An Attempt to Verify the Theory of the Long Spark of Loeb and Meek

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In an attempt to verify the theory of the long spark of Loeb and Meek, d.c. sparking potentials in a plane parallel gap in air have been measured as a function of plate separation and pressure at and below atmospheric pressure. Below atmospheric pressure, the sparking-potential curve as a function of gap length at constant pressure, displays a peculiar levelling-off at large gap lengths. This has been shown to be due to field distortion of a pressure-dependent type. This field distortion is, in large measure, caused by the walls of the large chamber used in this study. This field distortion prevented the verification of the Loeb-Meek theory. However, there is considerable evidence for believing the results at atmospheric pressure to be valid. Meek's equation represents the data accurately at atmospheric pressure. Water vapor causes a small but definite scattering in sparking potentials.

INTRODUCTION

THE streamer theory of sparking developed by Loeb and Meek[1–3] invokes processes known to occur in discharges at large values of the product of pressure and plate distance. From the theory sparking potentials may be calculated. Other equations are either empirical representations of data such as the one given by Peek[4] or else they are based on mechanisms known to be inoperative at large values of the product of pressure and gap length. Loeb and Meek[2,3] have extended the theory to include the long spark. They postulated that, at a given pressure, above a certain plate distance, δ_0, Meek's equation does not apply. According to Loeb and Meek the slope of the sparking-potential *vs.* gap-length curve should decrease with increasing gap length until δ_0 is reached. At this point the slope should increase and remain constant thereafter. The straight line above δ_0, if extended, should pass through the origin and should lie below the values of the sparking potential for gap lengths less than δ_0. It was also postulated that this inflection in the sparking-potential curve would occur at shorter gap lengths the lower the pressure. On the basis of the only data then or now available, Loeb and Meek calculated δ_0 for air to be 88, 15, and 3.3 cm at 1520, 760, and 380 mm of Hg, respectively. The theory is thus conveniently open to experimental test at pressures of the order of one-half an atmosphere.

The theory of Loeb and Meek as applied to the long spark is admittedly semi-empirical, and the constants are not too well known. While the underlying principles may apply, the quantitative bases of the predictions may be off considerably. The validity of the choice of constants has been discussed recently.[5]

Irrespective of the details of the calculation, which are somewhat in doubt, the very definite predictions require experimental verification, and toward this end, at the suggestion of Professor Loeb, the writer undertook to measure sparking potentials in air at half an atmosphere pressure. Unfortunately, it was just in the region of pressures and gap lengths which should prove of interest that the apparatus failed to function properly because of field distortion. In view, however, of the fact that very consistent sparking-potential data at atmospheric pressure were obtained, and that the instrumental difficulties encountered are of considerable interest, it is believed worth while to report the findings.

APPARATUS AND EXPERIMENTAL PROCEDURE

The chamber used was the one employed by Sanders[6] and Posin[7] for measurements of the

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[1] J. M. Meek, Phys. Rev. **57**, 722 (1940).
[2] L. B. Loeb and J. M. Meek, J. App. Phys. **11**, 438, 459 (1940).
[3] L. B. Loeb and J. M. Meek, *The Mechanism of the Electric Spark* (Stanford University Press, Stanford, 1941).
[4] F. W. Peek, Jr., *Dielectric Phenomena in High-Voltage Engineering* (McGraw-Hill Book Company, Inc., New York, 1929), p. 73.
[5] L. H. Fisher, Phys. Rev. **69**, 530 (1946).
[6] F. H. Sanders, Phys. Rev. **41**, 667 (1932).
[7] D. Q. Posin, Phys. Rev. **50**, 650 (1936).

first Townsend coefficient of air and nitrogen. This ionization chamber was constructed with the aid of a grant in support of Sanders' research by the National Research Council. A diagram of the chamber as originally used by Sanders (and also for some time by the writer) is given in Fig. 1. For a detailed description of the chamber one may refer to Sanders'[6] original paper. For the purpose of the present discussion it will suffice to recall just a few features of the chamber. The shell consisted of a cylindrical brass casting 45 cm in height and 50 cm in diameter. Both electrodes were 20 cm in diameter. The lower plate was the high voltage electrode and was profiled as shown. This electrode rested on a porcelain insulator, I_1; the insulator in turn rested on a circular metal plate P. The lower insulator, I_2, was made of Pyrex glass and was filled with oil. No mercury was used in the chamber in the present work.

With the arrangement shown in Fig. 1, at half an atmosphere corona from the high voltage electrode occurred at voltages too low to test the Loeb-Meek theory. Figure 2 shows the arrangement finally used. The high voltage electrode of Fig. 1 was replaced by another of equal diameter the edges of which had a radius of two centimeters. In addition, it was necessary to remove the supporting brass plate, P, to the bottom of the chamber. A new hollow porcelain insulator, I_1', was used which reached from the brass plate, P, to the high voltage electrode. This increased the distance from P to the high voltage electrode from 10 to 20 cm. A new oil-filled insulator, I_2', entered the chamber as before, but reached all the way to the lower electrode. With this arrangement, it was possible to reach 60 kv at 380 mm of Hg before corona appeared.

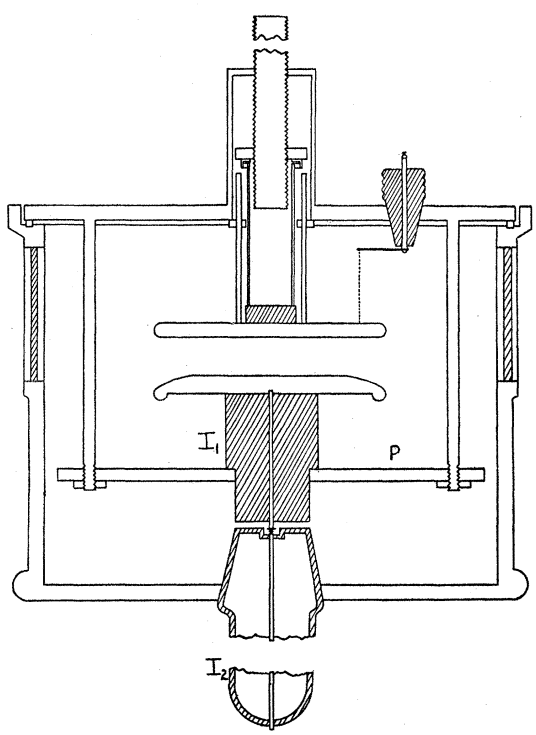

FIG. 1. Ionization chamber as originally used by Sanders.

The plates were levelled to within 0.002 inch outside the chamber by means of a telescopic plug gauge. Whether the plates remained level after the electrode system was lowered is unknown since mechanical stresses are set up. The electrodes were polished with emery paper and rouge, and the chamber surfaces were carefully washed with ethyl alcohol before being closed for a series of measurements. Fiducial marks were placed on both electrodes and gap distances were measured by means of these marks with a cathetometer. Gap separations were read to a few thousandths of a centimeter.

The d.c. potential source was of the same type as the one used by Sanders; it was stabilized by an electronic stabilizer of the saturable-core reactor type. In parallel with the spark gap were wire-wound Taylor resistors of 100 megohms. These resistors are manufactured by Shallcross and carry a one percent accuracy rating when used under the present operating conditions.[8] The voltage was read by potentiometer across 1000 ohms set on a Leeds and Northrup dial box in series with the Taylor resistors. The accuracy of the voltage measurements was therefore determined by the Taylor resistors and is of the order of one percent.

A current-limiting resistor of 0.1 megohm was placed in series with the chamber in order to prevent pitting of the plates and also to avoid excessive production of oxides of nitrogen. The Taylor resistors were placed directly in parallel with the chamber. Leakage across the current-limiting resistor and across the oil-filled insulator

[8] L. S. Taylor, Bur. of Stand. J. Research 5, 609 (1930).

introduced no uncertainty in the measurements. The chamber was grounded during the measurements.

The central portion of the cathode was illuminated by ultraviolet light in order to prevent appreciable time lags, and also to induce the spark to pass in the uniform part of the field. During the entire study, however, ultraviolet light had no effect on the sparking potentials, and in no way influenced the position of the spark. This situation must have been due to the presence of adequate initiating electrons in the chamber at all times.

Air from outside the laboratory was admitted through a capillary, the air passing over two traps of aged liquid air, and one of phosphorus pentoxide. At no time was liquid oxygen observed in the trap. The pressure of the gas was read on a mercury manometer to one millimeter. All pressures have been corrected to 22°C.

To measure a sparking potential, the voltage was raised in steps of 100 volts, the electrodes being in contact with the power supply at all times. After each setting, a 30-second interval elapsed before the voltage was increased again. The time lag was almost always so short that the 30-second wait was unnecessary. The voltage taken as the sparking potential was the reading at the passage of a spark. For a given reading, two measurements were taken with ultraviolet light incident on the cathode, and one was taken with no irradiation of the gap.

Previous observers[9,10] working with air have reported the lowering of sparking potentials because of the formation of oxides of nitrogen. In this study, no such effect was observed, the chamber being large enough to prevent impurities from building up to an appreciable concentration. The current-limiting resistor also helped to reduce the amount of chemical action during a spark.

Sparking potentials in the closed chamber in dry air for any one filling were reproducible to 100 volts regardless of the values of the sparking potential (10 to 60 kv). From one filling to another, the results scattered by about 300 volts. No large spread in individual measurements, as is often reported, was observed. This fact is

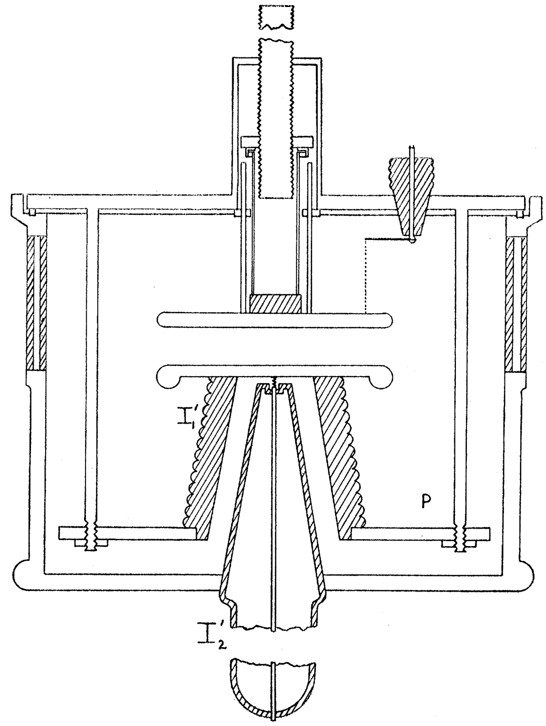

FIG. 2. Ionization chamber as used in the present work.

probably due to the exclusion of dust particles from the chamber, as well as to the presence of adequate initiating electrons. The exclusion of water vapor is believed to have increased the reproducibility of the measurements. On closing the chamber, or even after a new filling, sparks occurred at low voltages, but after five or ten sparks passed, the sparking potential became constant.

EXPERIMENTAL RESULTS AND DISCUSSION

Table I represents the results of a run, series I, at atmospheric pressure with varying gap length. The results are plotted in Fig. 3. Series I yields 30.1 kv as the sparking potential for a one-centimeter gap at atmospheric pressure at 22°C.

Table II gives the values quoted by Schumann[11] as a compendium of the results of a large number of workers, and also the careful observations of Spath.[12]

Values for corresponding values of $p\delta$ from series I are also given in Table II. Spath's values

[9] K. S. Fitzsimmons, Phys. Rev. **61**, 175 (1942).
[10] W. R. Haseltine, Phys. Rev. **58**, 188 (1940).

[11] W. O. Schumann, *Elektrische Durchbruchfeldstärke von Gasen* (Julius Springer, Berlin, 1923), p. 26.
[12] Reference 11, p. 173.

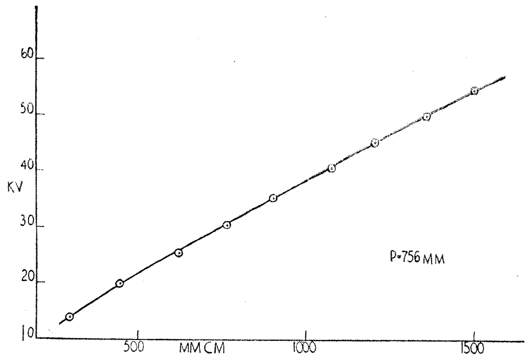

FIG. 3. Sparking potential *vs.* $p\delta$ for series I (near atmospheric pressure).

fall consistently below those given by Schumann, and this difference has been ascribed to Spath's use of ultraviolet light. The present results above 0.60 cm fall below those of Spath, but the agreement below 0.60 cm is excellent. Measurements made by Haseltine[10] give V_s as 15.4 kv at $p_{22}\delta = 324$ mm×cm as compared to 15.5 kv from the present data.

In Meek's equation, a constant, K, appears which is the ratio of the field due to the positive ion space charge to that of the applied field. It is assumed that at the sparking voltage K is a constant independent of pressure and gap length. That K is a constant independent of pressure has been demonstrated for streamer formation in hydrogen in inhomogeneous fields.[13] It is of interest to apply Meek's equation to consistent data in order to evaluate K. As a matter of fact, the reverse procedure may be an extremely valuable method of estimating the consistency of a set of data. As is commonly realized, V_s is an extremely insensitive function of K; therefore, K is an extremely sensitive function of the value taken for V_s. For example, if it is assumed that a one-centimeter gap in air at atmospheric pressure has the sparking potentials given in Table III, the values of K given there result. Thus, for these conditions a range of two kilovolts introduces a change in K of a factor of 1000; a one-kilovolt difference introduces a factor of 30, and a difference of 0.1 kv introduces a change of 20 percent. It is necessary, therefore, to be cautious in interpreting calculated values of K. In Tables I and II are listed values of the natural logarithm of K calculated from series I and from the measurements of Spath. It is seen that the present measurements give values of K constant to within a factor of two, while those of Spath give values of K which vary by a factor of 60. Thus one value of K can be used to represent the data of series I within the limit of experimental error; this is not true for the measurements of Spath. In Tables I and II are also listed calculated values of $\alpha\delta$ at sparking, and it is seen that the condition $\alpha\delta$ = constant represents the data of series I in a satisfactory way. Again this is not true for Spath's measurements.

The small absolute values of K calculated from Spath's and the present data are disturbing, since it is difficult to see how photo-electrons formed in the gas would have much tendency to feed into the positive space charge. Since, however, no great accuracy is claimed for the constants in Meek's equation, errors in this might account for the low value observed.

The fact that series I gives lower values of the sparking potential than are usually reported is in itself not too disturbing. Most of the former

TABLE I. Series I measurements of sparking potential at constant pressure [p(22°C) = 756 mm Hg] and varying gap length.

δ	$p_{22}\delta$	V_s	$\ln_e K$	$\alpha\delta$
1.985 cm	1501 mm×cm	54.7 kv	−7.6	12.3
1.801	1362	50.1	−7.7	12.1
1.606	1214	45.4	−7.2	12.4
1.425	1077	40.7	−7.9	11.6
1.207	912	35.4	−7.2	12.0
1.022	773	30.5	−7.5	11.5
0.831	628	25.5	−7.0	11.5
0.599	453	19.3	−7.0	11.5
0.401	303	13.8	−6.8	11.0

TABLE II. Comparison of present results with those quoted by Schumann** and with those of Spath.***

δ	$p_{22}\delta$	V_s (Schumann)	V_s (Spath)	V_s (This study)	$\ln_e K$ (Spath)	$\alpha\delta$ (Spath)
0.40 cm	306 mm×cm	14.4 kv	13.8 kv	14.1 kv	−7.3	10.6
0.50	382	17.4	16.8	16.9	−6.5	11.6
0.60	459	20.3	19.8	19.6	−5.9	12.4
0.70	536	23.2	22.75	22.3	−5.2	13.2
0.80	612	26.1	25.6	24.9	−4.8	13.8
0.90	688	28.9	28.6	27.5	−3.8	14.9
1.00	765	31.7	31.55	30.1	−3.2	15.6
2.00	1530	59.6		55.7		

** See reference 11.
*** See reference 12.

[13] L. H. Fisher and G. L. Weissler, Phys. Rev. 66, 95 (1944).

TABLE III. Values of the constant K of Meek's equation for various sparking potentials.

Assumed V_s	33.0 kv	32.1	32.0	31.0
K (calculated)	20	0.6	0.5	0.02

work used a.c. potentials. Loeb,[14] among others, has pointed out that a.c. sparking-potential measurements may be expected to be slightly higher than d.c. measurements. The peak value of an a.c. voltage is applied only instantaneously, and because of a statistical time lag, the gap may not break down until a value of the peak voltage is impressed which is somewhat greater than the true sparking potential. Reukema[15] found that the use of ultraviolet light reduced the average observed a.c. sparking potential by 3.5 percent.

Measurements of sparking potentials at half an atmosphere and with varying plate separation, series IV, are plotted in Fig. 4. It is seen there that the sparking-potential curve at half an atmosphere levels off at large values of the plate separation. In order to investigate this levelling-off, runs were made at pressures of 50 and 25 cm. Series V was made at 500 mm, and series VI was made at 261 mm. The results, including those of series I and IV, are plotted in Fig. 5. It is evident from Fig. 5, that for $p\delta > 800$ mm $\times$cm, Paschen's law is not obeyed, and some kind of field distortion comes into play, at least for pressures below one atmosphere. The data for series IV, V, and VI above $p\delta = 800$ therefore have no significance.

In order to understand the nature of the field distortion, a cylindrical piece of sheet metal was placed in the chamber and was grounded. This cylinder reduced the effective diameter of the chamber by two inches, and measurements were made again at pressures of one atmosphere, 50 cm, 38 cm, and 25 cm. The measurements at atmospheric pressure and at 50-cm pressure did not differ from the values obtained with the original chamber. Therefore, for these high pressures, the effect of reducing the size of the chamber by two inches was unimportant. This, however, was not the case for the lower pressures.

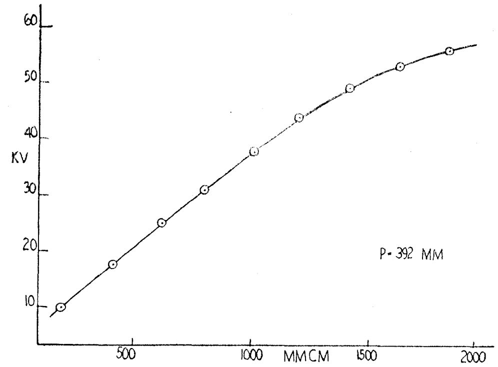

FIG. 4. Sparking potential *vs.* $p\delta$ for series IV (near half an atmosphere pressure).

The data for the 38-cm (series VII) and 25-cm (series VIII) pressure runs with the reduced size of the chamber are plotted. Series IV and VII are plotted in Fig. 6, and series VI and VIII are plotted in Fig. 7. The levelling-off of the sparking potential *vs.* plate-separation curves is more pronounced with the smaller chamber than with the original chamber at pressures in the neighborhood of 380 mm and below. It is clear, therefore, that there is at low pressures and large gap lengths a field distortion imposed by the walls of the chamber, and that the question of the behavior of the sparking potential *vs.* gap-length curve at half an atmosphere must wait until a larger chamber is available. Clearly, a chamber of much greater diameter will be needed in order to study sparking potentials at low pressures and large gap distances.

The question now arises as to the reliability of series I. Below $p\delta = 800$ mm$\times$cm, there seems to be little doubt that the values are reliable.

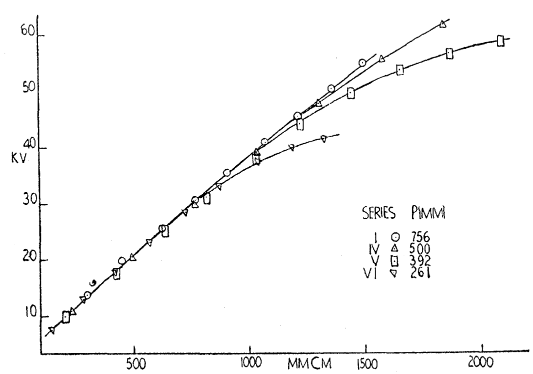

FIG. 5. Sparking potential *vs.* $p\delta$ at four different pressures.

[14] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939), p. 550.

[15] L. E. Reukema, Trans. A.I.E.E. **47**, 38 (1928).

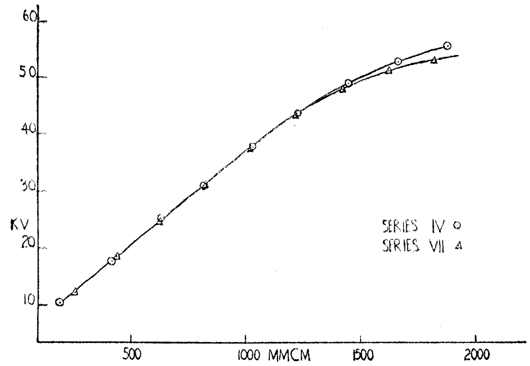

FIG. 6. Sparking potential *vs.* $p\delta$ at half an atmosphere pressure with original chamber (series IV) and with slightly smaller chamber (series VII).

Above this value of $p\delta$, one can only say that consistent values of K are obtained. There is thus some reason for believing series I to be valid in its entirety.

Various other attempts were made to discover in more detail how the geometry of the chamber affected the measurements. The polarity of the electrodes was reversed, and a complete set of measurements was taken at various pressures. The results were, within the experimental error, identical with the values obtained with the usual polarity.

To determine the effect of the small radius of curvature of the grounded electrode, the electrode that was used by Sanders as a cathode (the lower plate in Fig. 1) was inserted as the grounded electrode in the arrangement of Fig. 2. In spite of the decreased curvature of the new electrode, the results were again unchanged. This result indicates that the contour of the low voltage electrode made no contribution to the field distortion. Whether the contour of the high voltage electrode added to the field distortion is at present unknown. A model study is now in progress.

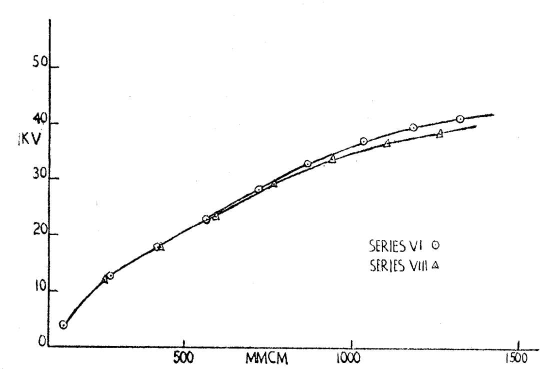

FIG. 7. Sparking potential *vs.* $p\delta$ at one-quarter of an atmosphere pressure with original chamber (series VI) and with slightly smaller chamber (series VIII).

The one fact which seems to require the high voltage plate to have caused some distortion is that the sparking potentials with the reduced chamber at a pressure of 50 cm were the same as for the large chamber at the same pressure, and yet the sparking-potential curves at pressures of 50 cm and 76 cm do not coincide when plotted as a function of $p\delta$.

The electrode system of Fig. 2 was lifted into the open room (the surrounding metal walls were effectively removed) and sparking potentials were determined; the electrode system was then lowered into position so that the electrodes were now surrounded by the metal walls, and measurements were made again. The two sets of observations (at atmospheric pressure) were identical. The complete removal of the walls, just as decreasing the diameter of the chamber, had no influence on the sparking potential at atmospheric pressure over the range of plate separations studied.

In the experiment described in the preceding paragraph it was found that the sparking potentials both in the open and closed system scattered considerably; this probably was caused by the presence of dust or water vapor. The scattering persisted even after considerable sparking and was not removed by ultraviolet light. When clean dry air was admitted in the normal manner, the sparking potentials were again reproducible. Water vapor was then allowed to diffuse into the chamber, and it was found that a small but definite spread of 300 to 500 volts is introduced in the value of the sparking potential.

The author wishes to express his gratitude to Professor Loeb who suggested the problem and under whose direction it was carried out.