On the sparking potentials of electric discharge tubes

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op Woensdag 28 September 1927, des namiddags te 3 uur

DOOR

JAMES TAYLOR

geboren te Sunderland

DRUKKERIJ G. J. WILLEMSE, DOMPLEIN 11 - UTRECHT

To my Aunt, Mrs J. D. THOMPSON
To Prof. HENRY STROUD

PREFACE.

The majority of the work described in the following pages was carried out at the Physical Institute of the University of Utrecht during the years 1926 and '27, under the supervision of Prof. L. S. Ornstein. It is a great pleasure to acknowledge my indebtedness to Prof. Ornstein for all the facilities which he so readily placed at my disposal, for the constant interest and help which he accorded throughout the progress of the work, and for the great inspiration which he so unfailingly supplies to all those who work with him.

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I have also great pleasure in acknowledging my indebtedness to the International Education Board for the Fellowship which enabled the work to be carried out, and to the Armstrong College Research Fund Committee for the grant towards the purchase of some of the electrical apparatus.

Sept. 1927.

CONTENTS.

CHAPTER 1.

Introduction.

Electrical discharge tubes present many and interesting problems, each requiring specialised experimental methods and technique. Among these problems is that of the sparking potential and its variations under different circumstances.

It is the object of the present work to examine the sparking potential from several aspects and to investigate its variations under different static and dynamic conditions, to consider it in relation to time lag effects in production of the discharge, to external ionising factors, and to gas and electrode-surface phenomena. Finally some sparking potential theories will be considered and a photoelectric theory of the process capable of explaining many of the exhibited phenomena, will be described.

General Discharge Tube Technique.

Discharge tube work suffers from grave disabilities. These are due in the main to the emission of impurities from the electrodes and containing vessel into the gas, the progressive changes of the electrodes with time and treatment, and to the electrostatic effects of space charge accumulated on the walls and insulating portions of the tube.

It is impossible to overestimate the necessity for a refined and meticulous technique in any work purporting to be a precise contribution to the subject of electrical discharges. Many of the phenomena are extremely susceptible to the smallest variations of conditions of purity of filling gas or electrodes, and to obtain exact and repeatable results is a matter of considerable difficulty. It is therefore desirable

to outline the main technical requirements which are considered necessary, and which have been adopted in the work of the present writer.

To avoid contamination of the filling gas by gas given off from the walls, tubes are best constructed according to an "all glass and metal-seal-in" technique. They can then be "baked out" for many hours at high vacuum to remove the condensed gases. In recent work the writer has utilised a "pyrax glass and tungsten seal-in" technique, so that "baking out" may be carried out at higher temperatures.

For exhausting, any of the recent techniques for high vacuum work can be used [1]) (see ref. at end of chapt.). A twostage mercury diffusion pump backed by some form of good oil pump is very quick and yields satisfactory results.

The progressive change of the electrodes with time and treatment will be considered at greater length later. It is sufficient to point out here that in order to avoid such effects as chemical interaction under the influence of the discharge, between the gas and the electrodes, the rare gases may profitably be utilised. It was partly for this reason that these gases were used for the majority of the investigations described in this work. They were purified by Soddy's method (heated calcium in quartz tube furnace) and by means of a liquid air trap. In the later investigations charcoal in liquid air was utilised for clearing up the residual active gas impurities (silica gel may also be employed in a similar manner) from helium gas.

Errors due to accumulation of space charge on the walls etc. may be avoided by having a disposition such that the electrodes are removed as far as possible from the sides of the containing vessel, and separated from one another by only a few cms.. Gas at a pressure of a few mms. is most convenient for the experimental requirements.

There next arises the question of the electrodes. In certain cases it is necessary to investigate the electrode surface changes, as progressive "outgassing" occurs. Almost

any type of electrodes are suitable for such a purpose, the preliminary "baking out" of the tube removes much of the condensed layers of gas but sufficient remains for many of the progressive changes with "outgassing" to be examined.

The problem of producing "pure" electrodes is one of considerable difficulty and importance. To "overrun" the electrodes at redheat is not sufficient for such a purpose, since "sputtered" electrodes always possess a gas content.

Pure Metal Electrodes.

In order to obtain pure metal electrodes — or rather electrodes of which the surfaces were as pure as possible — the present writer has used several methods [2]).

Sodium Electrodes.

Many years ago Warburg [3]) put forward a method for the introduction of pure sodium into discharge tubes, electrolytically through the glass walls. Several applications of the method were made [4]). Recently a similar process has been utilized by Burt [5]) for the introduction of sodium into metal filament lamps by utilizing a discharge between the heated filament and the glass walls which were partially immersed in a bath of molten sodium nitrate at about 350° C. A suitably high potential (about 300 volts) must be maintained between the heated filament (cathode) and the glass walls (anode).

In such a way pure sodium may be introduced upon the electrodes of such discharge tubes as neon lamps. The neon-discharge takes the place of the heated filament. The action is to a large extent reversible: by making the glass walls cathode instead of anode, sodium may be actually removed from the discharge tubes.

Sodium may also be introduced through pyrex and many other glasses.

Metal Electrodes.

In order to investigate the properties of electric discharges in rare gases between pure metal electrodes, the writer has used a discharge tube consisting of a tungsten wire electrode surrounded by a coaxial tungsten wire spiral, the geometrical disposition being such that discharge always took place from the inner tungsten wire to the surrounding spiral. The electrodes could be heated to white heat in high vacuum to obtain pure metal surfaces, and carefully purified argon or other gas could then be introduced. Alternatively, by heating one filament in the argon a deposit of tungsten could be condensed upon the other electrode and its properties investigated.

Further, pure metal electrodes of various metals may be constructed by a modification of the method of metallic evaporation described recently in connexion with celluloid films [6].

Definitions and Preliminary Ideas.

The Static Sparking Potential [7].

At the outset we shall define as "discharge-tube" any system of two electrodes placed in a gas and between which a spark or glow discharge may pass when conditions are suitable. Agents which can produce ionisation of the gas between the electrodes, or electronic emission from the electrodes, are termed "ionising factors," and the ionising factors of a tube at any instant are the sum total of all such agents acting upon the tube at that moment.

There are numerous definitions of the so-called sparking potential, and it is not easy to select one free from inherent weaknesses. Nevertheless, if the term "sparking" is employed it is wisest to define the sparking potential with reference to the actual spark [or, for lower pressures, the glow discharge, as this takes the place of the spark when

the pressure is sufficiently lowered], rather than with reference to the very small currents obtainable when the energy suppliable by the circuit is sufficiently limited.

Adopting this point of view it may be said that, under given conditions of pressure, temperature, and distance between the electrodes etc., a discharge-tube is characterised by a definite sparking potential if this is described in the following manner: — The discharge-tube is carefully protected from ionising factors — that is to say they are reduced to a minimum — and a gradually increasing potential from a steady source is placed directly across the electrodes. The potential is raised very slowly — in the ideal case infinitely slowly — and at a definite value of this potential, $V = v_c$, a spark or glow discharge occurs. This value, v_c, is termed the normal static sparking potential or static upper critical voltage, using a more plastic nomenclature [8]). This is the least potential that will initiate a discharge when there is no initial ionisation or electrons in the tube other than the occasional ion or electron produced in the gas or at the electrodes by small unavoidable ionising factors such as radiations from radioactive substances, etc. The above definition is not entirely free from ambiguity, in that the residual ionising factors are uncertain of character and intensity; it is more definite in nature, however, than one which excludes all mention of ionising factors, for these latter, as will be seen in a later part, exert a considerable influence on the sparking potential of certain types of discharge tubes.

The Dynamical Sparking Potential.

If the voltage across a discharge tube is altering in some manner not infinitely slowly with time (or in practice not very slowly with time) the voltage at which discharge is initiated will not in general be precisely of the value of the static sparking potential. Indeed in some cases where rapid

change of the potential across the tube is occurring, very serious divergences may be observed. Such sparking potentials measured under changing or dynamic conditions are termed dynamic sparking potentials or dynamic upper critical voltages, according to the notation adopted.

The divergences observed between the static and dynamic sparking potentials in a single "flash" or discharge *) arise mainly from "time lags" in the production of the discharge, but those observed in intermittent or oscillatory discharges arise additionaly from residual ionisation and space charge between the electrodes, and probably, in some cases, from a persistance of the metastable atomic states of the discharge gas. These phenomena will be considered later.

Time Lags in the Production of Discharge.

It has been known for a very long time that there is usually a time-lag in the production of the discharge after the voltage across the electrodes has attained the value v_c. This time-lag is a subject of considerable controversy, some experimenters regarding it as of variable magnitude and others as of approximately constant value [9]). According to Züber (*loc. cit.*) the time-lag is determined by chance, and obeys a probability law. Zeleny [10]), for the case of discharges from points, attributes the lags to surface layers of gas on the electrodes. Because of these lag effects and the practical methods usually adopted for the measurement of the sparking potentials, the obtained value do not, as a rule, correspond exactly to the static value.

Polarisation.

It is shown later that in many discharge tubes there is an increase of sparking potential with "flashing" or discharge.

*) "Flashing". This is the term used for a succession of "flashes", that is to say discharges (usually equally distributed in time) through a discharge tube.

The term "polarisation" is used throughout this work to denote this effect which gives rise to increases in the value of the sparking potential on the passage of a discharge.

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4) Drude, *Ann. d. Phys.* 16 (1905) 119. Dorn, *ibid.* 16 (1905) 784.

5) R. C. Burt, *Phil. Mag.* 49 (1925) 1168; *Journ. Opt. Soc.* 11 (1925) 87.

6) *Journ. Scient. Instr.* 3 (1926) No. 12, 400.

7) For these considerations see Taylor, *Phil. Mag.* 3, (1927), 368, from which the account is derived.

8) For these and many of the following considerations *cp.* Pedersen, *Ann. d. Phys.* lxxi, 317, (1923). Züber, *ibid.* lxxvi. p. 231 (1925); Campbell, *Phil. Mag.* xxxviii. p. 214 (1919) Mauz & Seeliger, *Phys. Zeits.* xxvi. p. 47 (1925). For nomenclature of upper critical voltages etc., see Taylor & Sayce, *Phil. Mag.* l. p. 918 (1925).

9) See ref. 8. Also Peak, "Dielectric Phenomena," New York, 1925; Hiller & Regener, *Zts. f. Phys.* xxiii. p. 129 (1924); Compton & Foulke, *Gen. Elec. Rev.* xxvi. p. 755 (1923); Zeleny, *Phys. Rev.* xvi. p. 102 (1920).

10) Zeleny, *Phys. Rev.* xvi. p. 102 (1920).

CHAPTER 2.

The Initiation of the Discharge.

Let us suppose that we maintain a voltage V across the electrodes of a discharge tube of which the cathode is irradiated by ultraviolet light or some ionising factor, in such a way that n_0 electrons are given off per second by the photoelectric action of the radiation.

The n_0 electrons are increased by ionisation by collision when they move under the electric field in the gas between the electrodes and a current flows whose magnitude depends upon the voltage V, the pressure of the gas, and the distance between the electrodes etc..

Provided V is below a definite value the discharge is unselfsustained and dies out immediately the ionising factors are suppressed. As V is increased the current grows at a rapidly increasing rate until at a definite value, the sparking potential under the given conditions, the discharge becomes selfsustained, and if there is a sufficiently small resistance in the circuit a spark or glow discharge occurs. This glow discharge persists even through the ionising factors are suppressed.

The following is a method of regarding the initiation of a spark or glow discharge [1]). When the potential across the tube is of the value of the static sparking potential or more, there is a probability that a chance electron will, when accelerated in the electric field between the electrodes, build up a sufficiently strong current by ionisation by collision to initiate a spark or glow discharge [2]). The condition whether a spark will or will not take place, will be determined by the nature and pressure of the gas, the form of the electrodes, and the actual place at which the electron is born [3]). Initially a

"dark," very small current will flow owing to the presence of ionisation due to the existing ionising factors; this then builds up into a luminous discharge, which in the case of neon discharge-tubes [4]) and argon-nitrogen tubes [5]) increases in luminosity towards the anode, and is similar to the corona type of discharge [6]). In this diffuse type of luminous discharge the field appears to be distributed almost uniformly throughout the gas (with parallel electrodes), not concentrated at the cathode as in the ordinary type of glow discharge. A space charge is set up by the discharge and at a definite current density the normal glow discharge or spark discharge sets in (Seeliger and Schmekel, *loc. cit.*) [4]).

The phenomena of this discharge, which flows before the normal glow or spark discharge, are not, as a rule, visible *) because they occur so near to the glow or spark. This is due to the fact that the external circuit is usually able to supply adequate quantities of energy to initiate the spark or glow extremely rapidly, and consequently the regime of the corona and Townsend types of current, associated as they are with very small energy transferences, is transitory and unstable. Nevertheles the regime, or one very closely akin to it, may be obtained by regulating the energy suppliable from the external circuit, by means of a high resistance or thermionic-valve control [7]). In this way, by careful adjustment of the energy suppliable by the circuit, the "corona regime" becomes stable and may be studied [4]). Characteristics of this type have been studied by Seeliger and Schmekel, and Penning, for neon glow-lamps [4]). It is also the starting point for the Holst and Oosterhuis theory of sparking potentials [4]).

It will be observed that, following an analogy of Seeliger and Schmekel, the word "corona" is employed here. The term is perhaps not very good, in so far as the corona which is obtained at higher pressures is of a rather different character.

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*) They may of course be studied stroboscopically, as Penning and Clarkson have done.

However, since in the following work it is employed throughout for the luminous discharges of small current density which precede the normal spark or glow discharge, or are obtained with high resistances in the tube circuit, there can be little ambiguity.

The features of the discharge may now be dealt with in relation to the volt-ampere characteristic of the discharge.

At the outset we may distinguish somewhat arbitrarily between two completely developed forms of glow discharge.

(1). In which the positive column and its concomitant phenomena are present.

(2). In which the positive column is absent, as in discharge tubes of which the electrodes are not more than a few cms. apart and the gas is at the pressure of the order of a mm. or so. Under these conditions there is the usual Crookes Dark Space, negative glow, and Faraday Dark Space. Under certain conditions there is in addition an anode glow.

The second type of discharge is somewhat less complicated than the first and is the type considered here in dealing with the volt-ampere characteristics for the higher current densities. Nevertheless no intrinsic difference exists between the types.

The Volt-Ampere Characteristic.

The general volt-ampere characteristic for such tubes is of the form shown in fig (1). A particular case for the small current region is shown in fig. (2).

The experimental details for the determination of such characteristics have been described previously [8]). The discharge tube is connected to an adjustable source of potential through a resistance (adjustable and of the order of several megohms maximum *) and the current is measured by an ammeter, microammeter or mirror galvanometer, according to its magnitude. The potential across the electrodes is determined by

*) Alternatively the current may be controlled by a thermionic valve. see Penning, *Phys. Zeits.* xxvii, (1926), 187.

Fig. 1.

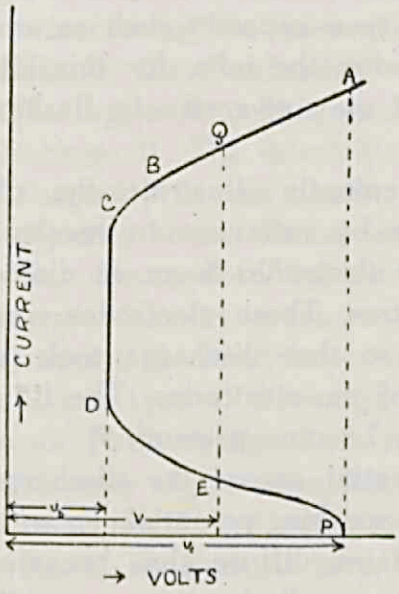
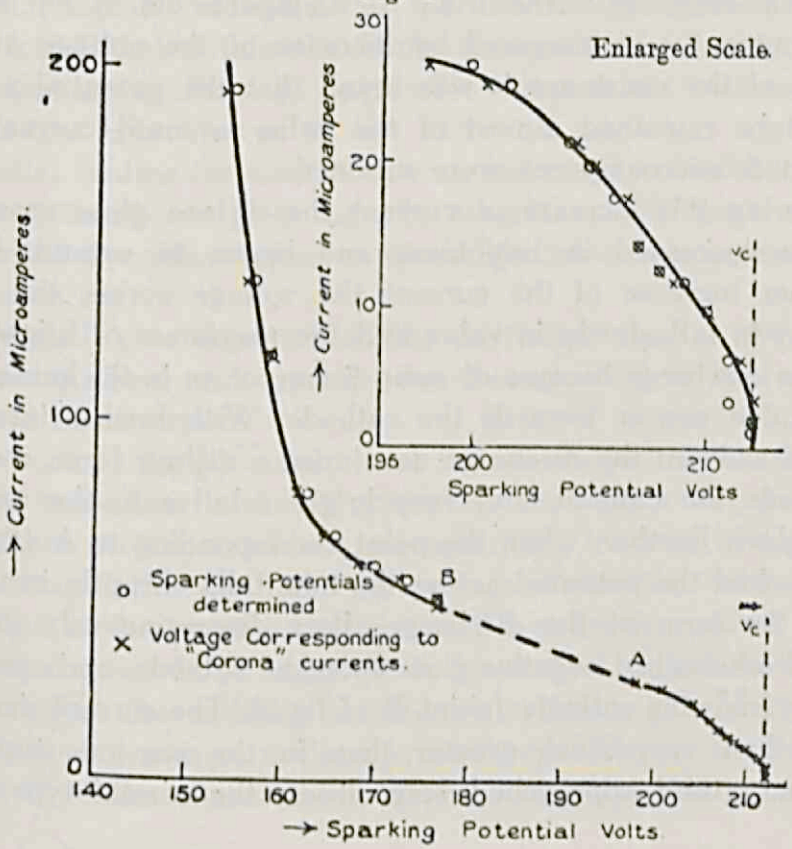

A
Q
B
C
D
E
P
CURRENT
VOLTS
V

Fig. 2.


Enlarged Scale.
Current in Microamperes.
Sparking Potential Volts
Sparking Potentials determined
Voltage Corresponding to "Corona" currents.
Vc
A
B
200
100
0
140
150
160
170
180
190
200
210
30
20
10
196

means of a thermionic-valve electrostatic voltmeter. It is not permissible to place a capacity such as an electrostatic voltmeter directly across the tube, for this alters the regime in certain cases and may give rise to flashing or discontinous discharges [8].

We may conveniently illustrate the phenomena of the "corona" currents by reference to results taken on a tube comprising nickel electrodes 5 cm. in diameter and 15 mms. apart at the centres. These electrodes were slightly curved (10 Cm. radius) so that discharge took place between the central portions of the electrodes. The filling gas was neon-helium mixture at 7.8 mm. pressure [9].

When the potential across the discharge tube electrodes reached the static sparking potential, v_c, with a high resistance in the circuit, a faint, diffuse glow became evident near the anode: this luminous discharge was easily observable for current densities o fthe order 10^{-9} amperes cm. [2], [10]. When the current was increased by increase of the voltage at the ends of the resistance it was found that the potential across the tube remained almost of the value v_c until currents of about 5 microamperes were attained.

During this increase of current the diffuse glow near the anode increased in brightness and began to extend. With further increase of the current the voltage across the tube began to fall slowly in value and the maximum of brightness of the discharge became of some 5 mm. or so in thickness and extended nearer towards the cathode. With further increase of the current the discharge developed a diffuse form, convex towards the cathode and very bright relative to the rest of the glow. Further, when the point corresponding to A (fig. 2) is reached the potential across the tube falls abruptly in value and the form of the discharge alters discontinuously into a small crescent of negative glow upon the cathode, and concave away from the cathode (point B of fig 2). The current density was then very much greater than in the previous type of discharge and approached very closely the normal type with

normal cathode glow etc., and indeed the normal form is reached on further increasing the current, and the voltage across the tube falls to the "extinction" or lower critical voltage value [11]. The region A to B is characterised by intermittence of the discharge [4]. The intermittency which occurs without additional capacity in the circuit would appear to be due to the self-capacity of the discharge-tube system. This is usually greater than the capacity calculated from the tube dimensions and varies with the pressure of the filling-gas. At the higher pressures it was extremely difficult to obtain a non-intermittent corona type of discharge, and indeed when the filling-gas was air (with similar form of tubes) a steady corona was obtainable only at pressures less than about 1 mm.

These faint luminous discharges exhibited to the right of the region D (see fig. 1) are termed here (as we mentioned above) "corona" currents and the corresponding part of the characteristic is referred to as the "corona characteristic". It was found that within the limits of experimental error, the potential across the tube required to start these faint corona discharges was always of the value of the static sparking potential (unless the electrodes were polarised, see later) even for resistances as great as 120 megohms. The phenomena exhibited by other types of discharge tubes are essentially the same.

We shall now depart from the particular case of the tube described above and consider the characteristic in its further general development.

As soon as the potential across the discharge tube has fallen to the extinction, or lower critical value, further decrease of resistance accompanied by a corresponding increase in current is without influence upon the voltage across the tube. This remains at the constant value v_b, the extinction value, over a comparitively large range. With increase of current however the area of the cathode covered by negative glow increases until the full area is utilised in discharge. This is the region D to C of the characteristic given in fig. (1). With further

reduction of the circuit resistance and increase of current, the voltage across the electrodes begins to rise again and finally with zero resistance in the circuit and increasing potential the volt-ampere curve becomes almost linear in character (region B onwards).

The further increase of current with still greater voltages does not concern the work in this subject and consequently need not be considered here.

Theoretical Discussion of the Volt-Ampere Characteristics.

(1) When a voltage equal to the static sparking potential is connected to the discharge tube electrodes, discharge commences and a relatively large current flows almost immediately, if there is no controlling circuit resistance. The current diminishes with decrease of potential until at a definite value v_b, the extinction or lower critical voltage, the discharge stops abruptly and the current falls to zero.

For this part of the characteristic the writer has shown from simple theoretical considerations [12] that the following relation holds,

$$i = k\,(V - V_a) \quad \ldots\ldots\ldots \quad (1),$$

where i is the current through the tube, k is the "conductance", and V_a, the cathode fall of potential. It has been shown experimentally for many types of discharge tubes and filling gases, that the above relation is approximately correct [13]. Exact verification cannot be expected since the region of the characteristic considered is one of abnormal cathode fall of potential, and this is not taken into account in the theory. The region B onwards to the right in the characteristic of fig. (1) corresponds to the above relation.

(2) With resistance in the circuit (portion B to C approx.) we have, provided the full cathodic area is still utilised in discharge,

$$i = \frac{E - V}{r} \text{ and } i = k\,(V - V_a),$$

where E is the total potential in the circuit, and r is the resistance.

Solving this simultaneous equation we obtain the following relation for the current carried by the tube,

$$i = \frac{E - V_a}{1/k + r} \quad \ldots\ldots\ldots\ldots (2),$$

which is of exactly similar form to the empirical expression given by Ryde for the Osglim lamp neon discharge tube.

The volt-ampere characteristics in the region where the full cathodic area is employed may be distorted from that given in the above equations, for the distance between the electrodes frequently varies from point to point and the tube may therefore act as a more or less composite one having several lower critical voltages. Furthermore, the heating effects when the current is as great as those obtained in such circumstances, tends to make the results unreliable.

(3) The vertical part of the characteristic (C to D) is a region of normal cathode fall. The maximum current that the tube can carry is evidently given by $\frac{E - v_b}{r}$, and there will be just sufficient of the cathode area employed (and covered with negative glow) to carry this maximum current. The current is directly proportional to the area of the negative glow which decreases as the resistance r is increased.

(4) The corona part of the characteristic (D onwards to right in fig. 1) has been described above for a particular case, and its theoretical significance will be clearer after the development of the Threshold Current Hypothesis.

The Threshold Current Hypothesis.

The hypothesis of Threshold currents appears to have been applied first to the problem of sparking potentials by Appleton, Emeléus, and Barnett [14], for the case of the Rutherford-Geiger counter. In the work of these observers the threshold

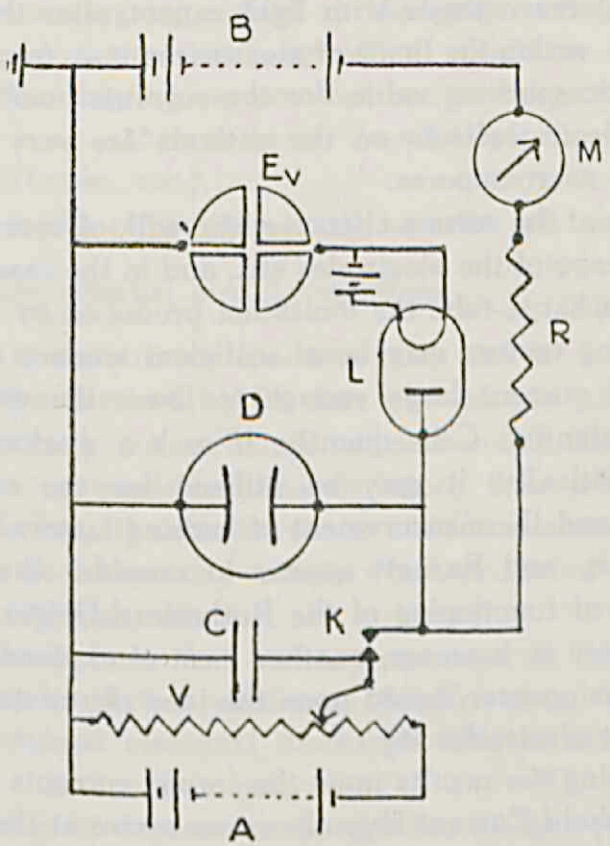
current idea was merely a suggestion for explaining some of their results.

We have seen that there is regime corresponding to the corona type of current, and that this regime precedes the normal discharge and corresponds to smaller currents. There is thus another part of the characteristic which falls below the normal one (see fig 1). It was further seen (fig. 2) that as the current in the corona regime was increased the potential across the tube fell in value from v_c, the static sparking potential, down to the value v_b, the lower critical potential, and the characteristic was such that if at any point corresponding to a definite value V ($< v_c$) of the voltage across the tube electrodes, the energy supplied by the circuit was increased, then the current through the tube would increase continuously. Considering fig. 1, ABDP represents the full characteristic [14], AB is the normal part (corresponding to no resistance in the circuit), and PD is the corona characteristic. The point E then corresponds to a voltage V across the discharge-tube electrodes, and a current i through it. If the energy suppliable from the circuit is increased whilst the voltage is maintained at the value V, then the current will increase continuously until the point Q on the normal characteristic is reached. It is thus evident that V is the sparking potential corresponding to a current i through the tube, and i may be termed the threshold current for the potential V [14]. The minimum sparking potential is thus the extinction or lower critical voltage v_b, and the threshold current is then given by the ordinate of the point C, that is the "extinction current".

Experiments proved to be in agreement with the above considerations. The method was as follows (see fig. 3). A current of the required magnitude was maintained through the discharge-tube D by a battery of adjustable E.M.F., B, and a high resistance R (1.3 megohms for the results of fig. 2). The current was measured by means of a microammeter M, and the voltage across the terminals was determined by the thermionic-valve voltmeter EvL (previously referred to). At

a given instant a voltage V (from the low resistance potentiometer AV continuously charging the capacity C of 0.5 microfarad) from an independent source was connected directly across the discharge-tube electrodes (in the same direction as the "corona voltage"), so as to ascertain whether a spark or

Fig. 3.



flash would occur at this voltage. The voltage was adjusted and increased until, upon shutting the contact key K, a flash occurred. This measured voltage then corresponded to the sparking potential for the threshold current measured by the microammeter M.

The graphs of fig. 2 illustrate the results obtained. It is seen that the sparking potential determined for the different threshold currents agreed almost exactly with the potential

across the tube as given by the thermionic-valve voltmeter. Further, for this tube, as shown in the enlarged scale graph (in fig. 2), the value of the sparking potential for threshold currents up to 4 or 5 microamperes did not differ appreciably from the static sparking potential v_c. It is at once seen that with a type of characteristic such as this, which is almost tangential to the line $V = v_c$ (for small currents), the effect of radiating the cathode with light cannot alter the sparking potential — within the limits of measurement — from the value v_c, the static sparking value, for the currents involved due to the photoelectric effects on the cathode are very much less than 4 or 5 microamperes.

The form of the corona characteristic will, of course, depend upon the shape of the electrodes etc., and in the case of certain types of discharge-tube the ionisation produced by α-rays and other ionising factors may be of sufficient amount to produce a threshold current large enough to lower the value of the sparking potential. Consequently, if such a discharge-tube is adjusted critically, it may be utilised for the counting of α-particles and the measurement of ionising factors [15]). Appleton, Emeléus, and Barnett appear to consider the above as the method of functioning of the Rutherford-Geiger α-particle counter. There is, however, another form of explanation of the action of this counter, based upon the idea of resistance layers on the point electrodes [16]).

Summarising the results upon the corona currents in relation to the Threshold Current Hypothesis we arrive at the following generalisation.

The corona characteristic is identical with the Threshold Current characteristic, and if in a discharge tube having a voltage V across its electrodes, a threshold current i is produced either by external or internal ionising factors, then a self-sustained discharge will be initiated if, and only if the voltage V across the electrodes is equal to or greater than the voltage on the corona characteristic corresponding to the current i.

We are now in a position to consider more fully the significance of the volt-ampere characteristics.

Considering the general characteristic ABCDP (fig. 1).

The trace of the line ABCDP (that is the so called characteristic) corresponds to the statical boundary conditions, and the portions enclosed by the trace correspond to dynamical conditions, that is to say they are only realisable when the discharge is undergoing a flash or changing current.

(1) AB is the statical boundary condition determined largely by the limiting current that can be taken by the tube when there is no resistance in the circuit (limit fixed by recombination, diffusion, etc.).

(2) CD is the region of normal cathode fall and is determined by the external circuit conditions $\left(i = \frac{E - v_b}{r}\right)$.

(3) DP is the corona characteristic, and is the boundary condition characterised by the fact that on any part of it the discharge is only just self-sustained. At points above DP the discharge is accumulative, that is, more than self-sustained, at points below, the discharge is unself-sustained and dies out as soon as the ionising factors which produced the original ionisation, are removed.

We shall see later that we may characterise this boundary condition by a relation similar to the Townsend relation for the self-sustained electrical discharge. This is namely,

$$1 = \gamma\,[\Phi\,(v, p, i.) - 1] \quad . \quad . \quad . \quad . \quad . \quad (3).$$

where $[\Phi\,(v, p, i.]$ represents the number of ions produced by ionisation by collision from one electron originally produced at the cathode, for a given voltage V and current i through the tube. γ is the ratio of the number of electrons produced by positive ions at the cathodic surface to the number of positive ions arriving there (assuming no ionisation by collision by positive ions).

$\Phi\,(v, p, i)$ varies with V and i because of variation of electrical field and space charge. *The region below DP is* consequently characterised by the relation

$$1 > \gamma\,[\varphi\,(v, p, i.) - 1] \quad \ldots\ldots \quad (4).$$

and the current must necessarily die out so soon as the external ionising factors are suppressed.

The region above DP is characterised by the relation

$$1 < \gamma\,[\varphi\,(v, p, i.) - 1] \quad \ldots\ldots \quad (5).$$

that is the discharge is cumulative.

Applications of the Threshold Current Hypothesis.

In the last section it was shown that for discharge tubes with plane parallel electrodes the threshold current characteristic was almost perpendicular to the voltage axis in the neighbourhood of the static sparking potential. Obviously for such tubes in which the electrode area is great, a small threshold current cannot produce any appreciable alteration of the space charge distribution etc. which determines the slope of the threshold current curve. With other types of electrodes such as a point anode near to a hemispherical cathode, there may be a considerable alteration of the field space charge with small currents, due to the relatively small mobility of the positive ions of the filling gas, in such a way as to entail what is effectively a decrease of the anode to cathode distance, and lowering of the potential across the tube. Indeed, with such a type of tube we should expect a threshold-current curve of very small slope in the vicinity of the static sparking potential. Such a form cannot of course be investigated in the same way as the characteristics for plane parallel electrodes because the part of the characteristic AB (see fig. 2) is unstable, a very small change in current bringing about a considerable depreciation of the voltage across the electrodes.

Irradiation of the cathode of such a tube by light or other radiations (of sufficiently great frequency) should produce a considerable depreciation of the sparking potential and this ought to be applicable to the measurement of radiation intensities.

Such a tube was constructed. The anode was a small

tungsten sphere of 1.5 mms. in diameter, situated at about 3 mms. from the centre of a nickel hemispherical cathode (about 2 cms. diameter). The tube was filled with neon-helium mixture to a pressure of about 5.5 mms. and the electrodes were sodiumated electrolytically.

The sparking potentials were found to be 105 volts with the tungsten sphere as cathode, and 136 volts with the nickel hemisphere as cathode. The tube further exhibited pronounced susceptibility to irradiation effects. In the dark the sparking potentials with the nickel hemisphere as cathode varied from 136.5 to 137 volts, and when the cathode was irradiated by a parallel beam of light from a ten volt half-watt lamp (light made parallel by system of lenses) the sparking potential fell to between 121 and 123 volts. The polarisations (see later) were small, not more than about a volt. With the tungsten sphere as cathode there was only a drop of 3 volts in the value of the sparking potential when irradiated under the same conditions.

These results are to be expected, in so far as the threshold current set up by irradiating the electrode of larger area must be many times greater than that set up from the small electrode, for the photoelectric effect of the radiation in the first case is very much greater than in the second case.

Such a system could be used for the measurement of the intensities of light and other radiations and is capable of great sensitivity.

There remained however one serious disadvantage, the polarisations although small were still existent and limited the performance of the instrument, since they brought about „zero change" and inconstancy of sensibility. The elimination of all polarisation effects is therefore necessary before exact application of the method can be made.

Since this work was carried out there has appeared two publications of Campbell in which similar methods of using photoelectric cells are described [17].

Such an explanation of the action of ionising factors upon

certain types of discharge tube, is also applicable to some of the forms of Rutherford-Geiger counter, and as pointed out above, is adopted by certain observers.

Another interesting application of the Threshold Current Hypothesis is to intermittent discharges or flashing. Such work has been carried out by Clarkson [18].

Persistence of small currents during the "dark" period of the discharge leads to lowering of the dynamical sparking potential, initiation of the selfsustained discharge occurring when the current through the tube reaches the threshold value corresponding to the instantaneous voltage across the the electrodes. The dynamic sparking potential decreases as the frequency of the discharge increases.

It is possible however, that when the dark interval between contiguous discharges becomes sufficiently small and comparable with the time of life of the metastable states of the atoms of the discharge tube gas, that persistence of the metastable states brings about a further reduction in the sparking potential.

The existence of excited, ionised, and metastable states must also, of course, account to a considerable extent for the particular forms of the threshold current characteristic, for it is scarcely probable that the electrostatic effect of the space charge is alone the governing factor.

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4) Penning, *Phys. Zeits.* xxvii. p. 187 (1926); Seeliger & Schmekel, *Phys. Zeits.* xxvi, p. 471 (1925); *cp.* Holst & Oosterhuis, *Phil. Mag.* vlvi. p. 1117 (1923).

5) Work of W. Clarkson, not yet published. The present writer also obtains similar results with parallel plate electrode discharge tubes with

air at pressures of less than about 1 mm. For higher pressures and point discharges see Zeleny, *Phys. Rev.* xxiv. p. 268 (1925).

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7) Geffcken, *Phys. Zeits.* xxvi. p. 241 (1925).

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10) *Cp.* Holst & Oosterhuis, *Phil. Mag.* xlvi. p. 147 (1923). Zeleny (*Phys. Rev.* xxiv. p. 258, 1924), in experiments on the discharge from points in air (of the order of atmospheric pressure), obtained luminosity that could be seen by the eye for currents as low as 2×10^{-9} amp. (electrode a steel needle point (point negative)).

11) This is merely descriptive. The lower critical voltage is itself subject to very considerable variations, but for the present purpose these do not concern us. For these variations see: — Penning, *Phys. Zeits.* loc. cit.; Taylor & Clarkson, *Phil. Mag.* xlix. p. 336 (1925); Taylor & Stephenson, *ibid.* xlix. p. 1081 (1925); Taylor & Sayce, *ibid.* l. p. 916. (1925).

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16) Zeleny, *Phys. Rev.* xix. p. 566 (1922); xvi. p. 102 (1920); xxiv. p. 255 (1925).

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CHAPTER 3.

Electrode Surface Effects.

Introduction.

In most observations upon the sparking potentials attention has been directed rather to the variation with different gases and pressures, than to the variation with the nature and condition of the electrodes. This is to be understood, for, according to the classical theory, the composition of the electrodes should be without material influence upon the value of the sparking potential.

Recently Holst and Oosterhuis have shown [1]) by direct experiments upon the sparking potentials in tubes having geometrically similar electrodes of different materials, the filling gas being neon (about 15 mms. pressure) that the sparking potential under similar conditions depends upon the cathode material. Thus in a special case the corresponding sparking potentials were found to be 145 volts for magnesium, 165 for iron, 170 for carbon. For silver and copper cathodes the values were still higher. It was determined "that the minimum sparking potential in neon can vary as 3 : 1, depending on the material of the cathode. The lowest value was found using rubidium or caesium as cathode, the highest value was observed with a carbon cathode". This variation is as great as the variation of the minimum sparking potentials for different gases.

The importance of surface films on the electrodes of discharge-tubes has been noted by numerous experimenters. Compton and Ross carried out some experiments on "charged surface layers formed on the electrodes of vacuum tubes" [2]). Züber observed a polarisation of sparking gaps [3]), but attributed the preponderant part of the effect to polarisation of the insulating material of the gap. In the usually accepted explanation of

the Rutherford-Geiger α-particle counter, it is assumed that a film of high resistance exists on the surface of the counter point [4]. Zeleny [5] considers the action as being due to a gas film on the pointed electrode, and on this basis explains many of his observations on point-to-plate discharges. He is further of opinion that the time-lag in the production of the discharge is accounted for by the presence of such films [6].

It has been observed that the first spark through a tube which has been unused for some time frequently passes more easily and without appreciable time lag at a lower potential than succeeding ones. On the other hand, it appears in certain cases that the first spark passes less readily than the following [7]. These and other observations point to a change in the electrodes on the passage of a discharge [7].

For the type of tube chiefly considered in this paper many electrode fatigue effects have been signalled [8]. It is known that the sparking potential is altered and is made much more constant when the electrodes have been purged and heated to redness for some time by means of an electric discharge. This stabilisation appears to result from the destruction or modification of certain gas-layers and impurities [9]. Certain results of Ryde [10] show that surface films may play a very considerable role in causing changes of the sparking potentials. Clarkson in some work upon argon-nitrogen tubes [11] concludes that many of the anomalies inherent in such tubes may be attributed to films of gas absorbed on the cathode.

Apart from changes caused by intense discharges which may radically alter the nature or condition of such surface layers, there are fatigue effects which occur in tubes where only small energy transferences are taking place [12]. Campbell, in experiments on point and sphere sparking gaps in air, concluded that "some very easily variable surface condition of the plug" played a considerable role [13].

The above results point to a very considerable influence of the electrode condition upon the processes of the discharge and upon the sparking potential itself.

Polarisation Effects. *)

We shall now describe the results of experiments upon the change of the sparking potential with sparking or flashing. These experiments were carried out for the most part, with tubes prepared according to the conditions given in Chapter 1. In some cases however, impurities were purposely introduced.

The sparking potentials were determined under definite conditions, and it was determined that the effects were not due to electrostatic effects on the walls of the discharge tube owing to accumulation of charge thereon. Further, owing to the actual form of the tubes the effects could not be due to charges on the electrode supports etc..

Experimental Methods.

In determining the sparking potentials the following method was usually utilised.

A source of steady and constant potential of which the value could be varied was placed in series with a resistance of about half a megohm and the discharge tube whose constants were being investigated. The latter was shunted by a capacity of half a microfarad, and the potentials at which discharges were produced were determined by means of the thermionic valve electrostatic voltmeter referred to in chapt. 1. (This voltmeter was used throughout so that the results obtained were directly comparable with those obtained in the experiments on the corona currents). In determining the sparking potential the voltage was gradually raised until a flash occurred. The time occupied in the process of raising the potential was usually about 15 or 20 seconds, but provided this was not excessively long consistent results were obtained.

General Results.

It was determined that there was frequently an increase in

*) The present account is taken largely from the *Phil. Mag.* iii. p. 753 (1927).

sparking potential with flashing. This increase was termed polarisation. Most tubes became stabily polarised (provided the flashes were not very intense) after at most, some ten or twenty flashes had passed.

The polarisation effects may be suitably illustrated by some particular results taken on a plane parallel nickel electrode tube, similar to the tube described in Chapt. 2, with a filling gas of neon-helium mixture.

TABLE I.

	Polarisation in volts. A. cathode.	No. of flashes.	Polarisation in volts. B cathode.	No. of flashes.
	5	4	8	5 or 6
	6.5	6 or 7	10	4 or 5
	7.5	6 or 7	10	6
	5.7	6	8	6
	8	6	6.5	8
	9.5	10	11	6
Averages . . .	7	6.5	9	6

Table (I) illustrates the results obtained. The first and third columns give the stable polarisations obtained with the two electrodes, and the third and fourth the respective number of flashes required to attain this stable polarisation.

It was found that when the tube had become polarised it could be depolarised or recovered in two ways:

(1) By passing a few flashes in the reverse direction (cathode changed to anode).

(2) By resting the tube for about half on hour.

The above results were obtained with the nickel electrodes. Certain results were taken after sodium had been introduced electrolytically into the tube, in order to investigate the change in the polarisation effects.

The sodium was initially introduced in very small quan-

tity sufficient to give some vapour. On examining the sparking potentials and polarisations it was found that they were precisely the same as before the introduction of sodium vapour. When however, the electrodes were sodiumated (in such a way that more sodium was introduced upon one electrode B, than upon the other electrode A) it was found that the static sparking potential had fallen to 192 volts for A as cathode, and the polarisation produced an increase of 6 volts. With B as cathode the sparking potential was 172 volts and the polarisation about one volt. Results taken ten days later showed but little alteration.

The first introduction of sodium into the side-tube (although in sufficient quantity to be visible) made no observable difference in the results, for it was not pulled over to the electrodes. It was evident therefore that it was not a "clean-up" of gas or the presence of sodium vapour which caused the differences. The seat of the phenomena must therefore be sought upon the surface of the electrodes themselves.

Experiments on many tubes showed similar results, but with those likely to contain traces of active gases, large polarisations were observed and many of these were irreversible.

The anode was found to be almost without influence in polarisation phenomena.

Classification of Polarisation Effects.

Polarisation phenomena may be roughly divided into three headings.

(1) Those which give rise to permanent changes.

(2) Those which give rise to changes which are temporary but not reversible, or are only partially reversible and are of large magnitude.

(3) Those which give rise to reversible and temporary changes of a repeatable nature.

(1) The effects included under this heading are those

which are brought about by heavy discharges such as are used in "overrunning" discharge-tubes for the stabilisation of their constants [9]) and which cause an actual alteration — usually visible — of the surface of the electrodes.

It is not certain whether these effects are primarily due to an actual alteration of the surface of the cathode or to a "clean-up" of the filling gas or impurities. It was therefore considered to be of interest to carry out some experiments with a view to elucidating this.

In many cases there can be but little doubt that some of the permanent changes are attributable to traces of active gases introduced into the filling gas by "overrunning" etc. for it is known that small quantities of active gas may produce profound alterations in the electrical properties of rare gases.

A series of experiments were carried out in which the sparking potentials were determined over a range of gas pressures (neon-helium mixture).

The discharge tube was then "overrun" for about half an hour, was exhausted and refilled with purified gas. The sparking potentials were redetermined over the same range of pressures and it was found than an increase of over 60 volts had taken place, though the gas was presumably of exactly the same nature as previously. The tube recovered somewhat with time but the voltages were still about 30 volts higher than the first results.

It is to be concluded therefore as extremely likely that the nature and condition of the cathode exert a very profound influence on the magnitude of the sparking potentials.

Experiments of a similar nature have been conducted recently by Janitzky [14]).

(2) Under the heading (2) are the effects observed in tubes which were likely to contain traces of active gases. The problem then arises as to whether the polarisation effects are due to the presence of active gases as impurity in the rare gases, or to some surface condition of the electrodes.

Experiments were carried out upon a tube filled with neon-helium mixture and provided with a palladium wire, which was fused into a side tube so that hydrogen could be introduced by diffusion. The electrodes were first of all sodiumated. Experiments showed that the polarisations were negligeably small.

Hydrogen was introduced in small quantity through the palladium tube, and the sparking potentials were again determined. There was an increase of 100 volts in the sparking potential but the polarisation was still negligibly small. We may conclude therefrom that the presence of the active gas hydrogen is not sufficient itself to produce polarisation effects. The same is probably true of other gases.

We may conclude consequently that the seat of the polarisation phenomena is the surface of the electrodes, and since abnormally large and erratic polarisation effects did not occur in those tubes whose electrodes had been thoroughly "baked out" and "overrun," or were "sodiumated," it is very probable that the effects are due to the presence of layers of active gases absorbed or occluded at the electrode surfaces. It is possible that many of the photoelectric effects signalled in connexion with the neon glow-lamp [15]) have arisen from such causes.

(3) The effects classed under this heading are those dealt with mainly in this work and appear to exist in tubes which have been carefully treated to avoid gases of the active kind in the neon-helium mixture and whose electrodes have been "baked out" for several hours at 300° C. and "overrun."

Summarising the results on the effect of the introduction of sodium upon all the discharge-tubes used, we find the following. The effect is dual. First of all there is a reduction of the actual sparking potential value, and secondly there is a very considerable diminution of the polarisation effects observed.

Theory of Polarisation Phenomena.

As we have seen, though it is probable that many of the permanent increases of the sparking potentials of discharge tubes, or indeed of the slow increases, are due to the introduction of traces of active gases into the filling gas, the reversible and rapidly changing effects are traceable to the cathode surface, which appears to be the chief seat of the polarisation phenomena.

The following theory of the polarisation phenomena arose out of the photoelectric theory of the sparking potentials described in Chapt. 6, but it is not absolutely necessary for the theory of the polarisation effects that such a theory shall be adopted. All that is necessary is that some theory of sparking potentials is adopted that stipulates that the self sustained discharge is initiated by a process that includes an action of the cathode surface in contributing electrons to the build up.

According to the photoelectric theory of sparking potentials the extra ionisation required to initiate the self-sustained electric discharge is brought about by the emission of electrons from the cathode, due to the photoelectric action of the radiation accompanying the neutralisation of the positive ions at the cathode surface. The sparking potential is consequently a function of the photoelectric emissivity of the cathode and will vary with changes of the latter in whatever manner they may be brought about.

We shall adopt the hypothesis that the polarisation effects are occasioned by the action of the discharge upon layers of gas absorbed or occluded upon the discharge-tube electrodes.

The explanation of the rotational fatigue effect (see note 12) becomes clear if we assume that there is a gas film at the cathode surface and that the part of this film immediately beneath the negative glow becomes positively charged by the electronic emission of the cathode and the bombardment by the positive ions of the discharge. This electrically charged double-

layer cannot immediately dissipate its charge, and consequently a polarisation layer is formed at the surface of the cathode. The effect of this layer is twofold. It actually decreases the field between the cathode surface and the edge of the negative glow, and further it inhibits the emission of electrons from the cathode. It is consequently easier for the discharge to pass at an adjacent portion of the cathode that has not been subject to the action of the discharge. The discharge may consequently rotate and the period of rotation depends on the time for the "recovery" of the cathodic gas-layer.

It is necessary to consider such films in their relation to the sparking potentials. The passage of a discharge will be accompanied, in a way described above, by a charging-up positively of the gas-layer at the cathode surface which is giving off electrons and is being bombarded by positive ions at the same time. Consequently a polarised layer is set up after a spark or discharge has taken place. The charge of this layer will disappear in a time depending upon the duration of the discharge, or upon the frequency of discharge if flashes are taking place, and upon the intensity of the discharge.

Now when a potential is placed across the polarised discharge-tube, the existence of the electrical double-layer will modify the conditions under which discharge occurs. In the first place, such a layer will introduce an apparent resistance in the circuit due to the increased contact potential of the electrode to gas surface, and decrease the value of the field between the electrodes for a given potential across the discharge-tube terminals. Further, it will diminish the capacity of the cathode metal for emitting electrons and considerably alter the photoelectric properties of the cathode by introducing a fatigue effect.

In most of the tubes the polarisation could be largely eliminated, as we saw, by passing flashes in the reverse direction. This effect is readily explainable. The positively charged outer layer of the cathode film becomes bombarded by electrons when the discharge is reversed, and this quickly

neutralises the positive layer and brings the tube into the unpolarised state.

In those tubes showing small and reversible polarisation effects the condition of the anode appeared to exert little influence. This is illustrated in many results. A polarised tube, on being reversed, never showed a sparking potential value considerably less than the static value, and in the tube upon which the results of Table (1) were taken polarisations of appreciable value were only obtained when the electrode which was relatively free from sodium was used as cathode. When the sparking potential with B (the electrode upon which there was most sodium) as cathode was 172 volts, the sparking potential with A as cathode was 192 volts and rose to 198 volts with flashing, that is to say there was a polarisation of 6 volts. Now when the polarised tube was reversed so that B was again cathode and the sparking potential immediately determined, it was found still to be of the value 172 volts, so that an effect on electrode A capable of producing a change of 6 volts when A was cathode produced no appreciable change when A was anode. From this it may be concluded that in these cases the chief effects are located on the cathodic surface.

It is difficult to understand how such large polarisations as those observed in some tubes can be produced if it is not due to an effect which either prevents the cathode from emitting electrons so readily or alters the photoelectric emissivity of the surface. The former explanation is applicable to the reversible polarisations and the latter to the electrode surface effects produced by intense discharges and "overrunning".

General Remarks on Electrode Surface Phenomena

The electrode surface phenomena in discharge-tubes are of an intricate nature and the previous considerations can merely be considered as illustrative and introductory.

It should be remarked that the magnitude of the polarisation effects depends upon the intensity of the discharges and their

time-duration, upon the previous treatment of the electrodes, and many other factors. Further, the effects are not observed in all tubes, and this appears to be intimately connected with the nature of the gas-layer on the electrode surface. Indeed, in one tube a slight depreciation of the sparking potential was observed after flashing for some time. In this case the electrodes had not been treated at all, and it was found that about 0.25 c.c. of gas at atmospheric pressure was given off on "overrunning". There was probably a considerable water-vapour content.

Application of the Polarisation Phenomena.

Irradiation Effects with Plane Parallel Electrode Tubes.

Experiments were carried out upon the effect of irradiating the cathodes of discharge tubes containing plane parallel electrodes, or tungsten sphere electrodes of equal size, the filling gas being a rare gas, usually neon-helium mixture. The investigations were of two types, the first being upon the sparking potentials and the time lag in the production of the discharge, and the second upon the flashing phenomena changes.

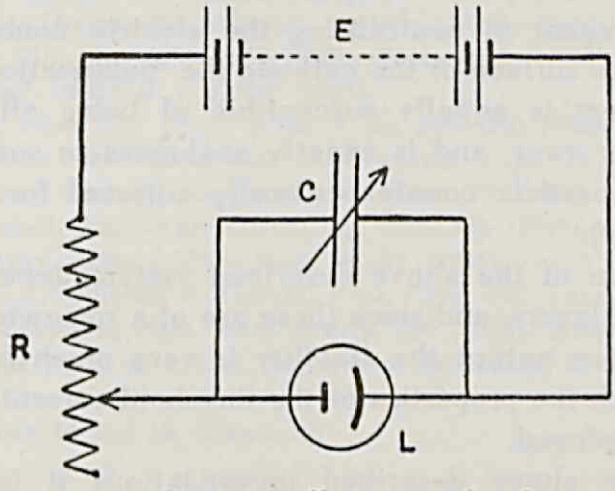
With regard to the first investigation it was found that the first or initial value of the sparking potential after a long period of rest of a discharge tube was in most cases independent of whether the cathode was irradiated or not, and that the time-lag in the production of the discharge was very small. After the passage of a discharge however, it was found that a lag in the production of discharge occurred and that this lag was reduced by irradiating the cathode, by an amount proportional to the intensity of the radiation incident upon the cathode surface. At the same time the numerical value of the sparking potential increased.

With regard to the phenomena of flashing it was found convenient to use a discharge tube consisting of parallel rectangular electrodes of iron (18.5 mms. by 18.5 mms.) and

3.5 mms. apart, filled with neon-helium mixture (about 78 percent neon, 22 helium.) at a pressure of about 10 mm.

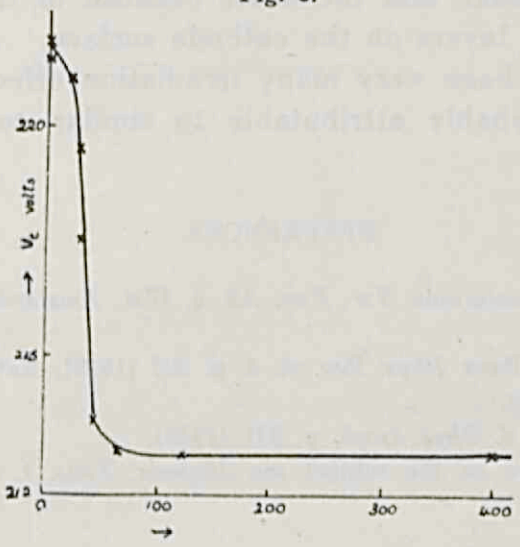
The circuit shown in fig. 4 was utilised and it was observed

Fig. 4.



that there was a distinct effect on the frequency of the flashes and of the average current by irradiating the cathode. The effect was located at the cathode surface and was largely produced by the blue end of the spectrum, when ordinary light was used as irradiating agent. The graph of fig. 5 illustrates some of the results obtained.

Fig. 5.



The above effects were traced to polarisation effects on the cathode. They did not occur when large polarisations of value much greater than the voltage corresponding to the radiation employed, occurred. It was concluded therefore that the effect was caused by the action of the light or other irradiating agent in neutralising the electric double layers set up at the surface of the cathode (i.e. polarisation layers).

The system is equally susceptible of being affected by X-rays and γ-rays, and is exactly analogous to some of the forms of α-particle counter critically adjusted for counting by flashes [16]).

The action of the above described system depends upon polarisation layers, and since these are of a somewhat erratic and transitory nature the stability is very much inferior to that in which the properties of the threshold current potential curve is employed.

From the above described investigations it is perhaps legitimate to conclude by comparison with the current results on α-particle counters, that there are at least two different actions involved in the various types of counter. The one type of counter functions because of the geometrical form of the threshold current voltage characteristic, which is of very small slope in the neighbourhood of the normal static sparking potential, and the other because of the existence of polarisation layers on the cathode surface.

There have been very many irradiation effects observed which are probably attributable to similar causes [15]).

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16) See refs 14 and 16, Chapt. 2.

CHAPTER 4.

Electrode Surface Effects continued. *)

In the last Chapter consideration of the polarisation effects led to the conclusion that the cathode surface modifications were of two kinds, one of a permanent nature which changed the electronic emissive power of the cathode, and was consequently accompanied by a change in the sparking potentials, the other of a temporary nature due to the changing up of the surface layers and the consequent formation of electrical double layers.

The work to be described in the present Chapter deals with the first type of electrode surface phenomena in which the changes of the sparking potential function are due, not to a transient charging up of the surface layer, but to permanent surface modifications.

Description of Apparatus.

For the purpose of investigating the sparking potential function for pure metal electrodes — or rather for electrodes of which the surfaces were as pure as possible — a discharge tube of special form was constructed [1]). It comprised an electrode in the form of a tungsten wire, surrounded by a coaxial tungsten wire spiral, the whole system being therefore of the same form as the filament-grid system of a thermionic valve. The geometrical disposition of the supports, etc., was such that discharge always took place between the inner wire and the surrounding spiral. It was "baked out"

*) The following Chapt. is derived largely from. *Proc. Roy. Soc. A.* vol. 114. p. 73 (1927).

for many hours at high vacuum at a temperature of over 300° C. The tungsten wire electrodes were thoroughly cleaned and "degassed" by heating them strongly electrically for six hours in high vacuum. When the electrodes had been brought to this condition which at least approximated to a clean, "gas free" state, carefully purified dried argon gas was introduced into the tube to the required pressure.

The filling-gas was continuously purified by utilisation of a quartz furnace containing heated calcium. In order to test the quality of the gas, a discharge tube with plane-parallel electrodes was included in the appartus. Any change in gas quality was denoted by a change in the sparking potential of this test-tube. Tests were made from time to time during the work, but the sparking potential was found to be constant, consequently in the later experiments this test was dispensed with, because of the excessive gas-capacity of the test-tube.

The experimental arrangements for the determination of the sparking potentials were similar to those used in previous work [2]. A source of constant and adjustable potential was connected in series with a resistance of 450,000 ohms to the discharge tube which was shunted by an electrostatic voltmeter. The potential was gradually raised until discharge occured. The discharge was of a feeble nature (usually of the "corona" type [2]), and of a few microamps. in magnitude), and was confined to the space between the wire and the coaxial spiral.

Experimental Results for Tungsten Electrodes formed in High Vacuum.

Experiments were carried out on two tubes of similar form and similar results were obtained in the two cases. Using S as cathode, it was found that the first discharge took place at a definite potential and the succeeding ones at progressively decreasing potentials. The value of the sparking potential

TABLE II.

S denotes tungsten spiral, W coaxial wire. The numbers at the side of the sparking potential values give the number of the discharge in the time order in which they occurred. Tungsten electrodes "formed" *in vacuum*. Pressure of argon 3.94 mm. Diameter of tungsten wire 0.3 mm.; diameter of spiral, 6 mm.; length, 16 mm.; number of turns, 10.

Sparking potentials.	S cathode. (1) 273 (3) 249 (5) 249 (7) 250 (9) 251 W cathode. (2) 245 (4) 235 (6) 237 (10) 237 W cathode. (11) 239 (12) 239 (13) 241 (14) 242 (15) 244 W cathode. (16) 245 (17) 246 (18) 247 (19) 247.5 Remained fairly steady at this value. S cathode. (20) 251 (21) 254 (22) 257 (23) 261 (24) 262.5 S cathode. (25) 263 remained fairly steady at this value.

decreased gradually under the action of the discharge to a minimum value after which it increased again. Table II is illustrative of the results obtained with one tube. In the results given the first discharge took place with S as cathode, so that the value (2) given for W as cathode does not represent the actual value for a vacuum-formed surface on W. In the example given the values for the sparking potentials with both S and W as cathodes finally attained values approximating to the initial ones. This, however, was by no means always the case. There appeared to be great differences in behaviour according to conditions, and the previous treatment of the wires [3]). In all cases, however, it was found that the sparking potentials for both S and W as cathode were higher initially with the "clean tungsten" electrodes (the initial sparking potential was constant and definite) and decreased with discharge to a minimum value which varied according to conditions.

After this point, in almost all, though not quite all, cases, a considerable but slow increase in the sparking potential values occurred. In some few cases the final values were even higher than those characteristic of the "clean tungsten".

Experimental Results for Tungsten Electrodes formed in Pure Argon.

A series of experiments were undertaken in which the tungsten electrodes previously "formed" in high vacuum were reheated for various periods of time in argon gas which was continuously purified.

The results obtained were almost the same as those for the vacuum-formed electrodes, except that the initial sparking potentials were usually lower than for those. Nevertheless, in many instances, the values approached those for the vacuum-formed surfaces. Tables III and IV give some of the results obtained.

TABLE III. — Pressure of Argon, 3.94 mm.

Sparking Potential of first discharge. S Cathode.	Treatment of Tube.
Volts.	
273	S and W heated strongly *in vacuum.*
268	S heated strongly for 10 minutes in the gas.
263	Ditto. Ditto.
264	S heated dull red for 0.5 minutes in the gas.
261	S heated strongly a few minutes in the gas.
264	S and W heated strongly a few minutes in the gas.
267	S heated very strongly a few minutes in the gas.

TABLE IV. — Pressure of Argon, 3.94 mm.

Sparking Potential of first discharge. W Cathode.	Treatment of Tube. (All heatings took place in the gas.)
Volts.	
249	W heated strongly for 10 minutes.
241	Do.
239	Do.
251	W heated strongly a few minutes.
245	S and W heated a few minutes together.
255	W heated very strongly for a few minutes.
251	W heated a few minutes.

The result of heating appears to be as follows: — If S was heated, then its final condition was very similar to that which it would have attained in vacuum, but the condition of W was unaffected except for an indirect effect due to the heating it underwent by conduction and radiation. If, however, S was heated very strongly, tungsten from its surface evaporated on to W and formed a new surface there. Whatever the nature of the surface layers that were formed under the action of the discharge they were modified or done away with when the wires were heated in the pure argon gas. The sparking potentials were not quite the same as those attained by heating in vacuum, so that it must be assumed that the heating did not drive off so much of the surface layers in the gas as in vacuum, or alternatively, that the change in the surface structure was not so great as that obtained by heating in vacuum.

Another important point which will be considered later, is that the actual relative values of the sparking potential for S and W as cathodes depended largely upon the condition of the electrodes and not merely upon the geometrical distribution of the electric field between the wire and the coaxial spiral, a result which follows the assumption, until recently held, that

the sparking potential was independent of the nature of the cathode surface 4). By comparing the results in Table IV for W as cathode, with those in Table III for S as cathode, it is seen that normally, when the electrodes were most probably in the same condition, the sparking potential was lower for W as cathode than for S as cathode. This is in accordance with the usually accepted results 4). In cases where S and W had undergone different treatment, and were, therefore, presumably of different surface conditions, the sparking potential for W as cathode could be less than, equal to, or greater than, that for S as cathode, according to circumstances. Table V gives some illustrative results.

TABLE V. — Pressure of Argon, 3.9 mm.

Sparking Potentials of first discharges.		Treatment of Tube. (All heatings took place in the gas.)
S Cathode.	W Cathode.	
Volts.	Volts.	
275	251	W heated strongly a few minutes.
244.5	245	S and W heated for a few minutes.
264	247	S and W heated strongly for 10 minutes.
247	255	W heated very strongly for a few minutes.
267	255	S heated strongly a few minutes.
251	251	W heated for a few minutes.

The condition of the anode was found to exert little, if any, action on the values of the sparking potential. We may conclude, therefore, that the value of the sparking potential depends upon the surface condition of the cathode.

Experiments with "Sodiumated" Electrodes.

Sodium was introduced electrolytically through a side tube provided for the purpose 5), and was evaporated on to the

tungsten electrodes. After the tube had been rested for a few hours, the sparking potentials were redetermined. Previous to introduction of the sodium the values were 265 volts with S as cathode, and 251 volts with W as cathode. These values were those determined after S and W had been heated to yellow white heat for ten minutes and then rested. When the electrodes were sodiumated the values were 122 volts with S cathode and 106 with W cathode. The falls of the sparking potential values were consequently great. The electrodes were then treated in a manner described in Table VI, in order to drive off some sodium from one or the other electrode. After each heating the tube was rested several minutes and the sparking potentials were then redetermined.

TABLE VI. — Pressure of Argon = 3.9 mm.

Sparking Potentials.		Treatment of Tube.
S Cathode.	W Cathode.	
Volts.	Volts.	
122	106	Both electrodes "sodiumated."
136	214	W heated at dull red heat for 1.5 minutes.
142	98	S heated for an instant to dull red.
152	95	S heated dull red for a second or two.
157	93	Do.
183	101	S heated dull red for 10 seconds.
230	108	Do.
254	110	Do.
254	111	Do.
253	112	S heated dull red for 20 seconds.

From the table (second line) it is seen that when W was heated to a dull-red for 1.5 minutes the sparking potential had risen by 108 volts (W cathode). The value attained was not that characteristic of the original tungsten electrode,

so that it is evident that the heating had not entirely reproduced a tungsten surface. At the same time S had evidently become heated to a slight extent by conduction and radiation, and some of the sodium had evaporated. This brought about an increase of 14 volts in the sparking potential with S as cathode. In the next operation S was heated for an extremely short time. It was found that the sparking potential (S cathode) had risen a further 6 volts, whilst the value for W had fallen from 214 volts to the value 98, showing that sodium had evaporated from S on to W. The table shows the continuation of similar treatments. It is seen that when S was heated for 10 secs. or more, that W also became heated by conduction, etc., and lost some of its sodium, so that the sparking potential increased in value.

The effect of introducing sodium upon the cathode is to diminish progressively the sparking potential as the amount of sodium is increased, until a constant value is attained when the electrode is completely sodiumated. The heating reduces the quantity of sodium per unit area. We may assume that a film of a few atoms in thickness will act in all ways as a sodium electrode. With an insufficient quantity to produce such a film there will be "bare patches" and the electrodes will be "mixed" ones.

Summary.

The above described results are in accordance with those given in the previous Chapter.

Summarising we may conclude that: —

The Sparking Potential is a function of the nature and condition of the cathode surface, and varies continuously with changes of the latter, depending upon the mean composition of the "working" part. In other words the Sparking Potential is a function depending upon a gross effect of ions acting upon the cathode surface.

We may reasonably attribute the effects of the change of the sparking potential in the case of the tungsten electrodes

to changes in the surface layers of gas on the cathode. This was the position maintained in previous work on the electrode surface effects. It is, of course, also conceivable that many of the above described effects were due to changes in the surface structure of the metal of the cathode; in any case, such changes would be accompanied by a corresponding change in the photoelectric emissivity and it is to this change that the alterations in the value of the sparking potential are attributed.

The results, indeed, are very analogous to some of those obtained for the variation of the photoelectric emissivity of metals [3].

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1) Taylor, *Proc. Roy. Soc. A*, vol. 114. p. 73 (1927).

2) Taylor, *Phil. Mag.* iii. p. 753 (1927); iii. p. 368 (1927).

3) Compare with experiments on the photoelectric emission of metals as influenced by temperature, *e.g.*, Welo, *Phil. Mag.* vol. 2. p. 463 (1926).

4) Townsend, *"Electricity in Gases"*.

5) For method see Taylor, *loc. cit. Cf.* Warburg, *Ann. d. Physik.* vol. 40. p. 1 (1890); Burt, *Phil. Mag.* vol. 49. p. 1168 (1925); *Journ. Opt. Soc.* vol. 11. p. 87 (1925). See also Taylor, *Journ. Scient. Inst.* vol. 4, p. 78 (1927).

CHAPTER 5.

Ionisation by Electrons and Positive Ions.

Ionisaton by Collision by Electrons.

The actual mechanism of the initiation of the self-sustained electric discharge is still obscure.

With regard to the development of currents in the regime before a self-sustained discharge is obtained, experimental evidence is fairly decisive "in showing that ionisation is principally due to the direct effect of collisions of electrons with molecules (or atoms) of the gas". Quite how this ionisation by collision is brought about is a matter of speculation.

According to the Classical Theory of Towsend the ionisation effect of an electron is characterised by a coefficient α which is defined as the number of electrons produced per cm., under a definite electric field and gas pressure etc., by collision [1]).

For parallel plate electrodes in which the cathode was irradiated by ultraviolet light or by X-rays, Townsend has shown that for a considerable range of distances x, between the plates, when the electric force X is constant,

$$n = n_o\left(\varepsilon^{\alpha x} - 1\right) \ldots\ldots\ldots (6).$$

where n is the number of + ions arriving at the cathode and n_0 is the number of electrons produced originally by the action of the ionising factors upon the cathode. This relation arises naturally out of the Townsend Theory of ionisation by collision, it further gives us one requirement for a satisfactory sparking potential theory, namely such a theory must

account for the fact that the "currents increase in geometrical progression as the distance increases in arithmetic progression".

On the other hand we may consider the phenomena from the point of view of the results obtained in recent years in the region of quantum physics by Franck and Hertz and other workers. According to these ideas the collision of an electron possesses an energy equivalent to the resonance potential or ionising potential of the gas considered.

It is not the purpose of the present work to consider such processes in any detail. In the case of diatomic, electropositive and electronegative gases, the complexity becomes such as to preclude any satisfactory treatment at all, for almost nothing is known about the mechanism and process of collisions in such cases. With the noble gases conditions are much simpler; they are monatomic and without large residual atomic fields of their own. It is therefore preferable for the simplification of conditions to utilise such gases in most work upon sparking potentials.

Electronic collisions against atoms of the rare gases are almost entirely elastic until some critical velocity equivalent to a resonance or ionising potential is attained. Consequently an electron in the electric field between two electrodes may move in any way from atom to atom and will acquire an energy equivalent to the fall of potential in the direction of the field that it has experienced, provided this fall of potential does not exceed a certain critical value. When the electron has in this manner attained an energy eV_i, where e, is the electronic charge and V_i, the ionising potential of the gas, it will ionise an atom on collision and give rise to a new electron. These new electrons will in turn produce more electrons under similar conditions. We may assume consequently that in the space between two charged electrodes an electron will ionise at distances characterised by a drop of voltage equal to the ionising potential.

In reality the process is not so simple as that given above,

for many questions arise, which up to the present remain unanswered. For instance we may ask what is the proportion between collisions occurring when the electron has an energy equivalent to the resonance potential and those occurring when the energy is equal to the ionising potential. Also what part does the radiation emitted by such processes play in the mechanism?

Such a process as envisualised above is embodied by Holst and Oosterhuis in their theory of the sparking potentials 2). They assume for an hypothetically ideal gas:

(1) "An electron loses no energy whatever in collisions as long as its velocity is below that corresponding to the ionising potential".

(2) "An electron will ionise as soon as its velocity is equal to the ionisation potential V_i".

With these assumptions an expression is arrived at, namely,

$$n = n_o\left(2^g - 1\right) \quad \ldots\ldots\ldots \quad (7).$$

which takes the place of equation (6) of Townsend's Theory, g is the number of ionising potentials in the total voltage across the discharge tube electrodes. This equation accounts for the geometrical progression form of increase of current with distance between the electrodes. The equation (7) was developed for the case of an ideal gas. In practice energy is lost by collisions. Holst and Oosterhuis consider this loss and introduce a second approximation to take into account the effects. The resulting expression is complicated and does not lend itself readily to calculations.

There is little doubt that up to the present the Townsend formula for ionisation by collision of electrons is superior to others from the point of view of applicability to working conditions of gases in bulk, but whether it satisfactorily describes the processes involved is open to doubt.

Assuming that the development of currents in the regime preceeding a self-sustained discharge is adequately repre-

sented by one or other of the above theories or their modifications, the question remains" which of the other modes of generating ions contributes the additional effect required in order to explain the disruptive discharge".

The source of this additional ionisation is generally sought in an action of the positive ions liberated by the ionisation of the atoms or molecules of the gas by the electronic collisions, or in a photoelectric action at the cathode of radiations produced in the bulk of the gas [3]).

Ionisation by Positive Ions.

The question of the production of ionisation and electrons by the action of positive ions is one which has engaged much attention and in which very many contradictory conclusions have been reached.

Our attention here is more especially directed to the action of positive ions of energy corresponding to not more than a few tens of volts, traversing gases, for these are the conditions corresponding to the regime of the self-sustained electric discharge in gases. Notwithstanding, it is of interest to consider somewhat generally the experimental findings in this branch of research.

Experimental Results on the Production of Ionisation by Positive Ions.

The ionisation of gases and the production of intense secondary electronic emission from solid targets, by the bombardment of α-particles is well known.

The α rays from radium C, possess energy corresponding to about 2,000 kilovolts, and represent the limit of energy possessed by any positive ions.

They shatter any atoms which they encounter, and in air at atmospheric pressure form several thousands of ions in every millimetere.

Canal rays (of maximum velocity about one hundreth of that of the α rays from radium C) also produce ionisation by collision against gas molecules and cause an emission of electrons from metal targets. Villard concluded that cathode rays were formed by bombardment of the cathode by positive ions of the discharge [4].

Seeliger [5] in some quantitative work, has concluded that the number of ions produced by positive rays is small compared with the energy of the positive particles, and that the number is almost independent of the velocity of the rays and of the pressure of the gas.

The emission of positive ions from heated wires and salts has received a considerable amount of attention in reference to the influence of the pressure and nature of the gas in which they are enclosed etc.. Definite researches to detect ionisation by collision of the emitted ions against the molecules of the gas and by impact against metallic electrodes have been carried out with varying and conflictory results.

Klein [6] detected a secondary emission from a nickel electrode upon which positive ions of 50 volts velocity impinged. The emission became 22 percent of the positive ion current value when the potential was raised to 380 volts.

In some recent experiments Jackson [7] has employed a beam of K ions from the iron catalyst source discovered by Kunsman [8]. "The secondary emission of aluminium, nickel and molybdenum under a variety of surface conditions up to 1,000 volts was measured. Heat treatment usually involved a diminution of the secondary electronic emission. The secondary electrons emitted were of low speed, a retarding field of a fraction of a volt was enough to stop nearly all of them".

Stark [9] in examining the current between a heated carbon filament and metal cathode in air, observed an effect of increase of current which he attributed to ionisation by collision of the molecules of the gas by the positive ions from the carbon.

Pawlow [10] carried out experiments from which he concluded that positive ions produce ionisation by collision in gases.

Franck and Bahr [11] obtained ionisation in air and hydrogen below the ionisation potentials of these gases. They also found that the lowest voltage for which ionisation could be detected was smaller for larger intensities of the source of positive ions.

More recently Horton and Davies [12] have conducted experiments upon the positive ions emitted by a tantalum filament in helium.They detected an increase of ionisation with positive ions which had fallen through potentials as low as 20 volts and attributed their results to the electronic emission from the walls of the ionisation chamber by bombardment of the positive ions. Further they are of opinion that positive ions do not produce further ionisation by collision when accelerated through potentials of 200 volts.

Saxton [13] has carried out experiments utilising the positive ions of hydrogen. The results were interpreted as giving "definite evidence of ionisation by positive ions accelerated through potentials as low as 18 volts".

In a recent paper "On the electric discharge through gases at very low pressures" Sir J. J. Thomson [14] deals somewhat extensively with the question of ionisation by collision of positive ions and discusses several objections to the hypothesis that low speed positive ions are able to ionise by collision against gas molecules. He discusses other methods by which the ionisation in the discharge, which is often attributed to the above action, may be produced, and puts forward an alternative and very interesting hypothesis according to which the positive ions liberate photoelectrons by the action of the radiation emitted when they are neutralised at the cathode surface. Continuing work in this direction Sir J. J. Thomson [15] examined directly the radiation effects due to the streams of cathode and positive rays through a gas. It was shown that the passage of the positive gas ions through the gas itself produced radiation from the gas. Further, it was found that the radiation produced by the positive rays striking against metallic targets was similar to that produced by the passage of the positive rays through the gas. The radiation was very

soft, not exceeding a quantum of the order of the ionising potential of the gas.

Work of a similar nature on the radiations of electric discharges in the rare gases helium, neon, and argon, at voltages across the electrodes of up to 400 and pressures of the order of a few mms. has been described by Dauvillier [16].

The conclusions differ somewhat from those of Sir J. J. Thomson. It is attested that no radiation attributable to the neutralisation of the positive ions at the cathode surface was observed. The impact of the positive ions of the discharge against the cathode is supposed to liberate electrons by electrostatic attraction.

Holst and Oosterhuis [17] discussing work upon discharges in rare gases, notably neon, regard the production of ionisation by collision of the positive ions in the gas as improbable and attribute the "building up" of the discharge to electronic emission from the cathode by the electrostatic attraction of the positive ions on the electrons in the cathode, and describe results in support of their theory. This hypothesis is also one of the bases of their theory of sparking potentials [2].

Townsend in a long series of researches carried out over many years maintains the position that ionisation by collision of positive ions against molecules or atoms of gas, even though these ions are of slow velocity, is the normal source for that additional ionisation required to account for the self-sustained electrical discharge in gases [1 & 3].

Theories of Ionisation by Positive Ions.

There are three main theories to explain the ionisation produced in gases by positive ions. The oldest is the now classical theory of Townsend of ionisation produced by collision of the positive ions against the molecules of the gas in which they are moving. This ionisation is brought about in much the same manner as that by the electrons. The second theory is that the effect attributed to ionisation by collision of low

velocity positive ions is really due to secondary photoelectric action of the radiation emitted by the gas molecules or atoms, and the third is that the "extra" ionisation observed is due to the electrons produced by the bombardment of the electrodes by the positive ions.

This latter theory may be divided into three headings.

(1) In which electrons are produced by the "knocking out" of electrons by the impact of the positive ions against the cathode.

(2) In which the electrons are supposed to be given off by the photoelectric effect of the radiation emitted during the neutralisation of the ions impinging on the cathode.

(3) In which the electrons are produced by the electrostatic attraction exerted by the positive ions upon the electrons in the surface of the cathode.

(1), (2), and (3) may be classed together under the heading "electronic emission due to positive ion impact".

The first and second of the main theories described above have been treated somewhat extensively by Townsend [3] and it is the object of the present work to deal more especially with the three divisions of the third main theory.

Electronic Emission due to Positive Ion Impact.

The experimental evidence given above leaves little doubt of the fact that the action of positive ions impinging upon metal targets gives rise to secondary emission of electrons. There are of course disagreements as to the magnitude of such an emission and as to the kinetic energy requirement for positive ions to produced such an effect, the mechanism of the phenomena and its dependence upon the velocity of the particles.

Theory (1).

This theory requires that the secondary electronic emis-

sion is produced by the impact effect of the ion against the atoms in the surface of the target. By virtue of the kinetic energy attained during their acceleration in the electric field between the electrodes, and that due to the electrical image attraction of the positive ions, these ions are able to ionise the atoms or knock out conduction electrons from the surface space lattice. The magnitude of such an action will depend upon the kinetic energy of the positive ion, and will increase with the latter. Further, since the majority of the electrons are likely to be liberated in the direction of the motion of the positive rays, the secondary electronic emission would not be expected to be large for small velocity ions, and indeed when the velocity is below a certain critical value no electron emission will be detectable.

Jackson's results which were quoted above are interesting from this point of view. "The secondary electron emission could not be detected (was less than 0.5 percent) at positive ion velocities less than 200 volts for Al, 300 volts for Ni, and 600 volts for Mo after heat treatment. The secondary emission increased from these values to 7 percent for Al, 4.7 percent for Ni, and 3.8 percent for Mo, at 1000 volts. Without heat treatment the emission was detected at lower voltages and reached about double the above values at 1,000 volts".

From these and other results we may conclude that the number of electrons liberated from the cathode of a discharge tube by such a process, by the very slow ions involved in such conditions as are usual in the initiation of a small self-sustained electric discharge, is very small. In some cases the small emissions mentioned above may be sufficient to explain the extra source of ionisation, but in the majority of cases it appears to be insufficient. Further, it should be pointed out that the emissions observed in such experiments as those of Jackson, may be attributed to the process described under heading (2). Potassium ions on neutralisation emit radiation of a maximum quantum that is much inferior to that from such ions as the rare gas ions etc. and conse-

quently the production of photoelectrons will be correspondingly less.

Theory (2).

This is the hypothesis put forward by Sir J. J. Thomson, and described above in the reference to this work.

We should expect that the photoelectrons produced by the radiation accompanying the neutralisation of the positive ions at the surface of the cathode will be largely independent of the velocity of the positive ions over a considerable range. This is in agreement with the experimental findings given previously. As the velocity of the positive ions increases however, the case may be different. We may imagine that, provided the velocity of the positive ion is sufficiently small, the photoelectric effect is simply due to the single neutralisation of the ion, but when the velocity is sufficiently increased (due to increase of the surface field) we may consider with Sir J. J. Thomson that "A positive ion striking against the cathode may alternate from the charged to the uncharged condition, if it has much energy, many times before it loses its charge for the last time; each change from the charged to the uncharged state would be accompanied by the emission of radiation." Thus with the higher velocity positive ions the effect may become considerably enhanced.

Further, the number of electrons emitted by the photoelectric effect will depend upon the magnitude of the quantum of radiation emitted by the ion on neutralisation. The maximum value of this quantum will, for a given ion, correspond to the energy associated with the ionising potential. We should expect consequently that the photoelectric emission produced by the positive ions from the rare gases for which the ionising potentials are high, will be greater than that for the ordinary gases.

Futher, it is to be expected that the emission will increase with the surface field.

Theory (3).

The third theory is that the secondary electron emission is produced by the electrostatic attraction which is exerted by the positive ions upon the electrons in the surface layer of the cathode. On this hypothesis the secondary emission would be largely independent of the velocity of the positive rays but would depend upon the intensity of the beam impinging upon the target. We shall call this theory the "Autoelectronic Theory".

Recent work carried out upon "autoelectronic emission," that is electronic emission from a metal electrode due to the maintainence at its surface of an electrostatic potential sufficiently high, are very interesting in the light which they bring upon the possibility of the process described above.

Of these results it is sufficient to quote those of Millikan and Eyring [18], which are relative to our purpose. Gossling has obtained very similar results [19].

Millikan and Eyring investigated the currents "from thoriated tungsten filaments in vacuum due to radial fields up to 2×10^6 volts per cm.". The results showed that the current increased from 10^{-12} to 10^{-3} amps. with increase of the field from 400 to 1100 k.v. per cm., and clearly indicated that the currents came only from a few active surface spots. The magnitude of the current was found to depend upon the previous treatment of the wire and was largely independent of the temperature over a wide range. It was suggested "that the field currents are due to conduction electrons pulled from minute peaks on the surface" and at these places the field must be considerably in excess of the average value over the wire surface.

If we make a rough calculation of the order of distance between a positive ion and electron required for the positive ion to exert a force of a million volts per cm., it is readily seen that the order is that of the electronic orbits of the atom and is such as makes it improbable that the electron

shall escape from becoming part of the atomic system of the ion by neutralising it.

This process will emit radiation and give rise to the effect described in Theory (2). We may conclude therefore in such circumstances as we have in near consideration, namely those corresponding to gases at several mms. pressure and voltages of low value, that the electrostatic attractions exerted by the positive ions which impinge against the cathode are insufficient to cause electronic emission except by an indirect process.

We may summarise by concluding that so far as the phenomena of the self-sustained electric discharge is concerned the source of the additional ionisation is to be found either in the process of ionisation by collision of positive ions described previously, or in the processes described under heading (1) and (2) of the theory of Electronic Emission due to Positive Ion Impact, and further, that there is a balance of probability in favour of the theory described under heading (2), that is the Photoelectric Theory of the the emission of electrons due to positive ion impact.

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CHAPTER 6.

On Certain Sparking Potential Theories.

Introduction.

In the last Chapter we developed different hypotheses which can explain the ionisation produced by electrons and positive ions. It now remains to select from among these hypotheses those best capable of providing a Sparking Potential Theory that will account for the various phenomena observed in the initiation of self-sustained electrical discharges. Such a theory must be capable of explaining Paschen's Law (Sparking potential is a function of the product of the pressure of the gas and the distance between the electrodes for plane parallel electrodes), the phenomena observed for the case of plane parallel electrodes, for discharges between a wire and coaxial cylinder, and the various electrode surface effects associated with discharge initiation.

The theories developed in the present chapter are more particularly for the case of pressures above those corresponding to the minimum sparking potentials, but their extension to other cases is evident.

Initially in formulating a theory we must account for the ionisation by collision produced by electrons, and this involves the acceptance of either the classical theory of Townsend (or one of its modifications), or a theory based on quantum considerations such as was adopted by Holst and Oosterhuis.

For empirical purposes Townsend's theory is satisfactory and easy to handle, and in default of further knowledge of the quantum reactions occurring in gases in bulk, it is perhaps the most convenient to adopt.

Secondly we must account for the "extra" ionisation

produced by the positive ions, which we supposed were the effective agents in this direction. *)

It was shown that there are several possible explanations of the ionising action produced by positive ions, and, a priori, we cannot be sure that in all cases of initiation of the discharge, the process is identical. We also do not know definitely that only one action of the positive ions is effective in any one case. There may be indeed, cases where the initiation proceeds from the joint effect of one or more of the actions described in the previous Chapter; it is more probable however that one effect alone will be predominent, and consequently the following generalisation may be made: —

The initiation of the self-sustained electrical discharge will be brought about by that particular action of the positive ions that is most easily accomplished under the conditions of experiment.

The statement is somewhat unrigid in wording but its meaning is clear. If in a given case for example, ionisation by collision with the molecules or atoms of the gas is more readily produced than photoelectric emission from the cathode by the action of the positive ions, then the former process will be chiefly responsible for the initiation of the discharge, and vice versa.

An exact theory would therefore emerge out of a knowledge of the relative probabilities of the processes summarised in the previous Chapter.

Townsend's Theory [1]).

In the Townsend Theory both electrons and positive ions are assumed to produce ionisation by collision with the mole-

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*) There is also the theory mentioned in Chapt. 5, that the "extra" ionisation is produced by a photoelectric effect of radiation emitted from the bulk of the gas. This is one of the cases considered by Townsend [5]). Owing to the lack of definite evidence in favour of such a theory it is not treated here.

cules of the gas. If n_0 electrons are liberated from a plane metal cathode and move in the uniform field between parallel plates, the number of ions n, gathered to the anode is, according to this Theory,

$$n = n_o \frac{(\alpha - \beta)\, \varepsilon^{(\alpha - \beta)x}}{\alpha - \beta\varepsilon^{(\alpha - \beta)x}} \quad \ldots \quad (8).$$

"where α is the average number of molecules ionised by an electron in moving through one cm. of the gas in the direction of the electric force, β is the average number ionised by a positive ion, and x is the distance in cms. between the plane parallel electrodes". Obviously then the condition for a self-sustained electric discharge to be produced is given by the relation,

$$\alpha \leq \beta\, \varepsilon^{(\alpha - \beta)x} \quad \ldots \ldots \ldots \ldots \quad (9).$$

and the sparking potential is consequently Xx where X, is the electric field between the plates.

The theory of Townsend accounts for Paschen's law and for the phenomena observed in the case of discharges between a wire and coaxial cylinder.

The Townsend Theory of ionisation by collision for negative ions or electrons is not universally adopted, but leaving this aside the objections that can be raised against the Townsend sparking Potential Theory are: —

(1) The hypothesis that low speed positive ions produce new ions by collision with the molecules of the gas in which they are moving is, as we saw from the results described in the previous Chapter, open to very grave doubt.

(2) According to this theory the sparking potentials should be independent of the nature and condition of the cathode surface, whilst in practice it is found to be largely dependent upon these.

Dubois [2] has modified the Townsend Theory to take into account an additional action of the positive ions in liberating

electrons from the cathode. The ratio of the number of ions impinging upon the cathode to the number of electrons set free by them is characterised by a coefficient γ, and the revised formula, corresponding to equation (8) becomes.

$$n = n_o \frac{(\alpha - \beta)\varepsilon^{(\alpha - \beta)x}}{\alpha(\gamma + 1) - (\gamma\alpha + \beta)\varepsilon^{(\alpha - \beta)x}} \quad . . \quad (9).$$

The Holst and Oosterhuis Theory [3].

In the last Chapter a description of the hypothesis adopted by Holst and Oosterhuis for the ionisation by collision of electrons was given.

To account for the additional ionisation by the positive ions they make two further assumptions.

(1) "n positive ions will liberate one electron at the cathode surface".

(2) "No positive ion ionises a gas molecule by collision".

The mechanism whereby the positive ions are supposed to liberate electrons from the cathode is that described in Theory (3) of the Electronic Emission due to positive ion impact (previous Chapter).

According to the theory of Holst and Oosterhuis the number of positive ions produced by an electron originally given off from the cathode is $(2^g - 1)$, (equation (7), Chapt. 5). The condition for the discharge to set in is consequently given by the relation,

$$2^{g_s} - 1 \geq n \quad . . . . . \quad (10),$$

g_s being a particular definite value of g.

The sparking potential v_c, is then given by the relation,

$$v_c = g_s V_i \quad . . . . . \quad (11),$$

V_i, being the ionising potential of the gas.

For the case of the hypothetical gas postulated by Holst and Oosterhuis the sparking potential would be independent

of the pressure of the gas and the distance between the electrodes.

The relation of equation (11) is arrived at on the assumption that no energy is lost in collisions of the electrons against the gas atoms at velocities below that corresponding to the ionising potential. On introducing an approximation for the loss of energy on collision, the following relation for the sparking potential is arrived at,

$$v_c = V_i \frac{273ap\sqrt{2k}\varepsilon^c + 1}{T.76.\lambda_n 4\sqrt{2}.\varepsilon^c - 1} \quad . \quad (12),$$

in which a, is the electrode distance in cms., p, is the pressure of the gas in cms. hg., λ, is the M.F.P. of a molecule of the gas at N.T.P..

$$k = 2m/M. \text{ and } c = \frac{273ap2\sqrt{2k}}{76.\lambda_n.g_s.4\sqrt{2}}.$$

"The departure from the ideal gas is due to energy losses of the electrons. If the number of collisions is small these losses will be less important. That is the reason why the minimum sparking-potentials for gases are not very far apart, the difference in sparking-potential increasing with pressure and electrode distance" 3).

Holst and Oosterhuis have shown that relation (12) holds approximately for neon.

The theory has the advantage of being capable of explaining the variations of the sparking potential with the nature of the cathodic surface, and of many of the observed surface phenomena. It is unfortunately of very limited application.

In a recent paper Townsend 4) criticises the theory and brings forward certain arguments against it.

In the light of recent experimental evidence it would appear doubtful whether the production of electrons from the cathode can be attributed to an electrostatic attraction effect. It must be noted however that the form of the theory remains

unchanged if either of the alternative hypotheses (1) or (2) as described in Chapt. 5, are adopted.

The Photoelectric Theory of the Sparking Potentials [5].

The Photoelectric Theory of sparking Potentials arises naturally out of the hypothesis of Sir J. J. Thomson described in Theory (2) of the hypotheses of electronic emission due to positive ion impact, Chapter 5. It was also an expression of the conviction that it is necessary to attribute a not unimportant part of the mechanism of the discharge to radiations given out by the gas.

If we assume that for n_0 electrons produced originally at the cathode, (by the ionising factors), $n_0 \Phi$ (V, p.) electrons are gathered to the anode, where Φ (V, p.) is a function depending upon the voltage across the tube and the pressure of the gas etc., then the number of positive ions arriving at the cathode is

$$n = n_0 \left[\Phi (V, p.) - 1 \right] \quad . \quad . \quad . \quad (13).$$

The neutralisation of these positive ions at the cathode surface is accompanied, we shall suppose, by the emission of radiation (see previous Chapter) some of which falls upon the cathode surface and produces the emission of photoelectrons. Let the ratio of the number of electron given off from the cathode by the photoelectric effect to the number of the positive ions neutralised there, be γ. Then we have the following condition for the production of a self-sustained electrical discharge.

$$\gamma\, n_0 \left[\Phi (V, p.) - 1 \right] \geqq n_0 \quad . \quad . \quad . \quad (14).$$

and consequently the sparking potential $v_{c,}$ for these conditions is given by,

$$\Phi (v_{c,}\ p.) = \frac{1 + \gamma}{\gamma} \quad . \quad . \quad . \quad . \quad . \quad (15).$$

If we adopt Townsend's theory of the function Φ (V, p.),

equation (15) resolves itself for the case of plane parallel electrodes, into the following relation,

$$v_c = Xx = \frac{X}{\alpha} \log \frac{1+\gamma}{\gamma} \quad \ldots \quad (16).$$

where X, is the electric field between the electrodes and x, is the distance apart.

Alternately if we accept the Holst and Oosterhuis theory of the production of ionisation by electronic collision the form of their expression for the sparking potential remains exactly the same (equations (11) and (12).).

Equation (3) is precisely the same as the equation given by Townsend, except that γ has a different significance [4].

The variation of the function γ, which is a measure of the photoelectric emissivity of the cathodic surface for the radiation accompanying the neutralization of the positive ions of the gas, would entail a whole manifold of possible variations of the sparking potential function v_c. γ would be variable according to the condition and mean composition of the "working" part of the cathode surface, and would be subject to variations with the gas-to-metal potential changes, and the transient electric double layers set up by electrical charges on the cathode surface.

The results, indeed, are very analogous to some of those obtained for the variation of the photoelectric emissivity of metals [6]. It is hoped to continue experiments in which both γ and v_c will be measured simultaneously.

It will be noticed that throughout this Chapter no specific reference has been made to any dependence of the sparking potential upon the magnitude of the ionising factors. It was shown in Chapter 2 however, that the sparking potential is dependent upon the magnitude of the threshold current.

The equations given above (with the exceptions of (13), (14) and (15).) must be taken as giving the static sparking potential as defined in Chapter 1.

This stipulation is obviously necessary when it is considered

that the Townsend Theory is only applicable to such cases where the distribution of potential between the electrodes is that given by the geometrical disposition of the electrodes and is not influenced or altered by the charges of the electrons and ions themselves. Further as regards the Holst and Oosterhuis Theory it is necessary that the currents passing due to the ionising factors, shall cause no appreciable excitation of the gas or production of metastable states.

In circumstances where threshold currents of appreciable magnitude are maintained through a discharge tube, the potential required to initiate a self-sustained electrical discharge will be lowered by an amount depending upon the form of the threshold-current-voltage curve (see Chapt. 2) and this curve is itself determined by the geometrical disposition and form of the electrodes, the nature and pressure of the gas, etc., etc.. The discharge will become self-sustained as soon as the voltage across the tube has risen to the value of the potential on the threshold current curve corresponding to the threshold current passing through the tube at that instant. In other words the discharge becomes self-sustained immediately the threshold current curve is intersected. Under such circumstances the function ϕ (V, p.) of equations (13) to (15) is dependent upon the distribution of space charge between the electrodes and the presence of ionised and excited states, and becomes of a complicated nature that we may represent by ϕ (V, p, i.), where i is the current flowing through the tube. The number of positive ions arriving at the cathode is consequently a function of the actual current flowing. To obtain the conditions for the initiation of the spark or glow discharge we must introduce the function ϕ (V, p, i.) into equations (13), (14), and (15).

Equation (14) defines the threshold current characteristic and the portion falling beneath it, which corresponds to an un-self-sustained electric discharge (see Chapt. 2). Unfortunately nothing is known of the function ϕ (V, p, i.) except that it is given empirically by the corona characteristic, which it explains physically.

Objections to the Photoelectric Theory.

In a recent paper Huxley [7]) has considered the Photoelectric Theory of Sparking potentials and concludes that it cannot be satisfactory. We may therefore consider the objections raised.

In paragraph (3) of Huxley's paper the discharge between a wire and coaxial cylinder is considered. It is stated that "it is found that the critical force X_1, at the surface of the wire necessary to initiate the discharge, is independent of the diameter of the outer cylinder provided the latter exceeds a certain value. Experimenters who have studied the phenomena are in general agreement on this point". In the opinion of the present writer the experiments on which this generalisation is based have been performed over a very limited range of conditions. Nevertheless the conclusion may be accepted as approximately correct, and Huxley deduces from it quite rightly that the function γ, in the Photoelectric Theory of Sparking Potentials should be independent of the force at the negative electrode for this case. (This does not imply however that γ is independent of the pressure of the gas.)

In Table VII are given some results of Watson quoted by Townsend [1]) in connection with the above generalisation relative to the electric force X_1, at the surface of the wire. It is seen that the ratio of the force X, at the surface of the outer cylinder to the pressure of the gas p, is of the order of one volt per cm. per mm. The gas for the case considered was air.

Huxley then considers the sparking potential for parallel plate electrodes and concludes that in this case there is a large variation of γ, with the value of X. This appears to be contradictory to the conclusion, arrived at for the case of cylindrical electrodes that γ was constant. This however is not necessarily the case. We see from the Table given by Huxley for air, that X/P for the cases considered is between 131 and 440 volts per cm. per mm.. In the previous case we saw that

TABLE VII.

E. A. Watson, The Electrician, 11, Feb. (1910).
Cylinder and wire. Outer cylinder diameter 20 cms. Air.

Pressure p mms.	Diameter of wire 2a cms.	X_1 kilovlts.	X kilovlts.	X/P (volts.)
760	0.1	75	0.375	0.49
560	0.136	55	0.375	0.67
360	0.211	34	0.358	0.99
760	0.2	61	0.61	0.8
560	0.272	44.5	0.605	1.08
360	0.422	28.5	0.6	1.67
760	0.5	46.5	1.16	1.52
560	0.68	35.0	1.19	2.12
360	1.055	22.0	1.16	3.22

p. mms.	radius wire cms.	C. cms.	X_1 kilovlts.	X_C kilovlts.	X_C/p volts per cm. per mm. pres.
760	0.5	0.66	40.0	30.3	40
360	..	0.82	23.0	14.0	39
108	..	1.12	9.45	4.21	39
25.2	..	1.73	3.4	0.98	39

C is the least value of the radius of the outer cylinder for which the condition relative to the critical field for starting a discharge, holds.

cp also Townsend and Edmunds, Phil. Mag., 27, 793 (1914), "Discharge of Electricity from cylinders and points". "In the results used in the following discussion X_c/p (that is X/p in the above results) was always less than 40".

this value was of the order of one volt. These differences for X/P in the two cases are striking, and it would appear that the velocity with which the positive ions impinge upon the cathode is much greater for the case of the plane parallel electrodes than for the cylindrical ones considered. We are thus led to infer that γ' (for a given pressure) may be constant provided the field at the surface of the cathode is not above a certain value, or, in other words provided that the positive ions do not strike against the electrode with too large a velocity. It can be assumed, as was rendered extremely plausible by the considerations developed in Chapter 5, that as the velocity of the positive ions increases so does the function γ'. It is also reasonable to suppose that the photoelectric emission will increase with increase of the surface field. It is further stated that the photoelectric theory is unable to explain the large difference between the force at the surface of a wire, required to start a negative discharge. This statement cannot be accepted. The electric field at the cathode is entirely different in the two cases and the circumstances of the genesis of the electrons from the cathode and the magnification by collision both lead to a difference in the required direction.

In paragraph (5) of the paper Dubois' results [2]) are mentioned and apparently assumed to be in contradiction to those of the present writer. This is most difficult to understand. If we do assume that Dubois' results are due to saline impurities on the electrodes it is necessary to give some explanation of their action. An unmodified Townsend Theory fails entirely to give such an explanation, indeed it implies that they are without effect at all. On the other hand, if the effect is due "to the action of positive ions in causing electrons to be set free, by bombardment from impurities on the surface", then we are immediately introducing a foreign hypothesis on top of the original one, and since ordinary electrodes exhibit large variations in the value of the sparking potentials the effect attributed to the new action be-

comes of large importance and the Townsend Theory must be modified (as for instance Dubois himself has done) to account for it.

Now it is well known that alkali metal impurities very considerably increase the photoelectric emmissivity of a metal surface and this strongly suggests that the correct explanation is afforded by the Photoelectric Theory of Sparking Potentials.

It is further stated that "Dubois' conclusions indicate therefore, that with ordinary metal electrodes the emission from the cathode is negligible compared with the action of the positive ions in ionising molecules of the gas....., for it is very improbable that the emission from all these metals is the same".

If Dubois' conclusions are correct and if the action is produced by the change of the photoelectric function γ, there appears to be no reason why γ should not be approximately the same for ordinary metals for the Schumann radiation which is the radiation chiefly responsible for the photoelectric emission, for, according to Compton and Richardson, the photoelectric sensitiveness is supposed to be the same for all metals, but for the electronegative metals the curve is shifted bodily towards the region of short wavelengths. It is obvious then that according to this idea the photoelectric emissivity of metals, whilst differing enormously for visible light (near the threshold frequency) may have no great percentage difference in the region of shorter wavelengths, that is in the Schumann region.

Again it is quite conceivable that ordinary metal electrodes formed in the same way may acquire surface films in the discharge of similar nature and yield similar results.

In conclusion it may be mentioned that no alternative explanation of the results obtained on pure electrodes and gases, and on the surface electrode phenomena is given.

Experimental Verification of the Photoelectric Theory of the Sparking Potentials.

It has been found possible to complete experiments upon the concomitant measurement of v_c and γ, for the case of helium.

A tube of the form described on page 12 was utilised. It was provided additionally with a side-tube containing a four electrode hot wire discharge tube device, (so that the cathode of the discharge tube could be irradiated by radiation coming through a window in the box.) and with a side-tube containing activated charcoal which could be put in liquid air to absorb all traces of active gases. The apparatus was thoroughly outgassed etc.. Carefully purified helium was introduced to pressures up to about two mms.

It may be assumed that the radiation proceeding from the low potential discharge box is of approximately the same character as that arising from the neutralisation of the positive ions. This radiation falls upon the discharge tube cathode and produces a photoelectric effect P, that is measureable by a sensitive galvanometer. It is evident that P will be a proportional measure of γ.

The electrodes of the four electrode device etc. were charged to suitable potentials so that no electrons or positive ions were collected by the discharge tube cathode. It was determined that the current measured between the cathode and anode of the discharge tube on irradiation, exhibited all the characteristics of photoelectric currents.

On performing experiments upon the variation of v_c with progressive purifying of the helium by the cooled charcoal, remarkable results were obtained. There occurred initially the well known rapid decrease of the values of the sparking potential until a minimum value was attained. As purification was continued, however, a slow rise in sparking potential took place until a value of anything from 30 to 600 volts (according to gas pressure etc..) higher than the minimum was attained.

Introduction of new helium to make up for the pressure lost by the cooling, showed definitely that the effects did not proceed from the pressure changes.

Concomitant measurements of P showed a fall from a maximum at the minimum sparking potential to a minimum at the final higher sparking potential.

After considering a number of explanations of the phenomena, the following was adopted: —

(1) The helium rapidly becomes pure, so that only slight traces of foreign gases remain, a fall of v_c occurs to a minimum and the properties of the gas then remain almost constant.

(2) The gas layer on the surface of the cathode undergoes slow change, probably by evaporation of surface gas molecules into the helium and final disappearance in the charcoal. This slow change of the cathode surface diminishes progressively its photoelectric emissivity (or its capacity for emitting electrons.) and increase in v_c occurs until the modification of the cathode has attained equilibrium under the existing conditions.

It was determined, for various pressures, that throughout this region the graphs showing the relation between the corresponding values of v_c and P were smooth curves, and the relation between v_c and log. 1/P was either linear or of slightly curved form. These findings are in agreement with equations (15) and (16). At the same time the values of α calculated from the relation of equation (16) agreed, within the limits of experimental error, with previously determined experimental values (for the higher pressures). We may consequently conclude that the results give strong evidence in favour of the Photoelectric Theory of Sparking Potentials.

My thanks are due to Mr. v. Hasselt who assisted with much of the observational work in this experimental verification.

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CHAPTER 7.

Dynamic Sparking Potentials.

Under dynamical conditions the sparking potential may differ considerably from the normal static value. It is only proposed to touch upon the most important points in this Chapter. For the more detailed results the works given in the bibliography at the end of the Chapter are referred to [1].

The case of a single flash not preceeded by other flashes, has been treated by the writer in collaboration with Stephenson [2], and more recently the subject has been investigated by Clarkson [3].

Under such circumstances, provided the threshold currents passing throught the tube or spark gap, are not large enough to cause appreciable changes in the sparking potential, the observed dynamic sparking potential may be considerably greater than the normal statical value, and it has been shown that the divergence of the sparking potential is brought about by a time lag in production of discharge behind the voltage tending to produce it [4]. If the function $\phi(t)$, gives the variation of potential with time, across the discharge tube terminals, and τ, is the time lag in production of discharge after the time t_c, at which the voltage across the tube is of the value v_c, the static sparking potential, then the dynamic sparking potential is given by the relation,

$$V_c = \phi(\tau + t_c) \quad \ldots\ldots\ldots \quad (17).$$

Alternatively if $\Theta(V)$ is the current flowing into the discharge tube system (Capacity C) for a given voltage V, across the electrodes, before discharge occurs then

$$V_c = v_c + \frac{\int_{t_c}^{\tau} \Theta(V).\, dt.}{C} \quad \ldots \quad (18).$$

For cases in which C, is large, as for example when a capacity of some microfarads is placed in parallel with the tube, and τ, is not very great, we have that V_c is of approximately the value of the statical sparking potential v_c, For small values of C, however, and for large values of τ, V_c may diverge very considerably from the normal statical value.

The case described above is important from the point of view of its technical applications to sparking gaps, sparking plugs etc. 5). Equations (17) and (18) are easily adaptible to the requirements of any particular case.

Time Lags in the Production of Discharges.

The existence of time lags in discharge production was mentioned in Chapter 1.

There are several theories on the subject, none of which are entirely satisfactory. The most usual theory is that the lags are brought about by a lack of electrons or ions (within the gas) to produce a discharge by ionisation by collision (see Chapter 2, "The initiation of the discharge"). This theory is supported by the results of Züber 6). According to Züber the time lag is determined by chance, and obeys a probability law. Zeleny 7) attributes the lags in the case of discharges from points, to the surface layers of gas on the electrodes. Peek 8 explains the lag as being the time of build up of the corona discharge. Pedersen 9) in work on lags of very small duration (of the order of 10^{-7} secs.) concludes that, for clean electrodes and dry gases, the lag is constant, independent of the electrode distance and of the intensity of the irradiation.

Time lags of long duration (half hour or more) may be observed if the potential applied to the discharge tube is just of the static sparking potential. The time of lag is variable, but the average time decreases with increase of the applied potential and finally becomes very small 4).

It has been found by most observers that irradiation of the

cathode (also irradiation of the gas in some cases) reduces considerably the time of lag, and if the ionising factors are sufficiently great the lag becomes inappreciably small [10]). *)

We must now consider the general effects produced by ionising factors.

Irradiation Effects.

(1). *Irradiation of the cathode and (or) gas of the discharge tube will ensure the presence of electrons or ions in the gas. Consequently the lags due to the lack of ionisation required to build up discharge will be suppressed or reduced to small values.* Certainly in the majority of cases lags of duration of the order of several minutes are suppressed in this manner [4]). This is not invariably the case however, indeed in certain tubes used by the present writer, no appreciable lag was observed when the potential across the tube was of the static sparking value, either in darkness or in the presence of ionising factors, but lags of considerable duration were observed either in the dark or in the presence of ionising factors when the tube became polarised. Indeed, it was found that with such discharges in rare gases, the time lag appeared to be connected essentially with a state of polarisation of the electrodes.

Later work by Clarkson [3]) has disclosed the extremely interesting fact that lags of considerable duration (of the order of a hundreth of a sec.) may occur in such tubes even when relatively large threshold chrrents are passing. Clarkson is further of opinion that the lags observed in his experiments are to be referred to the electrode surface effects on the cathode.

(2). *Irradiation of the cathode will modify the polarised*

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*) The smallest possible lag is of course given by the time required for the actual building up of the discharge, that is to say the time of relaxation of the gas. This time is usually extremely small, of the order of 10^{-8} secs.

layers on the surface and will consequently modify any lag phenomena which is caused by such effects.

When a potential equal to the normal statical sparking potential is placed across an unpolarised discharge tube, discharge will occur. The passage of the discharge is accompanied in many cases (see Chapter 3. "On polarisation Phenomena") by a charging up positively of the surface layer of the cathode (occluded gas layer). This action sets up an electrical double layer which will disappear with time, the time of disappearance varying according to the type of layer. The potential across the surface layer will depend, as we saw previously, upon the length of time for which the discharge has been running etc. When a potential is again placed across the discharge tube electrodes this polarised layer will modify the conditions under which discharge occurs.

In the first place if the potential across the gas layer is p volts, then if V is the potential across the tube, the actual effective potential across cathode to anode is (V-p) volts. The experimental results indicate that p is fairly small so that this effect need no be considered in any detail.

Secondly the charge of the layer will introduce a decrease of the photoelectric emissivity of the cathode, for the electrons must traverse the charged layer of gas and the work of extraction is consequently increased by the amount corresponding to the potential p. volts. According to the photoelectric theory of the sparking potentials this change of photoelectric emissivity will be accompanied by a considerable increase in the sparking potential.

Thirdly, if the surface layers on the cathode are of considerable thickness they may introduce a considerable increase in the resistance of the discharge tube and decrease the possible energy transference.

On these views a considerable part of the lag in the discharge behind the voltage tending to produce it, may be caused by the surface layer action.

The time lag would consequently be in some cases simply

the time taken for the disappearance or partial disappearance of the charge of the layer, in others the lag may proceed from the setting up of a layer in the initial stages of the discharges. Such mechanisms would introduce time lags of variable duration according to the previous electrical treatment of the tube.

It is not possible to state definitely of course that all time lags in the discharge are attributable to such a mechanism, indeed it is somewhat improbable, but that such an action enters into the lag phenomena is proved definitely by the writer's work, and the more recent work of Clarkson.

We see at once that the action of ionising lactors may introduce large variations in the lag. The effects of irradiation may be of several kinds.

The photoelectric action of radiation incident upon the cathode will cause the emission of electrons, which will hasten the neutralisation of the charged surface layer. The efficiency of the radiation will increase with the intensity and frequency. Further, if the quantum of the incident radiation is sufficiently great the photoelectrons will be ejected with sufficient velocity to penetrate the polarisation layer and supply electrons for the building up of the discharge. Both these actions will entail a diminution of the time of lag.

(3) *Irradiating the cathode or (and) gas will set up a threshold current which will lower the sparking potential.*

This effect was considered fully in Chapter 2. The magnitude will depend upon the intensity and frequency of the radiation, the form and geometrical disposition of the electrodes, the nature and pressure of the gas, etc.

Resultant Effect of Irradiation on the Dynamical Sparking Potential.

In any actual case the sparking potential under dynamical conditions will be determined by the two coexistent and coincident phenomena, the lag in discharge production, and the threshold current traversing the tube. It is evident therefore

that the dynamical sparking potential may be greater than, equal to, or less than the normal statical sparking potential according to circumstances.

For the case of continuous flashing in discharge tubes there is much experimental evidence in favour of the above hypothesis. In some recent work on the lag phenomena in flashing of certain types of discharges, Clarkson arrives at the conclusion that the sparking potential changes arise from the two effects of time lag in the production of discharge, and the persistence of threshold currents during the "dark" period [3].

It should be stressed here that persistence of the metastable states may also be a considerable factor in determining the sparking potential variations observed in such cases.

The working of the above described independent effects throws considerable light upon the divergent results obtained by numerous observers working under different conditions.

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4) *Handbuch der Physik.* xiv. p. 361 (1927).

5) Peak. "Dielectric Phenomena"; Campbell, *Phil. Mag.* xxxviii. p. 214 (1919); Wynn-Williams, *ibid.* 1. Feb. (1926); Morgan, *ibid.* 4. p. 91 (1927).

6) Züber, *Ann. d. Phys.* lxxvi. p. 231 (1925).

7) Zeleny, *Phys. Rev.* xvi. p. 102 (1920).

8) Peak, "Dielectric Phenomena".

9) Pedersen, *Ann. d. Phys.* 71, 317, (1923).

10) See e.g. Züber, *loc. cit.;* Taylor, Clarkson and Stephenson, *loc. cit.;* Taylor and Sayce, *Phil. Mag.* 1. p. 918 (1925).

11) *Phil. Mag.* iii. pp. 756—758 (1927).

Stellingen.

I.

The objection of Salet to the Theory of Solar Prominences of Julius does not necessarily disprove the theory.

P. Salet, C. R. cxliv, 1147, 1907.

II.

The statement „finally it seems quite likely that, when the total characteristic (including the parts with a negative slope) is taken into account, the well-known vibration of a neon-tube connected to a resistance and condenser in shunt may be similarly treated under the heading of relaxation-oscillations" is not correct.

v. der Pol. Phil. Mag., ii, Nov., 1926.

III.

Dauvillier's experiments on the pressure effects and radiations in rare gas discharges are not entirely satisfactory.

A. Dauvillier, Journ. de Phys., Dec., 1926.

IV.

The term „factor of merit of a galvanometer" as used in English scientific literature is misleading and in many cases has little significance.

Ayrton and Mather, Phil. Mag. xliv, 349, 1898.

V.

It is possible to measure under precise conditions, time lags in the production of spark or glow discharges, and such works as those of Campbell, Züber and Pedersen, have been done under conditions unsuitable for the development of the physical theory of the subject and are needlessly complicated.

Campbell, Phil. Mag. 38, 214, 1919.
Züber, Ann. d. Phys. 76, 231, 1925.
Pedersen, Ann. d. Phys. 21, 317, 1923.

VI

The policy adopted by the special Committee for the League of Nations Advisory and Technical Committee for Communications and Transit, in the consideration of calendar reform is unscientific.

„Report on the Reform of the Calendar", Geneva, 1926.

VII

The Coolidge type of x-ray tube can only be applied to the examination of the characteristic radiation of targets if great precautions are taken.

VIII

The statement that „the prestige of physics has exerted a harmful influence on the study of psychology" is not correct.

J. W. Sullivan, „Gallio or the Tyranny of Science". Page 56.

IX

The work of Boomer on the formation of helium compounds in the electric discharge is not entirely satisfactory.

E. H. Boomer, Proc. Roy. Soc. cix, 198, 1925.

X.

The application of the „exchange" system to the teaching profession would be attended by beneficial results.