T H E S I S

FOR THE DEGREE OF PH.D.

IN THE UNIVERSITY OF GLASGOW

by

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On

Ignition of Coalgas-air Mixtures by Corona Discharges

and

Current-Potential Characteristics of a Corona Discharge.

Contents.

PREFACE.

This thesis, with the exception of Chapter I, consists of an account of original experimental work carried out, by me, in the research laboratories of the Natural Philosophy Department of Glasgow University. Chapter I is a historical introduction. The quotations contained in the text are acknowledged as they occur.

I take this opportunity of thanking Professor E. Taylor Jones, who supervised this work, for giving me every help and facility for the experiments. I have also to thank the Research Department of Imperial Chemical Industries, Ltd. (who suggested the original problem) and the Trustees of the Houldsworth and Thomson Research Scholarships for personal grants.

Finally, I wish to express my gratitude to the teaching staff of the Natural Philosophy Department and to my fellow research students who made the years 1932 to 1935 so profitable and enjoyable.

INTRODUCTION.

The two main practical aims, in investigating the ignition of explosive gaseous mixtures, have been the prevention of accidents and the development of internal combustion engines. The experimental work described in this thesis was promoted to further the first of these aims. The accidents that were brought to my attention in this connection were cases in which a discharge of "static" electricity took place and in each case the electrification had been produced mechanically by the quick stripping of an insulating solid or by the splashing or spraying of an insulating liquid. The accidents, and cases in which it was suggested accidents were possible, may be classified as follows:-

1. (a) Cases in which a discharge took place between a driving belt of poor conducting material and a good conductor.

   (b) It was suggested, though no accidents were recorded, that the corona produced by the stripping of insulating tape, or the tearing of insulating fabric, might produce ignition.

   (c) A serious explosion took place in a celluloid factory when celluloid was stripped from a metal pan in which it had hardened.

2. (a) Cases in which a metal container became charged when an insulating liquid, such as petrol, was poured into it or agitated in it, and a discharge took place from the container, igniting the petrol or other vapour.

   (b) One case in which it was suggested that an explosion was caused by a discharge between charged clouds in nearly empty washing tanks. The tanks were made of conducting material.

In all the definite cases, the igniting discharge seems to have taken place between conductors or between an insulator and a conductor. I was asked, however, to investigate the possibility of ignition by a discharge between dielectric surfaces and by the "corona" discharge.

In the title, the word "corona" is taken to include discharges between insulating or high resistance electrodes, because it is reasonable to suppose that, in such a discharge, a sufficient current density could not be maintained for a time sufficient for the "normal" glow régime to be established.

The work led, naturally, to an investigation of the electrical characteristics of a discharge between point electrodes.

CHAPTER I.

History of the Investigation of Electrical Ignition.

(References are to the list of publications at the end of this chapter.)

In 1914, in a paper entitled "On the least energy required to start a gaseous explosion,"(1) Professor W. M. Thornton published experimental results, examples of which are shown in figs. 1, 2 and 3.

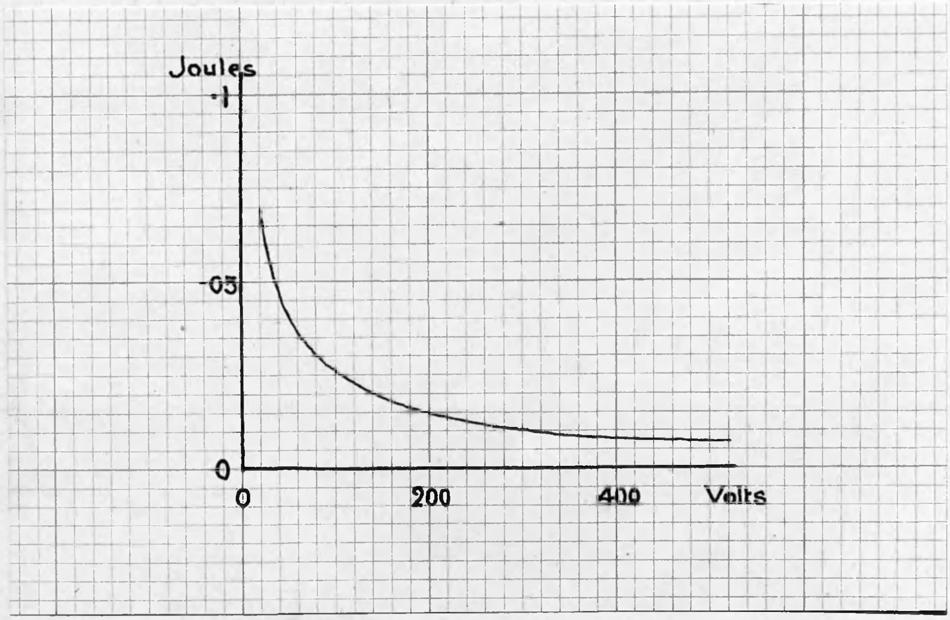

Fig. 1.

An 11% coalgas in air mixture was ignited by the transient arc caused by the separation of copper poles in a circuit in which a current was maintained by a steady e.m.f. For a given e.m.f. the energy dissipated in the arc was varied (apparently by varying an inductive resistance in the circuit - details are not given in the paper), until the least energy necessary for ignition was obtained. Fig. 1 shows the results.

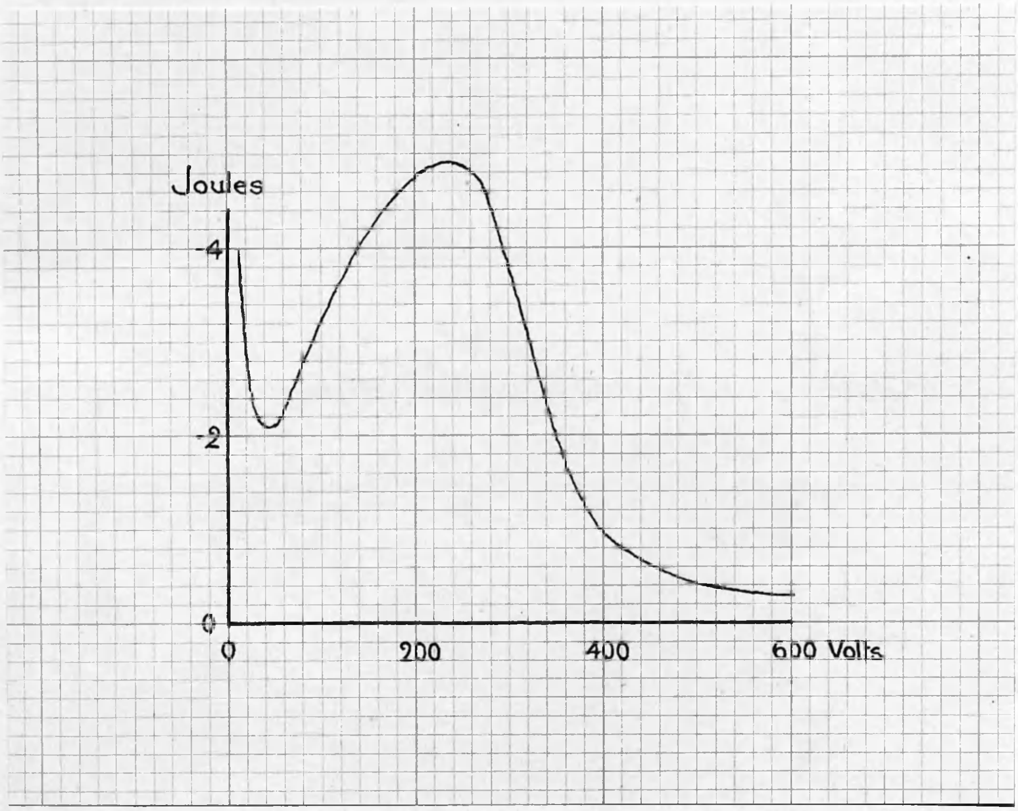

Fig. 2.

Fig. 2 shows the results obtained when a 40 cycles/sec. alternating e.m.f. was used instead of a steady e.m.f.

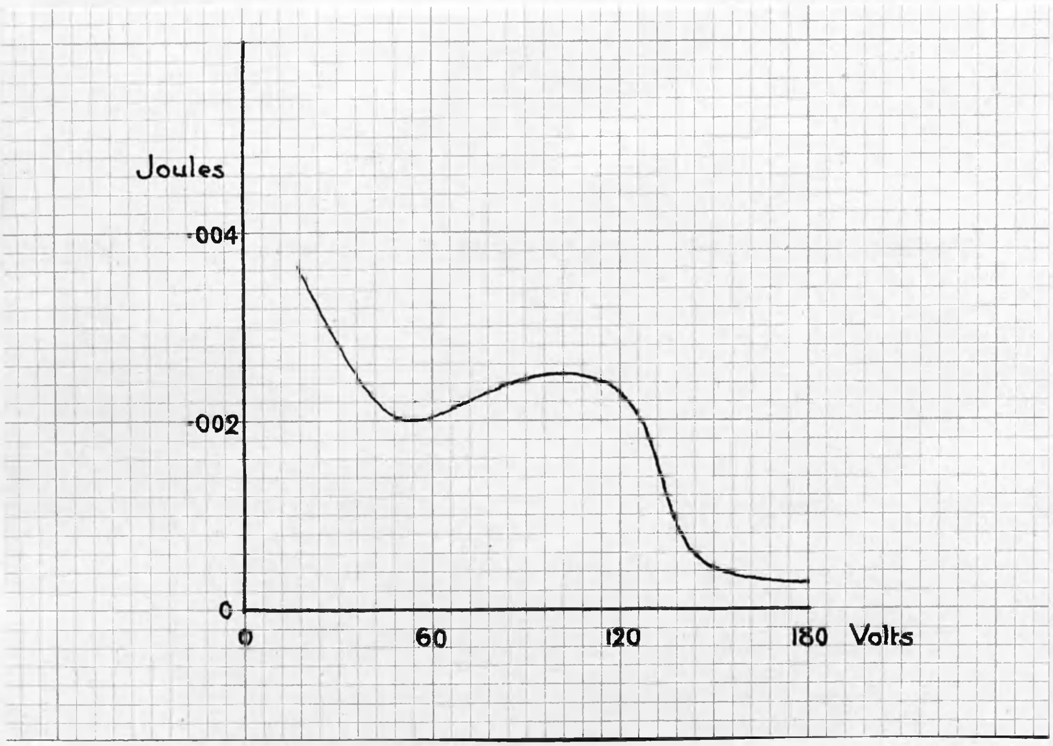

Fig. 3.

The energy required, in the "least spark," to ignite the same mixture by a condenser discharge, between platinum poles, is plotted against the potential across the condenser in fig. 3.

These results show that, when a gas mixture is ignited by the discharge of electricity through the gas, the "least energy" required to ignite the mixture varies with the type of discharge; that is, with the manner in which the electrical energy is dissipated in the discharge. Professor Thornton drew special attention to the importance of the length of time taken to supply the energy. After a qualitative discussion of the shape of the graph in fig. 2 he adds, "Everything, therefore, favours a thermal origin of self-ignition in the case of low-frequency A.C., but something much more intimate in the case of D.C." and, "with continuous current it is the material of the poles which is decisive, with alternating currents the nature of the gas."

Because of the apparent difference between the igniting effects of continuous and alternating currents and because of his evidence for "stepped ignition,"(3), (6),(10)

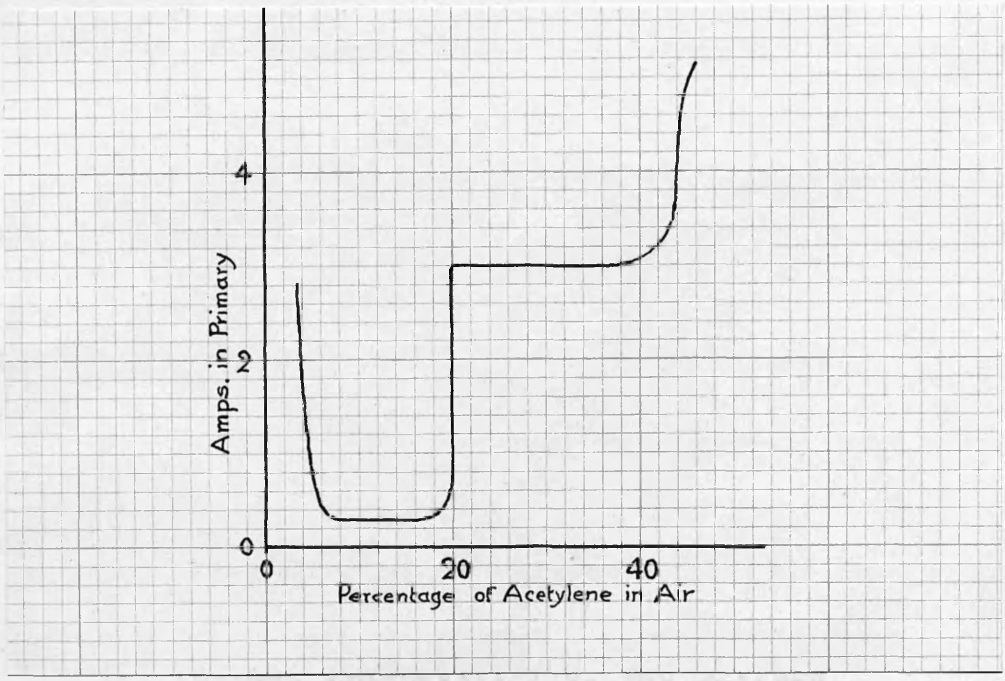

Fig. 4.(6)

Variation of "least igniting spark" (taking primary current as measure of "spark intensity") with Percentage of acetylene in air.

(Sastry(7) found no "steps" on such curves.)

Professor Thornton persisted in his search for an "electrical" or "ionisation theory" of ignition. In 1920 he asserts that "There is a critical intensity of spark, that is a certain number of ions produced per second to ensure ignition."[10] This is his nearest approach to a definite statement of his theory.

Messrs. Coward, Cooper and Jacobs[4] in 1914, the year of Professor Thornton's first paper, stated that their work throws no light on the "mechanism" of ignition, thus distinguishing between the investigation of the mechanism and that of the conditions necessary for ignition. The following extracts are worthy of quotation.

"For an electric discharge to initiate a flame in a gaseous mixture it is necessary that sufficient energy should be liberated by the discharge to maintain a sufficient bulk of the gas at or above its ignition temperature until the end of the pre-flame period."

and,

"Ease of ignition. . . . is a function of:-

(a) Ignition temperature. . . .

(b) Thermal conductivity of the mixture.

(c) Duration of pre-flame period.

(d) Specific heats of the gases present.

(e) Thermal value of the reaction (i.e. the combustion).

(f) Energy due to the electrical discharge."

This paper formed an excellent opening to the study of the conditions necessary for ignition considered as a macroscopic thermal phenomenon.

Four years later Professor R. V. Wheeler[11] put the first of these statements in the following form. "The requisite for a source of heat to initiate flame in a gaseous mixture is that sufficient energy shall be introduced to maintain for a sufficient length of time a sufficient volume of the mixture at or above its ignition temperature." He also states that his desire is "to obtain information regarding the mechanism of ignition," but his investigations concern only the conditions necessary for ignition. In the same paper he states his objections to the "stepped" form of some of Professor Thornton's graphs (fig. 4). Former publications[7],[8] has given curves with no "steps" (fig. 5).

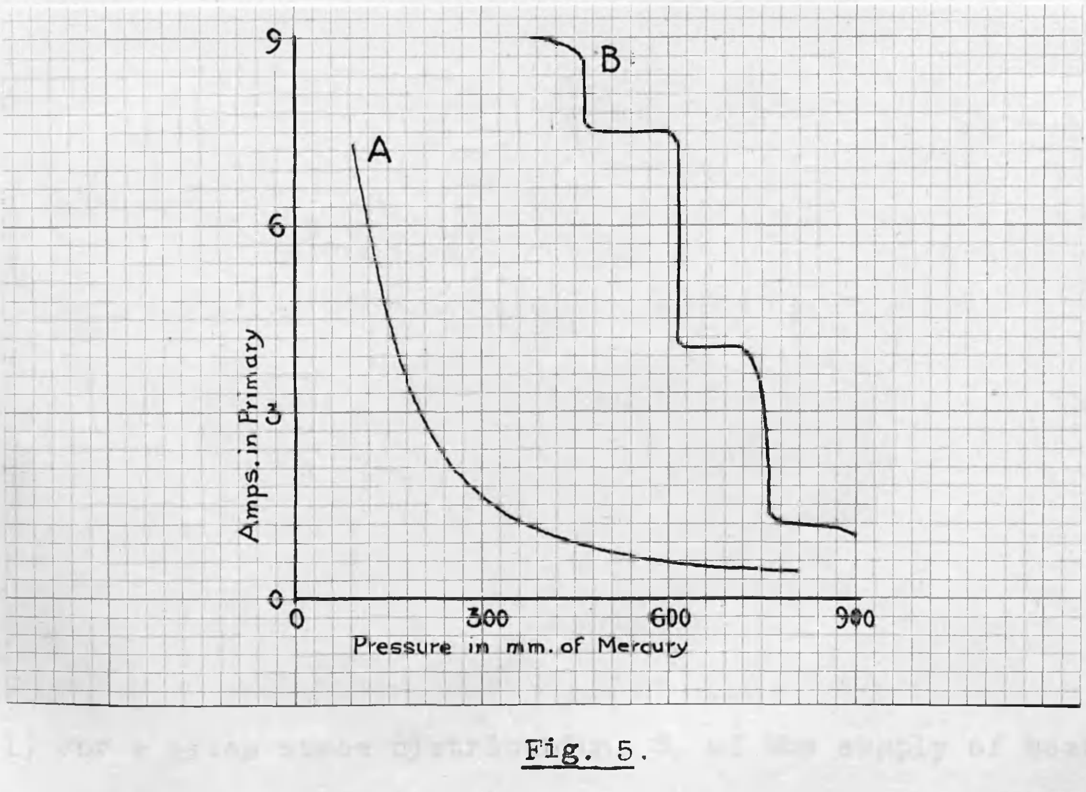

Fig. 5.

Curves (A, by Wheeler - B, by Thornton) showing the variation of primary current, necessary to produce a spark which will ignite a 9.5% methane in air mixture, with the pressure of the mixture.

The fact that ignition by induction coil discharges depends mainly or entirely on the "capacity component" of the discharge(9),(12) was the only further contribution to the subject published before the paper(13) which gave form to the thermal theory of the conditions necessary for ignition by the discharge of electricity.

The object of this paper was "to show that, given gaseous mixtures, or series of mixtures of constant composition, a variation in the energy of the electric spark required to ignite them, dependent on the character of the spark, is to be anticipated on thermal considerations alone." This was shown in the following manner.

Suppose that a quantity of heat Q is supplied to a gas

(1) instantaneously at a point, O,

(2) at a point, O, at a uniform rate during time T,

(3) instantaneously over the surface of sphere, centre O, radius a,

(4) instantaneously, throughout a spherical volume, centre O, radius a,

then, from the solution for each case of the equation of the conduction of heat, the temperature at a distance r from O at any time, t, may be calculated. From the examples given in the paper it is clear that the following statements are justified.

(1) For a given space distribution, S, of the supply of heat Q the maximum temperature, θ, to which a volume V, surrounding S,

rises, depends on the rate of supply of Q and the greater the rate (i.e. the shorter the time T) the higher is θ.

(2) For a given time distribution of the supply of heat Q the maximum temperature, θ, to which V rises is greatest if the heat is supplied uniformly throughout the volume.

If, then, it is necessary for ignition that a certain minimum volume V of a gas mixture be raised to a certain temperature θ, it is obvious that of two electric discharges of the same total energy, one might ignite the mixture and the other, say slower, might not. The fact that a certain minimum volume of a mixture must be raised to a particular temperature if the mixture is to ignite, i.e. that a flame must have a certain minimum volume if it is to spread through the mixture, has been deduced in the following way.

"If we suppose that a small spherical volume of the gas is heated by the source to the ignition temperature, the gas within this volume is burnt and its temperature is raised further by the heat resulting from the chemical action. At the surface of the sphere there will be, therefore, a large temperature gradient and rapid loss of heat by conduction. The rate of cooling of the sphere, due to this cause, is proportional to the ratio of its surface to its volume, and is very great if the sphere is very small. Consequently, the small flame started in the sphere will soon become extinguished by the conduction from its surface, and will, therefore, fail to spread throughout the gas, unless the volume of the sphere exceeds a certain minimum value."[27]

Since 1922 all the results of experiments on electrical ignition have been successfully explained, at least qualitatively, by considering it as a purely thermal effect. The best account is in the chapter from which the above quotation is taken.[27]

In 1925 Dr. J. D. Morgan[17] and Professor Wheeler[18] showed that there was no difference between the igniting effects of arcs at the break of continuous and alternating currents and so disposed of Professor Thornton's original reason for looking for an "electrical" theory of ignition. Messrs. Coward and Meiter[21] determined the volume of various mixtures burnt by sparks which just failed to ignite the mixtures — that is, according to the thermal theory, the volume of flames which just failed to be self-supporting — by chemical analysis, after the passage of a large number of such sparks, and found that their results were in accord with the theory.

In two papers published by the Royal Society, Messrs. Finch and Cowen[20] and Finch and Thompson[24] revived the suggestion that an "electrical" theory of electrical ignition was necessary. Dr. Morgan[28] has pointed out that their statements were not self-consistent and that their results can be explained by the thermal theory. The explanation of the results of Finch and Cowen had already been given by Dr. J. M. Holm.[23]

Dr. Holm[25],[26] later showed that the thermal theory agreed with the results of his experiments on the measurement of the limiting diameter of tube or aperture which would just allow the flame of an explosive mixture to propagate. He also obtained and photographed a flame in a 29.5% coalgas-air mixture whose volume was so near to the minimum possible volume that it burned without spreading for sixteen seconds.

It must be observed that the "thermal theory of electrical ignition" accounts for the conditions which an electric discharge must fulfil if it is to cause inflammation of a given gaseous mixture. The theory gives no account of the microscopic mechanism of ignition. Ignition is considered merely as an event, not as a process. The exact evaluation of the conditions for any given circumstances is difficult. The exact rate and distribution of the dissipation of electrical energy, the amount of energy absorbed by the electrodes, the variation of the physical constants of the gases with temperature and the effective ignition temperature are all difficult to measure or estimate. On the other hand the results of experiments show quite definitely that electrical ignition does not depend on any particular <u>electrical</u> quantity such as the current flowing in a discharge.

Previous workers on electrical ignition have almost invariably used capacity or induction coil "sparks" or transient arcs at the break of an induction circuit as the igniting agents. No quantitative results have been published, but the following references have been made to ignition by other types of discharge, Professor Thornton[29] states, in connection with a brush discharge that "gaseous mixtures cannot be fired by such a discharge or by the more active discharge from needle points at extra high pressure, unless a definite spark passes." On the other hand Dr. Morgan[30] states that the "glow or brush" discharge between the secondary terminals of an induction coil may produce ignition, and M. Tchang Te-Lou[31] has observed that the compressed, therefore, hot, gases in an internal combustion engine may ignite when the sparking plug passes a "corona" not a spark discharge.

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A short title or note, descriptive of the nature of the investigation, has been added to most of the following references.

(1) Thornton, W. M. Phil. Mag., 28, p. 734 (1914).

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(4) Coward, H. F., Cooper, G. and Jacobs, J. J. Chem. Soc., 105, p. 1069.
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(5) Thornton, W. M. P. Roy. Soc., A, 92, p. 9 (1915).
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(7) Sastry, S. G. J. Chem. Soc., 109, p. 523 (1916).
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(9) Paterson, C. C. and Campbell, N. P. Phys. Soc., 31, p. 168 (1919).

(10) Thornton, W. M. Phil. Mag., 40, p. 345 (1920).
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(11) Wheeler, R. V. J. Chem. Soc., 117, p. 903.
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(19) Coward, H. F. and Wheeler, R. V. — Safety in Mines R.B. Paper 8. "Ignition of Firedamp."

(20) Finch, G. I. and Cowen, L. G. — P. Roy. Soc., A, 111, p. 257. Amount of combustion (without inflammation) due to discharge at reduced pressures. (1926).

(21) Coward, H. F. and Meiter, E. G. — J. Am. Chem. Soc., 49, p. 396. "Chemical action in the electric spark discharge." Methane-air. (1927).

(22) Jones, E. Taylor. — Phil. Mag., 6, p. 1090. Spreading of discharge between spherical electrodes.

(23) Holm, J. M. — Phil. Mag., 11, p. 194 (1931). Rise of temperature in glow discharge.

(24) Finch, G. I. and Thompson, H. H. — P. Roy. Soc., A, 134, p.343. Discharge of oscillatory circuit.

(25) Holm, J. M. — Phil. Mag., 14, p. 18 (1932).

(26) Ibid. — Phil. Mag., 15, p. 329 (1933).

(27) Jones, E. Taylor. — "Induction Coil", (1932), Chap. VIII, p. 196.

(28) Morgan, J. D. — "Fuel in Science and Practice," 11, p. 452 (1932).

(29) Thornton, W. M. B.A. Report, p. 513 (1914).

(30) Morgan, J. D. J. Inst. El. Eng., 54, 254.

(31) Te-Lou, Tchang. Comptes Rendus, 198, p. 542 (1934).

CHAPTER II.

Ignition by the discharge of electricity from insulating surfaces.

Elementary considerations show that, if a dielectric surface is to be so charged that the discharge from it may be investigated then mechanical methods of charging are unsuitable. The surface density of charge on a body electrified by rubbing or striking is necessarily small, for, if it were large, a discharge would immediately take place between the body and the rubber or striker. In cases, such as the tearing of dry balloon silk, in which considerable surface charges do appear, a discharge does take place immediately and it is impossible to study the charge or control its discharge.

Charging by bombardment by positive or negative ions is equally unsuitable because the air or other gas in front of the surface is ionised and, therefore, conducting.

A glass surface in air at any small distance (.1 mm. to 5 cms.) from a sharp point connected to the secondary of an induction coil acquires a charge too small to be detected by an ordinary gold-leaf electroscope.

It is well known that, if a Leyden jar is charged and the inner and outer conductors are removed without discharging, the charge remains on the insulating jar. The surface density of charge which may be acquired in this way appears to be limited only by the dielectric strength of the jar. Most of the experimental work to be described consists of two modifications of this experiment, and observations of the igniting properties of the discharge of electrification so obtained.

Consider a condenser consisting of two metal plates between which are two plates of insulating material, all four plates being pressed together. (Fig. 6.)

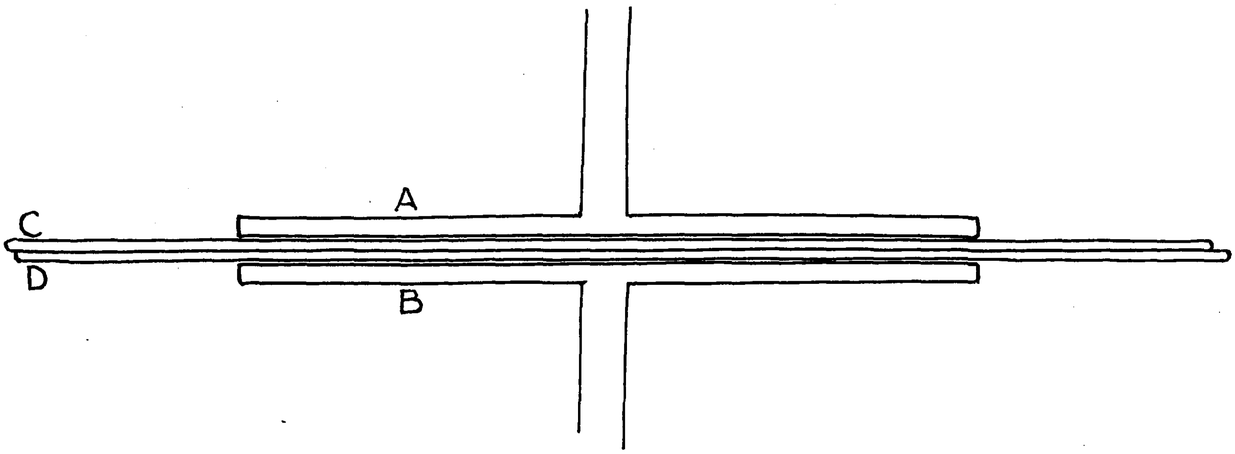


Fig. 6.

If the metal plates A and B are charged from opposite poles of a Wimshurst machine the following effects are to be expected. (1) The sides of C and D in contact with A and B would receive charges from A and B. (2) Some charge would be conducted through the dielectric plates. (3) The dielectric plates would be polarised. With good insulators the second effect would be small compared to the first, and the last effect is temporary and cannot produce a discharge from the insulating surface.

To investigate the first effect and to find the conditions under which a charge so obtained would discharge into air, I made such a condenser. A and B were brass discs 8 centimetres in diameter and C and D were plates of ebonite 30 cms. x 16 cms. and 0.16 cm. thick. When the condenser was charged and A and B were removed, charges remained on the outer surfaces of C and D held by their mutual attraction. If the original potential difference across the condenser was greater than 6,000 volts (the value is not definite), a discharge took place when C and D were separated. If the charged surfaces were now brought together another small discharge was sometimes obtained, but it was always possible to obtain a discharge from the electrified insulating surface to a conductor.

I measured the charge acquired by one plate in this way when the potential difference was less than 6,000 volts. The measuring system was a rectangular "ice-pail" with a narrow opening (17 cms. x 1 cm.), connected to a quadrant electrometer, across which was a .02 μF. condenser to reduce the sensitivity. The charge so measured was, in every case, much smaller than the value calculated from potential and capacity and did not vary in any regular manner with the potential. The amount of charge left after the discharge at separation on a plate which had been more highly charged seemed equally fortuitous. Neither did the charge acquired by the ebonite plates from brass discs of various sizes (diameters 2, 4, 6, 8 and 10 cms.) at any one difference of potential vary regularly with the area of the discs.

It would appear that no definite surface density could be obtained on an insulating surface charged in this way. This is no doubt due to the fact that the various surfaces make contact at a few points only. I tried, without success, to overcome this difficulty first by using mercury contacts with the dielectric, and later by using sheets of a compressible dielectric and forcing the metal discs against them. Something might be done with the method if all the surfaces used were worked optically plane by an experienced optical firm. I abandoned the method, however, because I was unable to ignite a coalgas-air mixture by any discharge of electricity so obtained in which only dielectrics were concerned, although these discharges were both audible and visible. It was often observed, however, that a discharge from the charged insulating surface to a conductor did ignite a coalgas-air mixture.

The system of fig. 1, which has been considered as a condenser, may also be regarded as a high resistance. If a current flows through this resistance, when the adjacent surfaces C and D are separated by an air space, then a discharge must pass between these surfaces. If the conductors A and B are in the form of rods and the insulators C and D in the form of tubes closed at one end and slipped over the rods, the system is a pair of high resistance electrodes. (Fig. 7.)

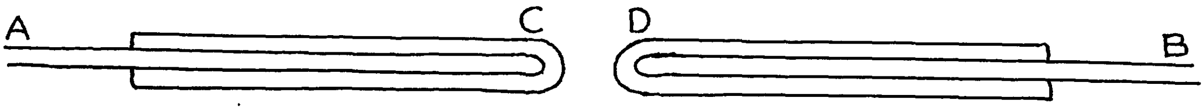


Fig. 7.

The advantage of the arrangement is that an investigation of a discharge between dielectric surfaces may be carried out without changing the metallic contacts between A and C and B and D, which, we have seen, are not exactly repeatable.

Two such electrodes were used as the poles of a Wimshurst machine. Pairs of tubes of paraffin wax, ebonite, glass, white fibre, lignum vitae, teak, mahogany. oak, greenheart, hemlock, plane tree, maple and whitewood, were tried for C and D.

In every case, except in the case of paraffin wax, it was possible to produce a discharge between the "insulating" surfaces. At short gap lengths, 1 to 10 mm., depending on the material, this discharge was one or two millimetres wide. The visible parts of the discharge were a blue glow close to the cathode and a redder, slightly narrower glow extending from the anode to within a short distance of the luminosity at the cathode. When the gap was lengthened the discharge narrowed and, if the dielectric did not break down, it ultimately resembled a faint brush discharge.

Neither the discharge between glass electrodes nor that between ebonite electrodes ignited a coalgas-air mixture admitted to the gap from a Fisher burner. When white fibre or lignum vitae was used ignition was obtained when the glow was sufficiently long (12 to 18 mms.). In the case of the other woods no ignition by the discharge took place. The wooden electrodes became punctured before a gap length of 12 mms. was reached. In every case the spark at breakdown of the electrode material produced ignition.

If the current in a discharge of this kind is steady, the current carried by the discharge will vary with the total resistance of the electrodes (other conditions being constant) and the concentration of the discharge and the area of the electrodes used by the discharge will vary with the specific resistance of the electrodes. If the discharge current is intermittent, the specific inductive capacity of the dielectric tubes will also affect the discharge.

The specific resistance of glass decreases rapidly with rise of temperature while the dielectric constant of glass varies little with temperature. When the experiment just described was repeated with glass electrodes heated to 100°C. the discharge (8 mms. long) produced ignition.

More accurate experiments of this kind are described in the following chapter.

CHAPTER III.

Ignition by electric discharge between high resistance electrodes.

A. Ignition Experiments.

After preliminary experiments in which glass tubes silvered* on the inside at the closed end, heated in an electric oven and slipped over brass rods, were used as the electrodes for an induction coil discharge, to ignite coalgas from a burner, the arrangement described in the following paragraph was adopted.

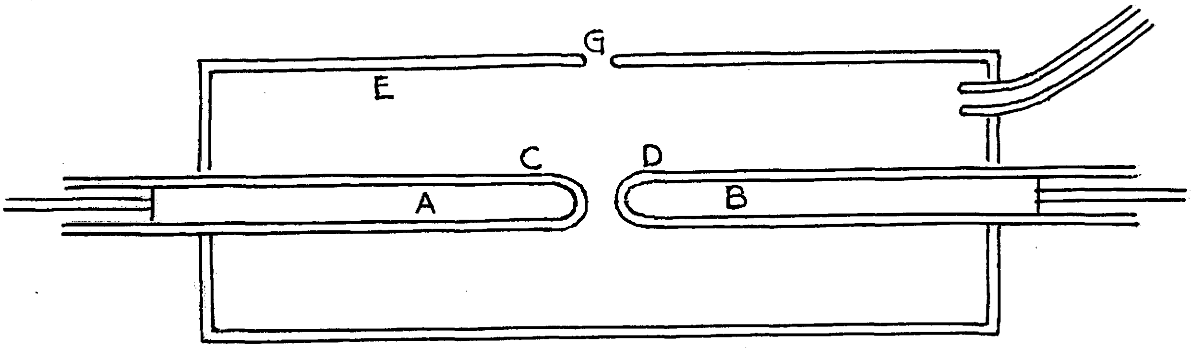


Fig. 8.

A and B (fig. 8) are carbon rods with brass rods screwed into them. C and D are tubes of soda glass 12 cms. long, 1.14 cms. wide and .16 cm. thick, painted with "Aquadag" colloidal graphite on the inside at the closed end, to make good contact

* The method of silvering used was that described in Phil. Mag. 39, p. 387 (1895) "Silvering glass in the cold."

with A and B. E is a cylindrical oven of unglazed earthenware 18 cms. long and 5 cms. in diameter. C, D and the glass tube F were sealed in with plaster of Paris. G is a circular hole of diameter 0.7 cm. Round the oven is wound a heating coil which will maintain the oven at 250°C. when the current is 1.25 amps. A and B were connected across the secondary of an induction coil and F led, through a stopcock and a safety packing of wire gauze, to a large gas container.

Observations were taken in the following manner. A mixture of coalgas and air was made up in the gas container. The oven was heated to about 120°C., the temperature being read on a thermometer inserted in the hole G, the heating current was switched off and when the thermometer reading had steadied at, say, 125°C., the thermometer was replaced by a cork. The interrupter was started, the primary current of the coil was switched on, and the mixture was allowed to flow into the oven, the outlet from which was the small space round the cork. If the gas mixture in the oven became ignited (as shown by the cork being blown out) the experiment was repeated at a lower temperature. If ignition did not take place the experiment was repeated at a higher temperature. The whole process was repeated until an "ignition" and a "no ignition" were obtained at not more than three degrees apart. The experiment was carried out with gas mixtures of different concentration.

The gap length, 5 mms., and the primary current were constant throughout. The amount of energy taken from the secondary circuit was small and varied little with the temperature of the electrodes, so that the peak potential across the leads to the electrodes, was constant. The spark given by the coil between copper spheres in air was 1.62 cms. long, indicating a potential of about 45 kV.

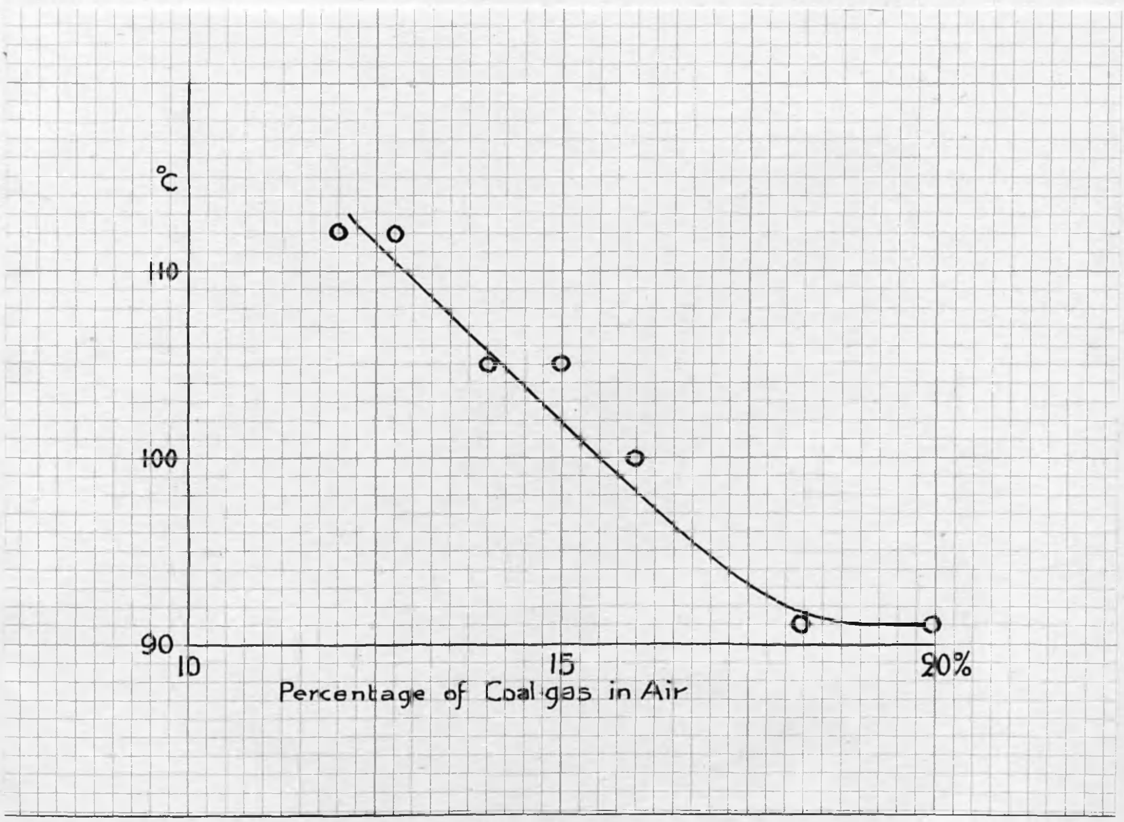


Fig. 9.

Fig. 9 shows the lowest temperatures at which the discharge used in the above experiment would ignite 12% to 20% coalgas in air mixtures.

The ignition of mixtures weaker than 12% did not move the cork so could not be observed.

B. Electrical Measurements.

1. The Variation of the Resistance of the Glass with Temperature.

The two glass tubes used in the ignition experiments were mounted so that their closed ends dipped into mercury, and were filled with mercury to the level of the mercury surrounding them. A 1,000 volt D.C. generator and a Gambrell moving coil mirror galvanometer were connected across the mercury electrodes inside the tubes, so that the resistance of the ends of the glass tubes was in series with the generator and galvanometer. The mercury could be heated by a bunsen flame and its temperature read on a thermometer in one tube.

In fig. 10, (see following page,) the current through the glass, read on the galvanometer, is plotted against the temperature of the mercury, which will be the temperature of the glass, since the heating was slow.

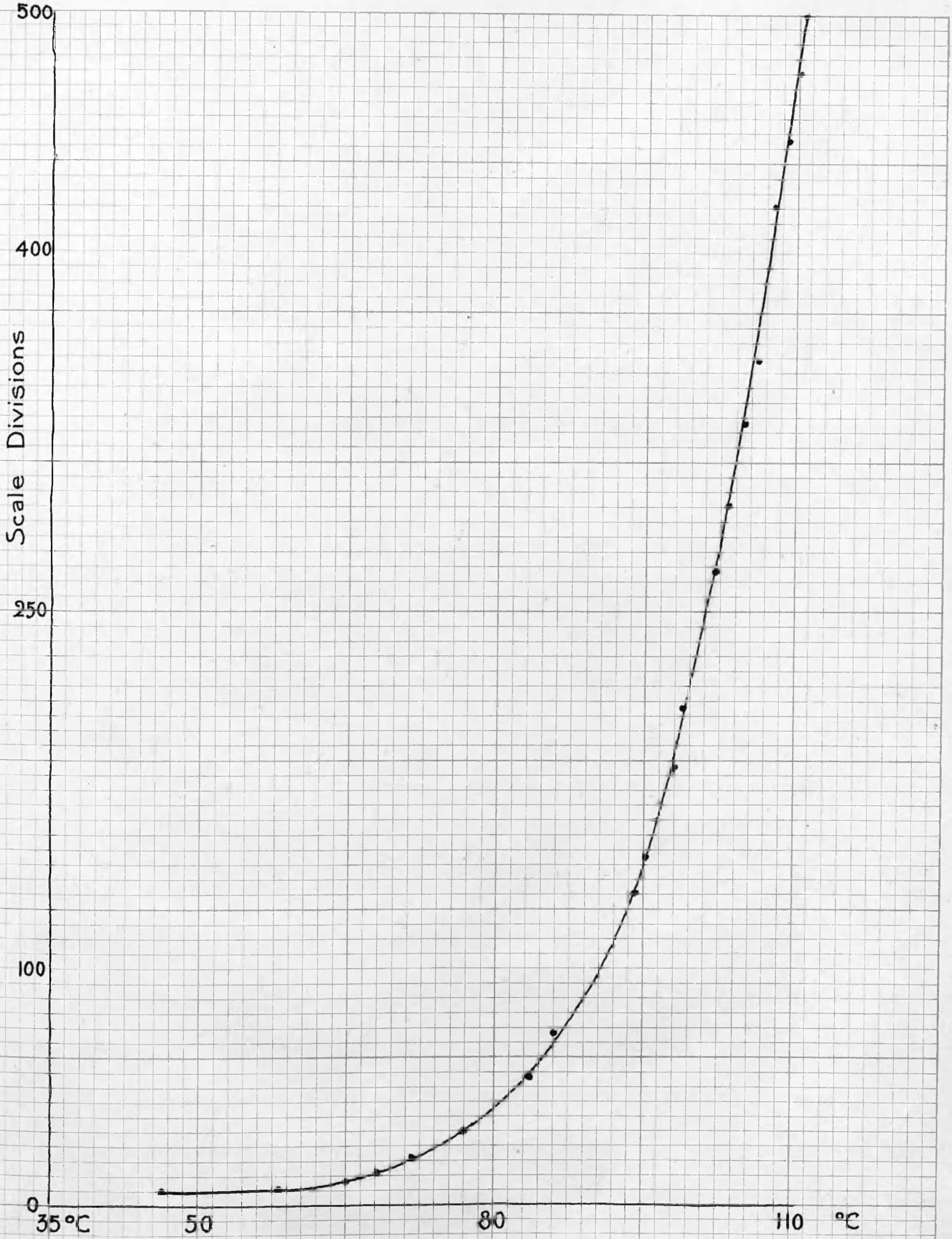


Fig 10

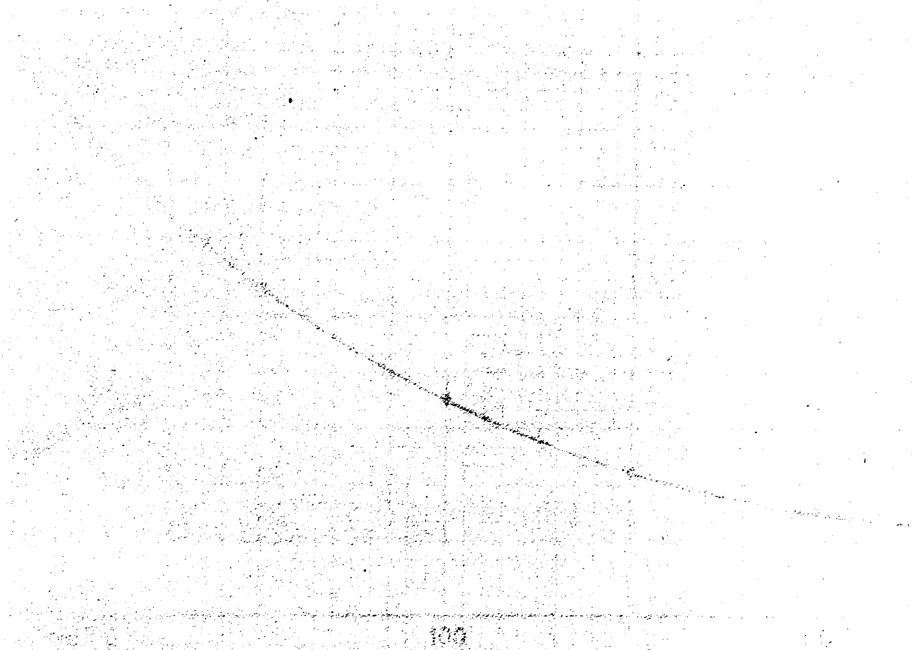


Fig. 11

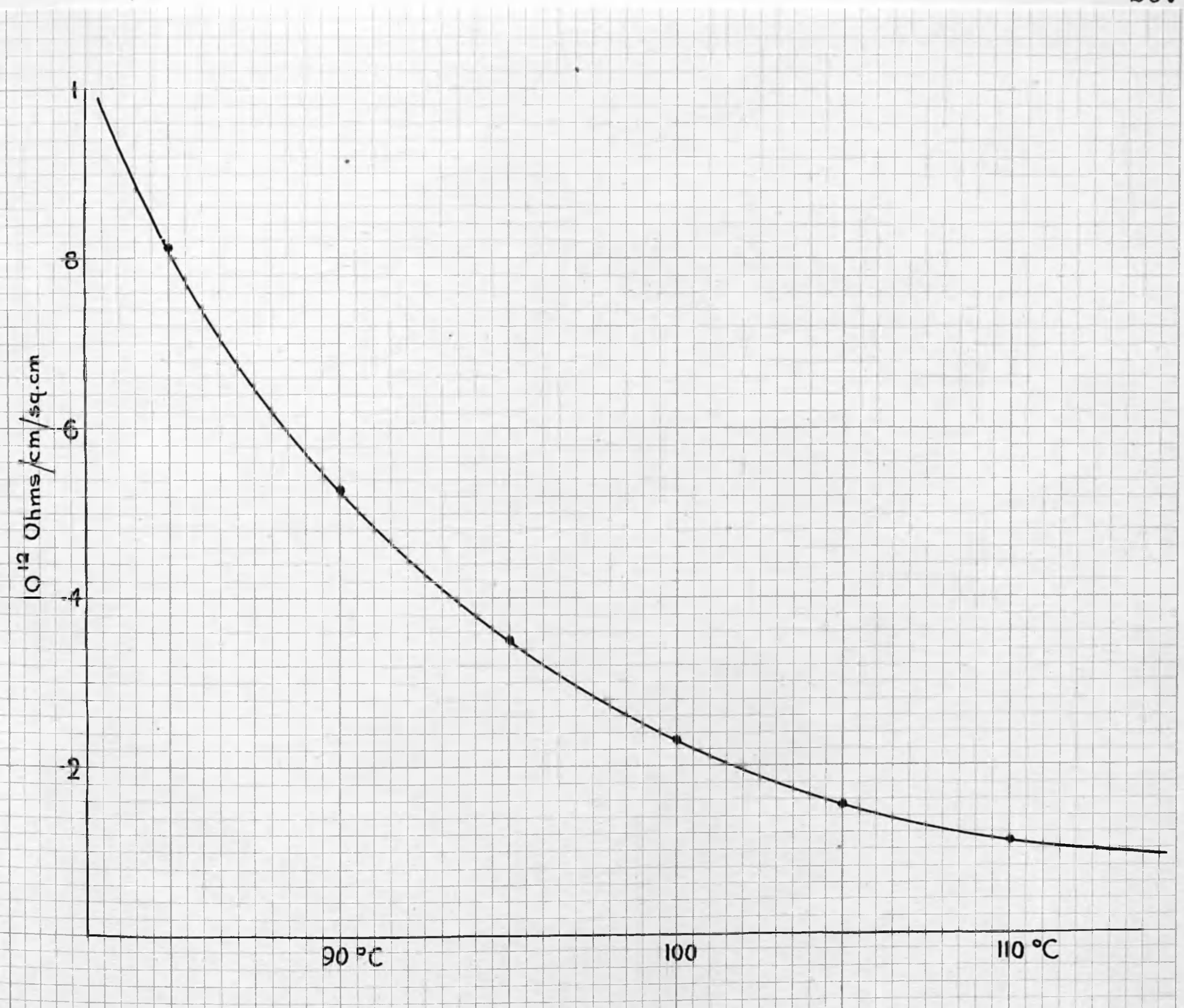


Fig. 11

Fig. 11 shows the specific resistance of the glass in millions of megohms per cm. per square cm., calculated from the readings, the galvanometer constant and the dimensions of the tubes, plotted against the temperature, over the range of temperature used in the ignition experiments.

2. The Potential across the Discharge.

The difference of potential between the outer surface of glass electrodes, between which a discharge is passing, cannot be measured directly because any conducting connection to the external glass surfaces changes the form of the discharge. The maximum potential difference applied to the electrodes by an induction coil may be measured, but there seems to be no method of determining the potential drop in the glass. Even if the potential were steady and the current known, the potential across the discharge cannot be deduced, because the form of the lines of flow through the glass, and, therefore, the resistance of the glass, is unknown. In the following experiment an attempt was made to overcome this difficulty.

A steady potential was maintained across the glass electrodes by a condenser charged by an induction coil through a diode valve (fig. 12). The current which flowed across the

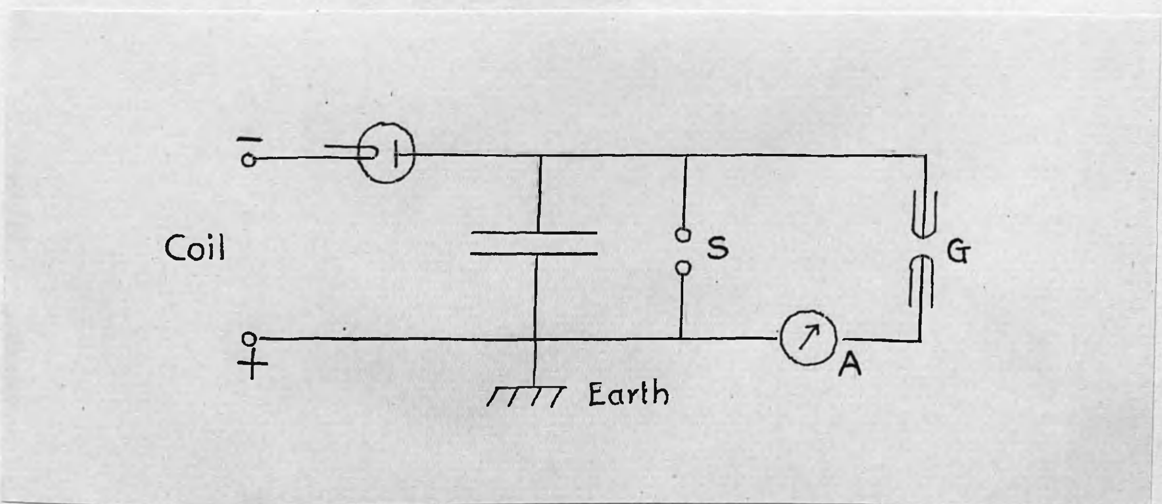


Fig. 12.

glass gap, G, was measured by the galvanometer A. The potential across the condenser could be measured by the sphere gap S. As in the ignition experiments the temperature of the glass could be varied. The current and the corresponding gap length were measured at various temperatures. The distance between the glass electrodes was 0.5 cm. as before.

Let E_1 volts be the potential difference across the condenser, e volts the potential difference across the discharge, i amperes the current in the discharge and R_1 ohms the resistance of the glass at θ_1°C. Then

$$E_1 = R_1 i + e.$$

Let R_2 be the resistance of the glass electrodes at θ_2°C. and let E_2 be the value to which the potential across the condenser has to be adjusted to cause current i to flow when the electrodes are at θ_2°C. Then

$$E_2 = R_2 i + e$$

if it is assumed the e is a single valued function of i.

Let
$$\frac{R_1}{R_2} = k$$

Then
$$e = \frac{E_1 - kE_2}{1 - k}$$

It seems reasonable to suppose that k is approximately equal to the ratio of the specific resistances of the glass at θ_1

and θ_2. Then k may be found from fig. 11 and e calculated. The results of these measurements are given in Table 1.

Table 1.

i	θ_1	θ_2	E_1	E_2	k	e
divs.	°C.	°C.	kv.	kv.		kv.
1.0	90	97	24.0	20.0	2.25	17.0
1.2	98	108	25.3	20.0	2.17	15.5
2.2	103	107	25.3	22.8	1.69	17.7

The accuracy is not high. Apart from experimental inaccuracy (the current, which had to be adjusted in the middle of each experiment, could be read with only 10% accuracy and θ_1 and θ_2 might vary 1°C. during the experiment) there are essential inaccuracies in the method. The ratio of the specific resistances cannot give the true value of k, for the resistances R_1, R_2 depend on the form of the lines of flow through the glass and this must vary with the specific resistance. Further, e will not be a single valued function of i, but will vary with the area of the electrodes used by the discharge which, again, will depend on the form of the lines of flow in the glass. Most important of all is the fact that it cannot be shown that the current in the discharge is steady.

The method, with all its inadequacy, appears to be the only possible one. It indicates that the potential across the discharge is approximately equal to the sparking potential between similar metal electrodes similarly situated.

3. The Quantity carried by one discharge.

The circuit shown in fig. 13 is the same as that used in the ignition experiments, with two modifications.

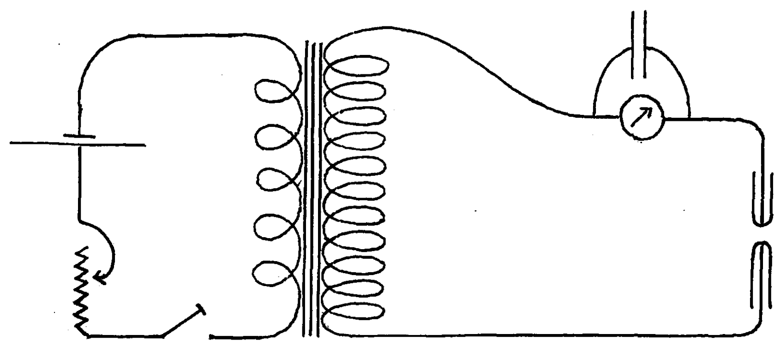


Fig. 13.

A ballistic galvanometer, protected from capacity surges by a Leyden jar across it, is inserted in the secondary circuit of the coil in series with the gap between glass electrodes, and a Meiklejohn hand interrupter is substituted for the trembler interrupter of the coil. The primary current was adjusted so that the secondary peak potential was the same as in the ignition experiments. When the primary current was broken the galvanometer deflection gave the quantity which flowed round the secondary circuit, that is, the quantity carried by the discharge. During the experiments the electrodes were at temperatures within the range covered in the ignition experiments. The results are given in Table 2.

Table 2.

Temperature °C.	Galv. defl.	q. .c.	j. joules.
90	110	.16	.0027
93	110	.16	.0027
97	115	.17	.0029
102	120	.18	.0030
109	130	.19	.0032

q is the quantity in microcoulombs, j the energy dissipated in the discharge; i.e. $j = q.V. 10^{-3}$ joules. The gap width was 5 mms. and V, the potential across the discharge, was assumed to be 17 kv.

C. Heating of the Gas by the Discharge.

To measure the amount of the energy of the discharge which appeared in the gas as heat, I enclosed the ends of the electrodes in an airtight ebonite chamber which formed the bulb of a dilatometer, connected with an open manometer containing water or oil (fig. 14). The circuit was the same as before (fig. 13), with the galvanometer removed from the secondary circuit. When the primary current was broken, a discharge

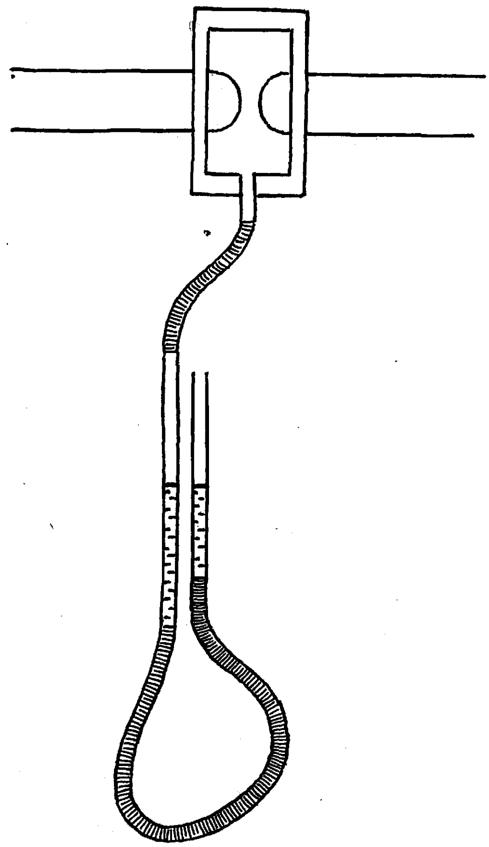


Fig. 14.

passed inside the ebonite chamber and caused the liquid in the manometer to move. The difference of levels produced in the manometer is due to three separate effects, namely: the pressure wave from the discharge; the change of volume of the gas due to chemical change; the expansion of the gas with rise in temperature. The chemical change is permanent and merely changes the zero of the air-thermometer so may be ignored if the zero is read at the end of the experiment. To estimate the amount of heat communicated to the gas, in spite of the complication caused by the pressure wave, two methods were used. In the first I measured the comparatively slow change of volume as the thermometer cooled to its new zero after the sudden change due to the pressure had disappeared. Water and Apiezon Oil "A" were used in the manometer. I used a viscous paraffin oil in the manometer, in the second method. The oil was too viscous to move under the impulse of the pressure wave but moved under the pressure due to the less transient heating effect. The methods provided only an estimate of the order of magnitude of the heating effect and were not accurate enough to show any variation with the temperature of the glass within the range of temperature used.

The change in level of the liquid in the manometer tube, which had an internal diameter of 2 mms., was observed through a graticuled microscope and was always of the order of .06 mm., corresponding to a change of volume of .2 cu. mm. Thus the quantity of energy that appears as heat after one discharge is about $6. 10^{-5}$ joules, if the thermal capacity of air per unit volume is .0003. This is of the order of 2% of the total energy dissipated in the discharge. No doubt the greater part of the energy is dissipated in heating the electrodes and does not immediately heat the gas.

D. Discussion.

In table 2 j was calculated from

$$j = q.V.\ 10^{-3}$$

and j was called the energy dissipated in the discharge. This is only justified if (1) a single discharge passes at each break of the coil and (2) the potential across the discharge remains at its original value throughout the duration of the discharge. If the capacity of the ends of the electrodes is discharged so that V = 0 when the discharge stops, then

$$j = \tfrac{1}{2}\ q.V.\ 10^{-3}.$$

A case, intermediate between these, is much more probable than either of them, and it is also possible that more than one discharge takes place at each break of the coil.

In any case, it is impossible to calculate the space and time distribution of the dissipation of energy, or the corresponding production of heat in the gas, and comparison with theory is, therefore, not possible. Three quantities, however, have been shown to vary with the temperature of the electrodes. These are the coalgas-air mixture which will just ignite, the conductivity of the electrodes, and the quantity of electricity which crosses the gap at one break of the coil. In fig. 15 corresponding values (i.e. values at the same temperatures) of the first two of these quantities are plotted against each other. The abscissae are taken from the smooth curve in fig. 9 and the ordinates are the reciprocals of the ordinates of fig. 11.

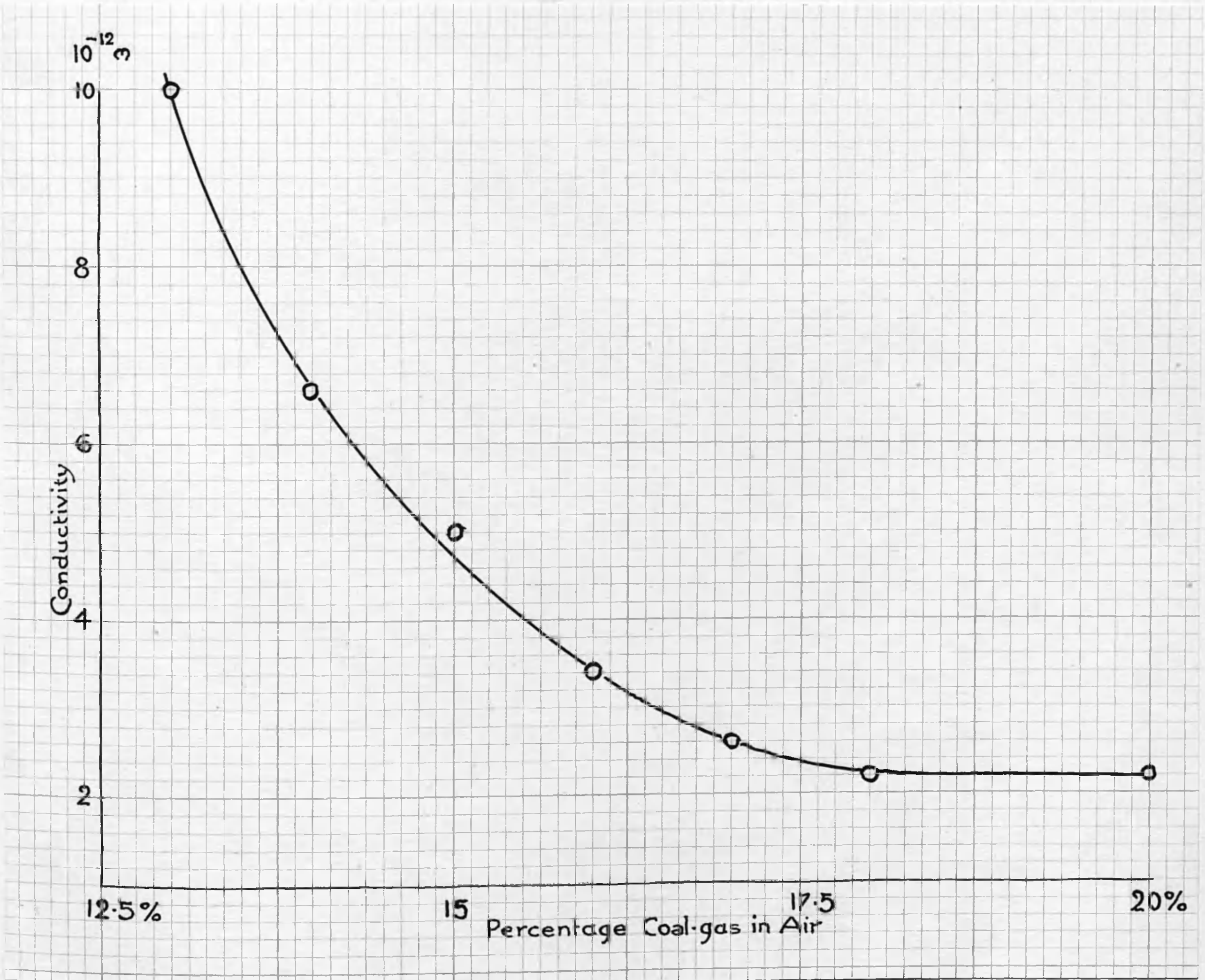


Fig. 15.

The last of these quantities multiplied by a constant and, as before, called j, is plotted against the first in fig. 16.

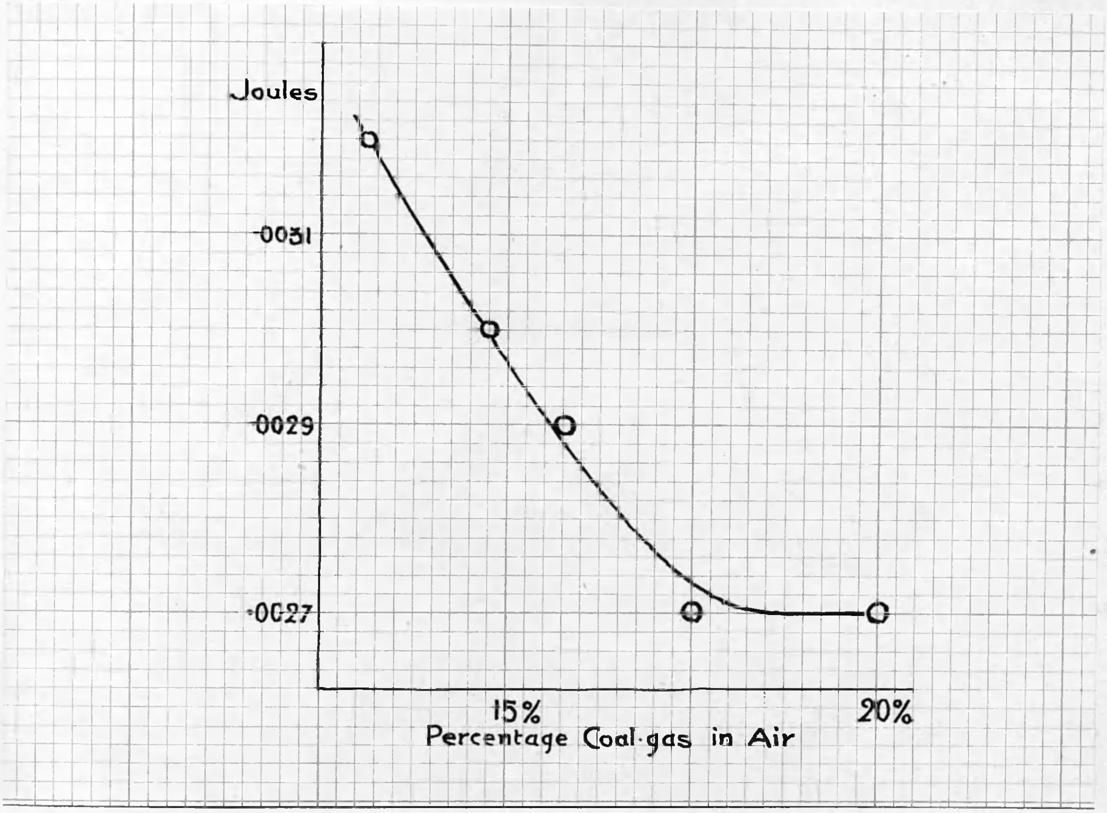


Fig. 16.

The igniting properties of the discharge are certain to depend on j which, in turn, varies with the conductivity. It is possibly more important, however, that the effective capacity of the electrodes will vary with the conductivity.

CHAPTER IV.

Ignition by discharge between high resistance electrodes (continued); Ignition by the corona discharge between points.

In the last chapter experiments were described which prove that coalgas-air mixtures may be ignited by the discharge of electricity between the surfaces of fairly good insulators (with specific resistance of the order of a million megohms per cm. per sq. cm.). Slate, of specific resistance about one fifth of a megohm per cm. per sq. cm., though often used as an insulator, is a good conductor compared to glass. Slate electrodes, across which a steady potential was maintained, were used in experiments to be recorded in this chapter. The reason for this change of electrode material is explained in the following paragraph.

When high resistance electrodes are in the form of tubes, it is not possible to find their resistance, because the area of electrode used by the discharge cannot be known. If, however, the electrodes are in the form of rods, which is not feasible with such a good insulator as glass, but is quite suitable when the electrodes are made of slate, one might expect that the greater part of the resistance of the electrodes could be measured, and that the end effect, due to the lines of flow converging to the area used by the discharge, would be a small part of the total resistance. The arrangement was used although this expectation was not fulfilled.

The apparatus which was used to maintain a steady high potential is represented in diagram in fig. 17. C is

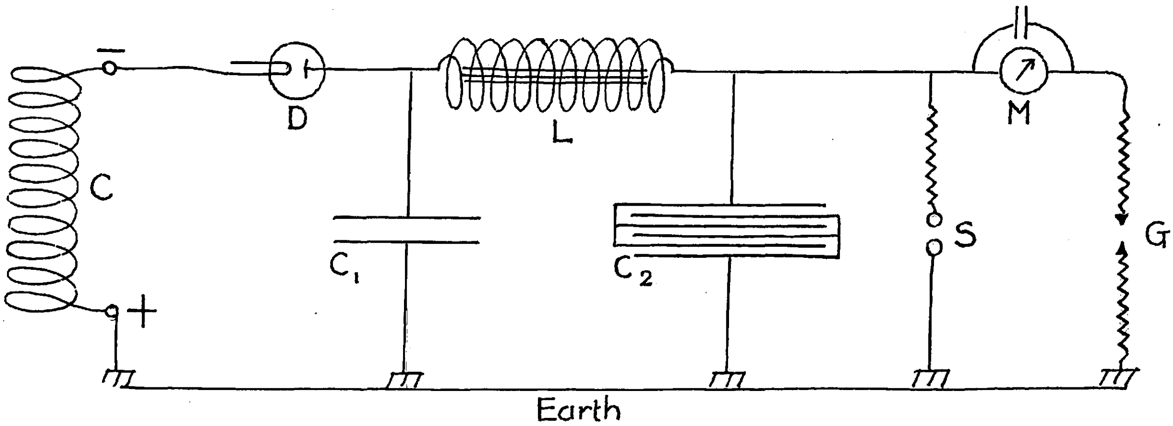


Fig. 17.

the secondary of a "36-inch" induction coil the primary of which was connected in series with a variable resistance and a mercury jet interrupter across the 250 v. mains. D is a diode valve, and the smoothing circuit consists of C_1, two "4-pint" Leyden jars, L, the secondary of an induction coil with an iron wire core, and C_2 a condenser of capacity about ·1 of a microfarad. M is a micro-amperemeter, S a sphere gap in series with a high resistance, and G is the gap at which the discharge is to be studied. The part of the circuit from D to G, which is kept at a high potential, is sheathed in paraffin wax with only the electrodes at S and G protruding.

When the apparatus was first set up it was observed that, when a discharge was passing between slate electrodes at G, the current through the meter M was not steady. Sudden, large variations in the current were due to flashing of the diode valve, which was replaced. When the basin, cone and mercury of the interrupter were cleaned and the interrupter motor was re-aligned and lubricated, slow variations in the current were no longer observed.

At this stage it was found that the least current between slate electrodes (slate pencils rounded at the end), about 5 mms. apart, which would light the coalgas-air mixture from a Fisher burner, was of the order of 200 microamperes. Thus, if there are one hundred interruptions per second the fall in potential across the capacity C_2 due to the current flowing in the discharge is

$$V = \frac{2 \cdot 10^{-4} \cdot 1 \cdot 10^{-2}}{C_2}$$

between two successive re-chargings from the coil, ignoring the effect of C_1 and L. C_2 (like C_1) was originally less than ·01 of a microfarad (two "4-pint" jars), therefore V was greater than 200 volts. Even with the smoothing effect of C_1 and L, the potential difference across C_2 coult not be called "steady." A condenser had to be obtained, of capacity ·1 of a microfarad, which would make the variations of the potential less than 20 volts, and able to stand, without break-down, the potential across the high resistance electrodes, - possibly 30,000 volts.

I made such a condenser of alternate sheets of ebonite, 44.5 x 34.5 x ·1 cm., and tin foil, 37 x 28 cms. Each sheet of tin foil had a tongue to which connection could be made. The tongues of alternate sheets projected at opposite ends. The strip, not covered by foil, round the edge of each ebonite sheet was liberally smeared with soft white paraffin. The outside sheets of ebonite were ·5 cm. thick and the edges and connections to the tongues were encased in paraffin wax. The ebonite was cleaned carefully before use. The capacity of the condenser is between ·10 and ·11 of a microfarad. A test section stood 40,000 volts without breakdown and I have not observed any leakage.

This condenser was added to the jars already in position at C_2. With this final arrangement it may be assumed that the circuit will not cause any unsteadiness in the discharge at G, although, of course, the discharge may be essentially unsteady.

When the discharge was passing at the test gap G, gas was allowed to flow from a Fisher burner below the gap. If the discharge failed to ignite the gas, the primary current was increased until ignition was obtained. If the gas ignited immediately, the primary current was reduced until the discharge did not ignite the gas, and was then increased as before. The least discharge current required, to cause ignition, was read on the microamperemeter, M, and then the earthed sphere of the sphere gap, S, was moved forward until a spark passed. The primary current was then switched off and the lengths of the sphere and test gaps were measured by taper gauges. The experiment was repeated with different test gap lengths.

The coalgas-air mixture passing through the test gap would vary in composition as the mixture from the burner mingled with the air. The burner was adjusted so that the mixture emitted contained an excess of coalgas. The mixture in the gap, therefore, would vary through the most easily ignited mixture.

In the first experiments, the test gap electrodes were slate rods, 5 mms. in diameter, with rough hemispherical ends. Their total resistance, when measured with the ends smeared with Aqudag and bound with wire, was $13.5 \cdot 10^6$ ohms. Their effective resistance, measured when the rounded ends were touching, and wire on Aquadag contact was made at the other ends, was 200 megohms.

The results obtained by the method just described are shown in Table 3.

Table 3.

Slate gap length.	Least igniting current.	Sphere gap length.
2.8 mms.	300 μa.	4.7 mms.
4.3	300	6.7
5.5	190	6.9
8.3	150	8.8

These are typical results, but they are not repeatable with an accuracy greater than twenty per cent. because of a certain electrode effect. When the discharge was started, it took place between the ends of the electrodes, but soon, within a few seconds if the electrodes had been used recently, the discharge left the end of the high potential electrode (the cathode) and proceeded from an area on the side of the rod. The cathode end of the discharge "wandered" and, usually, went further and further from the end of the electrode. During this time the current flowing might rise, or fall, or show no change, depending, no doubt, on the area of cathode used by the discharge.

New slate electrodes, 3.5 mm. in diameter, tapered at an agle of 30° to hemispherical ends, about 1.5 mms. in diameter, proved no more satisfactory. Least igniting currents were of the same order with the new electrodes as with the old. For instance, with a slate gap 5.2 mms. long, a current of 280 μa. lit the gas from the burner.

Since the discharge behaves in such an inconstant manner, it is obviously impossible to investigate its electrical characteristics. In particular, it is impossible to estimate the effective resistance of the electrodes or the potential difference across the discharge, and it cannot be known whether or not there is a rapid periodic variation in the discharge current essential to this type of discharge, as there is in the case of the spark discharge.

It seems that, though high resistance electrodes are convenient for the production of corona, metal point electrodes must be used if accurate measurements of igniting currents and electrical characteristics are to be made. At least one of a pair of such electrodes must be attached directly to a lead with a high specific resistance, such as a slate pencil, to ensure that no capacity spark passes.

A few measurements were taken by a method of this kind and are shown in Table 4. In these experiments, metal points (wires 3 mms. long by .25 mm. diameter, with convex ends) were attached to the ends of the slate electrodes and the least igniting currents were measured as before.

Table 4.

Point gap length.	Least igniting current.	Sphere gap length.
3.0 mms.	300 μa.	3.70 mms.
4.4	300	3.30
6.0	320	3.95

When metal points are used as electrodes, the potential difference across a corona discharge between them may be measured directly by an electrostatic voltmeter, provided that a high resistance is connected in series with the voltmeter, so that the capacity of the instrument cannot discharge suddenly across the gap. The insulation resistance of the voltmeter must, of course, be large compared to the series resistance. By this method it was found that the potential difference across a discharge, 3 to 4 mms. long, the current being 350 μa., was about 2,500 volts.

The results, recorded in this and the preceding chapter, are satisfactory in so far as they show, quite clearly, that an electric discharge between fairly good insulators may ignite coalgas-air mixtures and that the same is true of the corona discharge between metal points. On the other hand, it would appear that, if satisfactory experiments are to be designed, or any theoretical advance made, the characteristics of a corona discharge between points must be known. The remainder of this thesis is, therefore, an account of an investigation of the current potential characteristics of a discharge between points, in hydrogen, at various pressures.

Note.

It is difficult to choose suitable materials for high resistance leads. Slate rods with good permanent contacts at each end are fairly, but not very, satisfactory. Strips of celluloid with the ends of wires embedded in them were tried, but it was found that the resistance of a particular specimen varied quickly between wide limits, the largest value exceeding the least by more than two hundred per cent.

CHAPTER V.

Characteristics of point discharges in hydrogen.

In this investigation, hydrogen was used, rather than air, in order to eliminate chemical effects in the gas and at the electrodes. The discharge was studied at low pressures because more is already known of the discharge at low pressures and because of the smaller potentials necessary. To indicate the manner of variation with pressure, some characteristics were obtained at pressures up to 45 cm. of mercury.

The hydrogen was generated in a Hoffmann's apparatus, of a type designed by Dr. John Thomson, from which it could pass, through drying tubes, a capillary tube and a stopcock, to a discharge tube, the opposite end of which was connected to a mercury pressure gauge and through another stopcock, to a Hyvac two-stage rotary oil pump. Across the electrodes of the discharge tube was a high potential supply. Means for controlling and measuring the current through the tube and the potential across it, completed the apparatus, the details, and progressive changes, of which, will now be described.

The first discharge tube (fig.18) was a glass bulb, 15 cm. in diameter, with two open necks, opposite each other, each 2.5 cm. in diameter, on to the ends of which the flanges of copper electrodes were sealed with bees-wax and resin. The electrodes were copper wires, .2 mm. in diameter, soldered on to copper tubes.

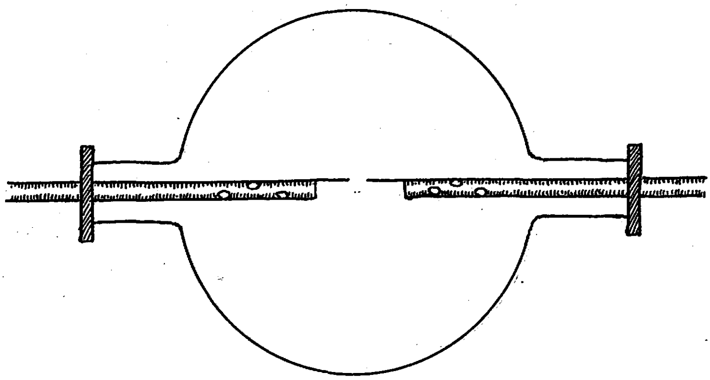


Fig. 18.

The tubes were open at both ends and had several holes drilled in the parts which projected into the discharge tube. Each was soldered into a hole in the centre of a copper disc, which formed the flange referred to above. The ends of the wire electrodes, which were 2 mm. apart, were carefully buffed and appeared rounded under the microscope. The copper tubes themselves served as the connections of the discharge tube to the hydrogen supply, on one side, and to the manometer and pump, on the other.

Copper leads were soldered on to the flanges of the electrodes and the tube was connected in the circuit shown diagrammatically in fig. 19. T is the discharge tube, across

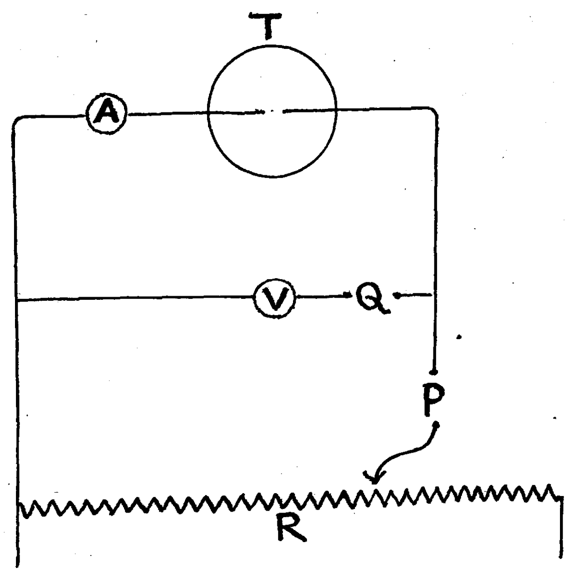


Fig. 19.

which a potential difference was maintained by the potentiometer, R, of 12,000 ohms, across a 3,000 volt D.C. generator. A was a current meter and V an electrostatic volt-meter. At P and Q there were devices to prevent a large current flowing through the tube, either from the generator or from the capacity of the electrostatic instrument. The permutations of two valves and two high resistances taken two at a time were tried at P and Q. When there was a valve either at P or at Q it was not found possible to prevent the tube from flashing when the mean current through the tube was less than that necessary to maintain a normal glow discharge. High resistances, in the form of short lengths of twine, were used.

After the tube had been evacuated and flooded with hydrogen a large number of times, a few curves of the form of fig. 20 were obtained. The abscissae are readings on a Kelvin, Bottomley and Baird electrostatic voltmeter, across the tube (at V, fig. 19), and the ordinates are corresponding readings on a Cambridge Unipivot table galvanometer (at A). These curves were not repeatable and the sparking potential of the tube, at

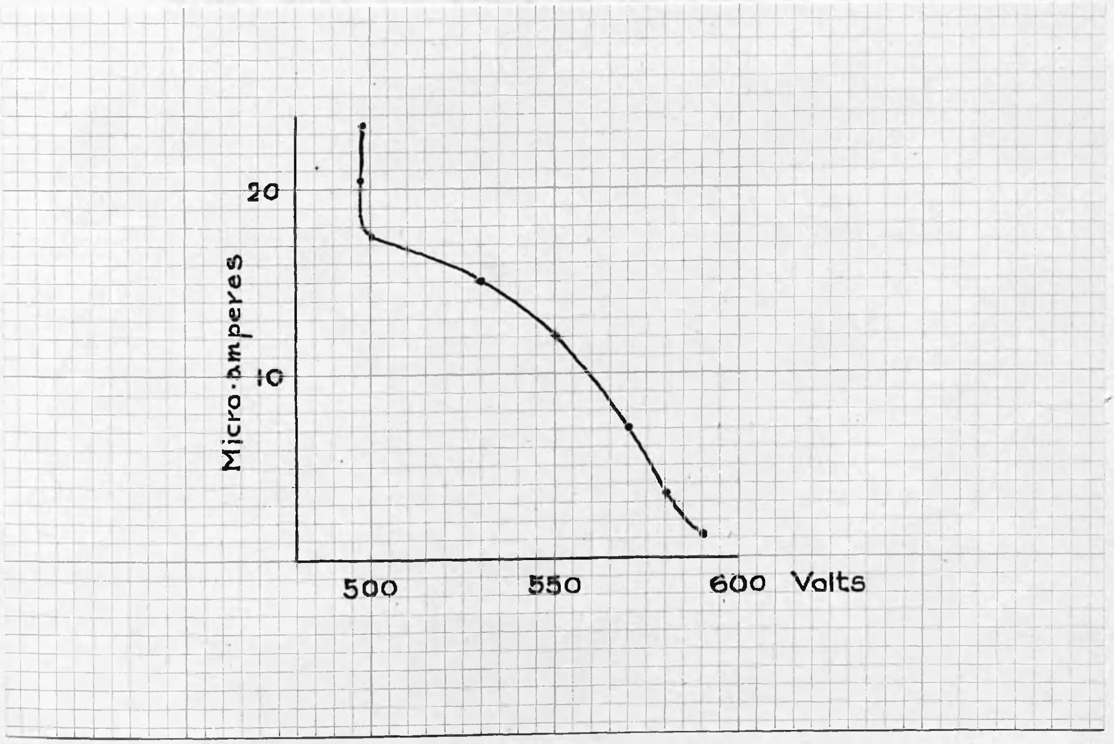


Fig. 20.

any given pressure, was very variable. It was assumed that these variations were due to impurities in the gas, given off from the electrode surfaces and from the walls of the tube. To clean up the tube, a high frequency discharge was passed inside it, while it was washed with hydrogen. The high frequency voltage was obtained from a large Tesla coil, 8 turns of which formed part of the tuned anode circuit of a triode oscillator. The whole coil was connected across the electrodes of the tube. After this clean up, the tube still did not behave consistently, so it was discarded.

A new tube was made, in the form of a T-piece of glass

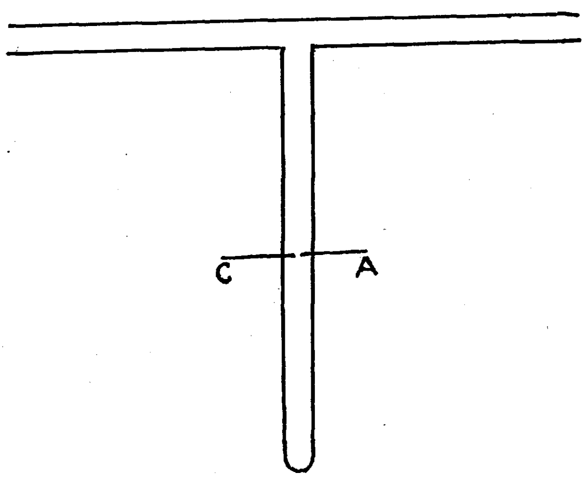


Fig. 21.

tubing of half-inch bore (fig.21). The vertical tube of the T was closed at the end and the horizontal tube, the ends of which were open, fitted the position in the vacuum system which had been occupied by the former tube. The electrodes, C and A, were platinum wires, .21 and .22 mm. in diameter, sealed through the walls of the vertical tube. The ends of the wires were 2.3 mm. apart.

This tube was pumped out and washed with hydrogen as the last one was. In this case, however, a high frequency potential was not applied to the electrodes, but an electrodeless high frequency discharge was made to pass in all parts of the tube.

The sparking potential of this tube at any given pressure was not constant, either when the lower end of the tube was surrounded by liquid air or when it was not. It was observed, however, that the largest differences were between the sparking potential when the tube was filled with gas which had remained in the drying system for some considerable time and the sparking potential in gas which had been pulled through the drying system fairly quickly. To make the drying system more efficient, a new drying tube was inserted between a capillary tube from the drying tubes already in position and another capillary tube leading to the first tap of the vacuum system. This tube was 120 cm. long and 2.5 cm. in diameter and it contained 6 oz. of phosphorous pentoxide. The whole system was again thoroughly washed with hydrogen.

With this arrangement, conditions in the discharge tube were not steadier, but much less steady. The only uncontrolled effects, which would obviously increase in magnitude with increasing dryness of the gas, were effects due to charges on the glass walls of the tube. These effects would be less important if the walls of the tube were further from the discharge. It was decided, therefore, to use the large tube again, with different electrodes.

The new arrangement is shown in fig. 22. The electrodes A and B were tungsten wires. Each was jammed tightly between the inside of a neck of the tube and the outside of a glass tube, C, D, bound with twine which was impregnated with vacuum wax, and fitted to the neck. The joints at the necks and to the rest of

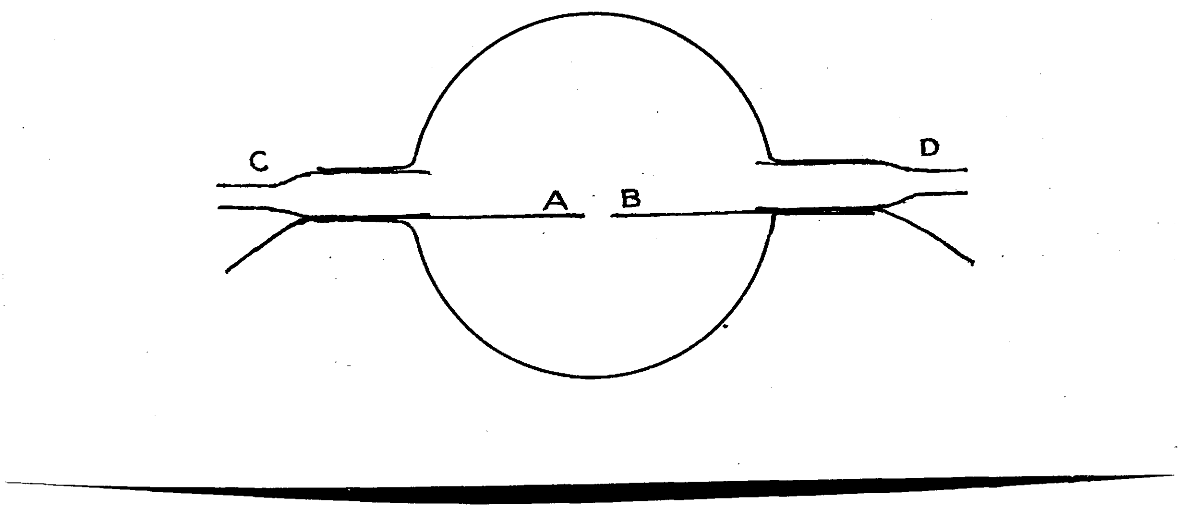


Fig. 22.

the system were sealed with the wax.

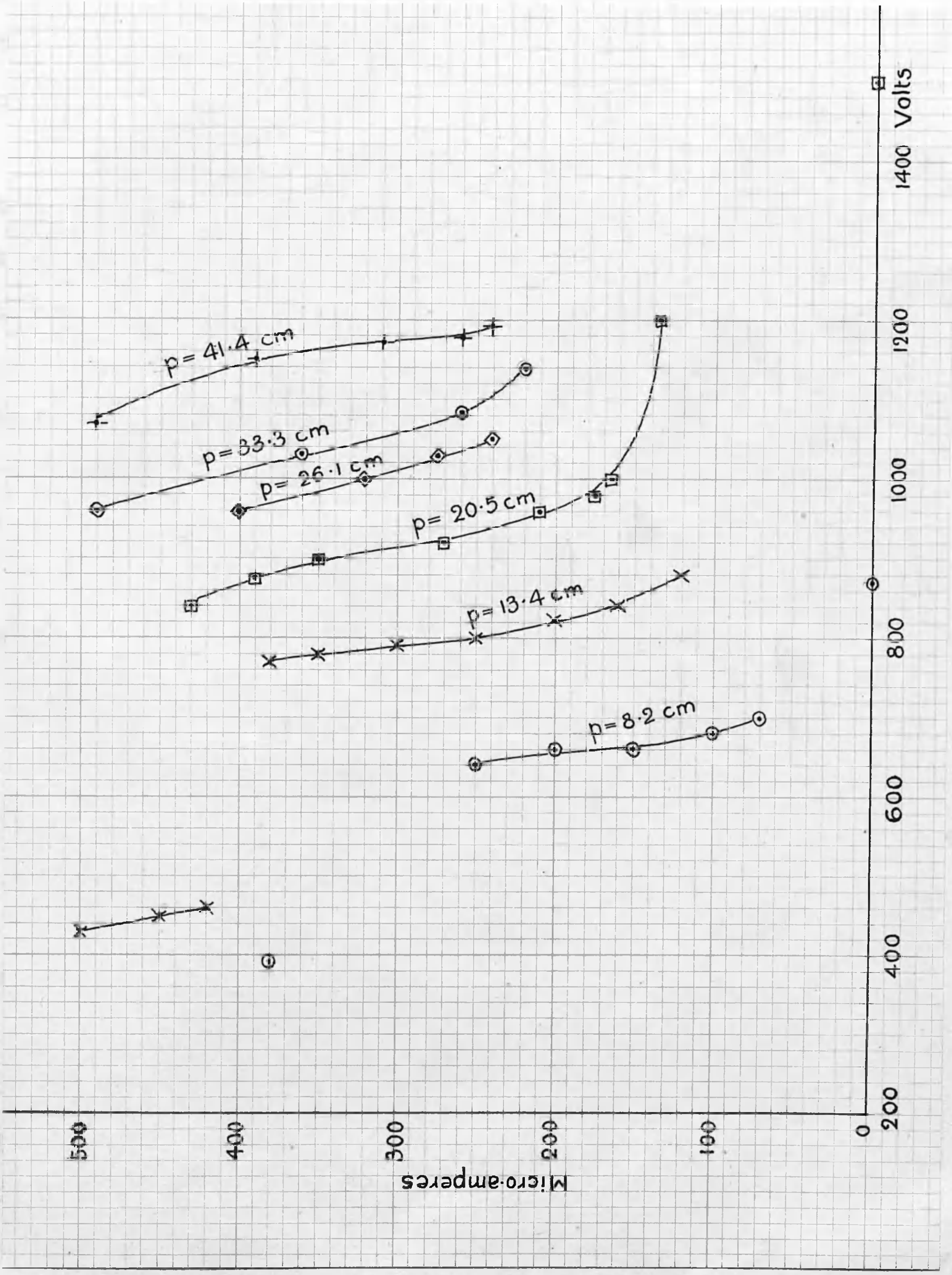
The first tungsten electrodes were wires, .2 mm. thick, separated by a gap 2 mm. long. When a discharge current of about 500 microamperes was passing between these electrodes, with a resistance of a megohm in the circuit, the current increased suddenly and the discharge became an arc. After the supply had been switched off it was seen that the dark oxide coating had disappeared from the anode, which had now the bright surface of the clean metal. Also, the anode was bent downwards and it was found, when the tube was dismantled, that the cleaned metal was very brittle and could not be bent back into position. I tried to strike the arc the other way (making the anode the cathode) but failed, either because the electrodes were now further apart or because the effect depended on copious emission of electrons from the oxide.

These electrodes were replaced by tungsten wires .5 mm. in diameter, and the tube was again pumped and cleaned. A small arc was struck, between the ends of the electrodes, when there was hydrogen, at a pressure of 16 cms. of mercury, in the tube. This arc removed the oxide coating from the ends of both electrodes, but more from the anode than from the cathode.

As this discharge tube showed much more constant characteristics than the previous ones, it was now possible to make definite observations on a phenomenon which had already been noticed, namely the time lag in the striking of the tube, when the potential across it had been raised above the sparking potential. The circuit shown in fig. 19 was used, with slate resistance at P and Q. When the pressure of hydrogen in the tube was 9.5 cm. of mercury, the sparking potential, taken to be the least potential at which a galvanometer, in series with the tube or the voltmeter at V (fig. 19), showed small "kicks", indicating that the tube was flashing, was between 900 and 950 volts. If no discharge had been passed through the tube, for an hour or more, and the potential across it were raised to 2,000 volts, no discharge would pass for some time. This time was usually 3 or 4 minutes, but sometimes less, and occasionally as long as 10 minutes. It is reasonable to suppose, therefore, that this initial time lag is a "chance" effect, depending, perhaps, on the random distribution of ions before the potential is applied.

When the potential difference, across the tube, and the resistance in series with it, was reduced until the current through the tube ceased, and then increased again, the tube started to flash at the sparking potential. As the potentiometer potential was still further increased, the tube continued to flash and the apparent sparking potential increased until, at a mean current of 50 microamperes, the potential across the tube dropped suddenly and, when 70 microamperes was flowing, the current and tube voltage became apparently steady. This steady value of the potential was 650 volts. The rise in apparent sparking potential, or "peak potential during a flash", and its connection with time lag, has been studied by Clarkson.(1)

By still further increasing the supply of power to the tube, a series of steady readings of the current through the tube and the corresponding potential across the tube were obtained. The current meter, by Crompton, had a full scale deflection corresponding to 500 microamperes and the electrostatic voltmeter, by Nalder Bros. and Thompson, covered the range from 300 to 2,500



Volts
200
400
600
800
1000
1200
1400
Micro-amperes
0
100
200
300
400
500
p = 41.4 cm
p = 33.3 cm
p = 26.1 cm
p = 20.5 cm
p = 13.4 cm
p = 8.2 cm

Fig. 23.

volts. Calibrations of these instruments are appended to this chapter.

The curves, plotted in fig. 23, show results obtained in this way, at various pressures. The points marked on the voltage axis indicate sparking potentials, and these, with others similarly obtained, are re-plotted, against the pressure, in fig. 24. The gradient of the straight line drawn in fig. 24 is 28.3 volts per centimeter of mercury per millimeter of gap width. The apparent initial cathode fall, i.e. the intercept that this line makes on the voltage axis, is 380 volts.

Fig. 23 illustrates the following experimental facts concerning this point discharge in hydrogen.

(1) At a given pressure there is a definite sparking potential.

(2) A steady corona discharge may be caused to pass across the gap, provided that the current is within a certain range of values, this range depending on the pressure.

(3) The steady corona current-potential characteristics have a negative slope.

(4) There are regions between the sparking potential and the corona characteristic and between the corona characteristic and the glow characteristic in which a static characteristic cannot be obtained.

It must be noted that the word "steady" means apparently steady on measuring instruments with ponderous moving parts. The electrostatic voltmeter used had a period of about a fifth of a second and was almost dead-beat. In the experiments to be

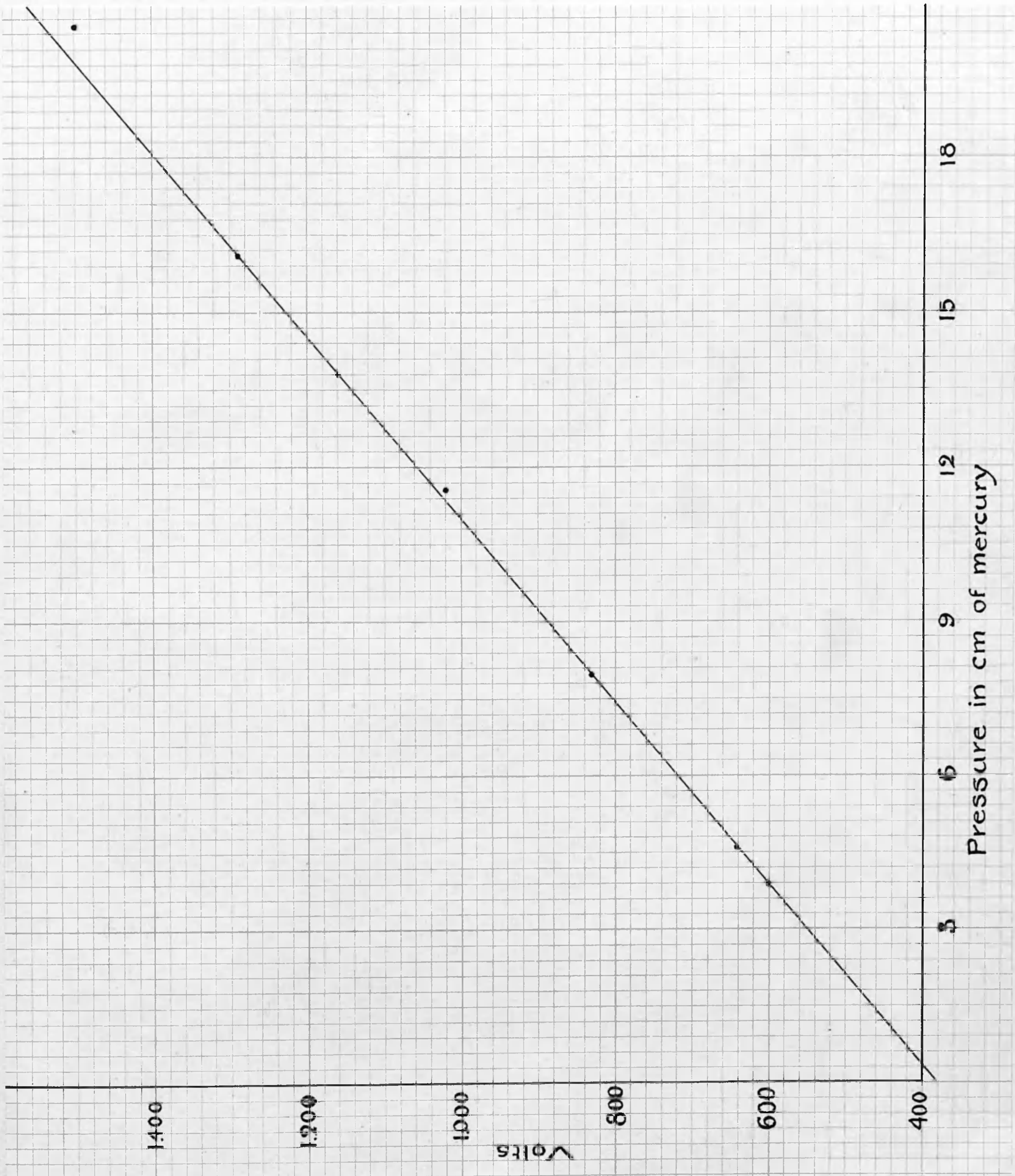

Volts
400
600
800
1000
1200
1400
Pressure in cm of mercury
3
6
9
12
15
18

Fig. 24.

described below it will be shown that, though each point on a characteristic of fig. 24 corresponds to a stable and repeatable condition, the points represent mean values of current and potential during a periodic variation of these quantities.

To investigate the variations of the current through the tube and the potential across it, while an apparently steady corona current was passing, some oscillograph records of these quantities were obtained. A Cossor cathode ray oscillograph was connected so that the pattern on the fluorescent screen was the graph of the current through the tube, as ordinate, against the potential across the tube at the same moment, as abscissa.

Several arrangements of the apparatus were tried and the one illustrated in figs. 25 and 26 were found most satisfactory. In fig. 25 the discharge tube used in the previous experi-

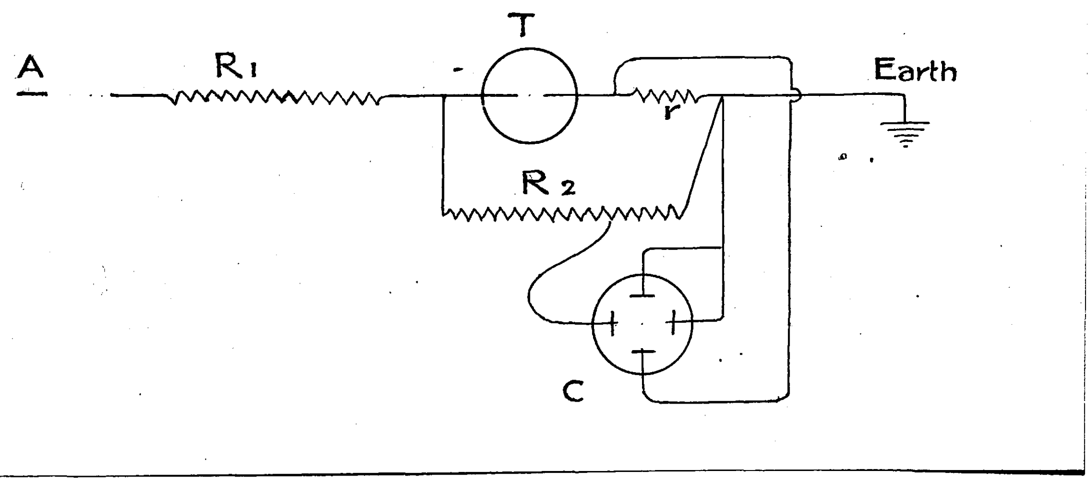


Fig. 25.

ments is represented at T. R_1 and R_2 were slate or "metalised" resistances and r was a wire wound resistance. The deflecting system of the cathode ray oscillograph is shown at C. The point A was connected to the high potential (negative) end of a high tension supply, similar to the system described in Chapter IV (fig. 17). It was necessary to use this method, to obtain the high potential across the tube and the series resistance R_1, as the voltages across R_1 had to be higher than before because the current through the parallel resistance R_2, as well as the current through the tube, had to flow through R_1. A current meter could be connected into the earth lead, and an electrostatic voltmeter across the tube. The connections to the other electrodes of the oscillograph are shown in fig. 26.

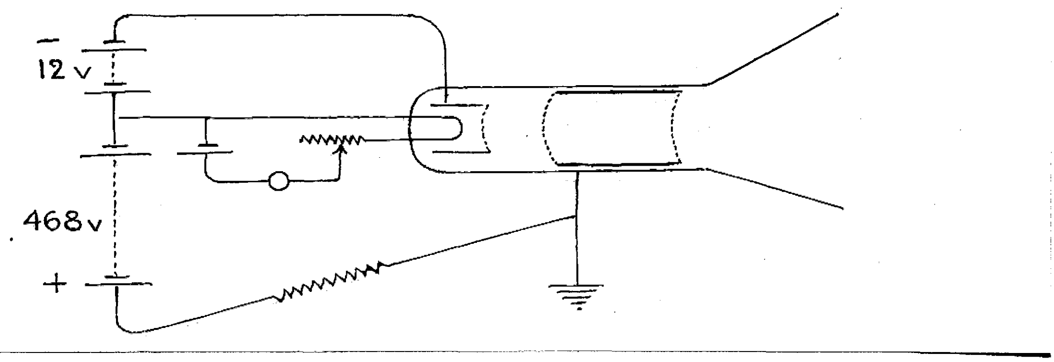


Fig. 26.

The horizontal deflection of the electron beam was proportional to the potential difference across the tube and the resistance r (fig. 25) and the vertical deflection was proportional to the current flowing through the tube. The potential difference across r (10,000 ohms) was always small compared to potential difference across the tube so that no change of axes to obtain the true characteristics, on that account, was considered necessary.

Since the oscillograph was not magnetically shielded and the zero position of the spot had to be adjusted by the field of a bar magnet, the actual axes on the fluorescent screen were slightly curved. Fig. 27, showing the shape of the axes, is taken from a photograph. The points were obtained by applying

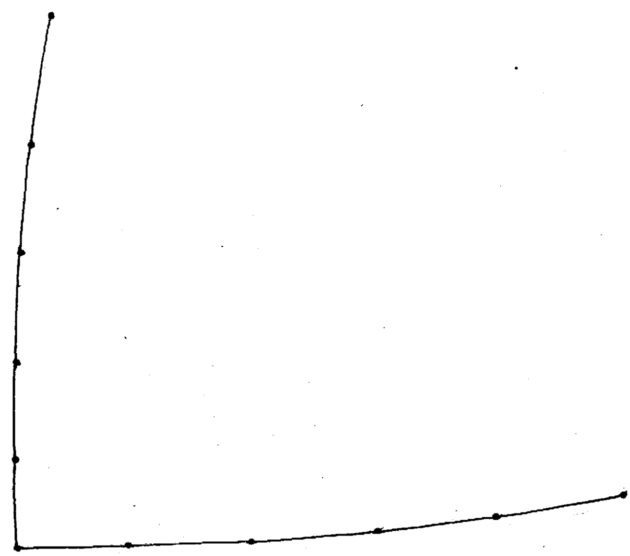


Fig. 27.

steady potentials to the deflecting plates.

The camera with which this, and the photographs referred to below, were taken, was a quarter-plate Thorton Pickard Imperial, with triple extension focussed to give unit magnification. The quartz lens was stopped down to f/64 and Imperial Ordinary plates (H. & D. 90) were used.

Photographs were taken in the following manner. The camera shutter was opened while the oscillograph spot was in its zero position. The interruptor of the induction coil was then started, so that, as the high potential system charged up, the spot moved along the potential axis until a discharge started in the tube. When this discharge was steady, that is to say, when the current through the tube and the potential across it had constant values, the spot on the screen took up a position corresponding to these values. The resistance in the primary of the induction coil was then varied in steps, so that a series of points were photographed, and then the camera shutter was closed.

When the discharge was not steady, the pattern, traced out by the periodic movement of the oscillograph spot, was photographed in the same way. Spots, indicating steady values of current and voltage, and a pattern or patterns, could be photographed on the same plate, and the current axis could be obtained by short-circuiting the potential plates of the oscillograph while a periodic discharge was passing through the tube.

The characteristics so obtained, at pressures from 5 mm. to 2 cm., showed no unusual features, and fig. 28 may be taken as typical. The pressure in the tube was 5 mm. of mercury. One two-volt cell, in series with a variable resistance, was used in the primary of the induction coil and the resistance in series with the tube (R_1, fig. 25) was varied in steps between one and seven megohms. The line AB (fig. 28) represents that part of the static glow characteristic on which points were obtained. Increasing the series resistance from one to seven megohms only lowered the lower current limit for steady readings from 135 microamperes to 120 microamperes. The loops at C were obtained

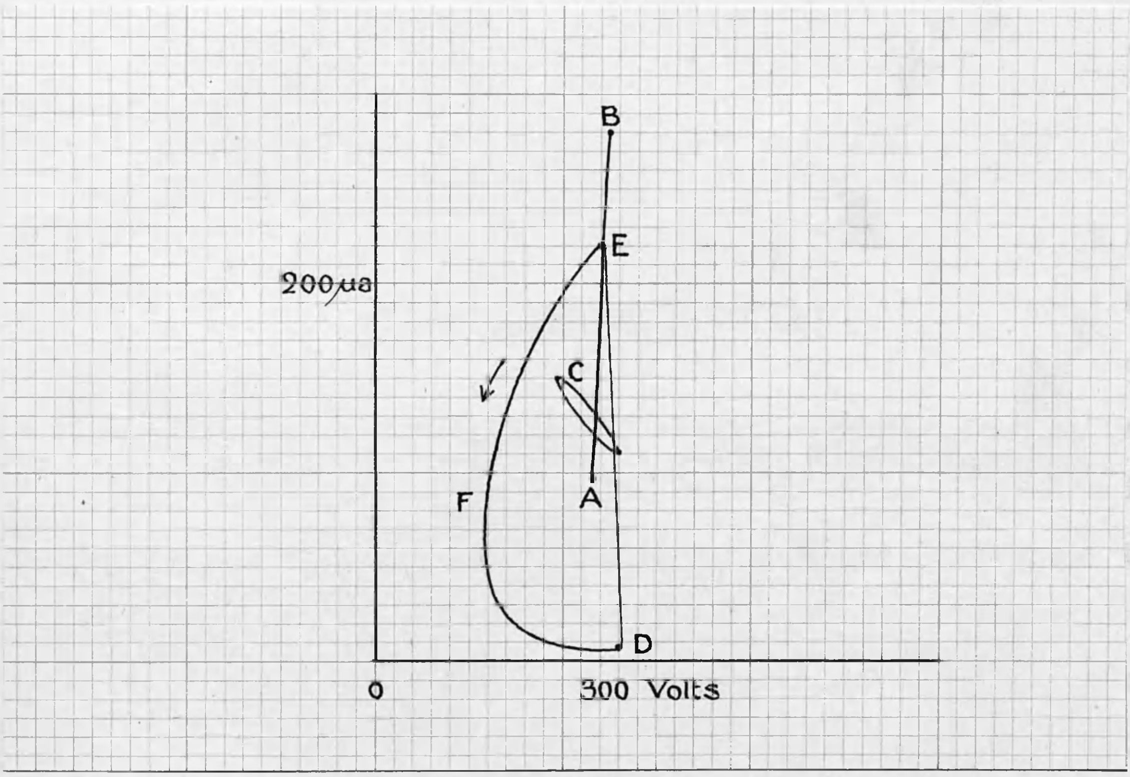


Fig. 28.

with one megohm in series and a mean current of 130 microamperes. When the supply of electrical energy was reduced until the mean current was less than 120 microamperes "flashing" set in. The curve DEF shows the cycle of repeated values assumed by the current and potential when the mean current through the tube was

60 microamperes. It will be observed that this curve confirms the assumption of previous workers that the discharge "builds up" when the representative point is to the right of the static characteristic and "clears up" when the point is to the left. It will be shown below that this is not always the case. It is interesting to compare the curve DEF with the curves assumed and drawn in a figure in a paper by W. Clarkson.[2] No static corona characteristic could be found.

At slightly higher pressures a new and surprising phenomenon was observed. It was found that the current through the tube and the potential across it could vary, through a cycle of values, without crossing the stable characteristic, although, during part of the cycle, the current was considerably larger than the smallest obtainable stable current. To explain this result, it is only necessary to assume that the discharge, through a given tube, at a particular pressure, does not assume the glow form immediately the current through the tube reaches a particular value, but that a current of this value, or in excess of it, must be maintained for some time, before the space charge distribution, associated with the glow form of discharge, is built up. If the duration of a flash is shorter than this time, a large current may flow while the discharge remains in the corona form.

This effect is shown very clearly in fig. 29, which is a contact print from the negative exposed to the oscillograph pattern. The pressure in the tube was 3.4 cm. of mercury and the

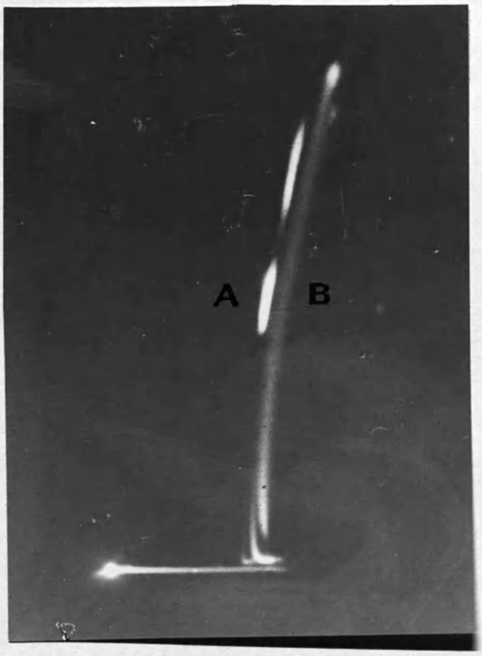


Fig. 29.

series resistance was one megohm. The short line, A, on the glow characteristic, and the corona dynamic characteristic, B, were visible at the same time, showing that the discharge was alternating rapidly between the glow and corona forms. Increasing the mean current moved the representative point up the glow characteristic. Other dynamic corona characteristics were obtained by decreasing the mean current.

As the pressure in the tube was still further increased the whole pattern retained its form and increased in size. That the form of dynamic corona characteristics is the same, at a pressure of 45.5 cm. of mercury, as at the lower pressures, is shown in fig. 30, which is from a photograph taken at this, the highest pressure used. Curve A corresponds to a mean current of

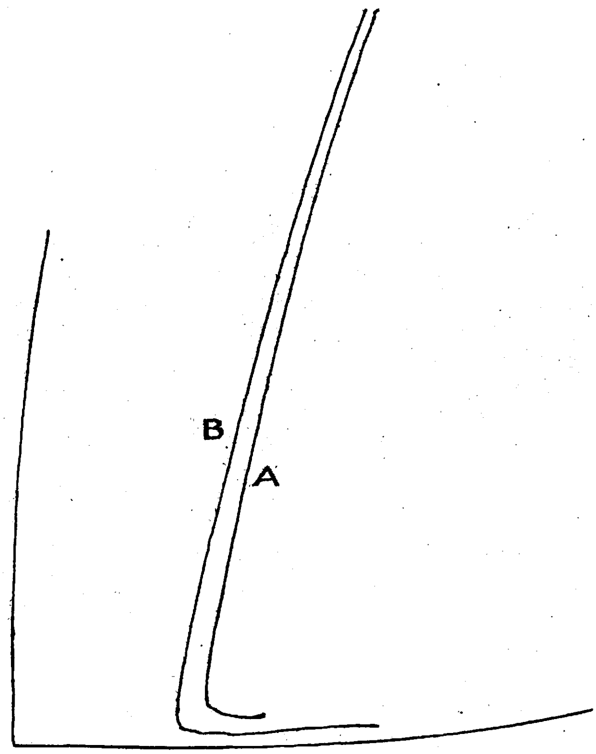


Fig. 30.

600 microamperes and curve B to a mean current of 450 microamperes. The "spark" or "build up", part of the characteristic is not shown because it was swept too quickly to appear on the screen.

It is instructive to compare the photographed characteristics with the curves drawn from meter measurements. In fig. 31, curve A was plotted from meter readings taken while the photograph,

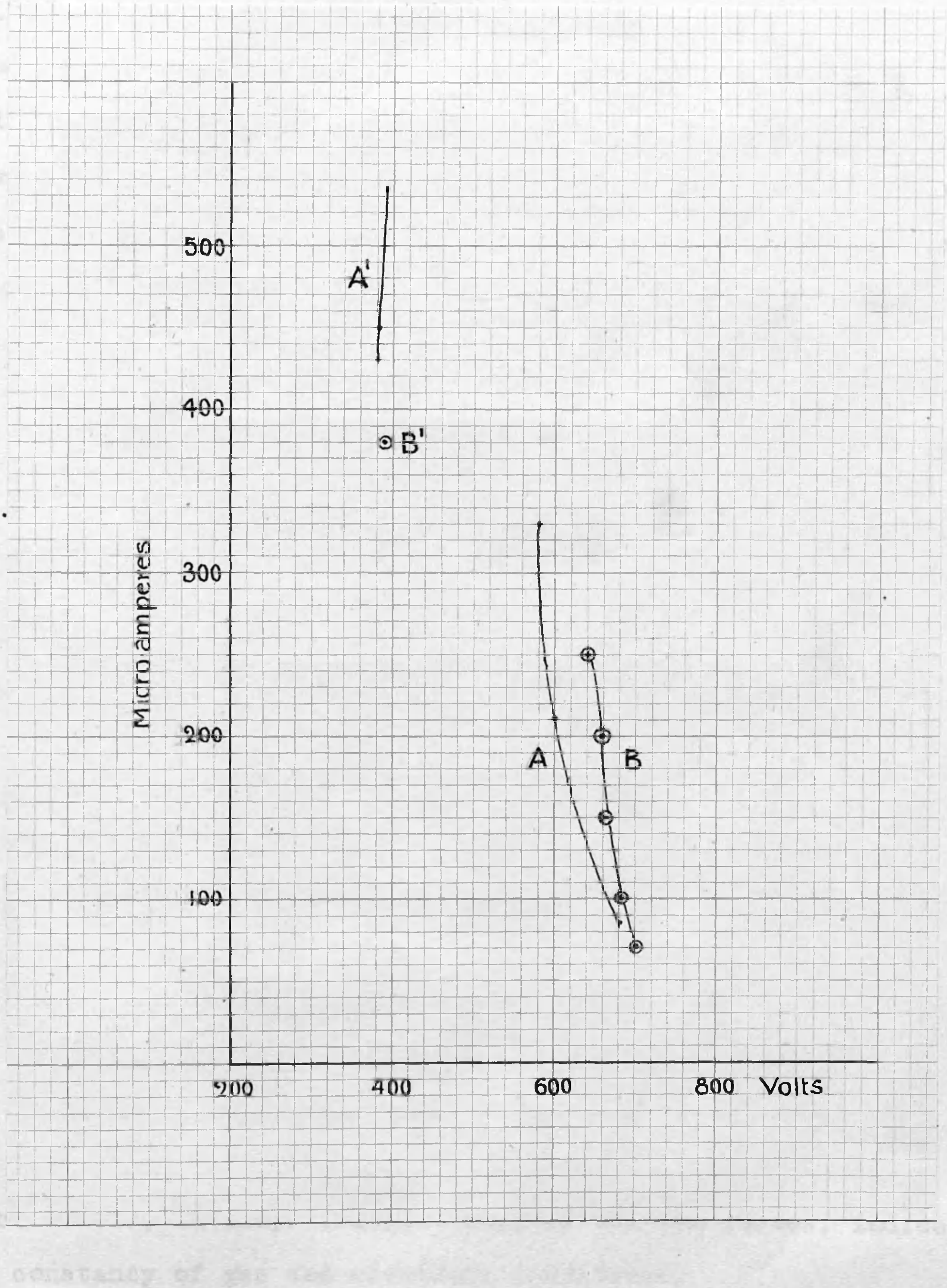


Fig. 31.

fig. 32 was being exposed. The part A' corresponds to steady values of current and voltage and the part A to mean values during corona flashes. The pressure was 7.9 cm. of mercury. Curve B is taken from fig. 23 and represents measurements taken at a pressure of 8.2 cm. of mercury. Two months elapsed between the recordings of the curves B and A.

Fig. 32.

The closeness, in shape and position, of the two curves, indicates good constancy of gas and electrode conditions.

It must now be deduced that each point, on the corona characteristics drawn in fig. 23, represents mean values of current and potential during the traversal, by the representative point, of a particular dynamic corona characteristic.

The investigation described in this chapter has led to results which, though interesting in themselves, tend to emphasize the very great difficulties to be overcome before a mathematical theory of ignition by corona discharges is possible, rather than to remove them.

(1) W. Clarkson.
"The Lag in Electrical Discharges".
Phil. Mag., IV, p.121. (1927).

(2) W. Clarkson.
"Condenser Discharges in Discharge Tubes".
Phil. Mag., IV, p. 1002. (1927).

Appendices to Chapter V.

I.

In order to compare the characteristics, of the discharge between points, with those of a discharge between electrodes of larger area, I photographed cathode ray oscillograph traces of the characteristics of a neon discharge lamp. The electrical connections to the oscillograph, an Ardenne tube, and to the lamp are shown in fig. 33. The cathode ray accelerating potential,

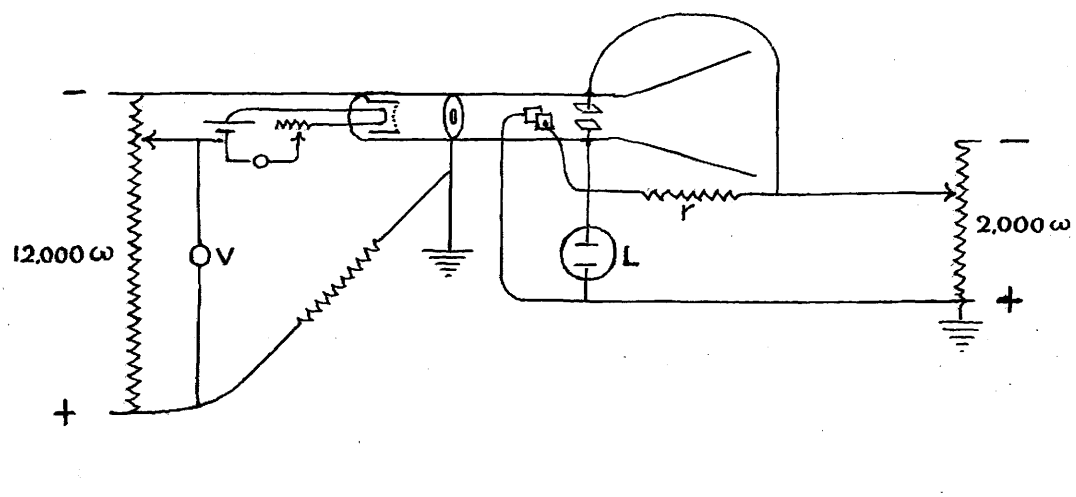


Fig. 33.

1500 volts, was obtained from a D.C. generator and the supply to the lamp, L, was a potentiometer across the 250-volt D.C. mains.

When r (fig. 33) was one megohm the discharge in the lamp took the corona form and was steady, so that the representative point remained on the static boundary characteristic. The static characteristic, therefore, could be photographed in the following manner.

The shutter of the camera was opened and the potential difference across the lamp was increased until the sparking potential was reached. The potential difference across the lamp and the resistance r was then further increased smoothly and slowly so that the path of the spot on the oscillograph screen was photographed. Fig. 34 is such a photograph. It will be observed that this static characteristic has a shape somewhat similar to the curves of fig. 23.

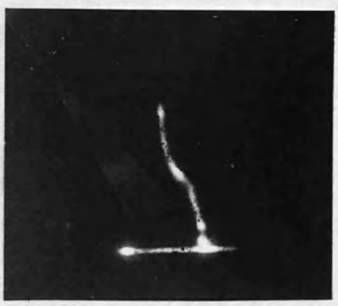


Fig. 34.

Part of the glow characteristic was obtained in the same way, with r equal to 100,000 ohms, and the corona and glow characteristics, for both polarities of the lamp, which is not symmetrical, are plotted on the same scale in fig. 35.

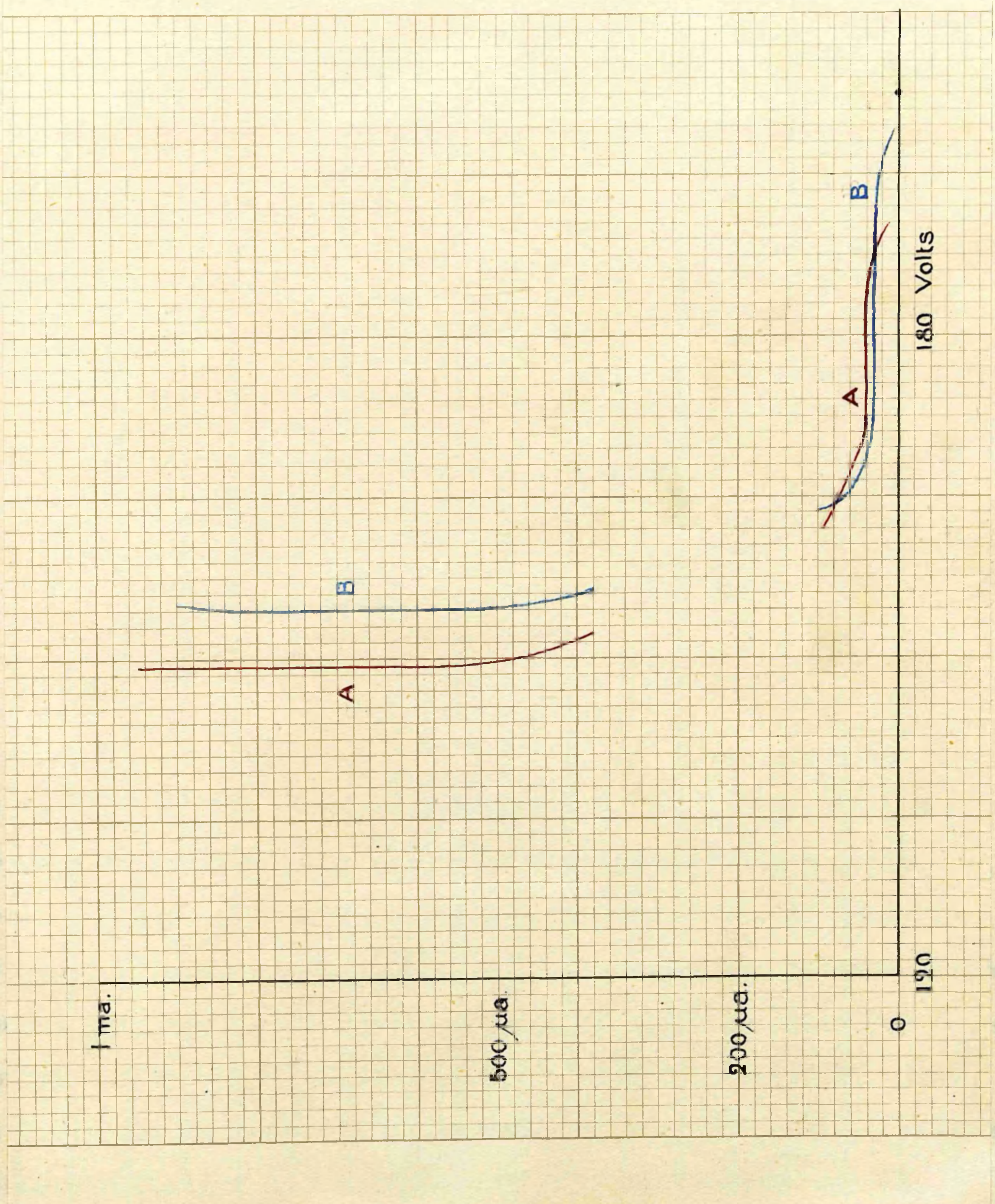


Fig. 35.

Fig. 36 shows the corona characteristics obtained when a condenser, of capacity 160 $\mu\mu$f., was connected across the lamp.

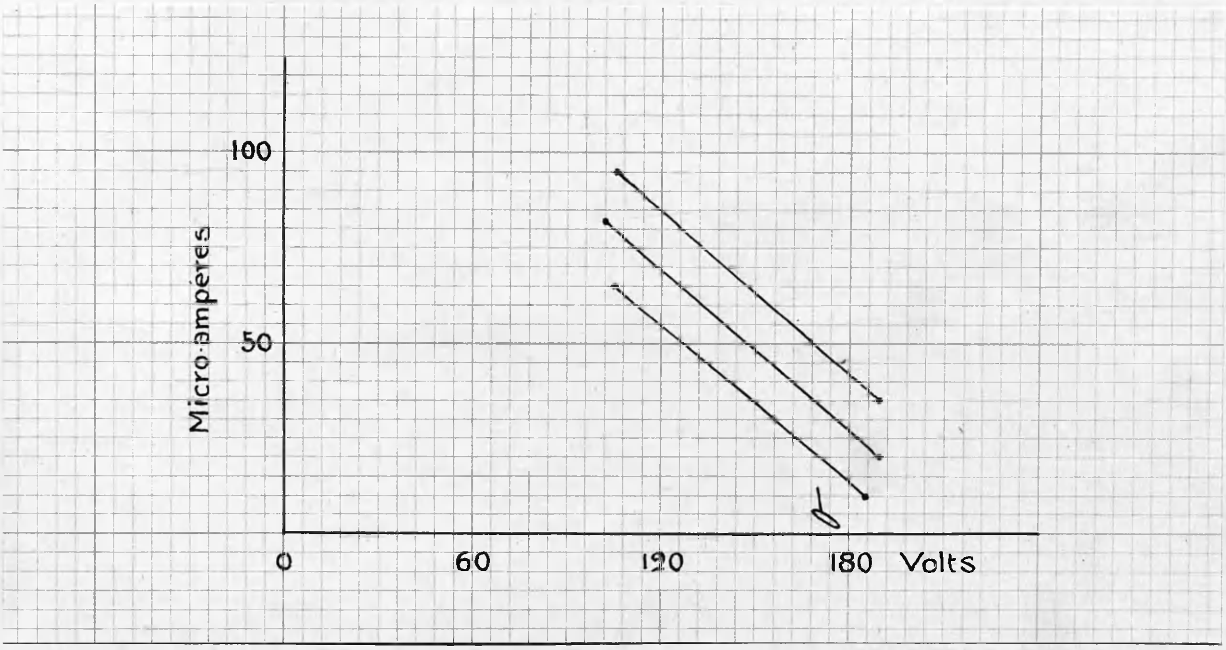


Fig. 36.

The small loop close to the potential axis is the dynamic characteristic of the discharge which takes place when the potential across the lamp is increased until a discharge just passes. When the power supply to this discharge is increased the current becomes steady, and, for a small range of current, a static characteristic, represented by the short line above the loop, is obtained. When the supply of power is still further increased the current becomes unsteady again and a line appears on the oscillograph screen. This line moved away from the potential axis as the mean current was increased.

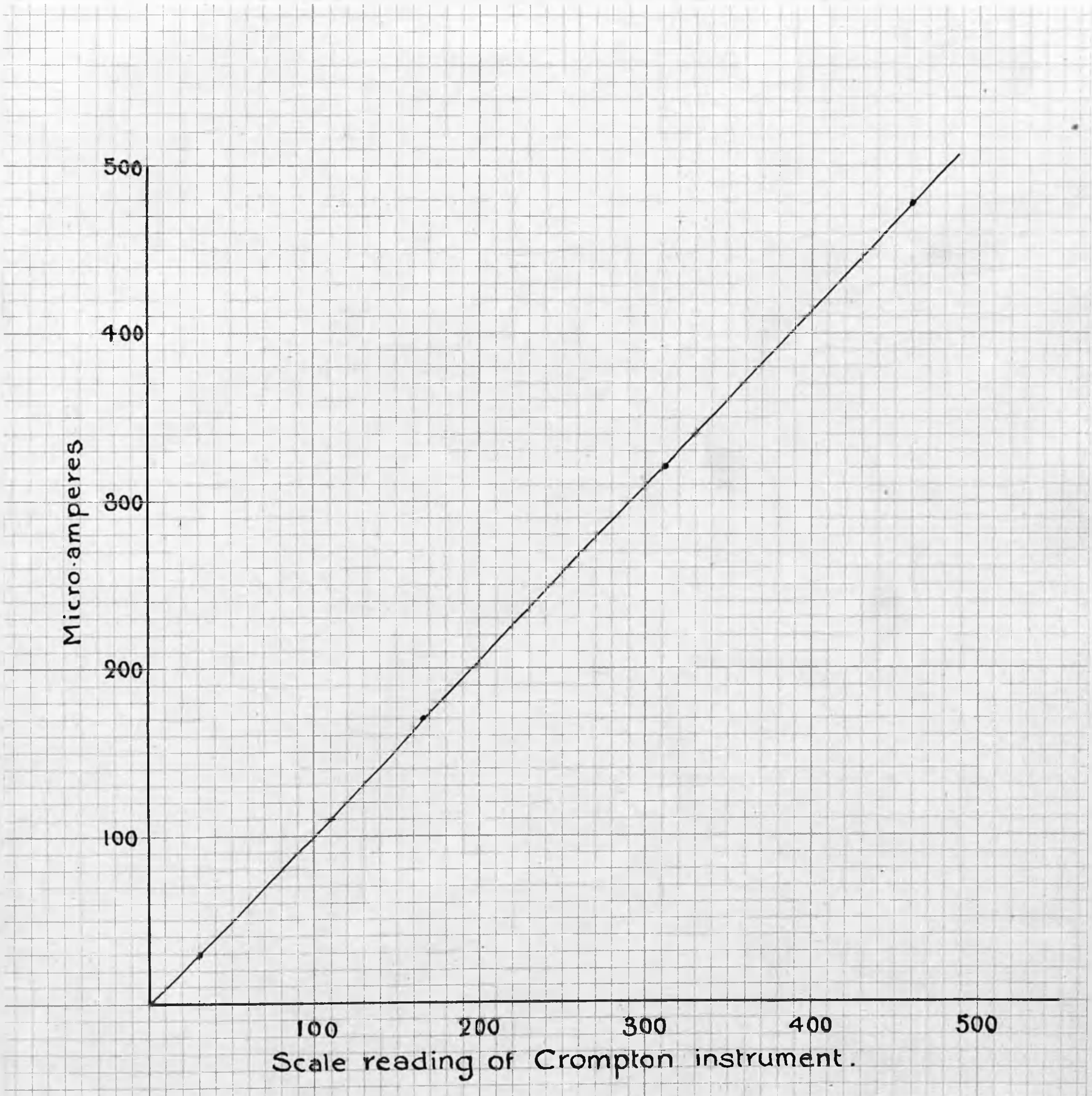

500
400
300
200
100
Micro-amperes
100
200
300
400
500
Scale reading of Crompton instrument.

Fig. 37.

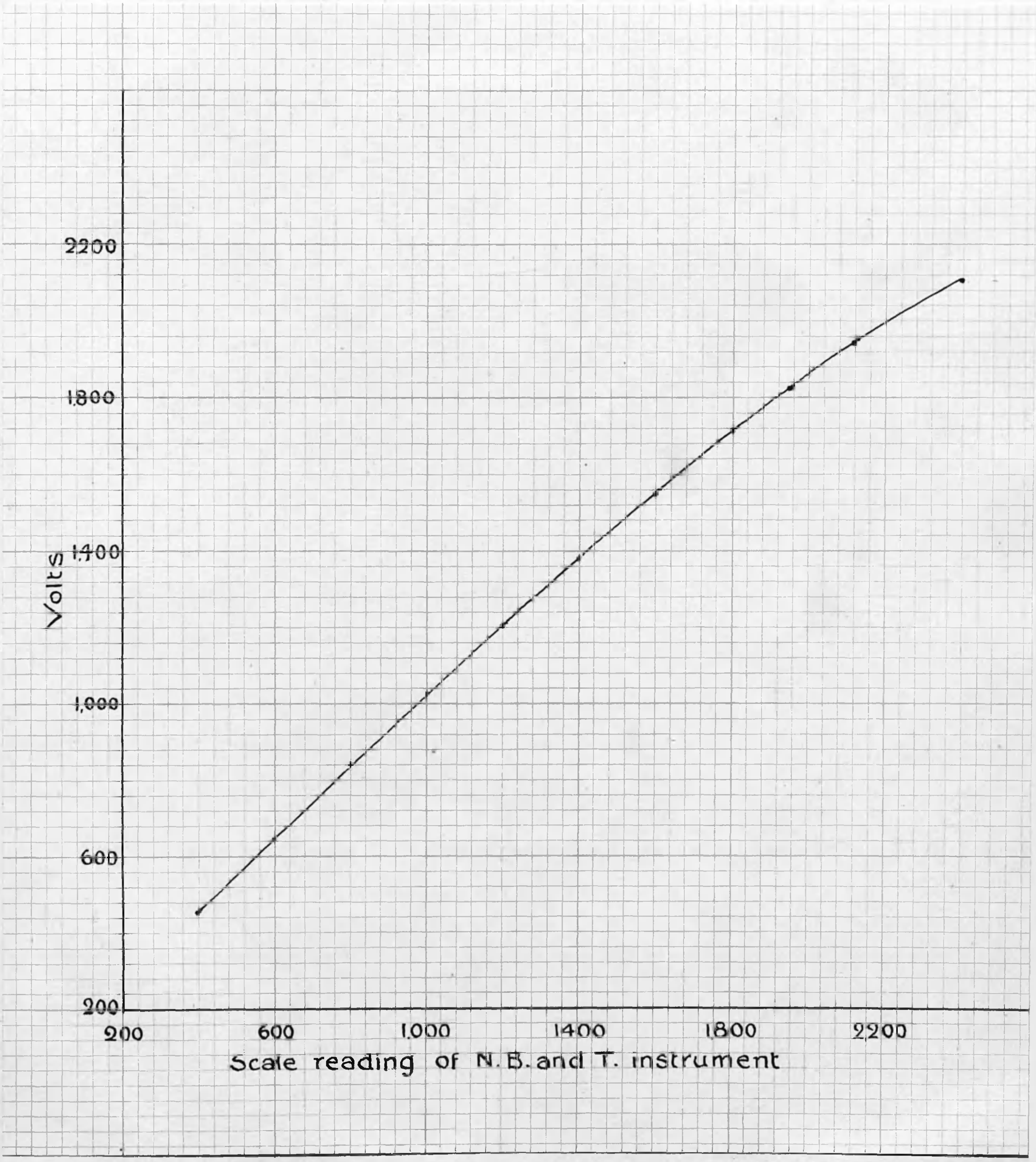

2200
1800
1400
1,000
600
200
Volts
200
600
1,000
1400
1800
2200
Scale reading of N.B. and T. instrument

Fig. 38.

II.

Fig. 37 is the calibration of the Crompton microamperemeter and fig. 38, of the Nalder Bros. and Thompson electrostatic voltmeter used in the experiments described in this chapter. The standards used were a standard megohm and a Weston standard voltmeter. A Kelvin, Bottomley and Baird electrostatic voltmeter was found to be correct against these standards to the accuracy with which the instruments could be read.

SUMMARY.

1. Ignition of inflammable gaseous mixtures by sparks and by break arcs has been investigated by many workers and a theory developed, but only passing and contradictory references have been made to ignition by corona discharges.

2. It was not found possible to perform, satisfactorily, experiments which depended on the charging of an insulating surface, to a given surface density, by contact with a charged metal surface.

3. Only negative results were obtained, when attempts were made to ignite coalgas-air mixtures by the discharge of electricity between the surfaces of good insulators, such as paraffin wax, ebonite, or cold glass.

4. It is possible to ignite inflammable coalgas-air mixtures by the discharge of electricity between the surfaces of less good insulators, such as white fibre, glass at 100°C., or slate.

5. Mixtures of 12 to 20 per cent. coalgas in air may be ignited by the induction coil discharge between glass electrodes at about 100°C., 5 mm. apart, when the total energy of the discharge is about .003 joules.

6. A steady corona discharge, between slate electrodes, 3 or 4 mm. apart, carrying a current of about 300 microamperes, will ignite the most easily ignited coalgas-air mixture.

7. The steady corona discharge, between metal points, 3 to 6 mm. apart, will ignite the most easily ignited coalgas-air mixture, when the current is greater than 300 microamperes.

8. Current-potential characteristics of a corona discharge between tungsten points, in hydrogen, at pressures up to 45 cm. of mercury, were investigated. It is shown that apparent "static" characteristics, obtained by measuring current and potential on massive instruments, are really, in this case, the loci of the centroids of dynamic characteristics.

9. The instantaneous value of a corona current may be very much larger than the least possible glow current, for the same electrode geometry and pressure.

10. Dynamic corona characteristics in hydrogen have the same form at a pressure of 45 cm. of mercury as at 3 or 4 cm. of mercury.