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AN OPTICAL STUDY OF THE FORMATION STAGES OF SPARK BREAKDOWN

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Abstract

With the electrooptical shutter described in the preceding paper a visual and photographic study has been made of the manner in which a static breakdown occurs in an air gap with an approximately homogeneous initial field. The study covered a range of pressures P from 20 to 76 cm of Hg and gap lengths δ from 1.25 to 10 mm. The manner of breakdown for any condition can be told by the product ($P^{1/3}\delta$): for values less than 11.9 the breakdown starts at the cathode; for values greater than 11.9 there are two initial breakdown regions, one at the cathode and one out in the gap. The exact manner in which the breakdown proceeds is shown and discussed in detail. The effect of space charges on the time required for the gap to completely breakdown is also shown and a possible arrangement of space charges is suggested which would explain the phenomena observed. Data on the rate of voltage fall of the gap are given.

Introduction

IN SPITE of the extensive amount of experimental work which has been done in the study of spark phenomena, the exact manner in which a gap breaks down, that is becomes conducting, has remained unknown. This is due not only to the complexity of the phenomena occurring but even more to the extremely short times required for this breakdown. Much theoretical work has also been done, most of which has been based on the theory of Townsend.[1] A fundamental difficulty encountered has been to explain how positive ions at the average fields existing at breakdown can supply a sufficient number of electrons in the vicinity of the cathode to maintain the discharge. As pointed out by Loeb[2] and others the difficulty is undoubtedly due to neglect of the distortion of the field caused by space charges. Several interesting attempts have been made to show more exactly how this distortion takes place. Von Hippel and Franck[3] in an attempt to explain the short times required for impact breakdown postulated a mechanism in which several successive electron bursts travelling the length of the gap produce an increase in field strength near the cathode sufficient to cause the positive ions to ionize. For the same problem Loeb[4] postulated a "chain" mechanism in which, under the action of a suddenly applied field, the ions existing in the gap from natural sources produce space charges in travelling 1 or 2 mm sufficient to cause *local* fields large enough to result in ionization by positive ions. Schumann,[5] considering static breakdown has made a more exact solu-

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[1] Townsend, Electricity in Gases, Oxford, 1915.

[2] Loeb, Jour. Frank. Inst. **205**, 305 (1928); also Science **69**, 509 (1929).

[3] Von Hippel and Franck, Zeits. f. Physik **57**, 696 (1929).

[4] Loeb, Science **69**, 509 (1929).

[5] Schumann, Zeits. f. tech. Physik **11**, 58, 131 and 194 (1930).

tion of the differential equation connecting the ionization processes and has shown that the dark currents immediately preceding breakdown can produce large distortions of the field, the field at the cathode being increased and that at the anode reduced. This would lead one to expect the breakdown to start at the cathode and proceed toward the anode. Schumann also showed that the magnitude of the field distortion should increase with gap length and with pressure. A limitation to this, as well as other mathematical theories, is that they are valid only during the dark stage of the breakdown and do not apply to the stage in which an actual conducting filament is forming.

Realizing the lack of any experimental basis upon which a more complete theory could be built, this experimental investigation was undertaken to determine, if possible, the exact manner in which a gap does break down, that is, whether the conducting filament builds out from the cathode as indicated above, or proceeds in some other manner. The investigation was confined to a study of static breakdown in air. Simultaneously with it a study of impact breakdown has been made by von Hámos.[6] The present work has been in progress since the publication of a previous paper[7] which recorded the results of a study of both the form and spectrum of sparks during stages *after* a conducting filament has formed across the gap.

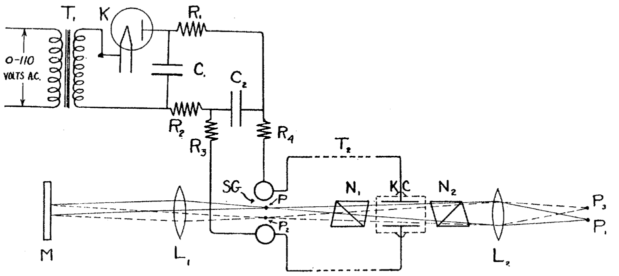

Fig. 1. Diagram showing electrooptical shutter with high voltage supply for spark gap.

Apparatus

The only feasible method of experimental attack seemed to be the optical one using the electrooptical shutter. However, the electrooptical shutter as previously used by the author[7] and others did not yield results. It was seen that considerably more knowledge regarding its manner of action was needed before satisfactory results could be obtained. Such a development was undertaken, the results of which are given in the paper preceding this one. Reference is made to it for the theory and technique employed in utilizing the shutter in this study.

A diagram of the electrical and optical essentials of the apparatus is given in Fig. 1. The diagram shows the electrooptical shutter as described in the preceding paper together with the source of high voltage d.c. (0–20,000 volts). The alternating current supplied to the transformer T_1 (1 kw, 25,000

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[6] Von Hámos, Ann. d. Physik **7,** 857 (1930).

[7] Lawrence and Dunnington, Phys. Rev. **35,** 396 (1930).

volts) was rectified by the kenetron K and filtered by the large filter condenser C_1 (0.024 mf). The spark gap SG was fed directly from the smaller condenser C_2 (0.008 mf). Upon breakdown, the discharge of the latter through the gap was aperiodic due to the slight overdamping of this circuit by the distributed linear resistances R_3 and R_4 (25 ohms each). The length of each lead connecting C_2 with SG was 75 cm, which means that the energy from the condenser began to feed into the gap 5×10^{-9} sec. after the beginning of the breakdown. The automatic recharging of C_2 from C_1 required possibly a tenth of a second due to the high resistances R_1 and R_2 (400,000 ohms each). The magnitude of the voltage impressed on the gap could be controlled by a potentiometer input to the primary of T_1 (not shown). The frequency of breakdown of the spark gap was controlled by a vernier adjustment of the voltage input, an increase in the voltage causing an increased frequency of breakdown, since the time lag is an inverse function of small overvoltages. All photographic work and part of the visual was done with essentially no overvoltage, the frequency of breakdown being quite erratic but averaging about 30 a minute. The other visual work was done with a frequency of about 60 to 120 a minute to give a fair persistance of vision, and required overvoltages less than a half of a percent. When possible such observations were checked at no overvoltage.

The spark gap SG consisted of two brass spheres of 4 cm diameter. These provided a fairly homogeneous field, the ratio of the maximum to the minimum field being 1.034 with a 2 mm gap and 1.173 with a 10 mm gap. The use of larger spheres to give a greater homogeneity made observation and photography difficult due to the large sidewise movement of the spark. The spheres were mounted in a glass chamber, the distance between them being varied by a screw feed working through metal bellows. The electrodes could be removed readily and were polished and cleaned with alcohol frequently. To provide constant experimental conditions, absolutely dry air was supplied to the spark chamber through a conventional drying system. Before each run, the system was pumped down for an hour or more at a pressure of about 10^{-5} mm of Hg. Liquid air traps on inlet and outlet sides of the spark chamber insured the absence of all vapors.

An essential auxiliary apparatus was a quartz mercury arc, the light from which was focused on the cathode of the spark gap to provide a continuous supply of photoelectrons. Since a perfectly black background is necessary for the observation of the faint early stages of the spark, all visible light from the arc was removed by use of a large quartz prism.

Another auxiliary apparatus was a specially constructed voltmeter to read the potential applied to the gap. A short period galvanometer, shunted to reduce its sensitivity to a full scale deflection (50 cm) at one milliampere, was placed in series with a twenty megohm resistance, the whole apparatus completely shielded and connected directly across C_2. Normally the voltmeter was disconnected after the breakdown potential had been measured. This allowed much better control of the voltage and left no steady current drain from C_1 and C_2 to cause a slight voltage ripple.

EXPERIMENTAL RESULTS

Preliminary results giving the type of breakdown at various combinations of pressure and gap length indicated the necessity of a comprehensive survey of the manner of breakdown over a range of pressures and gap lengths in order that the way might be paved for a general understanding of the phenomena. Such a survey was undertaken over a range of pressures from 20 to 76 cm of Hg and for gap lengths from 1.25 to 10 mm. The range of the survey was also limited by the breakdown voltage, no condition being studied with a breakdown voltage below 3,500 volts or above 20,000 volts. The results are presented in Fig. 2. Each rectangle shows the step by step development of the spark at the pressure indicated at the left and the gap length below. The polarity is indicated at the right. The number at the top of each spark gives the time at which the shutter began to close as measured from the beginning of the voltage drop on the spark gap (i.e. these numbers are path times—see Part I of the preceding paper). At the time this survey was made it had not been found possible to photograph single sparks, hence the results shown are very carefully made pencil drawings. Each drawing was made directly after observation and was checked many times in order that it would accurately represent a typical spark. The length of each spark has been drawn the same, no matter what the actual gap length, so that the change in scale must be allowed for.

In general it is seen that the manner of breakdown varies continuously with both gap length and pressure. The expectation that the breakdown would start at the cathode and proceed across to the anode is seen to be fulfilled for sufficiently short gaps or sufficiently low pressures. The predominant role played by space charges is evident from the discrete regions of initial breakdown. The increasing effect of these space charges is noted as the gap is lengthened and the pressure increased, inasmuch as the initial breakdown region separates from the cathode and moves farther and farther out into the gap. Under such conditions there are two initial regions of breakdown: one out in the gap and one at the cathode. Still further increase of gap or pressure tends to subdue the cathode region. In all cases there is a third distinct region at the anode which appears during later stages of development. The central region always connects with the cathode first and with the anode last.

Before discussing these results further, some points should be mentioned which it has been impossible to show in Fig. 2, or which, though shown there, should be emphasized:

Multiple filament. One of the most interesting observations made in this study was the multiplicity of the filament frequently seen in the region between the cathode and central bright region as the two are connecting. The filament there, though frequently appearing single, is many times composed of a bundle of intertwined filaments, each apparently representing a different electron path. This was noted at all observed pressures at gap lengths of 7 mm and greater. Another multiplicity was sometimes observed immediately in front of the anode as the central region and the quite short anode region

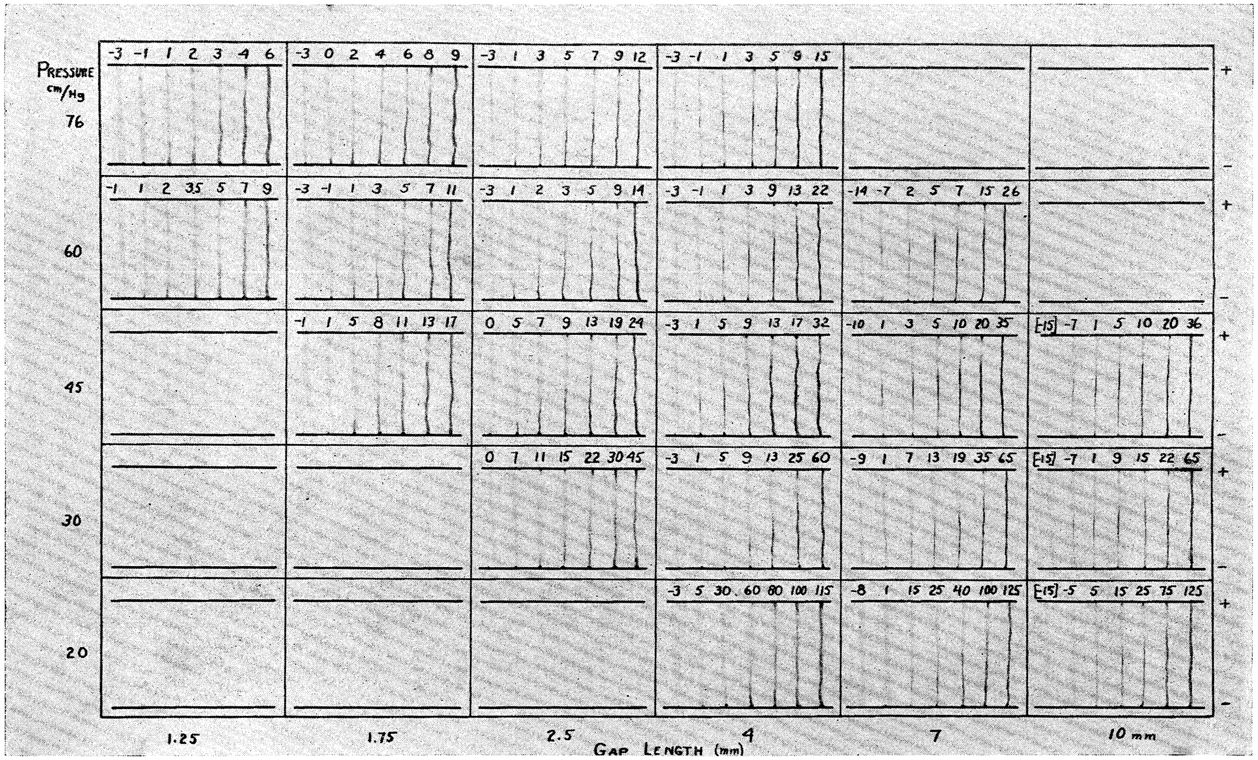

Fig. 2. Step by step development of the breakdown of a spark gap from an initially homogeneous field, shown as a function of pressure and gap length. Times given above each spark are in units of 10^{-9} sec.

began to connect. This multiple region was short and composed of two or three fairly well separated filaments. It was noted at medium to large gap lengths and pressures.

Fanning out of early haze. The hazy streak noted before the bright filament forms, and which extends from cathode (or the cathode region) to the anode, starts from a point at the cathode and widens out as it travels to the anode. This is probably due to the mutual repulsion of the electrons. Observed at medium to small gap lengths and pressures, especially at lower pressures.

Break in filament. A break or discontinuity in the filament was occasionally observed in the central part of the gap, or more frequently in the region between the center and the cathode. The break is probably due to two electron paths which have not quite joined together, and indicates that the *breakdown is not accomplished by electrons travelling the complete length of the gap but rather that it occurs in sections.* Observed under most all conditions but especially when space charges are large.

Irregularity of degree of development. No two sparks are ever exactly alike. Those shown in Fig. 2 are typical. Further the degree of development varies somewhat from breakdown to breakdown. Especially is this true for short gaps where the rate of development is rapid.

Intensity of image. The general intensity increases rapidly with increasing gap length (especially above 4 mm) and somewhat more slowly with pressure. This is entirely independent of the variation with voltage of the amount of light transmitted by the shutter. The intensity was *very high* for conditions corresponding to the upper right diagonal of Fig. 2 and *very low* along the lower left diagonal. There is a decided increase in sharpness of the image at longer gap lengths and higher pressures. Considering the relative intensity of various parts of the same image, there is undoubtedly an overshooting of the visual brilliance sensation, which overshooting increases with energy. This results in a greater apparent contrast (see Fig. 16 and discussion in preceding paper).

Since the completion of the survey given in Fig. 2, the photographic technique has been improved through the use of faster plates so that now single sparks can be photographed in a partially developed stage. Fig. 3 shows a series taken at a pressure of 76 cm of Hg and a gap length of 5 mm. The path times are given below each photograph. Two interesting breaks in the filament are recorded, one in the sixth picture where a short faint filament originates to the left of the end of the main filament and continues on to the anode and another in the next picture to the right where the break occurred earlier in the growth of the central region toward the anode and at the stage recorded has almost closed. It should be mentioned that no asymmetry has been observed in the present study in respect to the thickness of the filament at the cathode and anode in the later stages after the filament is completely across. The asymmetry reported in a previous paper[7] was apparently due to the shape of the electrodes used (parallel faces with sharp corners).

It is of interest to consider the relative effectiveness of pressure and gap length in increasing space charges and altering the manner of breakdown. The solid curve of Fig. 4 represents the condition in which the central region is just separating from the cathode region, that is, above the curve there are two initial regions of breakdown and below only one. The curve is not a hyperbola since the product ($P\delta$) is not a constant. However, as shown by the dotted line, the product ($P^{1/3}\delta$) is very nearly a constant and equal to 11.9 if pressure is in cm of Hg and gap length in mm. Thus we may conveniently say that if $(P^{1/3}\delta) < 11.9$ there is one initial breakdown region and if $(P^{1/3}\delta) > 11.9$ there are two such regions. *Pressure is therefore less effective than gap length in the production of space charges.* Space charges, however, increase with both, thus confirming Schumann's prediction.[5]

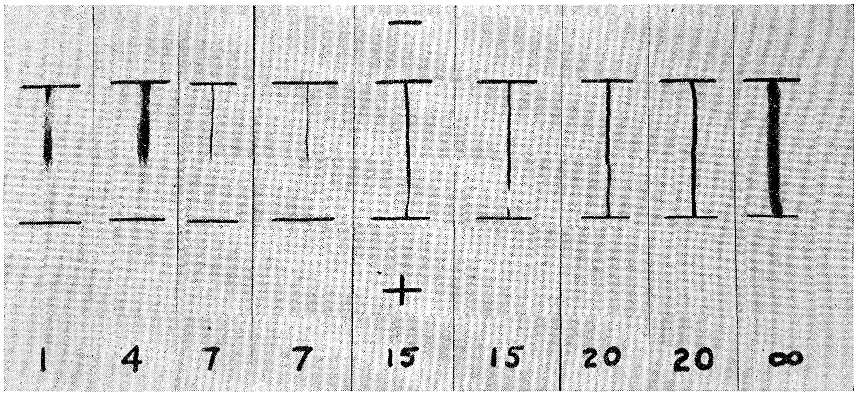

Fig. 3. Photographs of sparks showing the development of the breakdown. The first two are composite photographs, the remainder are single exposures. Pressure = 76 cm of Hg, gap length = 5 mm. Path times are indicated below in units of 10^{-9} sec.

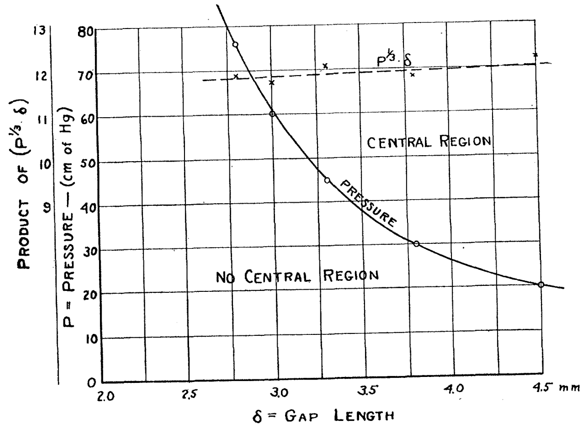

Fig. 4. Conditions of pressure and gap length which determine whether or not there is a separate central region of breakdown.

The movement of the central region (i.e. center of it) out from the cathode with increasing gap length is shown for various pressures in Fig. 5. The distance from the cathode is seen to increase almost linearly with increase in gap length but approximately only 0.6 as fast. The lower end of each curve stops at the gap length at which the union between the cathode and central region occurs (corresponding to the data of Fig. 4). The validity of the product rule determined above may now be further tested, for the $(P^{1/3}\delta)$ products of all combinations of pressure and gap length which give the same distance of the central region from the cathode should be the same. For example consider those which give a distance of 2 mm: the $(P^{1/3}\delta)$ products for the five pressures given on Fig. 4 are, in order of decreasing pressure, 19.1, 18.8, 18.9, 18.5, 18.2. The maximum deviation from the average of 18.7 is only 2.7 percent. Hence the product $(P^{1/3}\delta)$ may be used as an indicator of the type of breakdown to be expected from any combination of pressure and gap length: if the product is less than 11.9 the initial breakdown is at the cathode, if equal to 15.5 there is in addition a central region 1 mm from the cathode, if 18.7 the latter is 2 mm from the cathode, if 24.0 it is 3 mm, if 29.4 it is 4 mm, etc.

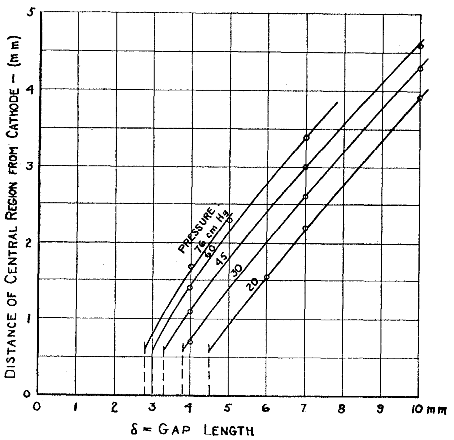

Fig. 5. Distance of the central breakdown region from the cathode, shown as a function of the length at various pressure.

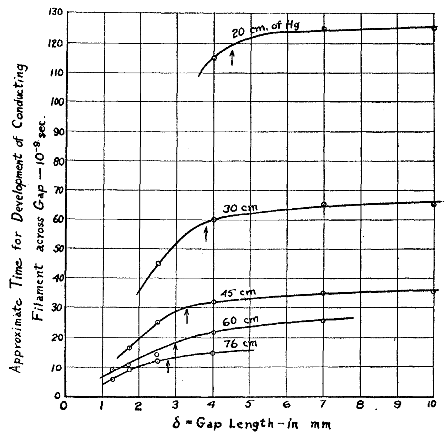

Fig. 6. Approximate time for development of conducting filament across the gap.

The last time given in each rectangle of Fig. 2 represents the path time at which the filament first appears to be developed completely across the gap. A plot of these times as a function of the gap length is given in Fig. 6. The increase of time with increasing gap length is almost linear for short gaps, then there is a break, beyond which the time is nearly constant. The interesting fact is that this break occurs in each case at just that set of conditions at which the central region begins to separate from the cathode. That is, the break occurs at the conditions corresponding to any point on the curve of Fig. 4. These conditions have been indicated by arrows on Fig. 6.

This means that *for gap lengths beyond this break-point the increased space charges produce an increase in field strength just sufficient to speed up the breakdown so that, in spite of the longer gap, the breakdown is completed at about the same time.* The increase in time with decreasing pressure, the gap length being held constant, should also be noted, the increase being especially rapid below a pressure of 45 cm. This increase is to be expected both from the decrease of space charges with decreasing pressure and also the decrease in the ionization coefficients.

The effect of the distance of the reservoir condenser (C_2, Fig. 1) from the spark gap has a marked effect on the rate of development of the breakdown. Thus with a pressure of 76 cm of Hg and a 5 mm gap, the path time for development completely across with the condenser 75 cm away is 16×10^{-9} sec., while if the condenser is 300 cm away 22×10^{-9} sec. are required. Further the intensity of the filament is much less in the latter case in spite of the later time. In relation to the variation of the intensity at a given stage of development, see Fig. 15 of the preceding paper.

The effect of ultraviolet light on the cathode should be mentioned. No detailed study was made, but in general the breakdown without the ultraviolet light was very irregular in form. For instance, in a breakdown normally having a distinct cathode and central region at a certain stage, the two regions are frequently completely joined together and this single filament may extend beyond where the central region would normally be, or it may end short of where the normal central region would be. This indicates that *the space charges built up by the steady photoelectric current just prior to breakdown have a considerable influence on the manner of breakdown.* This is also shown in the well-known increase in breakdown potential when the ultraviolet light is removed. The results of Masch[8] on this point were checked in order of magnitude. Thus at atmospheric pressure the increase with a 3 mm gap was about 0.4 percent and with a 5 mm gap about 3 percent.

The effect of overvoltage is quite similar to that of the removal of the ultraviolet light in both the irregularity of the breakdown and the behavior of the central region. The development is usually somewhat more complete at any given time of cut-off.

Oxidation of the sparking surface of the electrodes which gradually occurs during a number of successive breakdowns produces almost exactly the same effect as removal of the ultraviolet light when the electrodes are clean. This is probably due to the fact that the photoelectric effect from the oxide surface is very small or nil. Hence when the spot on the cathode has become completely oxidized and of sufficient size there is no longer an appreciable number of photoelectrons crossing the gap in the region of the highest field strength. The breakdown then becomes both irregular in time as well as in form and requires a slightly higher potential.

There remains one important point, namely the interpretation of the path times given in Fig. 2 and 3 in terms of actual times at which the stage of development recorded took place. In Fig. 19 of the preceding paper an

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[8] Masch, Archiv. f. Elektrotechnik **24**, 561 (1930).

experimentally determined correction curve was given for the increase in lag of the shutter relative to that at the time $t_p = 0.7 \times 10^{-9}$ sec. This curve applies for a pressure of 76 cm of Hg, a gap length of 5 mm and the particular Kerr cell used (capacity $= 14.7 \times 10^{-12}$ farads). In Fig. 15 of the same article the effective time of complete closing for the same set of conditions was found to be 10.3×10^{-9} sec. However, in Fig. 13 giving the computed closing curve T_1 for the same conditions and an assumed intensity increase I, it is seen from the transmitted light curve IT_1 that the stage of development would be about that at 7×10^{-9} sec. The actual time t_A corresponding to any path time t_p can now be computed as follows:

$$t_A = [7.0 + (t_p - 0.7) + L_p] \times 10^{-9} \text{ sec.}$$

where L_p is the increase in lag as obtained from Fig. 19. The accompanying table gives the results:

Path time $t_p =$	0.7	2	4	6	8	10	12	15	18	$\times 10^{-9}$ sec.
Actual time $t_A =$	7.0	9.5	13.0	16.2	19.1	21.8	24.3	27.9	31.5	$\times 10^{-9}$ sec.

As indicated before these results are for the set of conditions: pressure $= 76$ cm of Hg, gap length $= 5$ mm and Kerr cell capacity $= 14.7 \times 10^{-12}$ farads. A rough determination of the correction curve with the same Kerr cell but with a pressure of 37 cm and a 10 mm gap gave a curve substantially the same but lying slightly above. Time and the magnitude of the task prevented the obtaining of the actual times for other conditions. In general the actual time corresponding to any given path time will increase slowly with increasing length of time for completion of the filament across the gap (effect of rate of voltage fall on tap—see Fig. 8 of preceding article) and will increase more rapidly as the breakdown voltage is reduced (effect of increasing capacity of Kerr cell necessary at lower voltages—see Fig. 11 of preceding article). In making the survey a group of Kerr cells was used having capacities varying from 10 to 50×10^{-12} farads.

DISCUSSION

The most outstanding feature of the results of this study is the demonstration of the predominant role played by space charges in influencing the manner of breakdown. No theoretical treatment or explanation of these space charges will be attempted here but the following simple and very approximate suggestion as to the probable distribution of charges in the gap may be of interest. Application of Gauss' theorem to a differential length of a tube of force in an electric field gives the well-known result that the field gradient dE/dx at any point x is proportional to the charge density ρ at the point. If now, the assumption is made that the field strength existing in the first stage of breakdown—that is, at the time the initial breakdown regions begin to appear—is approximately proportional to the luminous energy distribution, the upper curves of Fig. 7 are obtained. The group (1) corresponds to a breakdown such as that at a pressure of 76 cm and a gap of 4 mm, the group (2) to a breakdown such as that at a pressure of 20 cm and a gap of 4 mm. The average field $\bar{E}$ is indicated by the dotted lines. Using these E curves and the mathematical relation stated above, the space charge curves given in the lower half of Fig. 7 result. In the two region type of breakdown there are seen to be three major space charge regions, two being positive and one negative, while in the one region (cathode) type of breakdown there is only one major region, it being positive and of irregular strength. In both cases there is probably a small negative charge in front of the anode. Comparison of the two density curves shows that the separation of the central breakdown region from the cathode region is due to the appearance of a negative charge in the middle of the original long region of positive charge. It is interesting to note that the multiplicity of filament frequently observed in later stages of the breakdown occurs in exactly the regions occupied by the negative charges in Fig. 7.

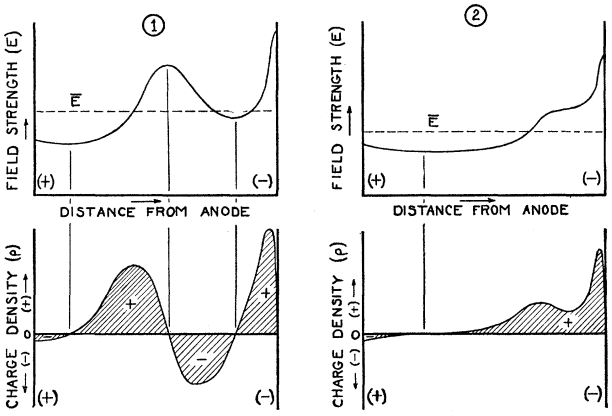

Fig. 7. Approximate field strength and distribution of space charges in the first stage of breakdown, (1) in type with cathode and central bright regions, (2) in type with cathode region only.

It is to be emphasized that the assumption on which the foregoing discussion is based may or may not be correct. It certainly would not be valid for any later stages when a partial filament has formed, for then the field would be highest just at the end of the filament (where the intensity is low) and lowest in the most completely developed (i.e. brightest) part of the filament. The above treatment, if valid, applies to the field and charges which *produce* the first section or sections of the filament.

Considerable work has been done with the cathode ray oscillograph in the study of the manner of voltage drop across the spark gap during an impact breakdown but as far as is known to the author only one picture has been obtained of a static breakdown. This picture, obtained by Rogowski and Klemper[9] indicated that at atmospheric pressure and a breakdown potential of 9000 volts (about a 2.5 mm gap) a time of 25×10^{-9} sec. was required for the voltage to fall to about 25 percent of its original value. As

[9] Rogowski and Klemper, Archiv. f. Elektrotechnik **24,** 127 (1930).

mentioned in the preceding paper, this present study gives further information on the rate of fall. At atmospheric pressure and a 5 mm gap, experimental data combined with theory indicate a voltage collapse to 20 percent of the initial value in 14.3×10^{-9} sec. (that at 2.5 mm would probably be smaller). An additional study at a 37 cm pressure and 10 mm gap gave a time of 28.5×10^{-9} sec. for the voltage to fall to 20 percent. A paper by Street and Beams[10] has just appeared giving potential collapse curves computed by a new method developed by them. In their results the exact location of the beginning of the voltage break on the gap is indefinite, but estimating it as closely as possible their results indicate a time of 21×10^{-9} sec. for the voltage to collapse to 20 percent at a pressure of 76 cm of Hg and a potential of 17.7 kv (about a 5.4 mm gap). Comparing their potential time curve for this condition with that of the author for the same pressure and a 5 mm gap (see Fig. 6 of preceding paper, $m=0.21\times10^9$), the slope is found to be almost the same for voltage values from 80 to 40 percent of the initial, but the curve falls more slowly for higher and lower values. Their results involve the assumption that the static and impact breakdown values are identical under the conditions of their experiment. Hence, the times obtained by them are equal to or greater than the true values. The time from Rogowski and Klemper's work can be similarly classified, while that obtained by the author is equal to or less than the true value. Hence, the only conclusion now possible is that, at atmospheric pressure and a gap of the order of 5 mm, the time for the voltage to collapse to 20 percent of its initial value lies somewhere between 14 and 25×10^{-9} sec. The author's results are incompatible with a value as large as the latter.

It should be emphasized that most of the experimental results of this paper were possible because it was discovered that the eye is a far more sensitive recorder of these extremely short pulses of light than any photographic plate. Even in the more recent photographic work, such as shown in Fig. 3, much of the detail is lost due to the present photographic limitations. Photographic studies, if feasible, would of course be far superior to visual observations.

The present study has hardly more than opened up a large field for investigation. The work will be continued, with a spectroscopic study of the light one of the immediate objectives.

It is again a pleasure to thank Professor E. O. Lawrence for many helpful suggestions.

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[10] Street and Beams, Phys. Rev. **38**, 416 (1931).

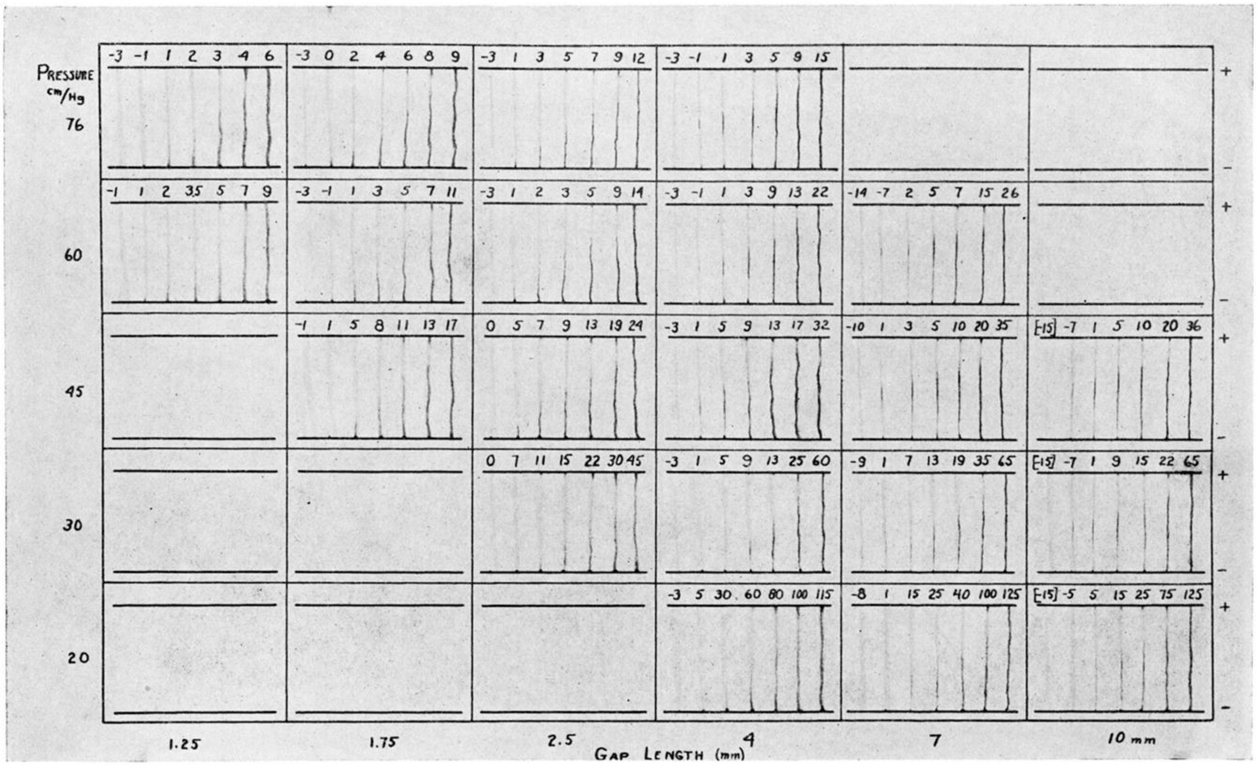

Fig. 2. Step by step development of the breakdown of a spark gap from an initially homogeneous field, shown as a function of pressure and gap length. Times given above each spark are in units of 10^{-9} sec.

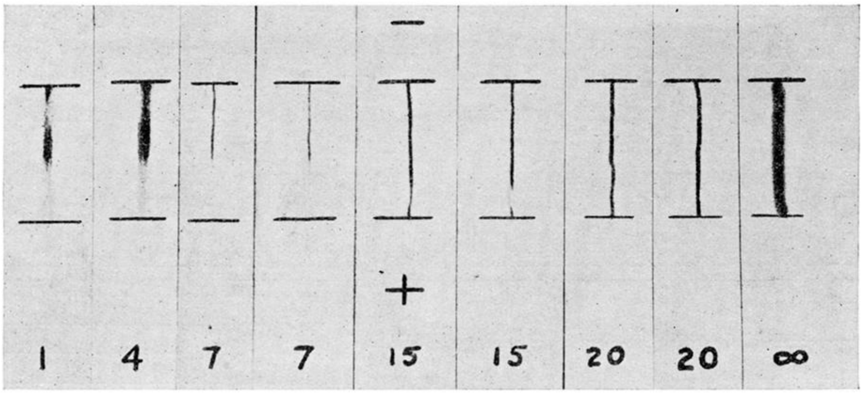

Fig. 3. Photographs of sparks showing the development of the breakdown. The first two are composite photographs, the remainder are single exposures. Pressure = 76 cm of Hg, gap length = 5 mm. Path times are indicated below in units of 10^{-9} sec.