SPARKING POTENTIAL AND ELECTRODE MATERIAL

By Leonard B. Loeb
Department of Physics, University of California

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Abstract

A consideration of the character of the normal spark breakdown in air with external ionization and involving time lags of greater than 10^{-4} seconds indicates that with the assumption of space charges the original Townsend theory of sparking can be maintained and that the spark mechanism as is experimentally found will be independent of electrode material. It is shown that the results of Duffendack, Wolfe and Randolph in which they find a dependence of sparking potential on the work function of the electrodes is due to their special experimental arrangement and in no sense contradicts the Townsend theory as asserted by them. It is shown that short time (less than 10^{-5} seconds) surge impulse breakdown in gaps of small area with insufficient ionization necessitates a new breakdown mechanism involving probable impact ionization at the cathode by positive ions to replace the deficient ionization. On the basis of this point of view further much needed investigations are indicated.

Introduction

The countless investigations on the sparking potentials in air and other gases at atmospheric pressures and above have all been unanimous in ascribing a relatively unimportant role to the electrode material [1,21] and considerable importance to the nature of the gas and the gas density. This of course assumes the absence of thick nonconducting oxide films or water films on the electrodes. It also applies largely to conditions where the *potential of the gap is gradually raised to the sparking potential* so that overvoltages are not involved. If the cathode is illuminated by ultraviolet light or the gas in the gap is ionized these *sparking potentials are closely the same* for a given shape of electrodes and are remarkable constant. If no ionization is provided the results may be erratic and average possibly one or two percent above the values for the same gaps when electrons or ions are present, the variation depending on how the potentials are raised. In fact the constancy of these phenomena is such that this method is a *standard* method for measurement of high potentials *without any specification as to electrode material.*

Recent investigations of Duffendack, Wolfe and Randolph[2] using spark plugs and an induction coil or magneto discharge led these observers to

[1] J. J. Thomson, Conduction of Electricity through Gases, 2nd Edition, Cambridge Press' 1906, Chapter 15, especially p. 437; W. O. Schumann, Elektrische Durchbruchsfeldstärke von Gasen, Julius Springer, Berlin, 1923, pp. 17, 20, 156, 159; J. S. Townsend, Electricity in Gases, Oxford Press, 1914, Chapter X; E. Warburg, Handbuch der Physik (Geiger and Scheel) Vol. XIV, Chapter 7, page 367; R. Seeliger, Einführung in die Physik der Gasentladung, Barth, Leipzig, 1927, p. 85.

[2] O. S. Duffendack, R. A. Wolfe and D. W. Randolph, Development of an Electron Emitting Alloy, paper delivered before the Electrochemical Society April 23–25, 1931, printed in preprint form only.

results which appear to disagree with the above common observation. They found by an oscillographic study of the spark between wires in a spark plug that the sparking potential at breakdown, measured over short time intervals was high and very variable with ordinary spark plug wires of nickel alloy. When, however, alloys were used with about 0.04 percent of Ba or Mg present these sparking potentials became uniform and as much as 30 percent lower than before. At the same time they found that the work function of the metal was materially lowered, and in fact that the sparking potentials *as measured by them* were definitely connected with the work function. They therefore asserted that the work function of the metal does influence the sparking potential of the metal and that the overwhelming mass of previous data must be in error.

That an *apparent* contradiction exists in unquestionably correct. However, *this contradiction is in reality only apparent* and inasmuch as it involves questions of considerable importance in theory it may not be amiss to point out the obvious cause for the discrepancy, which in itself is not uninteresting.

Effect of Electrode Material on Sparking

The previous investigations have all been carried out as stated by slowly raising the potential until a spark occurred and by measuring the potential. The lack of dependence on electrode material indicated, as Townsend[3] had long ago shown, that the essential spark mechanism depended on the production near the cathode of electrons through ionization of the gas molecules by some mechanism, presumably by positive ions.[21] At very low pressures (less than 1 cm) in inert gases Holst[4] and Oosterhuis and also James Taylor[5] had shown a dependence on electrode material, the sparking potential being the lower the lower the work function. Neuman[6] in this laboratory confirmed these findings but found that between 1 and 2 cm pressure in argon the mechanism changed and the potential became independent of the electrode material. He there pointed out the obvious conclusion that when the gas density is so low that the electron formation near the cathode essential to a self-sustaining discharge can only come from bombardment of the cathode by positive ions the work function of the cathode must play an important role. As the pressure reaches a point where the probability of ionization of the gas in the high space charge near the cathode by positive ions becomes commensurate with that at the cathode surface, the discharge mechanism changes to one independent of cathode material. This view is doubtless correct. All these experiments were performed by the gradual raising of the potential up to sparkover.

[3] J. S. Townsend, Electricity in gases, Oxford Press, 1914, Chap. IX, pp. 322 and 30; Phil Mag. **45**, 444 (1923); Marx: "Handbuch der Radiologie" Vol. I, p. 241.

[4] G. Holst and E. Oosterhuis, Phil. Mag. **46**, 1117 (1923); Physica **1**, 78 (1921); C. R. **175**, 577 (1922).

[5] J. Taylor, Phil. Mag. **3**, 753 (1927); **4**, 505 (1927); Proc. Roy. Soc. **A114**, 73 (1927); also H. G. L. Huxley, Phil. Mag. **3**, 1056 (1927).

[6] L. J. Neuman, Proc. Nat. Acad. Sci. **15**, 259 (1929).

The Time Lag in Spark Discharge

In the work of Duffendack, Wolfe and Randolph the potential was raised in a small fraction of a second (the time scale was in 10^{-5} of a second) and the breakdown potential was measured by oscillograph. Further no source of ionization was furnished at the cathode, unless in some experiments the cathode was at red heat due to gasoline explosion.* Hence their experimental procedure constitutes an obviously new approach to the problem, which involves as its chief feature the rate of rise of potential. In other words, a time element is introduced into this investigation which was absent in other investigations. This time element brings into consideration a different aspect of spark discharge, i.e. that of the well-known time lag. This is a factor which has been little studied and still less discussed in its bearing on the breakdown potential. Since the time element has certain interesting features it will repay one to consider the role of time in spark discharge.

A study of the effect of time on the breakdown of spark gaps reviewing past literature was made by Zuber[7] in 1925 and was mathematically discussed by Laue.[8] Since Zuber's work some new features have been added in the work of Rogowski[9] and others using the high speed cathode-ray oscillograph, and by others, essentially Lawrence and Dunnington[12] and Beams [10,11] using the Kerr cell shutter. Zuber studied the spark lag, i.e. the time between the point where the potential reaches the sparking value, or some small overvoltage of one or two percent, and the time at which the spark passes. He finds that down to about 0.1 second the number of time intervals, between arriving at the sparking potential and the passage of the spark, which exceed t seconds is given by $n_t = n_o e^{-p\beta t}$. Here β is the chance that an electron is formed in the gap by ultraviolet light, radiation from radium or by natural processes and p is the chance that such an electron can in the gap lead to a spark discharge. Thus the average time lag of the spark is $\bar{t} = 1/p\beta$. The quantity p depends on overvoltage, the nature of the gas and the spark gap. Zuber did not go to shorter time intervals because of the physical limitations of his measuring circuit. He also found that $\bar{t}$ was in reality a function of β, and for *very small* overvoltages that it was about proportional to the intensity of ionization. He further found that overvoltages also reduced $\bar{t}$ and that moist air acted in a similar fashion. The interpretation of these results in terms of later knowledge is of considerable importance.

* In their paper before the Electrochemical Society no accurate description of the spark chamber was given, an omission which makes discussion somewhat difficult.

[7] K. Zuber, Ann. d. Physik **76**, 231 (1925).

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

[9] W. Rogowski, Archiv. f. Elektrotechnik **20**, 19 (1928); and O. Beyerle, Archiv. f. Elektrotechnik **25**, 267 (1931); P. O. Pedersen, Ann. d. Physik **71**, 317 (1923); R. Tamm, Archiv. f. Elektrotechnik **20** (1928); Burroway, Archiv. f. Elektrotechnik **16**, 14 (1926); J. J. Torok, Trans. A.I.E.E. **47**, 177 (1928); **48**, 46 (1930).

[10] J. W. Beams, Jour. Franklin Inst. **206**, 809, 1928; Phys. Rev. **28**, 475 (1926); Phys Rev. **35**, 24 (1930).

[11] J. C. Street and J. W. Beams, Phys. Rev. **38**, 416 (1931); L. von Hamos, Ann. d. Physik **7**, 857 (1930).

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

With the limitations of his apparatus Zuber could not determine whether there was *a real lower limit to the time t* at which a spark could occur. The writer[13,17] had in 1928 postulated that a space charge mechanism was required to cause a spark to occur according to the Townsend theory; and assuming the charge due to positive ion migrations in a long gap he indicated that below $t = 10^{-5}$ to 10^{-4} seconds such a mechanism could not take place. It was accordingly predicted that *the minimum spark lag must lie at time intervals of this order of magnitude*. This point in fact has never been investigated. It is the writer's belief that the space charge mechanism is probably correct for what will be termed the *normal spark breakdown*. Shortly thereafter the work on *surge impulse breakdown* of spark gaps of Pedersen,[9] Rogowski, Tamm, Burroway, Torock and Beams[10,11] indicated that for considerable overvoltages the time lag lay in periods of 10^{-8} or even 5×10^{-9} seconds. The later researches of Lawrence and Dunnington,[12] and Dunnington[14] show, however, that for actual breakdown without overvoltage and the electrodes illuminated with ultraviolet light the time lag is always finite and large, as observed by Zuber. Once, however, breakdown started it was found to be accomplished in time intervals of the order of 5×10^{-9} seconds up to 10^{-7} seconds. The results of Pedersen, Rogowski, *et al* led the writer[15] to abandon the positive ion mechanism for the space charge accumulation *especially in the case of surge impulse breakdown* and to formulate a mechanism of space charge formation based *entirely on the movement of mobile electrons*. Independently Franck and von Hippel[16] formulated a similar theory using a slightly different idea requiring longer time intervals. Schumann[17,18] later developed the Franck and von Hippel idea quantitatively by equations which in the main agree well with Dunnington's[14] observations concerning the mechanism of breakdown. Both the Franck and von Hippel and the Schumann theory apply beautifully to the case of *normal breakdown with time lag*, although they are probably not completely essential. It is further probable that the *electron ionization mechanism* as postulated by the writer and Franck and von Hippel may not be *completely adequate for short time surge breakdown* of spark gaps and that an *added factor to be discussed later may enter with inadequate ionization*.[21]

The Mechanism of the Normal Spark Breakdown

The new developments lead one to the following conclusions. Spark discharge in gases in the atmospheric pressure range, when occurring near the minimum sparking potential, occur essentially on the basis of the mechanism assumed by Townsend. That is electrons must be generated by *positive ion impact on gas molecules* near the cathode in such numbers that the discharge becomes self-sustaining. *This mechanism only can account for the independence of the work function of the electrode surfaces universally observed* for spark dis-

[13] L. B. Loeb, Jour. Franklin Inst. **205**, 305 (1928).
[14] F. G. Dunnington, Phys. Rev. **38**, 1535 (1931).
[15] L. B. Loeb, Science **69**, 509 (1929), also Jour. Franklin Inst. 1930.
[16] J. Franck and A. von Hippel, Zeits. f. Physik **57**, 696 (1929).
[17] W. O. Schumann, Zeits. f. Technische Physik **11**, 131 (1930).
[18] W. O. Schumann, Zeits. f. Technische Physik **11**, 194 (1930).

charge of this character. In order, however, that the Townsend mechanism can occur space charges must be produced near the cathode of such magnitudes that the Townsend mechanism can take place (i.e. space charges giving gradients of the order of five to ten times the initial uniform sparking potential gradient). The consequences of the existence of space charges have actually been observed in the early periods of spark discharge under minimum sparking potential conditions by Dunnington.[14]

The space charges require for their formation 10^{-4} to 10^{-5} seconds if they are to be produced by positive ions and 2×10^{-8} to 10^{-7} seconds if they are to be formed by electron movement only, provided they can be and are so produced. It is quite possible that to form the space charges by electron movement only, overvoltages are required.[17,18,19] It is in fact only in surge impulse breakdown with overvoltages that we have any definite knowledges of time lags less than 10^{-4} seconds. It may therefore be that for space charges and breakdown in less than 10^{-4} seconds considerable overvoltages, electron ionization and possibly a new mechanism for causing this process may be required, especially in the absence of ultraviolet light, while this is not essential for normal breakdown. Consequently while the time lags in spark breakdown measurements for the minimum sparking potential are such as to always insure the space charge formation and the Townsend mechanism,[21] this may in no sense hold for shorter time intervals.[17,18,19]

Returning to the question of space charge formation in longer time intervals, it is clear that under the conditions of minimum spark potential investigations the actual limit for space charge formation and for breakdown is of the order of 10^{-4} seconds or a bit less. The question then arises as to what causes the observed statistical lags of Zuber extending in some cases into minutes. The essential feature that affects the time lag and makes classical sparking potential measurements differ from the overvoltages breakdown *must depend on some rare fortuitous combinations of circumstances whose occurrence ends in the building of a space charge under the minimum potential conditions*. Since high fields exist across the gap any ionization occurring in such a fashion as not to lead to an appropriate space charge will be swept away and one must await the occurrence of the right combination of events to give a spark. As Zuber showed, the occurrence of appropriate conditions is a most complex phenomenon. It depends first on the occurrence of at least one electron in the gap where the then undistorted field is highest. In addition it must depend on whether this electron is near enough to the cathode to be effective in building up a space charge. This is influenced by the sort of gas, by the small overvoltage, by gap design and by the pressure of the gas. It may as postulated by Franck and von Hippel and by Schumann not depend on *one electron, but on a succession of electrons liberated in proper time sequence near the cathode.* It may again depend on a proper spatial orientation of electrons in the gap as postulated by the writer's chain mechanism; or it may depend on a proper space time sequence. In the limit if no artificial ionization is present such a fortuitous combination of events may on the average occur very rarely

[19] W. O. Schumann, Zeits. f. Technische Physik **11**, 58 (1930).

and we observe time lags which preclude any accurate approach to the true sparking potential (i.e. such lags that owing to human impatience the potentials appear 2 percent high). With ionization at the cathode the results are more uniform, the time lags are shorter and conditions are much improved so that the potentials are slightly lower. In spite of this, however, there are time lags of a finite amount (exceeding 0.1 of a second) indicating definitely a spatial, or temporal spatial, succession of electronic events which is not too common. Once, however, these occur the space charges are built up, the ionization by positive ions begins and the spark takes place in a very short time.

The Surge Impulse Breakdown Mechanism

One may now turn to the problem presented by Duffendack, Wolfe and Randolph's method. These observers measure the actual potential at breakdown of presumably an *un*illuminated spark plug gap whose actual minimum breakdown potential as it occurs in air is not measured by the static method. Such gaps have so small a volume of air to be ionized by the normal atmospheric processes that the chance of a proper occurrence of circumstances leading to a normal spark is most remote. In addition the fields between spark plug terminals are far from uniform and it can occur that, with considerable overvoltages, fields far greater than those causing sparking under ordinary conditions obtain. These observers measure at what potential in a rapidly rising potential wave the gap actually breaks down. The time between that when the true minimum potential on the spark coil wave is reached and that when due to a considerable overvoltage (of the order of several tens of percent) the spark passes at the observed potential is of the order of 10^{-5} seconds. Hence they observe a phenomenon that depends on just the type of surge breakdown mechanism in which the electronic space charge mechanism is completely unknown and has at best only been conjectured. There is in this operation no time for the *fortuitous and apparently efficient set of occurrences* which give the true minimum sparking potential. Instead on a rapidly rising potential wave the field strength at the points on the electrodes rises to absolutely unknown values. It continues to rise until conditions of ionization in the gap are such that perhaps just any one electron or ion located anywhere in or near the gap can start a space charge building mechanism. The impulse may even pass without a spark. It is most probable that the intense fields near points on the cathode catch the first positive ion appearing due to natural ionization, and if this when accelerated can produce on *impact with the cathode* a new electron, a mechanism for space charge formation of the Franck and von Hippel type is set up. It is unlikely that in such intense radial fields the field at any distance from the minute point on the cathode would be great enough to generate ions by collision of the positive ion and gas molecule. This is emphasized first by the fact that for ionization of a gas by positive ions with any efficiency much higher fields are needed than those for liberation of electrons from the cathode surface by positive ions; and secondly by the fact that the high fields probably lie about *rough points* on the cathode and are not of sufficient intensity at several ion free paths to give the positive ion a chance to ionize other gas molecules. It therefore appears not unreasonable to assume that in this *forced discharge at very high fields* the space charge mechanism is built up by electrons from the positive ion bombardment of the electrode surface. This mechanism then replaces the adequate ionization obtaining in other sparks. Such an electron and space charge source must depend on the work function of a particular spot on the cathode. A similar conclusion was also reached independently in one of Schumann's splendid papers.[21] If the work function for this spot is low the potential needed for a spark will be lower than for a point of high work function. By making electrodes of uniformly low work function the surge impulse breakdown potential will be markedly lower and more uniform. It will, however, never be really uniform (as can be seen by the photographs of Duffendack, Wolfe and Randolph) for the potential rises quickly and the points are not uniform. It is most probable that considerable uniformity could be introduced into such experiments with perhaps even lower potentials, if really intense ionization at the cathode is introduced by an external agent (e.g. ultraviolet light on the cathode). In this case the potential should be independent of work function, except insofar as the photoelectric efficiency of the source varies markedly with this quantity. This condition has been studied to some extent by Rogowski and Tamm[20] and is in accord with the above.

It thus appears that the work of Duffendack, Wolfe and Randolph in no sense invalidates the generally accepted theory of the ordinary spark breakdown mechanism, nor does it cause us to revise it in the least. Their work deals with conditions radically different from the ones used in classical studies. In fact they have discovered that *by removing almost all natural chances of ion formation between the electrodes* by short time intervals and small electrode area *it takes a new mechanism requiring much higher fields to produce a space charge and a spark*. In the absence of ionization and under their special conditions as to electrode form it is probable that the most efficient mechanism depends on electron emission from the cathode by positive ion bombardment.[21] This is definitely dependent for its effectiveness on the work function of the metal. It is conceivable by still further altering conditions in shortening time intervals and using smaller electrodes that one might be able to suppress sparking entirely until one reached field strengths leading to the well-known field currents. This would also depend on work functions and yield still another spark mechanism. It may be that recent results of Street and Beams[11] apply to just this situation. This phenomenon would hardly, however, disprove the Townsend interpretation of the spark under entirely different conditions.

It is imperative as seen from this discussion that experiments be made to really measure the shortest time limit in normal spark discharge. It would also be of great interest to find for what time intervals and fields the new electrode-material dependent mechanism begins to manifest itself. It should also be of interest to see whether in all short time surge impulse breakdown the nature of cathode material does not play a role, and to determine the effect of intense external ionization on such breakdown.

[20] W. Rogowski and R. Tamm, Archiv. f. Elektrotechnik **20**, 107 (1928).
[21] W. O. Schumann, Zeits. f. Technische Physik **11**, 143 (1930).