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A Survey of Time Lag of Sparkover in a Uniform Field

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An original instrument for measuring time lag of sparkover has been developed. This is capable of measuring lags over a range from one one-hundred-thousandth of a second up to *any* longer values. This entire time range is available for any individual measurement without readjustments and independently of the method or wave shape of voltage application. Spark lags are found to fall into three distinct domains. First, long *initiatory* lags (10^{+1} to 10^{-3} second or less) of random distribution spent in awaiting a favorable fortuitous space and time arrangement of the somewhat insufficient supply of initiatory electrons. Second, intermediate *formative* lags (of the order 10^{-4} second) distributed about a definite peak value of the order of time required for a positive ion to cross the gap and assist in building up a space charge gradient. Third, short formative lags (of the order 10^{-7} second) distributed about a definite peak value of the order of time required for an electron to cross the gap. A picture of the mechanism of sparkover in an initially uniform field is presented accounting for the existence of these three domains. The available experimental reports are correlated and shown to be consistent with each other and with the proposed explanation.

INTRODUCTION

As is well known the theory of sparkover has long been based on the original formulations of Townsend. Increasing knowledge brought to light serious difficulties in this formulation. First, at the field strengths envisaged, the positive ion could not possibly attain an energy requisite to produce ionization. Second, because of the difference in electron and positive ion mobilities, a space charge is produced which must render the field at the time of sparkover decidedly non-uniform. From theoretical consideration of these factors, Rogowski[1] and Loeb[2] independently concluded that the Townsend mechanism did occur but at field strengths greatly multiplied locally by distortion caused by the space charge. They pointed out that this modified Townsend mechanism demanded a definite formative time for the sparkover of the order of time required for a positive ion to cross the gap, e.g., 10^{-4} second, and that a measurement of the time lag of sparkover under conditions which eliminated the random variations found by Zuber[3] would therefore provide a crucial verification of the conclusions reached. Shortly thereafter much shorter time lags, e.g., 10^{-8} second were observed for impulse sparkover at substantial overvoltages by Beams,[4] Tamm,[5] et al. This apparent direct contradiction left the subject in confusion.

Because of the possible variety of phenomena occurring under different conditions this divergence did not in fact invalidate the above mentioned theory. This was specifically pointed out by Loeb in an ensuing paper[6] and in a seminar which it was the author's good fortune to attend in 1931. Loeb pointed out that it still remained necessary to check the theory by means of a time lag measurement under those conditions of static sparkover *for which the theory had been formulated*, namely, small overvoltage and initial ionization adequate to eliminate random variations.

It was, accordingly, the object of this present work first to ascertain under which conditions the spark lag distribution was random and under which the distribution curve was peaked about some definite value. Secondly, it was desired to measure the time lag for the important case, hitherto unexplored, of adequate initial ionization and small overvoltage. Third, by means of these results it was desired, if possible, to correlate the available data on spark lag and on the nature of its dependence on initial ionization and on overvoltage and thereby, perhaps, to clarify the mechanism of sparkover in a uniform field.

APPARATUS AND PROCEDURE

The timing instrument evolved used common three electrode vacuum tubes in a resistance-coupled amplifier so biased that a small increment of gap voltage at minimum sparking

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[1] Rogowski, Archiv f. Elektrotechnik **16**, 761 (1926).
[2] Loeb, J. Frank. Inst. **205**, 305 (1928).
[3] Zuber, Ann. d. Physik **76**, 231 (1925).
[4] Beams, J. Frank. Inst. **206**, 809 (1928).
[5] Tamm, Archiv f. Elektrotechnik **19**, 235 (1928).
[6] Loeb, Phys. Rev. **38**, 1891 (1931).

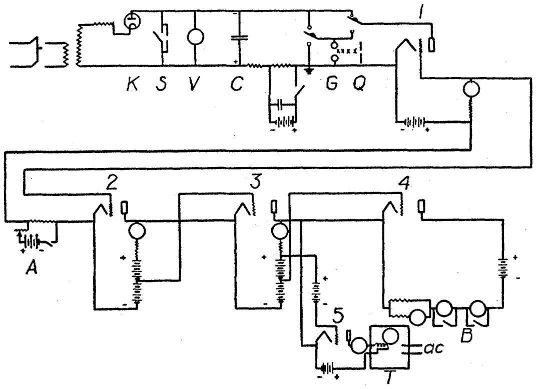

FIG. 1. An instrument to measure time lag of sparkover. *K*, kenetron rectifier tube; *S*, safety gap and discharge switch; *V*, electrostatic voltmeter; *C*, storage condenser 7.2×10^{-10} f; *G*, test gap; *Q*, quartz mercury arc; *A*, bias adjustment; *T*, synchronous timer; *B*, ballistic galvanometers.

Tube	Plate battery voltage	Plate circuit resistor
1 OM 5	156	1.92 MΩ
2 CX 340	180	0.5 MΩ
3 CX 345	180	0.1 MΩ
4 CX 340	90	0.25 MΩ
5 CX 345	180	500 Ω

voltage was steeply amplified and applied to a tube whose output current was thereby swept from zero to a constant maximum value. This constant current flowed until the sparkover occurred. The current was passed through a ballistic galvanometer whose throw was directly calibrated in seconds, thus measuring the spark lag.

The wiring of the instrument is fully shown in Fig. 1. Tube 1 is directly across the spark gap, acting as an inverted vacuum tube voltmeter and reducing the voltage to a conveniently small value. This reduced voltage in series with an adjustable bias is applied to the input of tube 2. Tubes 2 and 3 act as a two-stage, resistance-coupled, linear amplifier. The output of tube 3 applied to the grid of tube 4 swings this grid from a substantial negative voltage to a substantial positive voltage causing the output current of tube 4 to sweep from zero to the maximum obtainable (i.e., plate supply voltage divided by external plate resistance) for a small rise in voltage at the gap. The adjustable bias determines at which gap voltage increment this sharp response takes place and is set so that the minimum sparking voltage of the gap gives half maximum output current. It is evident that for the approximately trapezoidal wave shape of current the total charge measured by the galvanometer divided by the known maximum value of current gives the time that the current has remained above *half* maximum value, hence the bias setting mentioned. The galvanometer throw is calibrated to give directly in seconds the time that the voltage at the gap has remained higher than the value for which the bias was set, i.e., higher than the minimum sparking voltage of the gap. Thus the galvanometer reads directly the time lag of sparkover of the gap. The output current is passed through two ballistic galvanometers of different sensitivities in series. It is feasible manually to short circuit one or both of these after the beginning of its swing when necessary to prevent its being damaged by an excessive swing. Tube 3 also supplies the input of tube 5 which operates a synchronous timer from which any time intervals greater than 0.05 second are easily read. Theoretically computed transients in simple series circuits were applied to the instrument and these gave a calibration check to better than 4 percent. The instrument reads times from 10^{-5} second up.

The timing circuit itself serves also for measurement of voltage. It is to be noted that the curves of output current of tubes 2, 3 and 4 may be calibrated and used to read the relative voltage at the gap, i.e., the difference between the voltage at the gap and the minimum sparking voltage for which the bias has been adjusted. Tube 2 allows readings over a wider range before saturation is reached but with a lesser precision than tube 3; similarly in comparing tube 3 to tube 4. In most of the tests the plate current of tube 2 was used to read directly with a precision of about 1/4 percent overvoltages less than 7 percent of the sparking potential (which was near 4000 volts).

When the resistances of the instrument were adjusted for maximum amplification a shift of *six* volts at the gap, i.e., 0.15 percent of 4000 volts, produced a change in the output current from zero to the maximum. Thus even if the voltage were raised slowly, e.g., at the rate of 100 percent of sparking potential per 0.01 second, the time required for the output current to rise from zero to maximum would still be only 1.5×10^{-5} second. Thus the instrument can be readily used to measure lags of this or any larger

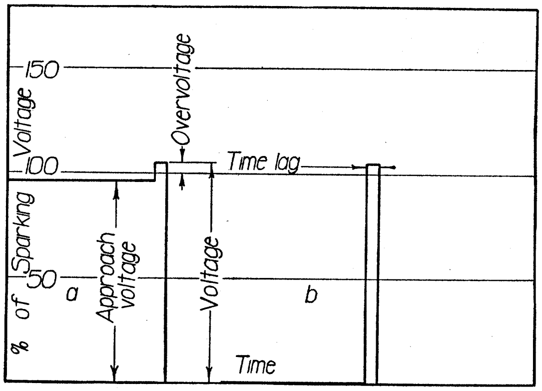

FIG. 2. Voltage wave shapes. *a*, "static" sparkover; *b*, "impulse" sparkover. (The time for the voltage changes drawn vertically is about 1/1000 of the smallest spark lags measured.)

order even for such slow rates of voltage application and, of course, for any more rapid rates. (In the present test series the tube 4 plate resistance was readjusted to give a larger current than at the above mentioned setting, necessitating the use of larger voltage increments at the gap than mentioned above. There was no difficulty on this score, however, as in this test series increments of more than 100 volts were used throughout.)

In order that the effect on the spark lag of the magnitude of the overvoltage might be clearly evident, it was decided to use a rectangular voltage wave shape. That is, the circuit was arranged so that the time duration of the voltage rise from minimum sparking potential to the constant maximum voltage applied to the gap throughout the time lag interval, and also the time duration of the drop of voltage from its full value to the minimum sparking potential, were each very much less than the time lag being measured. The voltage was swept past the sparking voltage very rapidly by applying all or an increment of the voltage suddenly, i.e., within some 10^{-8} second. In most cases this was accomplished by applying the voltage to the gap by closing a switch having higher insulation resistance than the gap. An auxiliary spark was thus obtained at the closing switch which served, therefore, to apply the voltage to the gap very quickly. Two wave shapes were utilized (Fig. 2). For the first, which conveniently approximated "static" sparkover, the main d.c. voltage on the gap was set at 96 percent of sparking potential and a bank of "B" batteries was then thrown across a resistance in the circuit to suddenly raise the gap voltage to some percent above sparking potential. The second wave shape, constant d.c. voltage suddenly applied, approximated "impulse" sparkover but at small overvoltages. The d.c. voltage was obtained from a synchronously driven self-excited motor-generator set, transformer, kenetron tube and condenser. Time lags of sparkover were obtained for both these voltage shapes, for various voltages, mostly in the neighborhood of 105 percent of static sparking potential, and for ultraviolet illumination of measured intensity varied over a very large range.

Ultraviolet light from a quartz mercury arc illuminated the test gap and also a plate of clean nickel in vacuum—both of these being illuminated through identical quartz windows. The intensity of illumination was measured by measuring the saturation current liberated from the nickel photo-cell. This was allowed to flow through a specially constructed resistor consisting of a micarta strip buried in paraffin; the voltage drop across the resistor was measured by a Dolazelek electrometer, the resistance being measured after each voltage measurement by means of the voltage time decay curve when the illumination was intercepted. The spark gap used consisted of copper spheres at small spacing in dehydrated air at atmospheric pressure.

The coherence of the distribution curves increases decidedly as the number of sparkovers per run is increased, but so too, does the work involved. Accordingly, as a compromise, a run of 50 points for the random distribution and of 25 for the peaked was selected as a standard procedure. It may be noted that the adherence of the points to the curve is always best at the top where the points are most numerous and poorest at the bottom where the scale is stretched and a small number of points is used to locate a statistical distribution. For this reason the curve is placed so that the number of points above it equals the number below, no weight being allowed to the added "moment" of the straggling points at the lower end of the curve.

Data and Results

Fig. 3*a* shows three curves of spark lag distribution at "static" sparkover at three different voltages and at one intensity of initial ionization. As labelled this intensity is measured by the current I, in micro-micro-amperes per square centimeter, ejected from a plate of clean nickel in vacuum by the ultraviolet illumination utilized. The lower left hand corners of the light curves give the actual data points which are plotted by listing all the spark lags of the set in order of magnitude and listing also the percent order of magnitude. Thus the fourth largest of a set of 50 is 8 percent etc. This percentage is plotted against the time duration of the particular lag. The equation of the resultant curve is $n_t = 100e^{-pt}$ wherein n_t is the percentage of the total number of lags which are greater than the time t and p is the probability of a lag terminating within unit time. It is evident since the curves are linear on semi-logarithmic paper that p is constant and the distribution truly random. As is well known,[7] the average time lag $T = 1/p$ and can be taken from the curve at $n_t = 36.8$.

The average time of these distributions is plotted against percent overvoltage in Fig. 3*b*. From this curve the average time at 5 percent overvoltage is readily interpolated, thus giving a point on the master curve 1 of Fig. 5. Each of the curves similar to 3*b*, i.e., average time *vs.* overvoltage, was roughly exponential for overvoltages from 1 to 6 percent and the several exponents were approximately the same.

As the illumination was further increased, however, a different transitional distribution appeared wherein some 70 percent of the lags formed a true random distribution and one, moreover, fitting the same master curve 1 of Fig. 5, as shown by its dotted portion. The other 30 percent of the lags were grouped into an entirely different type of distribution. As the illumination was further increased larger percentages of the total were in the second group, and for somewhat greater illuminations yet all the lags fell on the second type of distribution curve. This was a highly peaked distribution containing a few large and many small deviations from a definite peak value. In fact, some 40 percent of the total lags fell within a single time increment only 10 percent as large as the maximum time intervals represented in the distribution. For the peaked distributions no appreciable shift in the time lag was produced by slight changes of overvoltage nor by extensive further increase in illumination. This also is shown on the curves of Fig. 5. Fig. 4 illustrates the two distributions and the transitional distribution by curves at different illuminations and near 5 percent overvoltage.

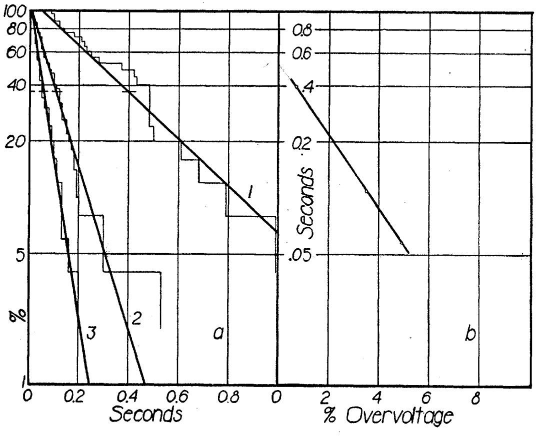

FIG. 3. Domain one spark lags. *a*, spark lag distributions, percent of lags greater than given by abscissa; *b*, average lag *versus* percent overvoltage. Approach voltage = 96 percent; overvoltage, curve 1 = 0.7 percent; overvoltage curve 2 = 3.5 percent; overvoltage, curve 3 = 4.9 percent; $I = 0.00183$.

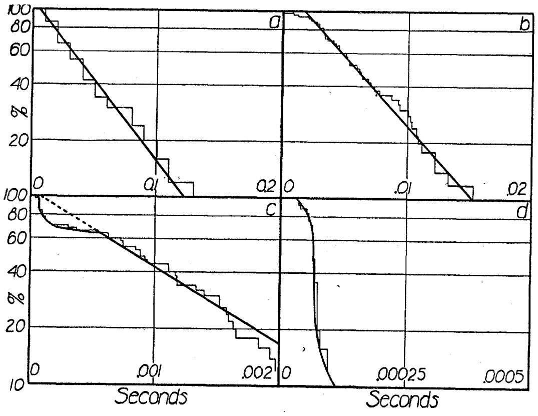

FIG. 4. Spark lag distributions for different illuminations; *a*, random at $I = 0.00183$; *b*, random at $I = 0.0258$; *c*, transitional at $I = 0.365$; *d*, peaked at $I = 5.75$.

A series of tests similar to the above was repeated for the "impulse" wave shape with very similar results which are also plotted on Fig. 5 as

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[7] von Laue, Ann. d. Physik **76**, 261 (1925).

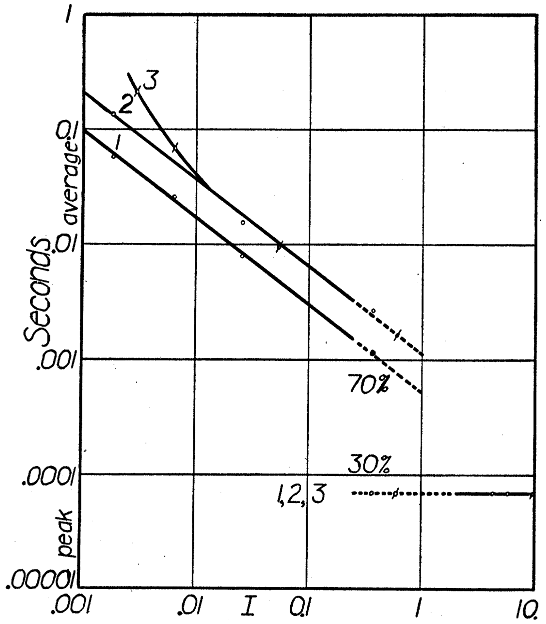

FIG. 5. Master curve of average or peak values. Time lag of sparkover *versus* illumination

Curve	Approach voltage	Voltage
1	96%	105%
2	96%	103%
3	0%	105%

curve 3. Throughout the random distributions the lags at impulse sparkover are longer by a factor of two or more than those at static sparkover. Apparently the only difference is that the 96 percent approach voltage, due to cumulative ionization, causes a greater concentration of initial ions to exist in the gap than exists with the 0 approach voltage. At the smallest ionizations studied, i.e., at the upper end of the impulse sparkover curve 3 of Fig. 5, the curve takes on a greater slope. This is perhaps to be expected as at the lower ionization density one would expect a unit slope. That is, a tenfold increase in ionization should effect a tenfold shortening of the time lag. For higher initial ion densities the lesser slope observed indicates that the increasing ultraviolet illumination becomes in some way progressively less efficient in precipitating sparkover.

It is apparent that if this 96 percent approach voltage is lowered, the random spark lags will be lengthened and that at some low approach voltage, for which the cleansing action entirely outweighs the ionization caused, the random lags must reach a maximum duration greater than that at zero approach voltage. This was checked by a brief test series at 50 percent approach voltage which gave nearly three times as great an average lag as that for zero approach voltage. A few brief tests were taken, also, with overvoltages as high as 50 percent. As was expected increasing the voltage, thus, substantially decreased the observed spark lag. At 50 percent overvoltage, again, a peaked distribution was obtained at a high illumination $I=9$, but a somewhat lower illumination, $I=1.75$, which had been adequate to give a peaked distribution at 5 percent overvoltage was inadequate to give a peaked distribution at the higher overvoltage. That is for $I=1.75$, at 5 percent overvoltage the initiatory lags were negligible compared to the formative lags, but at 50 percent overvoltage the greatly shortened formative lags were negligible compared to the initiatory lags.

The results of these tests may be summarized as follows: Spark lags are found to fall into three distinct domains. First, long *initiatory* lags (10^{+1} to 10^{-3} second or less) of random distribution spent in awaiting a favorable fortuitous space and time arrangement of the somewhat insufficient supply of initiatory electrons. Second, intermediate *formative* lags (of the order 10^{-4} second) distributed about a definite peak value of the order of time required for a positive ion to cross the gap and assist in building up a space charge gradient. Third, short formative lags (of the order 10^{-7} second) distributed about a definite peak value of the order of time required for an electron to cross the gap.

In the first domain with small overvoltages for the gap studied (copper spheres of 0.952 cm radius at 0.0683 cm separation, and 3820 volts static sparking potential) the average time lag is given by:

$$t=f(v)I^{-0.76}, \qquad (1)$$

where t = *average* time lag in seconds of a group of sparkovers taken under identical conditions.
I = intensity of photoelecric illumination as measured by the current, in micro-micro-amperes per square centimeter, exepelled from a clean nickel plate in vacuum.
$f(v)$ = a function of the applied voltage wave shape and magnitude.

Although $f(v)$ varies somewhat with the illumination, it may be inclusively stated for the "static" sparkover (i.e., voltage suddenly shifted from 96 percent of static sparking potential to a constant value more than 100 percent) as:

$$f(v)=0.0037e^{-(0.39\pm 0.08)v} \tag{2}$$

and for the "impulse" sparkover (i.e., a constant maximum voltage suddenly applied) as:

$$f(v)=0.0078e^{-(0.39\pm 0.13)v} \tag{3}$$

where v = the *percent overvoltage*

$$=\frac{\text{max. applied voltage}-\text{static sparking voltage}}{\text{static sparking voltage}}\times 100.$$

Eqs. (2) and (3) hold for from 1 to 6 percent overvoltage; outside of this range the function is not exponential. The central value of exponent indicated is correct at 5 percent overvoltage in every case. For static sparkover Eq. (1) holds for illumination from $I=0.002$, the lowest studied, to $I=0.5$ where transition to the second domain occurs. For impulse sparkover the curve deviates slightly, the exponent becoming greater as I decreases; Eq. (1) is adequate, however, from $I=0.02$ to $I=0.5$.

At the transition to domain two, i.e., at $I=0.5$, 70 percent of the sparkovers occur in a distribution whose average exactly fits equation (1) of domain one and 30 percent fit into the domain two distribution. For successively larger illuminations a successively smaller percentage of sparkovers come into domain one and a larger percentage into domain two.

The existence of the *second domain*, which had been anticipated by Rogowski,[1] and specifically predicted by Loeb,[2, 6] is now *experimentally verified for the first time*. From $I=0.5$ to $I=10$, the highest studied, for this gap and either of the voltage wave shapes mentioned and for overvoltages of from 2 to 6 percent, the lags have a highly peaked distribution, some 40 percent of them falling within one 10 percent increment of the maximum time intervals encountered. Throughout this region the formative time lag, as given by the peak of the distribution curve, remains at $(0.70\pm 0.15)\times 10^{-4}$ second. The above mentioned prediction[2] applied to the present gap length calls for a formative time lag of 0.5×10^{-4} second, an excellent agreement.

When the voltage is raised to 150 percent of static sparking potential at $I=9$, the lags become less than 1.5×10^{-5} second, this being about the smallest interval that could be measured. At 150 percent voltage and $I=1.75$ a fraction of the lags are larger, falling in domain one and illustrating roughly the transition from domain one directly to domain three at higher voltages. This transition, as well as the existence of the domain one distribution for quite brief spark lags, is more comprehensively illustrated by the excellent experimental work of Strigel,[8, 9] although his interpretation of domain three is confused. Domain three at higher overvoltages has received considerable investigation by means of the cathode ray oscillograph from Rogowski's students[10, 5, 11] and from various engineers[12] studying impulse sparkover at high overvoltages. It has also been studied optically.[4]

The time of propagation of the breakdown path and the completion of sparkover once it has been adequately produced involves still shorter time intervals.[13] These may add appreciably to time lag only in the case of long gaps (i.e., initially non-uniform field) and do not concern us here.

Sparkover Mechanism

The mechanism of sparkover in an initially uniform field is envisaged as follows.

Domain one

With somewhat *inadequate initial ionization* the *initiatory lag* in awaiting the fortuitous occurrence of electrons so located as to be capable of commencing sparkover is very much greater than the formative lag. In general, since this fortuitous occurrence is as likely within one time interval as within any other, distribution of these initiatory lags is truly *random*. The order of magnitude of the initiatory lag depends on the external ionizing forces and may be extremely large if these are small. In general, with a probable exception at voltages barely large enough to produce breakdown upon the appearance of a single electron at the cathode, it is the *density of ionization* in the gap that controls the initiatory lag rather than the *rate* of production of *new* electrons. As the initial ion density is

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[8] Strigel, Wissenschaftliche Veroffentlichungen a.d. Siemens-Konzern **11**, 52 (1932).

[9] Strigel, Archiv f. Elektrotechnik **27**, 137 (1933).

[10] Buss and Masch, Archiv f. Elektrotechnik **25**, 787 (1931).

[11] Viehmann, Archiv f. Elektrotechnik **25**, 253 (1931).

[12] Torok, A. I. E. E. Trans. **47**, 349 (1928).

[13] Dunnington, Phys. Rev. **38**, 1535 (1931).

sufficiently increased the entire initiatory lag becomes negligibly small and the formative lag of either domain two or three as the case may be, prevails.

At one level of ionization density we may visualize the variation of initiatory lag with voltage variation as follows. The initiatory time lag is the random time spent *in awaiting the arrival* of the suitable initiatory electrons within a specific *effective* volume in the gap. The extent of this volume effective for the initiation of adequate electron avalanches obviously increases with increased voltage. Thus for sparkover at the very lowest overvoltages, e.g., 0.1 percent, it is certainly necessary for the initiatory electrons to appear at the *very surface of the cathode* and it is also necessary—in all probability—for several to appear almost simultaneously, each one taking advantage of the gradient produced by the space charge of its predecessor. For somewhat higher voltages it is certainly sufficient for sparking that the initiatory electrons appear anywhere within an "effective" shell of appropriate depth extending from the cathode; also, a smaller number of electrons probably suffices. As the voltage increases the thickness of this effective shell increases. For *very high* voltages certainly it is sufficient that a *single* initiatory electron exist *anywhere* within an effective volume including all the gap except a thin shell at the anode. Further voltage increases will then have little effect in shortening this initiatory lag.

Domain two

For a *sufficient initial ionization* the formative lag prevails. Each initial electron avalanche leaves behind it an increasing phalanx of positive ions pointed toward the cathode and hence a space potential which increases about exponentially as one leaves the cathode and starts towards the anode. The slope of this curve gives the field strength at each point. Using *low overvoltages*, e.g., 3 percent and a small gap length, this field strength is at no point great enough at the first instance to cause positive ion ionization. As the whole phalanx of positive ions, however, proceeds relatively slowly toward and into the cathode, the resultant field between the cathode and the next row of positive ions becomes successively steeper. As the last row of positive ions approaches the cathode, the field there becomes great enough to cause positive ion ionization giving a tremendous self-accelerating increase in the number of new electrons formed. As soon as this burst of electrons reaches the anode, the voltage begins its complete drop and sparkover is very rapidly completed. *The total elapsed time is about that required for a positive ion to cross the gap.*

With slightly higher overvoltages (e.g., 15 percent) since, as Sanders[14] has shown, the Townsend coefficient for the initial electron ionization is greatly increased as the voltage increases, the exponential potential curve mentioned above is much steeper. Hence a sufficient gradient for positive ion ionization is created as soon as a *portion* of the positive ion phalanx is swept into the cathode. Thus sparkover ensues after a lag corresponding to time for a positive ion to cross a fraction of the gap length. As the overvoltage is increased this fraction becomes smaller.

Domain three

For an *adequate initial ionization* and a *higher overvoltage* on the same gap (or the same *percent* overvoltage in a longer gap[13]) another effect intervenes. Owing to the intense electron ionization at increased voltage[14] the exponential curve mentioned is itself steep enough near the anode so that positive ion ionization commences there at once. (If this secondary ionization is extremely close to the anode it might not be sufficiently cumulative until this active rear portion of the positive ion phalanx has moved an adequate distance *away from* the anode.) For still *higher overvoltages* (e.g., 60 percent), however, the potential curve caused by the passage of the initial electron avalanche is steep enough to give positive ion ionization at some point in the middle of the gap *at once* before the positive ions have moved any appreciable distance. The mammoth flood of electrons released by this positive ion ionization starts for the anode before the original avalanche has reached there and arrives, starting the voltage drop, one step behind the initial avalanche, as it were. *Thus the time lag is of the order of time for an electron to cross the gap.* The above explanations for domains two and three are worded, for simplicity, as if a single electron avalanche sufficed for spark-

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[14] Sanders, Phys. Rev. **41**, 667 (1932).

over. It may well be that the space and time coincidence of several is essential under most conditions; this does not, however, alter the general argument. (Because of such coincidence a marked increase in initial ionization may tend slightly to shift the sparkover from the second domain to the third but not to the same degree as an increase in voltage.)

Correlation of the Literature

It is particularly gratifying that in the light of the above explanation the various available experimental reports are seen to be consistent with each other and with the spark mechanism envisaged, whereas hitherto they had appeared isolated and even contradictory. The more important of these are briefly presented.

Zuber[3] and von Laue,[7] working at *low initial ionization* showed that the spark lags were very long (running into seconds) and of *random distribution* and that they decreased as the ionizing illumination was increased. They established the nature of, but not the determining conditions for, the *first domain*. Strigel,[8, 9] using fairly high ionization and fairly high overvoltages, also found a random distribution of spark lags at much smaller times, illustrating that for test conditions giving a short formative time domain one extended into quite short intervals. Strigel established that the magnitude of the random time lags varied greatly with the composition and condition of the illuminated *cathode*. Strigel also observed, but was at a loss to interpret, the transition from the random distribution to a specific, formative time lag.

Because no instrument existed combining the necessary swiftness with sufficient precision as to voltage to allow measurements of the formative lags of sparkover at low overvoltages, adequate measurements in the *second domain* have not hitherto been obtained. Perhaps the only previous experimental work bearing on this matter is Reukema's[15] study of the shift of a.c. sparking *voltage* at high frequency, which gives strong indirect verification of the necessity of positive ion motion for completion of sparkover at small overvoltages.

Among others, Buss and Masch[10] using the cathode-ray oscillograph and Beams[4] using the Kerr cell, working at *high overvoltages*, found that the spark lag was very *brief*, e.g., 3×10^{-8} second, and had the *definite value* of the third domain. Viehmann[11] used the oscillograph in conjunction with a saw tooth wave shape of voltage whose slope was changed from test to test. This, together with the small number of sparkovers per series, entirely obscured the difference *in kind* between the various lags he observed. He did, however, observe lags in all three domains and demonstrated roughly the tremendous range of spark lags existing and their very great shortening as the ionizing illumination or overvoltage is increased.

Observations of the initiation of the visible spark directly establish that spark initiation may occur by one of two distinct mechanisms. This was first observed, in a qualitative way by Torok.[12] Dunnington's[13] precise Kerr cell observations at various pressures and gap lengths and at small overvoltages, supplemented by the similar work of von Hâmos[16] at high overvoltages, establish two types of sparkover. First, one in which the visible spark initiates exclusively at the cathode. Second, one in which the spark commences somewhere in mid gap. It is further established that this second sparkover type is caused to replace the first, either by increasing the gas pressure or the gap length while using the same percent overvoltage, or by increasing the percent overvoltage. It is to be noted that any one of these three increases corresponds merely to an increased magnitude of electron ionization. Thus for the test conditions of *domain two*, whose time lag indicates a travel of positive ions to the cathode, the spark is *seen*, literally, to initiate *at the cathode*. For the conditions of *domain three* at which more intensive electron ionization must occur, the time lag does not allow for positive ion migration but calls for positive ion ionization at once and the spark is *seen* to commence at once *in mid-gap*.

In closing, the author wishes to express his indebtedness to Professors L. F. Fuller, L. E. Reukema and L. B. Loeb for their kind and unfailing guidance throughout the course of this investigation; to Professor D. D. Davis and Mr. L. E. Evans for their invaluable cooperation in furnishing equipment; and to his brother, Mr. I. H. Tilles, for assistance in the laboratory.

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[15] Reukema, A. I. E. E. Trans. **47**, 38 (1927).

[16] von Hâmos, Ann. d. Physik **7**, 857 (1930).