the high temperature of the gas, the conditions of current strength and pressure must have been very different from any that I have investigated, since in no case have I found the temperature to be over 100°.

The curve showing the temperature fluctuations in the stratified discharge at low pressure (0.1 mm.) is shown in Fig. 6 (lower curve), the straight line showing the room temperature, and the drawing beneath indicating the character and position of the discharge with reference to the curve. The maximum in the anode light is not as marked as it is at higher pressure, owing to the smaller changes of temperature. In Fig. 7, which is for a pressure of 0.5 mm., it is very evident, as is the existence of two spots, one on each side of the maximum, where there is no change on going from a light to a dark space.

A careful set of observations was made of the periodic change in the stratified anode light, five points being taken for each cylinder of light.

The results are shown for three consecutive disks in Fig. 6 in the small drawing above the curves. The conditions are the same as in the tube represented below, only the ordinates are taken on a larger scale, and more points are taken.

The temperature is steady for a certain distance, then rises gradually to a maximum, situated in the brightest part of the disk, turns and drops suddenly as we pass out of the sharply defined edge of the disk. The difference in temperature between the

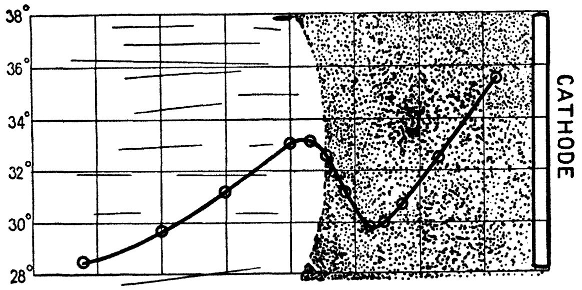

Fig. 8.

light and dark spaces varies from 0°.5 to about 1°.5, depending on the degree of exhaustion and current strength.

§ 15. Assuming that the electrical energy is wholly converted into heat, these temperature curves *should* resemble closely the curves representing the potential fall in different parts of the discharge. At the present time no very accurate maps have been made of the potential fall between the anode and cathode. What is already known agrees with the results found in this investigation, which may be expressed thus:

Positive light	Medium potential fall	Medium temperature.
Dark space	Small potential fall	Low temperature.
Negative light	Large potential fall	High temperature.

§ 16. It may not be out of place to mention here one or two phenomena that were observed in working with stratified discharges, though they have no direct bearing on the subject. Though in general the bolometer wire passes through the strata cleanly without moving them or altering their position, at certain pressures I find that the wire drags the stratum through which it is passing (moving from + to − electrode) into the one immediately below it, the two dissolving into one. At this moment, however, a new stratum springs off the anode, so that as we work down the tube dragging each stratum in succession into its neighbor, the total number remains always the same.

Another effect to which I have alluded before, is the apparent resistance which the sharply defined edges of the strata offer to the penetration of the wire. The edge acts as if it had an elastic skin, or a sort of surface tension, bending in as the wire pushes against it, and finally snapping back to its original position, leaving the wire well within the luminous disk. Too little is known about the strata to make any discussion of these two facts worth while, and I merely record them without comment.

§ 17. A few experiments were made with hydrogen, but owing to the difficulty of maintaining a steady current in this gas, they were not carried very far. The fact was established, however, that under similar conditions of pressure and current strength the heating was only about 11 per cent of that found in the case of nitrogen, this being due to the fact that the potential fall is less, and also to the fact that hydrogen is a much better conductor of heat than nitrogen. With hydrogen at 1.8 mm. pressure, with a current of 0.0015 ampere, a rise of temperature of only 2°.5 was observed. Referring to Table II., the rise obtained for nitrogen under similar conditions was 21°.7, about nine times as great. Warburg calculated the temperature rise for hydrogen at 5 mm. with a current strength of 0.001 to be 4°.1, and for nitrogen under nearly similar conditions 41°.3, or ten times as great.

§ 18. While working with hydrogen at very low pressures, I found evidence of a fall of temperature on passing from the negative light into the Crookes dark space, and have found mention made of this by Wiedemann,[1] who worked with a thermo-element applied to the outside of the tube. It is only to be found when the length of the dark space is considerable; at higher pressures, if it exists at all, it is completely masked by the very rapid rise in temperature on approaching the cathode. This was also noticed by Wiedemann. This same temperature minimum was found in nitrogen by subsequent trials.

It is not always to be found, however, even with hydrogen. One tube with comparatively small rectangular electrodes, showed it very distinctly (Fig. 8), while another, with large aluminium plates, gave no indication of it. In the latter tube the Crookes dark space was more or less filled with blue negative light, which may have accounted for the absence of the minimum. It will be interesting to see whether future measurements of the potential fall in this part of the discharge show a corresponding minimum.

§ 19. Commenting in general on the results found in this investigation, I consider the curves obtained with the movable bolometer to indicate the relative temperatures in different parts of the discharge with considerable accuracy. As to the results found with the stationary wire and variable current strength, the irregularity of the series $\frac{W}{i}$ shows that there is a source of error somewhere. This, I think, may be the instability of the conditions in the tube, such as the varying length of the anode light, to which I

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[1] E. Wiedemann, Annalen, 20, p. 775, 1883.

have already alluded. The values may, however, be considered correct to within two or three degrees, I think. They agree well with theory, though a too strict comparison cannot be made on account of the probable convection currents in the tube and the radiations from the always more or less warm cathode.

I have, in concluding, to thank Professor Warburg for the kind interest that he has taken in the progress of the work.

Berlin, Physical Institute of the University.

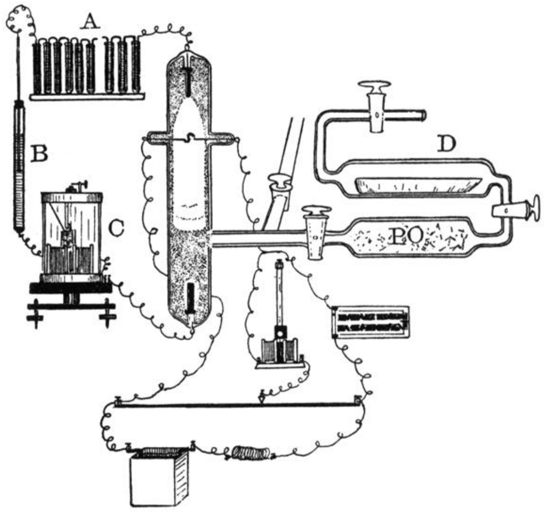
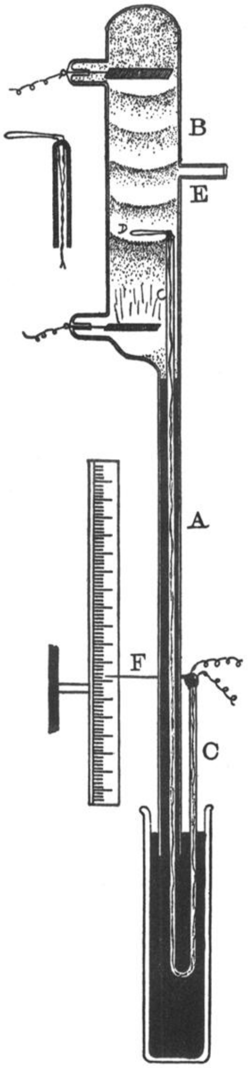


Fig. 3.



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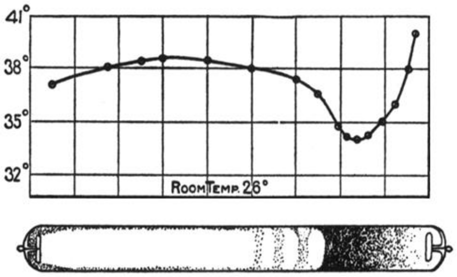
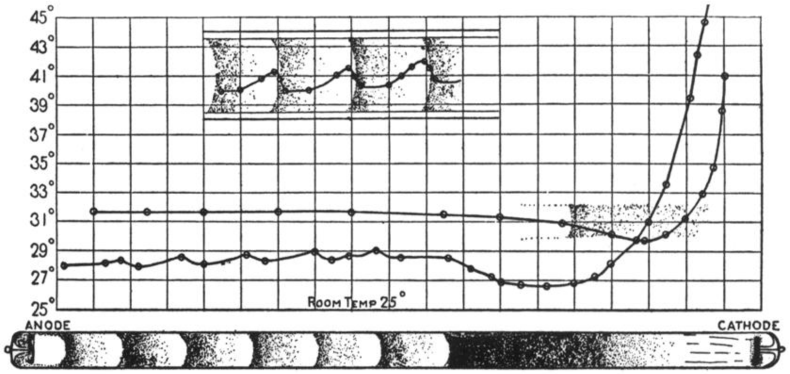


Fig. 5.



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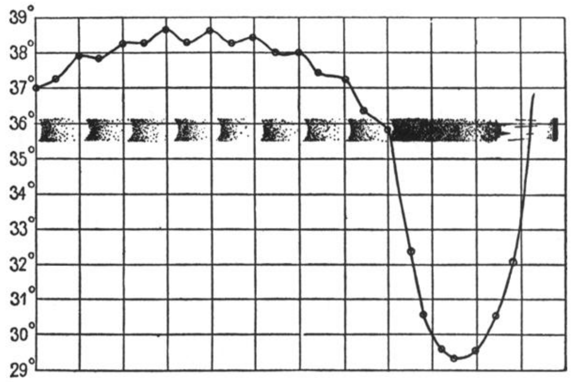

Fig. 7.

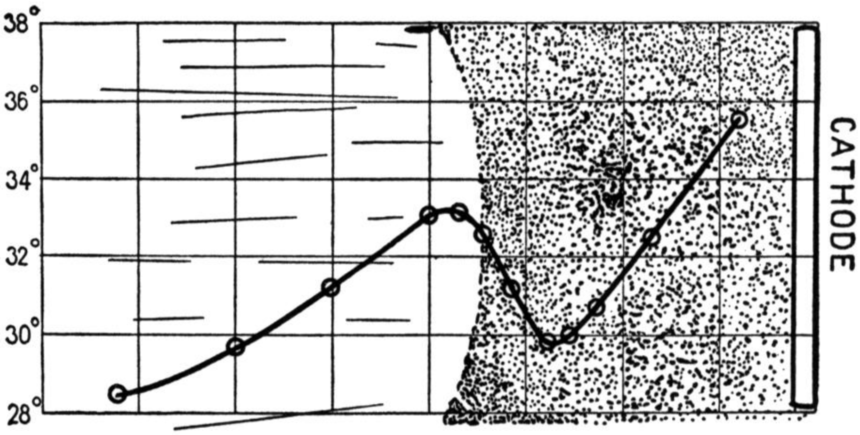

Fig. 8.