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The Channel of the Spark Discharge*

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The luminous channel of the spark discharge and the discharge current are simultaneously measured. It is concluded that the spark discharge in air attempts to establish a channel in which the current density is a constant value of the order of 10^3 amperes/cm^2. During the formation of the channel, which takes place by an expansion process producing a pressure or sound wave, the current density is much greater. Throughout most of the formation time and the subsequent history of the channel, the light energy which is radiated is proportional mainly to the current within the channel. From potential measurements and the photographic records, the energy requirements for development are considered, and some possible relations of these requirements to the electrical circuits are discussed. The data are also discussed in relation to the progression of streamers. The pilot streamer theory of the lightning discharge is indicated to be unsatisfactory by comparison with measured discharge characteristics, and the associated roles assumed for diffusion and recombination processes in the spark discharge channel do not appear valid.

THE spark discharge in air at atmospheric pressure is characterized by a sudden electrical transition accompanied by the radiation of light and sound. Although the channel which provides the electrical conduction is often considered to be indistinct and varies greatly in size, Beams[1] has shown that with a suitable photographic system the luminous source during at least part of the development of the discharge has a definite boundary which expands with the development. The photographs obtained by Lawrence and Dunnington,[2] and Dunnington,[3] using a different method, also show a clearly defined channel with the same characteristics in the development over the complete path observed. Suits[4] has considered the expanding luminous channel observed with exploding wires as the source of the sound wave similar to that originating from the spark in air, and has indicated that the sound energy may be much greater than the light energy. To determine more fully the significance of the luminous channel, an investigation has been made of a wide range of spark discharges which are known to be the sources of both intense sound and light.

PHOTOGRAPHY OF THE DISCHARGE CHANNEL

The photographic methods used are schematically shown in Fig. 1. In Fig. 1a, a suitable slit is placed before the discharge path and perpendicular to its direction. The slit image is recorded upon a moving film with the direction of the image perpendicular to the direction of the motion of the film. The length of the recorded image of the slit provides a measure of the channel width at any time, and a known time resolution is provided by the values of the slit image width and film speed when precautions are taken with respect to the film exposure and the density developed. A more flexible method is shown in Fig. 1b. The discharge currents have been provided by various arrangements of high voltage and high current impulse generators of large capacitance. The circuit connections and the cathode-ray oscillograph methods are essentially standard.

A number of photographic records for which simultaneous current measurements were obtained are shown in Fig. 2. Measurements from these individual records which were obtained by the method of Fig. 1a are given in Table I with corresponding measurements from the current oscillograms. Examination of the images reveals that the discharge channel manifested by the intense light is relatively small at the beginning of the intense light, and is expanding at a velocity much greater than that of sound in the sur-

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* Part of the experimental results presented here have been reported at the Cambridge, Massachusetts meeting of the American Physical Society, February, 1941 [Phys. Rev. 59, 685 (1941)].

[1] J. W. Beams, Phys. Rev. **35**, 24 (1930).

[2] E. O. Lawrence and F. G. Dunnington, Phys. Rev. **35**, 396 (1930).

[3] F. G. Dunnington, Phys. Rev. **38**, 1535 (1931).

[4] C. G. Suits, Gen. Elec. Rev. **39**, 430 (1936).

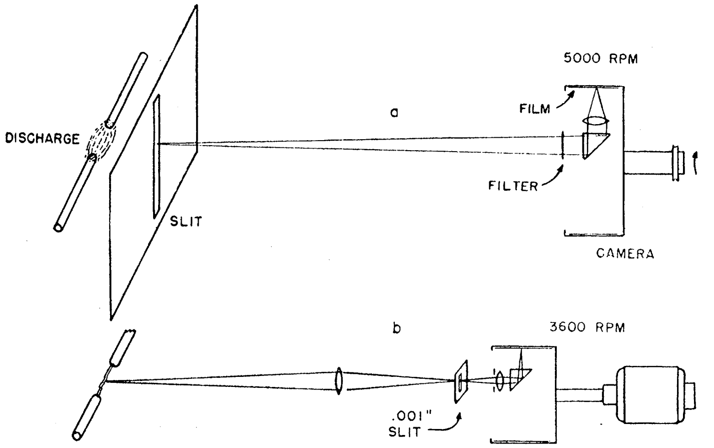

FIG. 1. The photographic systems. The distribution and the intensity of the light emission of the discharge may be recorded as a function of the time.

rounding air. The expansion appears to continue after the current has attained a maximum value although at a reduced rate, and the channel size appears to be larger for higher current values.

To provide additional information about the maximum channel size, it is necessary to sustain the currents by circuits with large time constants. This is accomplished by inserting the necessary resistance in the discharge circuit. In Fig. 3 are shown representative records of the sustained discharges obtained by the method of Fig. 1b. It is evident from Fig. 3 that an essentially constant channel size is attained for a given current after the initial expansion process has taken place. By this method the channel diameters have been investigated for current values from 10 to 10^5 amperes although for values above 10^4 amperes the time constants become insufficient to permit the maximum channel size to be attained. Discharge paths of 8- to 9-cm length allow freedom from electrode vapor near the central portion of the path for times of the order of 100 μsec.[1, 2] This is greater than any time which has been found necessary for the expansion.

Upon the assumption that the luminous boundary and the current conduction boundary are the same, the average current density in the channel may be obtained. For sustained channels conducting from 100 to 10^4 amperes, the current densities so determined are very nearly equal. Complete results are given in Fig. 4 where a linear relation is indicated between the current and the channel cross section. Above 10^4 amperes the observational points should fall upon the straight line with sufficient additional generator capacitance. Below 100 amperes uncertainty exists because of reduced image sizes and low film densities obtained with a fixed resolving time and optical reduction. However, below some value of the current, the current density may be expected to decrease because of the increasing fraction of current carried by a surface layer of fixed depth in which the surrounding gas produces

TABLE I. Correlation of data obtained from the photographs of the channel as shown in Fig. 2 and from the corresponding current oscillograms. The diameter measurements give the channel size when the current has attained the maximum value. The current densities also correspond to the time of maximum current.

Discharge film no.	Maximum current amp. $\times 10^3$	Channel diameter cm	Current density amp./cm^2	Time to maximum current sec. $\times 10^{-6}$	Average expansion velocity cm/sec. $\times 10^4$
*33	17	1.6	8,500	8.0	10
*34	18	1.4	12,000	6.0	12
*38	22	1.3	17,000	3.3	20
20	25	1.5	14,000	5.0	15
*26	26	1.8	10,000	8.0	11
23	38	2.7	6,700	16	8.5
37	39	3.2	4,900	35	4.6
28	40	3.2	5,000	35	4.6
39	53	1.9	19,000	5.6	17
7	94	2.3	23,000	5.0	23
**8–1	94	2.1	27,000	5.0	21
8–2	94	2.4	21,000	5.0	24
27	90	3.5	9,400	17	10
**35	90	4.3	6,200	17	13
29	100	3.2	13,000	17	9.4

* Damped wave.
** Probably two channels formed.

disturbances. The measurements given in Fig. 4 are average values and relatively free from effects associated with variable film densities. When the exposure time of a spark photograph extends over a period during which the channel is greatly changing, variations in the film density brought about by altering the photographic speed can greatly alter the image size. This is the usual situation when long sections of sparks are photographed upon a moving film. When this is the case, a fixed channel boundary with maximum contrast cannot be determined. Only by sufficient time resolution can a boundary be determined which is relatively free from reasonable changes in exposure. The transverse slit arrangement greatly facilitates attaining the necessary resolution. The significance of the boundary then determined is indicated by the condition of approximately constant current density within the channel. From the slope of the line drawn in Fig. 4, an average value of 1.1×10^3 amperes/cm^2 is obtained for the current density. This value is within a range of values derived by Ollendorff[5] from a theoretical treatment of a steady state equilibrium. However, his assumptions lead to a channel with a constant radius of the order of 1 cm rather than to a constant current density.

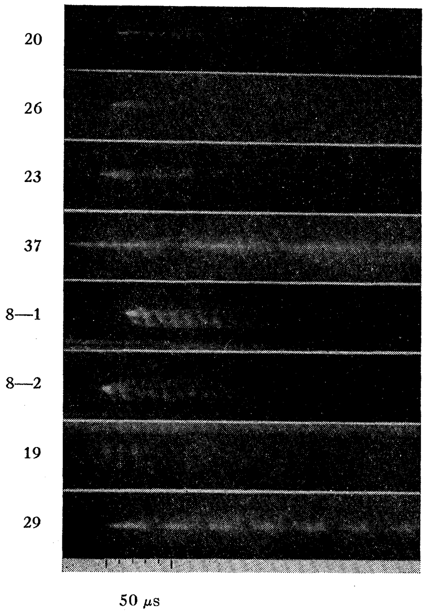

FIG. 2. Luminous channels of high current discharges obtained by the method of Fig. 1a. Increasing current from top to bottom. No. 26 does not oscillate. No. 19 is a discharge in vacuum. Additional data is given in Table I.

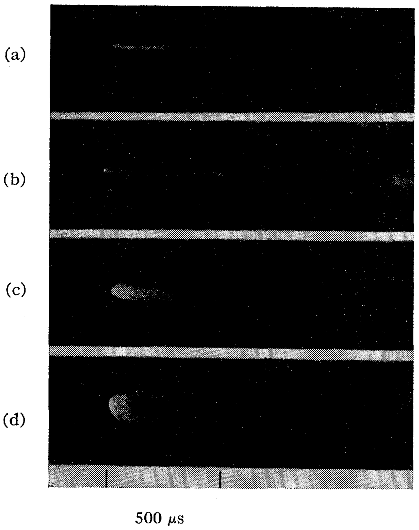

FIG. 3. Discharge channels in air with sustained currents obtained by the method of Fig. 1b. (a) 78 amperes sustained by the discharge of 6 μf and 1150-ohms series resistance. (b) 350 amperes, 6 μf and 255 ohms. (c) 940 amperes, 6 μf and 95 ohms. (d) 2900 amperes, 6 μf and 31 ohms. Current values obtained from oscillograms.

From Fig. 2 and the data of Table I, it is evident that the current density decreases during the expansion of the channel. In Fig. 5 the current density at maximum current is given as a function of the average rate of current rise. High current densities are associated with high rates of current rise. The expansion velocity as a function of the rate of current rise shows a similar characteristic which indicates proportionality between current density and expansion velocity as can be seen in Table I. No noticeable variations are observed for spherical or pointed electrodes. Also electrode spacings of five cm and one cm produce no noticeable difference.

LIGHT RADIATION FROM THE CHANNEL

Uniform development of the records permits some investigation of the light intensities in the channels. The exposures of the films were carefully controlled so that maximum film density values of about 2 were usually obtained. In Fig. 6 is given a density analysis for the central region of each of two images shown in Fig. 2. Image No. 19 is that from a discharge in commercial high

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[5] F. Ollendorff, Archiv. f. Elektrotech. **27**, 169 (1933).

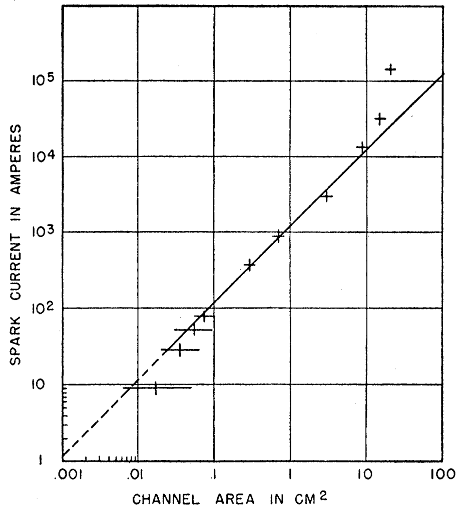

FIG. 4. The relation of current and maximum channel cross section for the spark discharge in air. The maximum channel attained for any current value is such that the current density attains an average value of 1.1×10^3 amperes/cm^2.

vacuum between copper electrodes with approximately the same current as given for the air discharge No. (8–2). From the roughly known photographic characteristic it is possible to transform density values to linear light intensity values. This has been done in Fig. 7 for some of the discharges. It is evident from Fig. 6 and Fig. 7 that the light intensity, i.e., the radiation per unit of channel surface, is much greater during the expansion process than subsequently. This is the case for all of the air discharges although it is less noticeable for low rates of current rise. From both the calculated time resolution and the analysis of the vacuum discharge which is known to deionize rapidly, it is also evident that for the air discharge the light radiation persists in the channel when the current has ceased momentarily during the oscillation. This persistence is more noticeable as the frequency is increased. In the region of 200 kc only the vacuum discharge is resolved.

A comparison of light intensity and current in Fig. 7 makes it clear that a direct proportionality between the two is not attained. The nearest approach is for discharge *E* of Fig. 7 which is the lowest frequency and which also has the lowest rate of current rise and expansion velocity. This suggests that the expansion process and the associated channel variation is also of importance in the departure of proportionality and that if the total radiation from the channel is used, i.e., the product of intensity and channel surface, the proportionality with current should be much closer. That this is the case is shown in Fig. 7 by the arbitrary ratios between current envelopes and intensity envelopes. The ratios vary with time in the same manner as the channel radii. This is to be expected if proportionality between total radiation and current is the case since the total radiation is related to the product of channel radius and intensity. Additional support for the proportionality of current and total radiation is given by the analysis of photographic records of lightning for which current values are also known,[6] and where the recorded image size is such that the total light radiation of the stroke is measured. The total radiation of light from the channel can also be considered to be in phase with the current where the proportionality exists between total radiation and current magnitude. This follows from experiments with the electro-optical shutter[1–3] where the light radiation and the potential wave from a spark are known to be closely related at very short times of measurement. Thus, the beginning of the luminous expanding channel as recorded corresponds essentially to the beginning of the main current wave. However, a probable condition, unobservable here, will be discussed later for the start of current flow where other factors enter.

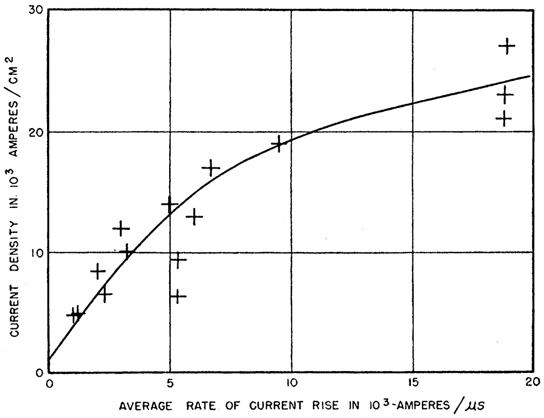

FIG. 5. Current density at maximum current as a function of the average rate of current rise in attaining maximum current in the channel.

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[6] J. W. Flowers, manuscript in preparation.

VOLTAGE GRADIENTS IN THE CHANNEL

To supplement the observations of the channel, the potentials between the electrodes during some of the discharges have been recorded. In view of the times and path lengths involved and the usual range of velocities associated with streamers, such measurements provide some information about the voltage gradient in the channel. Various difficulties occur in the measurement of the potential, particularly for lower values. Important phase relations between voltage and current have been determined from oscillograms of voltage as a function of current obtained by applying voltage deflection and current deflection to the perpendicular axes of the oscillograph. This procedure is capable of revealing measurement difficulties which are not readily apparent in the ordinary oscillogram.

In Fig. 8 separate voltage and current oscillograms are shown for a high current oscillatory discharge and in Fig. 9 for a damped discharge. From these and other measurements it is apparent that higher voltage gradients exist during the time of the channel expansion, and that considerably more energy is furnished during this time than at any other.

ENERGY REQUIREMENTS IN THE CHANNEL DEVELOPMENT

The formation of the channel requires considerable energy. There can be scarcely any doubt that the sound wave originates from the expansion process. The view of Ollendorff,[5] which proposes to relate channel explosion and current interruption, cannot be accepted since it is readily observed in the laboratory that enormous sound differences exist for different current magnitudes although the currents decrease slowly to negligible values. The radiation of light and other losses require a continuous supply of energy, but not necessarily greatly more during the development time. During this time, however, the energy required for the ionization must be considered. The current conduction can be considered to take place mainly by the movement of free electrons under conditions of essentially equal positive and negative charge densities. This, at least, must be nearly the case for streamers of great length such as in lightning, otherwise unreasonable space charges become involved. The current is then given by

$$I = \pi r^2 N e v,$$

where r is the channel radius, N is the electron density or ion density, e the electronic charge, and v the electron velocity. The energy of ionization is that required to form $\pi r^2 N$ ion pairs. Very little is known about the ion density. Lawrence and Dunnington[2] give a value of $10^{19}/\text{cm}^3$ which must be considered high where appreciable expansion has occurred. Although r and I may be determined, it is necessary also to determine v in order to fix the value of N. Estimates of v are difficult, and estimates obtained for N are unreliable where there is directly or indirectly implied the condition of thermal equilibrium with an associated temperature. Experiments with arcs show that a time of 1000 microseconds is required for thermal equilibrium to be approached in the arc.[7] Thus, the beginning of the bright channel corresponds to a highly transitory

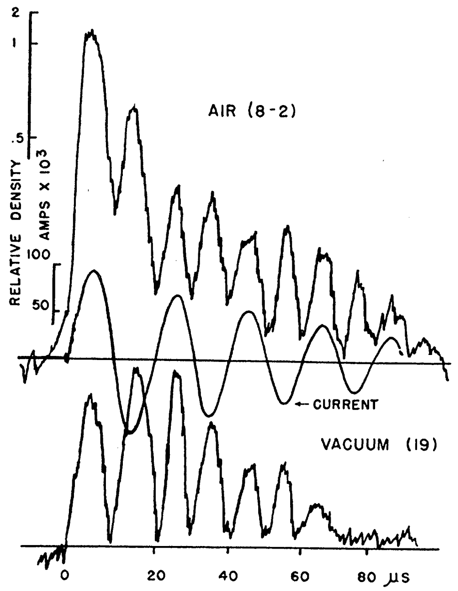

FIG. 6. Photometric analysis. The vacuum discharge, Fig. 2(19), exhibits no noticeable expansion process and the light radiation falls essentially to zero value with the current in contrast to the air discharge, Fig. 2(8–2). The current oscillogram is that obtained for the air discharge. The current was not measured for the vacuum discharge, and differences in impedance may have slightly altered the current magnitude.

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[7] C. G. Suits, Gen. Elec. Rev. 38, 194 (1936).

condition and steady state assumptions such as made by Ollendorff[5] and others are not permissible at this stage.

In view of some of the limitations it is nevertheless of value to calculate the energy required to attain the maximum current in an oscillatory discharge. For the case of the discharges Nos. 8–1 and 8–2 listed in Table I and shown in Fig. 2, the generator capacitance stores 9700 watt-seconds before the discharge. At maximum current of 94,000 amperes, attained in 5 microseconds, 7700 watt-seconds remain in the generator inductance. To develop this current in the circuit and 8.5 cm of discharge path requires 2000 watt-seconds. From the average decrement of the current oscillogram shown in Fig. 6, a value of 0.044 ohm is obtained for the effective resistance of the circuit, excluding the first cycle from the measurements. This resistance dissipates 990 watt-seconds which may be considered to account for circuit losses as well as light radiation and diffusion losses in the discharge path. The energy required in ionization for a path length of one cm is $\pi r^2 NW$, where W is the effective ionization potential. Using a value of $10^{19}/\text{cm}^3$ for N, 15 volts for W, and 1.2 cm for r as given in Table I, one obtains a value of 920 watt-seconds. For the sound wave, the energy may be approximated by considering the displacement of the air by the expanding channel.[4] The energy of the expansion is $\frac{1}{2}MV^2$, where M is the mass of air displaced and V the expansion velocity. The value of M will depend upon the change in density from a nonconducting condition to the conducting one. This is probably sufficiently great so that for estimation, M may be calculated from the density of air at room conditions. For a velocity of 2.4×10^5 cm/sec. and a channel diameter of 2.4 cm as given in Table I, a value of 130 watt-seconds is given for the sound energy. The three calculated values provide 2040 watt-seconds which essentially accounts for the measured value of 2000 watt-seconds. Extended discussion of possible variations in these values is of no particular point. Uncertainties in voltage and current produce greater uncertainties in energy values. Relative to the ionization, N may be high, but W is likely to be too low to be complete. Also, the sound wave front probably extends outside the luminous boundary, thus providing a larger value for the sound energy. While all the values are rough, they indicate some of the energy requirements in the formation of the channel. The relation between the possible energy requirements and the electrical characteristics are expressed in

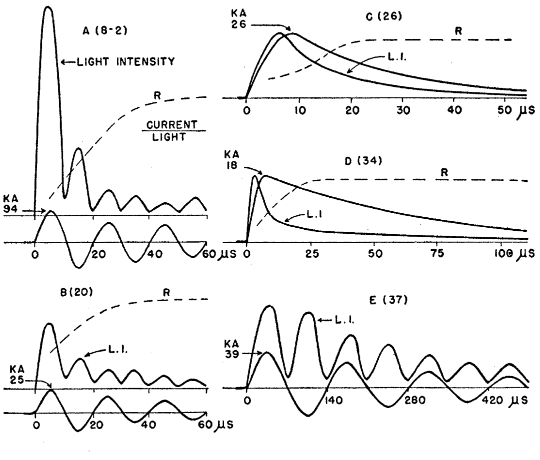

FIG. 7. Light intensity and discharge current. Intensity values are arbitrary and not based upon any common value of current.

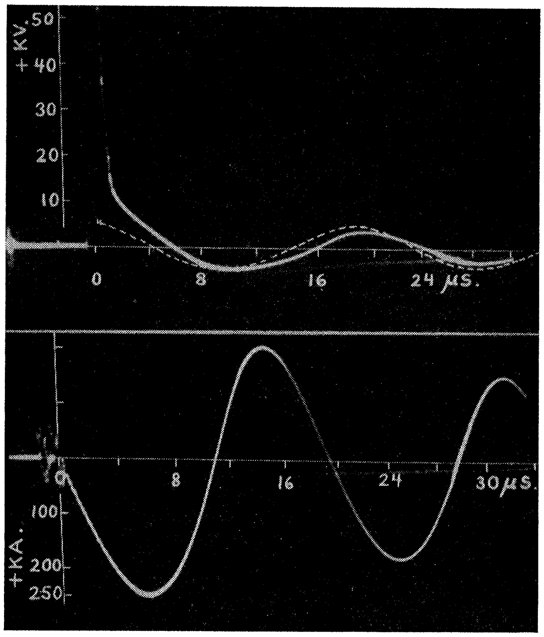

FIG. 8. Cathode-ray oscillograms of voltage and current for a discharge between 0.5″ square brass rods separated 8.8 cm. The induced voltage obtained from a separate oscillogram and a short-circuited gap has been drawn in the correct phase position. The maximum voltage attained but not shown by the voltage oscillogram is 100 kv. Oscillogram axes are slightly oblique.

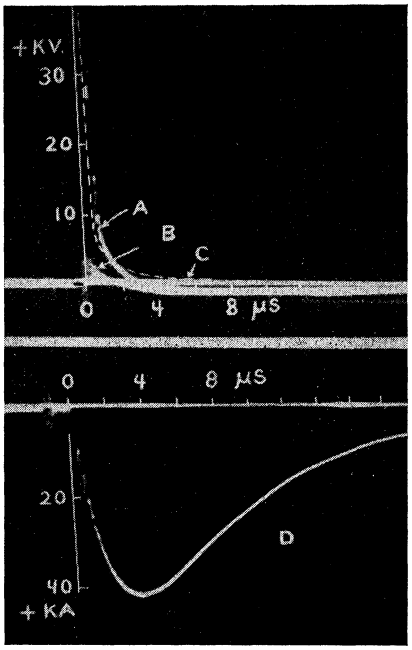

FIG. 9. Cathode-ray oscillograms obtained with a damped discharge between 0.5″ square brass rods separated 8.8 cm. (*A*) recorded voltage; (*B*) induced voltage or distortion; (*C*) discharge voltage free of distortion derived from the difference of (*A*) and (*B*); (*D*) current.

Fig. 10 from an analysis of the oscillograms of Fig. 8. Part of the measured voltage as in Fig. 8 and Fig. 9 is produced by extraneous effects such as induction in the measuring leads and some unbalanced conduction along the leads. This voltage is separately determined for the short-circuited condition of the discharge gap. Voltage contributing to the light radiation and diffusion loss is considered to be in phase with the current throughout, while the third component, necessitated by the ionization and the sound, constitutes the remainder of the voltage after the induced and light components are accounted for. For the 250,000-ampere discharge in the 8.8 cm path, the maximum power is of the order of 800,000 kw.

DISCUSSION

The Bright Channel

It would appear that the spark in air at atmospheric pressure is characterized by a bright channel which always starts as a narrow thread expanding radially. The formation of this channel requires that energy be supplied at a very high rate. Although the field strength may vary widely depending upon the current variations and the corresponding channel energy requirements, the bright channel is characterized by low field strengths in comparison to initiating values. The beginning of the bright channel in any portion of a gap indicates that the field strength is decreasing in that portion. The current in the bright channel is indicated, at least roughly, by the rate of energy radiated in light. The rapid expansion of the channel produces the sound wave of the spark. This expansion is the result of additional energy imparted to the gas in the spark path. It would appear that, for a sustained current, an equilibrium is attained when the channel radius reaches such a value that the rate of energy supplied is equivalent to the losses from the channel boundary. For a wide range of current values, this equilibrium is attained when the current density is reduced to 10^3 amperes/cm^2. However, other slower changes may take place to alter this value gradually. To attain thermal equilibrium within the channel may require appreciable time. Eventually, conditions are completely altered by vapor from the electrodes.

The Progression of Streamers and the Breakdown of Air Gaps

The progression of a bright streamer either in a gap of a few millimeters length or in the lightning discharge may be considered as the progressive development of the bright, expanding

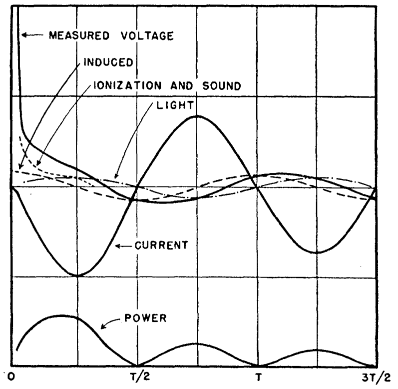

FIG. 10. Analysis of the development voltage. The measured voltage is considered to have three components, the induced voltage, the light voltage, and the sound and ionization voltage. The current oscillogram is shown inverted in the manner similar to record of Fig. 8.

channel. Associated with the streamer is a progressing potential wave with the high field strengths near the tip of the streamer. This view is supported by experiments on the propagation of potential waves in discharge tubes at lower pressures where the luminous wave travels with essentially the same velocity as the potential wave.[8] Maximum fields extend in front of the bright tip by virtue of the space charge carried with the tip by conduction in the bright channel. In the high field before the tip, the current must be considered both as a displacement current and as a conduction current afforded by a few high velocity ions. Sufficiently far ahead of the tip and for long paths, only the displacement current exists. Some of the possible relations are expressed in Fig. 11 for a streamer which has partially traversed the path between two electrodes. Figure 11 is a modification of the picture given by Rudenberg,[9] and provides for the expanding characteristic of the luminous channel as well as the more complete view of conduction current.

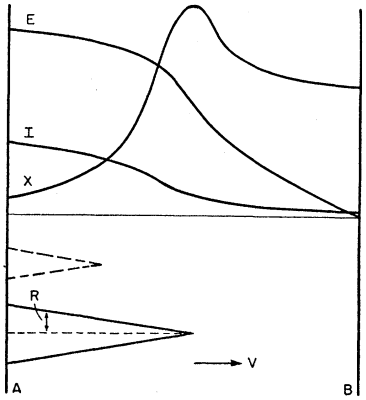

FIG. 11. Diagram of a bright streamer which has partially traversed the path between two electrodes A and B. E, the potential distribution between electrodes; X, the axial field strength; I, the conduction current. The bright channel at an earlier stage is also shown.

The breakdown of an air gap, that is, the fall of potential at the gap electrodes, depends not only upon the process which occurs in the air gap but upon the electrical circuit as well. Thus, the termination of a bright streamer resulting in the luminous bridging of a gap does not necessarily correspond to the breakdown of the gap although this is the usual and perhaps, in general, the practical consideration, since the termination probably marks the time when the impedance mechanism of the complete gap undergoes the greatest transition. However, if one considers a circuit of zero internal impedance and unlimited storage, that is, an infinite bus, no fall of potential would occur; instead an unlimited development of the discharge channel should set in. This condition cannot be realized, but consideration of it points to the dependence of the potential characteristic upon the electrical circuit as well as to the mechanism within the gas. The dependence of the potential characteristic upon the circuit is demonstrated in the experiments of Allibone and Meek[10] who employed circuits of the opposite extreme. For such circuits, with high series resistance and gap electrodes of small capacitance, the fall of potential must occur before the streamer has progressed an appreciable fraction of the gap. The fall may be only temporary, and after preliminary breakdowns and recoveries, the gap may be finally bridged. However, the intermittent streamer process is conditioned by the circuit and does not necessarily apply to all spark discharges. The interrupted streamer effects are probably associated with the limitations of energy, since energy requirements for the establishment of any channel may have considerable influence upon the overall behavior of the system in which the discharge occurs and upon the apparent discharge mechanism. The measurements of Allibone and Meek using the high resistance circuits show that relatively high currents are attained in the intermittent process as compared to the maximum current through the resistance. The discharge circuit elements effective in the formation of the transient current do not establish a small current. Instead, a channel is started as a streamer conducting such a current that the energy available from the charged electrodes is not sufficient to extend the streamer completely and form the channel between the electrodes. The subsequent surges which extend the streamers do so by virtue of the partial recharging of the electrodes and the channel characteristic which permits the storage of energy in the channel for a limited

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[8] L. B. Snoddy, J. R. Dietrich, and J. W. Beams, Phys. Rev. **52**, 739 (1937).

[9] R. Rudenberg, Wiss. Veroff, Siemens-Konz. **9**, 1 (1930).

[10] T. E. Allibone and J. M. Meek, Proc. Roy. Soc. **A169**, 246 (1938).

time. From Fig. 10 it is apparent that the first half-cycle of current requires by far the greatest expenditure of energy as compared to subsequent half-cycles. This indicates that energy is stored in the channel during the first half-cycle and less is required from the circuit subsequently. The storage of energy is also revealed by the persistence of luminosity. Thus, where the intermittent streamer or stepping process occurs, most of the available energy is used in extending the streamer, that is, in forming the new step. Thus, the main circuit is able to supply in steps the energy for the whole channel while it is unable to do so in one step at the rate demanded.

Processes Preceding the Bright Channel

In the procedure of the discharge process, it is unlikely that the initial conduction path is of the same character as the bright expanding channel. The initial ionization must develop in a region of high field strength while the bright channel signifies a reduced field. Evidence for high field conduction as represented in Fig. 11 is given in the observation of Dunnington[3] of the faint haze preceding the bright channel. The experiments of Slepian and Torok[11] and Torok and Fielder[12] also suggest a faint channel of a diffused nature while the current which causes high voltage breakdown to depend upon the generator circuit as shown by Hagenguth[13] probably flows by means of such a channel. The conduction before the formation of the bright channel very likely accounts for the condition which permits the formation of cloud-chamber tracks as observed by Flegler and Raether[14] and others.

The faint channel is difficult to observe or photograph because it is usually obscured by the bright channel. There appear to be several reasons for this obscurity. For a given current, the total number of ions in a unit path length is less in the faint channel than in the bright channel since the field strength and ion velocities are greater in the faint channel. From the assumption that the light radiation depends upon the number of ions,[6] it follows that the light radiation for a given current is less from the faint channel. The current density in the faint channel is probably much smaller than that in the following bright channel while the current is also smaller. Together all of these factors may easily produce a brightness ratio of 100 or more. Finally, the short time involved makes an extremely short time resolution necessary for the observation.

Upon the initiation of the discharge, ionization probably spreads rapidly in the region of sufficiently high field strength by a photoelectric process. The necessity of a photoelectric mechanism has been discussed by Loeb[15] and others. However, it seems necessary to consider that many ion pairs are created by photons emitted by electron avalanches shortly after the initiation, rather than to consider that the channel forms by the continued development of one or two avalanches. Those pairs of ions which are formed within the high field region do not alter the field by their presence but only by their subsequent movements which start many individual avalanches and create the faint channel. The continued development of the avalanches eventually results in the bright expanding channel with the associated decreasing field strength. As the tip of the bright streamer forms, the centrally located avalanches of the faint channel probably merge and lose identity, while the outer ones are suppressed as the field reduces and become lost by recombination. The high field is carried forward by the progressing space charge which is maintained by the good conduction of the bright streamer channel while space charge effects within the bright channel are relatively small. Concerning the differences between positive and negative streamer development which have been observed,[10, 11] there is the possibility that such differences are associated with the transition from the faint channel to the bright channel tip and with the sign of the space charge carried by the tip. The differences between positive ion and electron mobilities suggest that the positive streamer formation may have the more efficient process since the electrons are gathered by the positive tip. In the negative streamer, they are driven away with the resultant lower density of

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[11] J. Slepian and J. J. Torok, Elec. J. **26**, 107 (1929).

[12] J. J. Torok and F. D. Fielder, Trans. A. I. E. E. **49**, 352 (1930).

[13] J. H. Hagenguth, Trans. A. I. E. E. **60**, 803 (1941).

[14] E. Flegler and H. Raether, Zeits. f. Physik **99**, 635 (1936)

[15] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, New York, 1939), p. 429, 430.

ionization ahead of the negative streamer. Thus, the bright positive streamer progresses into a region of higher energy density and therefore requires less energy expenditure to progress.

The Pilot Streamer Theory

In an attempt to account for measured velocities associated with the progression of luminosity in the lightning stepped leaders, Schonland[16] has proposed an unrecorded pilot streamer which is considered to precede the luminous tip of the leader. Subsequent assumptions have been made by Meek,[17] and the general picture described by Loeb[18] and Loeb and Meek.[19] The proposed pilot streamer and its associated leaders have assumed channel characteristics which are greatly different from those of the spark channel. Since there appears no reason to suspect any difference between the channel of the lightning discharge and the laboratory spark when the transient currents are the same, it is well to consider carefully some of the assumptions in the pilot streamer theory. Among the difficulties in the theory, the most specific are concerned with the relation between electron diffusion and channel size, with the role of the recombination of ions and with the energy relations within the discharge channel.

Electron diffusion is assumed to be the controlling factor in determining the channel size of the pilot streamer[17, 18] as well as subsequently formed bright streamers.[18] The effect of diffusion is assumed to be determined from the cloud chamber observations of Raether.[20] However, if it is necessary to invoke photoelectric processes to explain the progression of the ionization as observed in the cloud chamber,[15] as it seems to be, then it appears doubtful that by such experiments the effects of electron diffusion or electron mobility can be separately distinguished. Moreover, the bright channel of a spark is clearly limited in diameter in a manner which cannot be accounted for by diffusion alone. Other factors, in addition to diffusion, probably enter to determine the size of any possible faint channel. Thus, the derivation of a channel diameter of 0.6 cm for the pilot streamer[17, 18] is questionable. Also, this channel is considered to conduct a current of 0.1 ampere; yet, a bright channel of the same diameter conducts a current of over 300 amperes or 3000 times this amount as can be observed from Fig. 4. The great difference between the pilot channel and a bright channel is clear. It may not be argued that the pilot channel is of the nature of the faint channel previously discussed because the pilot streamer is assumed to have reduced field strengths during part of its history. It does not seem reasonable that for a sustained current the field strength can drop without the formation of the bright expanding channel, so that the faint pilot streamer with its sharp drop in field strength followed by a slow rise does not fit into any of the channel characteristics which have been discussed.

It is assumed that in the pilot streamer channel, and in the bright leader channel as well, the resistance increases because of the depletion of ions by recombination.[17] This is proposed as a fundamental process to account for the intermittent character or stepping of the streamers. Such a controlling process does not appear to occur and is discounted by Bruce and Golde.[21] In addition to raising questionable energy relations, such a role would make the necessary changes in total ionization within a channel difficult to explain. In Fig. 8 and Fig. 9, there is little doubt that the ionization increases after the initial fields are greatly reduced. It is unreasonable that a discharge could predetermine and provide the necessary number of ions at a high field that are to be employed by current surges that follow at lower fields. The radiation of light roughly in proportion to the current supports these statements. The assumption of Schonland[16] and others that the intense light in streamers is associated with intense ionization at high field strengths followed by a decay of luminosity because of recombination and channel aging does not appear to be valid. The luminosity decays because the current decays. For some conditions of photography the luminosity may appear to decrease because of the changing image size associated with the expanding channel.

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[16] B. F. J. Schonland, Proc. Roy. Soc. **A164**, 132 (1938).

[17] J. M. Meek, Phys. Rev. **55**, 972 (1939).

[18] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, New York, 1939), p. 544, 549.

[19] L. B. Loeb and J. M. Meek, *The Mechanism of the Electric Spark* (Stanford Press, 1941), p. 98.

[20] H. Raether, Zeits. f. Physik **107**, 91 (1937).

[21] C. E. R. Bruce and R. H. Golde, J. I. E. E. Part II, **88**, 487 (1941).

The law of energy conservation would appear to be violated within the spark channel for conditions proposed in the recombination theory of Meek and Loeb.[17–19] The assumption of constant current and increasing resistance demands an increasing rate of energy supplied to the channel. It is difficult to account for this increasing energy as mentioned by Szpor.[22] The increasing energy rate is more than necessary to maintain the original ion density proposed, yet it is assumed that the ion density decreases. Thus, a channel of slowly varying diameter, decreasing ion density, and decreasing light radiation provides no adequate reservoir for such energy as would be added. This conception of a discharge of constant current and a rising field strength without increased ionization[16–18] appears to be incorrect. Once current is established by an ionized path any increase in field strength produces an increase in ionization and a greater increase in current. The experiments of McCann and Clark[23] using long duration discharges with superimposed surges reveal the rise in field strength associated with the surges. Only when the electrical circuit is unable to maintain the required field strength does the ionization decay.

Schonland's difficulty in explaining the high leader velocities would seem, in part, to arise from the assumption of a limited or fixed field strength. Since the breakdown of a gap, in general, begins with the bridging by a streamer, it can be inferred from the usual reduction of breakdown time with overvoltage that the velocity of a streamer is dependent upon field strength. The experiments of Snoddy, Dietrich, and Beams show directly the dependence of the streamer velocity upon the applied potential, while this can also be deduced from the experiments of Allibone and Meek where potentials are undoubtedly rapidly reduced at the discharge electrodes upon the start of a streamer and relatively low streamer velocities are attained. In the case of the initiation of a streamer at the surface of an electrode of considerable size and adequate regulation, it is not unreasonable that the field strength should tend to increase as the streamer projects from the surface as would be expected if a wire or metallic conductor were projected.[9] The potential regulation of the point of initiation and the distribution of potential upon the surface are obviously important factors, and a cloud electrode is difficult to consider in such a respect. However, the assumptions leading to the constant velocity pilot streamer to explain lightning streamer velocities would seem to be far more doubtful than the assumption that the field strength at the streamer tip has a tendency to depart from a fixed initial value.

In conclusion the author wishes to express his appreciation of the efforts of Mr. A. F. Rohlfs, Mr. I. B. Johnson, Mr. C. McIntosh, Jr., Mr. R. A. Johns, and Mr. R. B. Gustafson in obtaining the data in the High Voltage Laboratory.

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[23] G. D. McCann and J. J. Clark, Trans. A. I. E. E. **62**, 45 (1943).

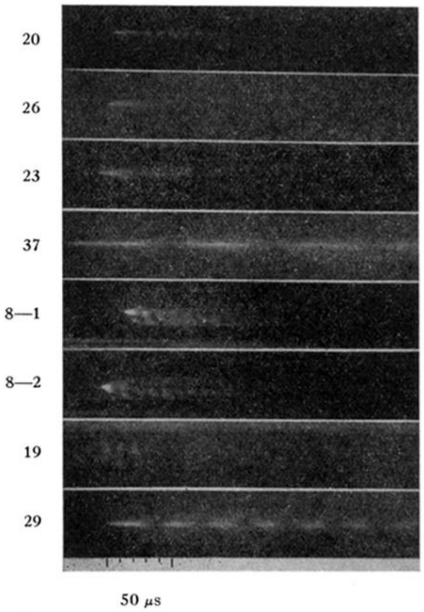

FIG. 2. Luminous channels of high current discharges obtained by the method of Fig. 1a. Increasing current from top to bottom. No. 26 does not oscillate. No. 19 is a discharge in vacuum. Additional data is given in Table I.

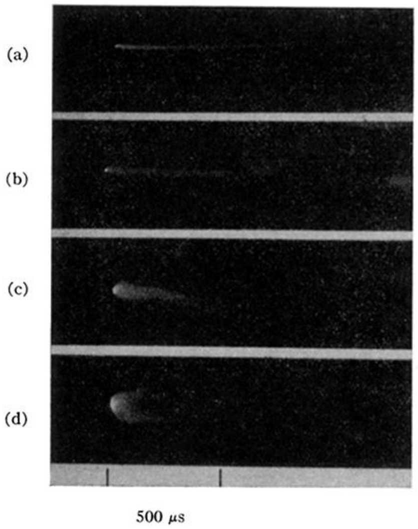

FIG. 3. Discharge channels in air with sustained currents obtained by the method of Fig. 1b. (a) 78 amperes sustained by the discharge of 6 μf and 1150-ohms series resistance. (b) 350 amperes, 6 μf and 255 ohms. (c) 940 amperes, 6 μf and 95 ohms. (d) 2900 amperes, 6 μf and 31 ohms. Current values obtained from oscillograms.

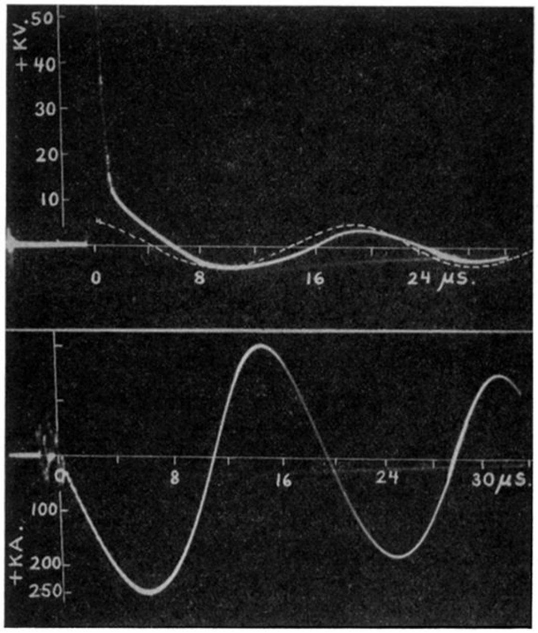

FIG. 8. Cathode-ray oscillograms of voltage and current for a discharge between 0.5″ square brass rods separated 8.8 cm. The induced voltage obtained from a separate oscillogram and a short-circuited gap has been drawn in the correct phase position. The maximum voltage attained but not shown by the voltage oscillogram is 100 kv. Oscillogram axes are slightly oblique.

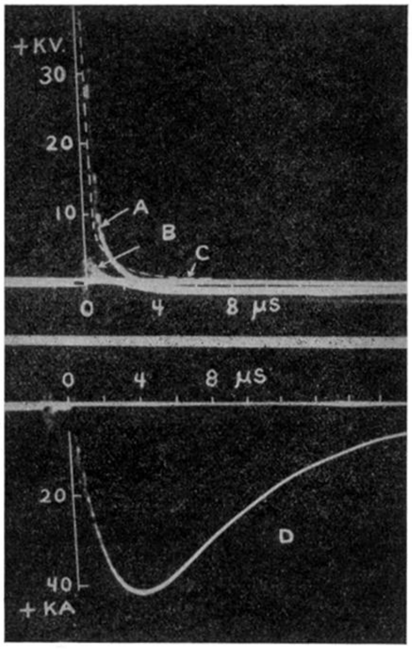

FIG. 9. Cathode-ray oscillograms obtained with a damped discharge between 0.5″ square brass rods separated 8.8 cm. (*A*) recorded voltage; (*B*) induced voltage or distortion; (*C*) discharge voltage free of distortion derived from the difference of (*A*) and (*B*); (*D*) current.