The Influence of Discharge Chamber Structure Upon the Initiating Mechanism of the High Frequency Discharge

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(Received November 25, 1939)

It is shown that a breakdown in a rarefied gas with high frequency e.m.f. of the order of megacycles may occur through three different processes. Mode *a* is characterized by a breakdown voltage of about half the d.c. discharge value. Mode *b* occurs at lower gas densities and is characterized by breakdown at a voltage somewhat above the corresponding d.c. discharge value. Mode *c* is the high frequency counterpart of the Paschen law phenomenon, in that when the density is too low to support an inter-electrode discharge, the latter seeks a longer path. It is shown that all three of these modes may operate in the same discharge chamber, sometimes simultaneously, and that the breakdown-process may shift from one mode to another with change in pressure or frequency. Many of the baffling complexities in earlier h.f. striking-voltage data may thus be understood. It is pointed out that mode *c* breakdowns are of little value for quantitative interpretation. A type of discharge chamber is described in which the breakdown may be held definitely to modes *a* and *b*.

INTRODUCTION

THERE have been marked discrepancies in the striking voltages observed by various workers, under apparently similar conditions, in a rarefied gas, with high frequency e.m.f. of the order of megacycles. The variations in V_s with change in pressure and especially with change in frequency have been baffling and contradictory. Darrow remarks[1] that "the data do not form a complete or coherent system." A definite choice between the several proposed pictures of the mechanism of the breakdown,[2–12] or between the accompanying mathematical predictions of the striking voltage, is impossible. Enough variety exists in the data both to give some support to, and to create some difficulties for, each of the current explanations.

Some of the disagreements may be attributed to the use of unreliable potential-measuring methods. The difficulties involved have been recognized.[7, 13, 14] It is believed by the writer, as a result of his investigation of the potential-measuring devices used by earlier workers, that in some cases, reported values and variations in striking voltage did not exist and were falsely indicated because of harmonic resonances in the apparatus used. This has probably delayed a better understanding of the h.f. discharge mechanism. Therefore, a calibrated high frequency generator was built especially for use on this problem and was designed so as to eliminate or minimize the error-producing factors. It has been described.[15]

MODES OF DISCHARGE

An extensive study has been made of the influence of discharge chamber and electrode structure upon the initiating process of the h.f. discharge. It appears that there are three modes of h.f. breakdown, which may be described or localized as follows.

Mode *a*: Where the breakdown occurs between the electrodes, with the application of a peak potential difference approximately equal to half of the voltage required to produce a d.c. discharge under otherwise identical conditions.

Mode *b*: Where the breakdown occurs between the elec-

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[1] K. K. Darrow, Bell Sys. Tech. J. **12**, 91 (1933).
[2] Bergen Davis, Phys. Rev. **17**, 501 (1903).
[3] Bergen Davis, Phys. Rev. **20**, 129 (1905).
[4] E. O. Hulbert, Phys. Rev. **20**, 127 (1922).
[5] J. J. Thomson, Phil. Mag. **4**, 1128 (1927).
[6] John Thomson, Phil. Mag. **10**, 280 (1930).
[7] John Thomson, Phil. Mag. **18**, 696 (1934).
[8] Fritz Kirchner, Ann. d. Physik **77**, 287 (1925).
[9] Fritz Kirchner, Ann. d. Physik **7**, 798 (1930).
[10] Lothar Rohde, Ann. d. Physik **12**, 569 (1932).
[11] J. S. Townsend and R. H. Donaldson, Phil. Mag. **5**, 178 (1928.)
[12] John Thomson, Phil. Mag. **23**, 1 (1937).
[13] Lothar Rohde, Zeits. f. tech. Physik **12**, 263 (1931).
[14] P. Mercier and G. Joyet, Helv. Phys. Acta **8**, 310 (1935); (also in Bulletin de l'asso. Suisse des Electriciens No. 20 **25** (1935).
[15] Sherwood Githens, Rev. Sci. Inst. **8**, 48 (1937).

trodes, with the application of a peak potential difference somewhat greater than the d.c. discharge voltage.

Mode *c*: Where the breakdown takes a longer path than the inter-electrode space and occurs in the area between the electrodes and the walls of the chamber.

It is found that the mode of the discharge depends upon the chamber and electrode structure, the pressure, and the frequency of the applied e.m.f.; and that two or all three of these modes may occur, separately or concurrently, in the same discharge chamber. Most of the earlier work presupposed a single initiating mode.

There appears to exist for each of these h.f. modes of discharge a single-minimum V_s-*vs.*-p relationship resembling that of the d.c. discharge. For example, consider the 5-megacycle striking voltages observed in chamber A (described later) shown in Fig. 1. The V_s-*vs.*-p curves for the three modes are indicated, partly by dashed lines. Near the intersections of the curves the striking voltage is lower than it would be for either mode acting alone, and follows the portions marked *ab* and *bc*.

The shift of the breakdown mechanism from one mode to another as the pressure is changed produces a plurality of minima in the unanalyzed V_s-*vs.*-p relationship. Such plurality has been observed by several workers.[12,16-18] The possibility of various types of discharge has been noted,[12] and the work of Gill and Donaldson[16] strongly suggests a dependence upon the electrode and discharge chamber orientation, but a

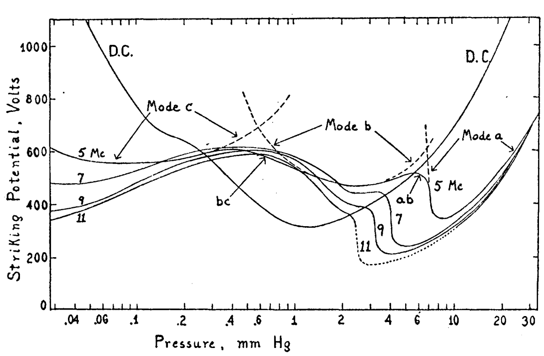


FIG. 1. Striking voltages in chamber A in neighborhood of the critical pressure. Electrode separation = 10.5 mm.

[16] E. W. B. Gill and R. H. Donaldson, Phil. Mag. **12**, 719 (1931).

[17] C. and H. Gutton, Comptes rendus **186**, 303 (1928).

[18] C. J. Brasefield, Phys. Rev. **35**, 92, 1073 (1930).

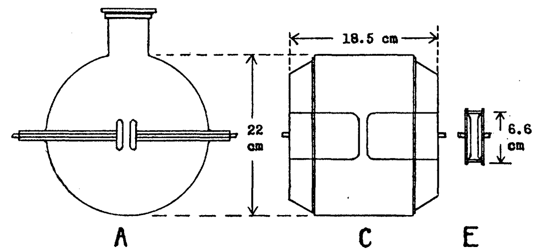


FIG. 2. Central longitudinal cross sections of three discharge chambers, to scale.

systematic analysis of this plurality has not been reported.

Over 11,000 observations of striking voltage have been made by the writer with a number of chambers falling into 7 types. The salient facts concerning the modes of discharge and the influence of chamber construction can be observed in the behavior of the type A, C and E chambers. The others yielded information of a corroborative nature.

THE DISCHARGE CHAMBERS

Several types of chamber yielded capricious values of striking voltage or relationships defying interpretation. It was learned that such results are caused by: (1) Chamber walls of too extensive area; (2) electrodes of complicated design; (3) insufficient radii of curvature at the edges of electrodes; (4) electrodes of such large capacity as to disturb the action and voltage calibration of the h.f. oscillator.

Five types of chamber which avoid these faults yielded useful information. They may be described as follows, with the aid of scale drawings in Fig. 2: Chamber A is a spherical 5-liter Pyrex flask. Its electrodes are supported by brass rods surrounded by Pyrex tubing. Chamber C is composed of a Pyrex cylinder and two Pyrex pie plates (dimensions shown on diagram) united with Apiezon wax W. Type E is a short length of 65-mm Pyrex tubing to which end plates, rounded as shown, are waxed. Chambers B and D, not illustrated, are identical with C except that B possesses a longer cylinder and longer electrodes, to give an over-all length of 28.5 cm; while D has no central cylinder at all, shorter electrodes, and an over-all length of 5.5 cm.

All electrodes are of polished brass, those in B and C being hollow. The flat portion of their interfaces is 25 mm in diameter in A, and 55 mm in the others. The electrode separations used mostly were as follows:

Chamber	A	B	C	D	E-1	E-2
d (in mm)	10.5	9.5	9.6	10.2	10.0	9.8 .

In assembling, the faces of the electrodes were polished on a lathe with fine emery and rouge cloth and the parts of the chamber immediately assembled untouched by the hands, the glass parts having been prepared with bichromate acid cleaning solution and well washed with distilled water.

Auxiliary Apparatus, Procedure and Accuracy

The breakdowns were observed in hydrogen at pressures ranging from 0.001 to 150 mm Hg. This gas was selected to facilitate comparisons, for the earlier work was done preponderantly with hydrogen. It is admitted into the vacuum system from a steel cylinder through an electrically-heated palladium tube at a temperature just sufficient to pass the hydrogen. The gas thus filtered is extremely pure. The pumps and manometers employ Apiezon oil to avoid the possibility of mercury contamination.[7] The production of hydrocarbon vapors by the breakdown of Apiezon products under the influence of the discharge is apparently insufficient to influence the breakdown potential to a noticeable extent. As an added precaution, a low temperature trap has been used between the pumps and the rest of the system. Evacuation and as much baking-out as is possible is continued for a couple of days after the time when a discharge within the system cannot be produced with a three-inch spark coil.

The system and chamber are filled to the highest pressure to be investigated. The plate voltage of the oscillator is slowly raised until a breakdown occurs, whereupon it is immediately switched off. The reading of an ammeter in the oscillator circuit at the moment of discharge is recorded, to be converted into voltage later by calculation. Two to six such observations are made at each of 12 evenly-distributed frequencies in the range from 5 to 11 megacycles, and also with d.c. Some of the hydrogen is then pumped out and a similar set of observations is made. The pressure is thus lowered in about 15 steps, until a discharge is no longer producible. This large number of repeated observations is made with the same sample of gas without evidence of contamination. The absence of a change in the nature of the gas has been verified frequently by re-evacuation and insertion of new hydrogen at lower pressures. The new striking-potential curves have always matched the old within three percent. This variation is considered normal, for earlier observers have reported variations between different samples of hydrogen ranging up to five percent.[7,19,20]

The pressure is measured in one of three ways, depending upon its magnitude: by an open mercury manometer with a few centimeters of Apiezon oil floating on top of the mercury; by a differential oil manometer; or by calculations based upon a process of sharing between two chambers of known volume. The accuracy ranges from 1/10 of one, to one percent.

The oscillator produces h.f. potential ranging from about 100 to 2500 peak volts. All potentials quoted are voltages between electrodes, the value at the peak of the cycle. The relative accuracy in voltage measurement as a function of frequency is within 1.5 percent. The absolute accuracy varies directly as the magnitude of the deflection of the r.f. ammeter used in the oscillator. Two such meters, having a rated accuracy of two percent of full scale value, were employed in the work reported on. Their ranges were selected so that the average error below 600 volts is less than two percent, and is within three percent above this value; although in a few individual cases, because of extremely small meter deflection, the error is known to rise as high as eight percent. On the whole, the accuracy obtained is ample for the present work, since in general we are interested in qualitative values.

In analyzing the data obtained the average breakdown voltages for a given pressure were plotted first as a function of the *frequency* of the e.m.f.; i.e., isobaric curves were made. Then the voltages appearing on these curves at the frequencies of 5, 7, 9 and 11 Mc were plotted again as a function of *pressure*, in two ways: The strik-

[19] F. L. Jones and J. P. Henderson, Phil. Mag. **28**, 185 (1939).
[20] F. L. Jones, Phil. Mag. **28**, 192 (1939).

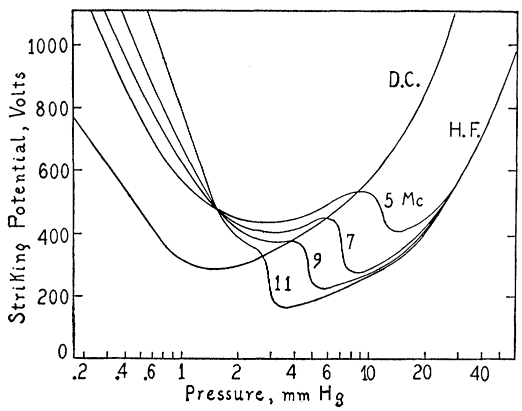


FIG. 3. Striking voltages in chamber E in neighborhood of the critical pressure. Electrode separation = 10.0 mm.

ing potentials at the higher pressures were plotted with a linear pressure scale; while those at the lower pressures were plotted against a logarithmic scale, to produce a convenient spreading of the data in this region of pressure.

V_s AT THE HIGHER PRESSURES (ABOVE 40 MM HG)

In all five of the chambers described above it is found that when the pressure is high enough for the breakdown to fall distinctly in the mode a class, the striking voltage is essentially independent of the frequency. With a 10-mm gap and frequencies between 5 and 11 Mc, and between pressures of 40 and 150 mm Hg: (1) The h.f. discharge voltage is independent of the frequency; (2) The h.f. and d.c. V_s–*vs.*–p curves are linear; (3) The h.f. values are almost exactly one-half as great as the d.c. values. Grouping together the data for all five chambers in these ranges, the ratio of the h.f. to the d.c. breakdown voltage is 0.49 ± 0.03. This is tantamount to saying that the h.f. and d.c. linear portions are not parallel, as in a previously reported case,[7] but that they intersect, and do so on the pressure axis. With the chambers and gaps herein reported on, this intersection fell at -17 ± 3 mm Hg. The slope of the h.f. linear portion is 12.2 ± 1.0 volts per mm Hg per cm gap length, and that of the d.c. curve of course is twice as great.

STRIKING VOLTAGE AT THE LOWER PRESSURES

Results of typical runs made at low pressures with chambers E-1 and A are shown in Figs. 3 and 1, respectively. In Fig. 3, we see: (1) The transitions from mode a to mode b. The lower the frequency, the higher the pressure at which the transition occurs. (2) A convergence and crossing of the mode b curves at the pressure of 1.55 mm, which is also the critical pressure on the d.c. curve. (3) The rapid rise in striking voltage below the critical pressure; the higher the frequency, the more rapid the rise.

In Fig. 1, illustrating chamber A discharge potentials, it is to be observed first that, down to 2 mm pressure, the nature of the variation in V_s with pressure and frequency is identical with that in the type E chamber; second that below 2 mm, the h.f. curves fail to converge as they do in Fig. 3. The striking voltage, instead of rising rapidly, falls below the d.c. curve again and follows a mode c type of curve. It is also noted that in the mode c range of pressure, the lower frequency curves rise first, which is the same order as is observed in the mode a to b transitions.

CHANGES IN APPEARANCE OF THE DISCHARGE

It must be emphasized that individual appearances cannot be correlated closely with striking voltages, for the voltage drops 5 to 80 percent immediately upon ignition. Conditions under sustained discharge are quite different from those at the moment of initiation. However, the *succession* of changes in appearance as the pressure is decreased is quite suggestive. The appearances of the discharge in chamber A are shown photographically in Fig. 4. At the highest pressures the glow is a narrow, striated column, which spreads out laterally as the pressure is decreased until it finally fills the chamber. The letters just above the pressure axis in Fig. 1 show the *approximate* pressures at which each appearance occurs. It is to be noted that: (1) The glow emerges from between the electrodes at about the pressure at which mode c initiation is encountered. (2) The 5-Mc discharge goes through this succession of appearances from one to two steps ahead of the 11-Mc discharge, as the pressure is decreased. This agrees with the fact that the lower frequency striking potentials go through their succession of changes ahead of the higher frequencies.

Of course, in chamber E the succession of ap-

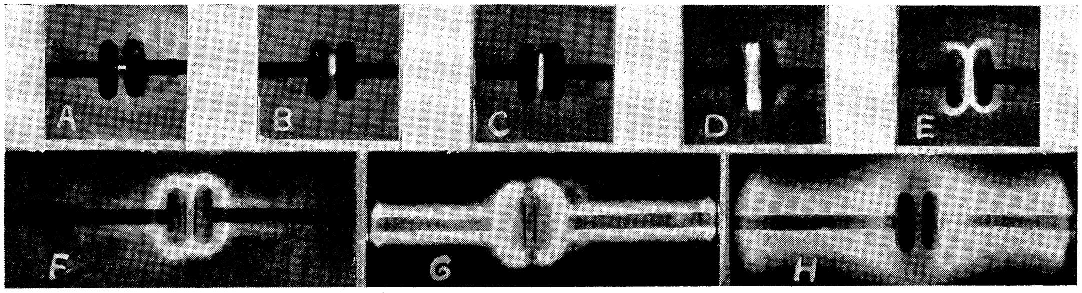


FIG. 4. Successive appearances of the glow discharge in chamber A as the pressure is decreased. Stage I, not shown, consists of a dull glow extending throughout the chamber except for darkness between the electrodes and at the inner surface of the Pyrex sphere.

pearances gets no further than stage D. Here the glow becomes fluttery, jumps around inside the chamber, and rapidly refuses to strike at all as the pressure is further decreased. This behavior is in agreement with the curves shown in Fig. 3 and is to be expected from Paschen's law.

Stability and Consistency of Striking Voltage

In a type E chamber

The voltage at which breakdown occurs is sharply defined at all pressures above the critical value (1.55 mm in Fig. 3) except during the transitions from mode a to b, where the curves are steep. Here, individual trials may vary from the mean by as much as five percent. The striking potential below the critical pressure becomes progressively more poorly defined as the pressure is decreased, and at the lowest pressure the range of values obtained on successive observations may equal 30 percent of the mean. The time interval allowed between observations does not affect the striking potentials.

In the type A chamber

Observations may be made in rapid succession only at pressures above 10 mm, approximately. Below this pressure, if the potential is applied too soon after a previous discharge, the glow may strike at a subnormal voltage, from 10 to 50 percent lower than the value it would have had if a certain amount of time had been allowed to elapse. The necessary recovery time is a function of the frequency of the e.m.f. applied, as well as of the pressure. Subnormal discharges may be avoided by making observations periodically with a clock. Table I shows the times between observations which were found satisfactory. When these periods are employed, the sharpness of definition of the h.f. striking voltage in chamber A agrees favorably with that described above for the type E chamber.

In both types of chamber the d.c. striking potentials are very sharply defined above the critical pressure but show increasing randomness below this value, though not to such a marked extent as in the h.f. case. When the insertion of a new sample of gas results in a slight uniform change in the h.f. striking voltages as mentioned earlier, the d.c. values shift also.[19]

Mode c Discharge an Extra-Electrode Process

There is much evidence to indicate that the mode c discharge does not occur between the electrodes but is produced in the electric field which extends from the sides or backs of one electrode to those of the other or toward the walls of the chamber. In addition to the appearance of the discharge in the mode c pressure region, and to the fact that mode c initiation is encountered in every type of chamber *except* type E, which is the *only* type that does not possess an extra-electrode space, we have the following facts.

(1) In chamber A, if the electrode gap is reduced, the h.f. striking voltages in the mode a and b regions of pressure are considerably lessened, while the reverse is true if the gap is increased. But in the mode c regions of pressure the striking voltage remains the same. The gap

length does not appreciably affect the mode *c* discharge voltage.

(2) Subnormal discharges are never experienced in pure cases of mode *a* or *b* discharge, while they are always encountered in mode *c*, *bc* and *ac* discharges. They are evidently caused by the presence of charged residues on the nonconducting walls of a discharge chamber.[7, 21] Locher's theory[22] and Paetow's work[23] are of interest in this connection. The presence of the charges would aid a discharge in which the walls play a part, but would be of little consequence when the initiating process is localized between the electrodes. The increasing troublesomeness of the subnormal discharge phenomenon as the pressure is lowered indicates that the neutralization and dispelling of these charges takes longer as the hydrogen density decreases.

Interelectrode Nature of Mode *a* and *b* Discharges

Since modes *a* and *b* are both found in the *E* type chambers it necessarily follows that both must be inter-electrode in nature, by virtue of the construction of this type of chamber.

The mode *a* discharge appears to be associated with the *oscillatory* motion of charged particles, for the pressure at which mode *a* becomes impossible is dependent upon both the electrode separation *and* the frequency of the applied e.m.f. At the higher pressures there is ample space between the electrodes for this oscillatory motion. That the breakdown is accomplished with about half as much voltage as the d.c. discharge would require is no doubt due to the trapping of space charge between the electrodes. As the pressure is decreased the electrode separation becomes too short for the necessary oscillatory amplitude, and when insufficient space charge can be built up to create a mode *a* discharge, the breakdown can occur only by mode *b*. The order of the frequencies at which this transition occurs agrees with considerations of the motion of a charged particle in an oscillatory field: with or without an effective resistive force due to collisions with gas molecules, the lower the frequency, the greater the amplitude of oscillation, other conditions being equal. This analysis is borne out further by the fact that when the electrode separation is *decreased*, the pressures of transition from mode *a* to *b* all shift to ***higher*** pressures; and conversely.

It is evident that at some frequency below 5 Mc the trapping effect and build-up of space charge between the electrodes must cease, and the striking voltage will rise to the d.c. value.

A similarity between the mechanism of the mode *b* breakdown and that of the d.c. discharge is indicated. It would be expected that if the breakdown is of the static type and occurs during a half-cycle, the voltage required to strike would be greater than the corresponding d.c. voltage because of the short duration of the half-cycle. The convergence of the mode *b* curves at a common point, at a pressure equal to the critical pressure on the d.c. discharge curve, was observed in both of the type *E* chambers. Whether this last feature was due to chance remains to be further investigated.

Overlapping of Modes of Discharge

When there is a considerable expanse of electrode side-surface the breakdown at pressures normally favorable (on the basis of electrode gap and frequency) for mode *a* or *b* discharge, may occur in part through extra-electrode ionization. The two processes acting simultaneously (mode *ac* or *bc* discharge) result in striking potentials lower than the mode *a* or *b* values. This is shown by typical striking voltages for chamber *C*, Fig. 5. Between 0.5 and 10 mm pressure the values are all considerably lower than the corresponding mode *a* and *b* values in Figs. 1 and 3. In the data pertaining to chamber *D*, the shortest chamber of this type, this depression of the striking volt-

Table I. *Time required between observations in chamber A to give consistent striking voltages.*

Pressure mm Hg	Frequency of e.m.f. 4.96–6.67 Mc	7.86–9.15 Mc	10.47 Mc
3–130	1 min.	1 min.	1 min.
2	1	2	2
0.3–1.2	1	2	3
0.17	2	2	3
0.072–0.037	3	3	4
0.019	4	5	5
0.0009		5–7 min.	
0.0046		8–10 min., or longer.	

[21] John Thomson, Phil. Mag. **21**, 1057 (1936).
[22] See L. B. Loeb, *Fundamental Processes of Electrical Discharges in Gases* (Wiley, New York, 1939), p. 498.
[23] H. Paetow, Zeits. f. Physik **111**, 770 (1939).

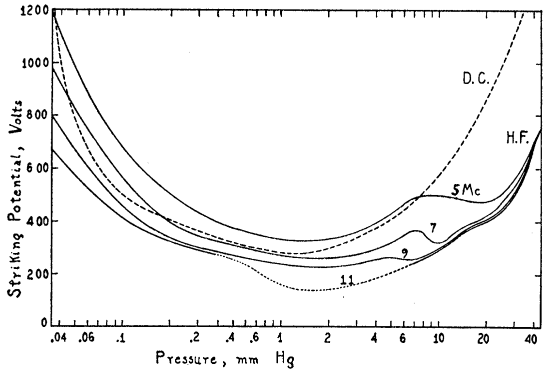


FIG. 5. Striking voltages in chamber C in neighborhood of the critical pressure. Electrode separation = 9.6 mm.

age is much less marked; while in the case of chamber B, the longest of this type, the depression is extreme, and exists up to 50 mm pressure for the higher frequencies.

Furthermore, in these three chambers considerable difficulty with subnormal strikings is encountered when taking observations in these regions of voltage-depression. Long waiting periods between observations are required. In chambers B and C, periods ranging up to one hour are necessary at the very lowest pressures to prevent subnormal discharges.

When the breakdown in what should be the mode a or b pressure region is thus assisted by extra-electrode-gap ionization, the "effective striking distance" is not equal to the electrode separation. Therefore a quantitative interpretation of the *bc* or *ac* type of breakdown is difficult if not impossible.

Relationship to Earlier Data

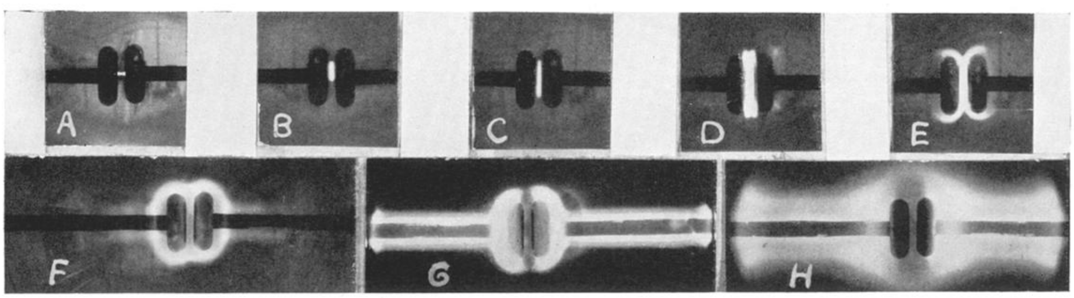
By considering the structure of the discharge chambers employed, most of the qualitative features of the striking voltage data obtained by earlier workers can be recognized and classified into the suggested modes. The bulk of the work appears to have fallen in the mode c, *bc* or *ac* classes.

In the most accurate work in this field, that by Thomson,[12] there appears to be one excellent example of pure mode a and b discharges, shown in curve 1 of his Fig. 7, which was obtained with 1.8-Mc potential. That the transition from mode a to b occurs at the low pressure of 5.5 mm is to be expected because of the larger electrode gap (25.8 mm). As noted above, the transition-pressure shifts to a lower value upon increasing the electrode separation, and vice versa. The gradients of the linear portions of curve 1 are about 13 and 12 volts per mm pressure per cm electrode separation, for modes a and b, respectively. These values agree nicely with the value 12.2 ± 1.0 quoted earlier in this article.

It therefore would appear that Thomson's other curves represent mode c, *bc* or *ac* discharges. If so, their gradients should not be compared with the value 12.2 ± 1.0, which applies to mode a discharge. Whatever the mode, the curves indicate clearly that as long as the frequency was high enough to avoid mode a or b discharges, the breakdown stayed in the same mode and in the linear portions was independent of the frequency.

Further measurements with type E chambers of varying sizes and gap lengths are planned, for it appears that further treatment of the mechanism of the h.f. discharge can best be accomplished with chamber conditions which produce pure mode a and b discharges.

The writer is grateful to Dr. Otto Stuhlman, Jr., who suggested this problem, and to Dr. Arthur E. Ruark for advice on the apparatus and facilities.



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