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1977 J. Phys. D: Appl. Phys. 10 1761

(http://iopscience.iop.org/0022-3727/10/13/011)

J. Phys. D: Appl. Phys., Vol. 1977. Printed in Great Britain. © 1977

Electrical breakdown of mineral oil under uniform fields

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Received 4 January 1977, in final form 27 April 1977

Abstract. The direct breakdown voltage of degassed and oxygen-saturated oil has been measured as a function of gap length (28–200 μm) using different combinations of etched aluminium, anodized aluminium and stainless steel electrodes. Polarity reversal tests revealed the presence of a crossover point in the breakdown characteristics analogous to that obtained for non-uniform field geometries. It is therefore inferred that the breakdown mechanism is initiated at local asperities on one of the electrode surfaces. The shapes of the characteristics were found to be either concave or convex with respect to the gap axis, depending on the material of the electrodes used. A concave shape could lead to a minimum in the average breakdown strength against gap length characteristic.

1. Introduction

It is well known that the presence of oxide films or barriers on the surfaces of the electrodes can markedly affect the breakdown properties of liquid insulants (Zaky and Hawley 1973, Gallagher 1975). The oxidation procedure used by previous workers consisted essentially of conventional polishing of the electrode surfaces followed by subsequent oxidation by exposure to an atmosphere of dry air or oxygen. More recently Evangelou *et al* (1975) used etching and anodization techniques for the preparation of aluminium electrodes, thereby obtaining a greater degree of surface condition reproducibility. These techniques were used to study the effect of surface oxide films on the breakdown voltage against gap length characteristics of mineral oil under non-uniform field conditions (Zaky *et al* 1976a, b).

The present paper gives the results obtained from an investigation of the effect of gap length and surface oxide films on the breakdown voltage of mineral oil under uniform field conditions (sphere–sphere) using the same electrode preparation techniques. The breakdown voltage against gap length characteristics were obtained for various electrode combinations for both degassed and oxygen-saturated oil. These characteristics revealed two interesting and hitherto unreported effects:

(*a*) the similarity between the breakdown characteristics for uniform and non-uniform fields, as indicated by the common presence of a crossover point in the characteristics obtained from polarity reversal tests;
(*b*) the dependence of the shape of the characteristics on the electrode material used; this shape could be either concave or convex with respect to the gap axis.

2. Experimental procedure

Experiments were carried out on transformer oil (Shell Diala B) complying with BS 148 (British Standards Institution 1959). The liquid samples were filtered through a 0·3 μm Millipore filter and degassed at a pressure of 10^{-2} Torr for 10 h; during degassing the liquid was continuously stirred. For experiments carried out on liquid samples saturated with oxygen, the dry and filtered gas was allowed to bubble slowly into the degassed liquid, which then remained in contact with the gas at atmospheric pressure for 16 h before being admitted into the test cell.

The electrodes consisted of either stainless steel or aluminium spheres of 5 mm diameter, which were mounted on horizontal shafts that passed into the cell through suitable vacuum seals. The stainless steel electrodes were mechanically polished to a mirror finish, whereas the aluminium electrodes were either etched, or etched and then anodized. The technique used for etching and anodization of the aluminium electrodes has been described elsewhere (Evangelou *et al* 1975). Breakdown measurements were carried out using direct voltages; a diverter circuit was used in all tests. For each gap setting new electrodes and a fresh liquid sample were used. Each breakdown voltage reported was the average of 20 breakdowns and the coefficient of variation varied between 5 and 14%.

3. Experimental results

The breakdown voltage against gap length characteristics were obtained for degassed and for oxygen-saturated oil using the nine possible combinations of the three types of electrodes, namely stainless steel (SS), etched aluminium (AE) and anodized aluminium (AA). To facilitate the identification of the different electrode combinations they will be referred to as cases A, B, ... I for degassed oil and cases A_o, B_o, ... I_o for oxygen-saturated oil as follows:

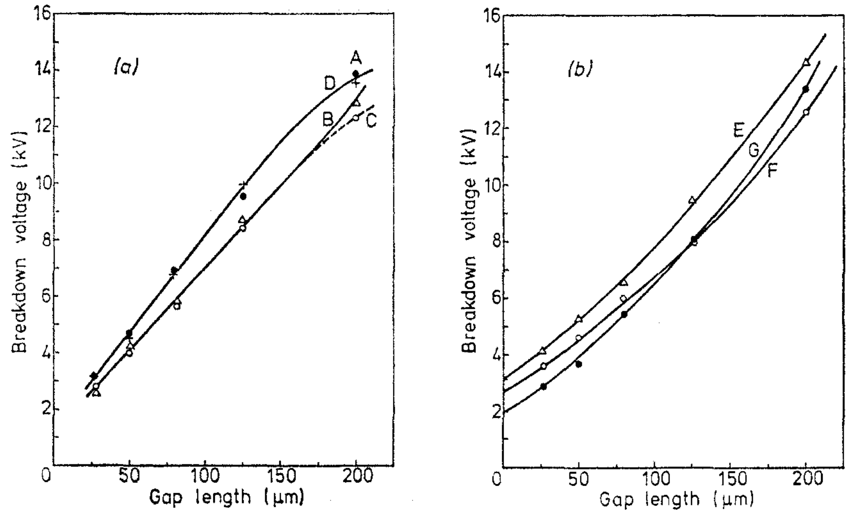
Cathode/anode		Case
SS	SS	A, A_o
AE	AE	B, B_o
SS	AE	C, C_o
AE	SS	D, D_o
AA	AA	E, E_o

Cathode/anode		Case
AA	AE	F, F_o
AE	AA	G, G_o
AA	SS	H, H_o
SS	AA	I, I_o

3.1 Degassed oil

Figure 1(*a*) shows the breakdown voltage against gap length characteristics for electrode combinations corresponding to cases A, B, C and D. A comparison between the four characteristics indicates that for the same anode material the characteristics are practically identical. The fact that for all gap lengths the breakdown voltages in cases B and C were lower than those in cases A and D indicates that the decrease in voltage is due to the change of the anode material from stainless steel to etched aluminium.

Figure 1(*b*) shows the characteristics for cases E, F and G. The results of the polarity reversal tests (curves F and G) indicate the existence of a crossover point corresponding to a critical gap length of about 120 μm, at which the strength is the same for both polarities.



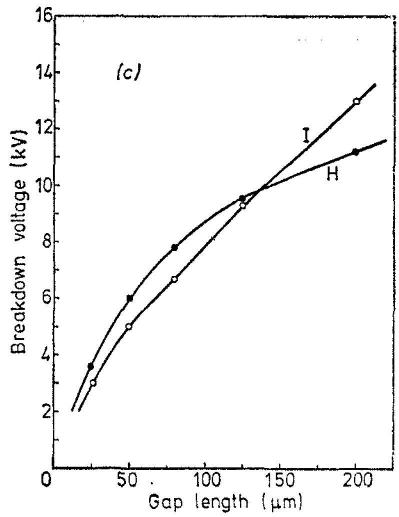
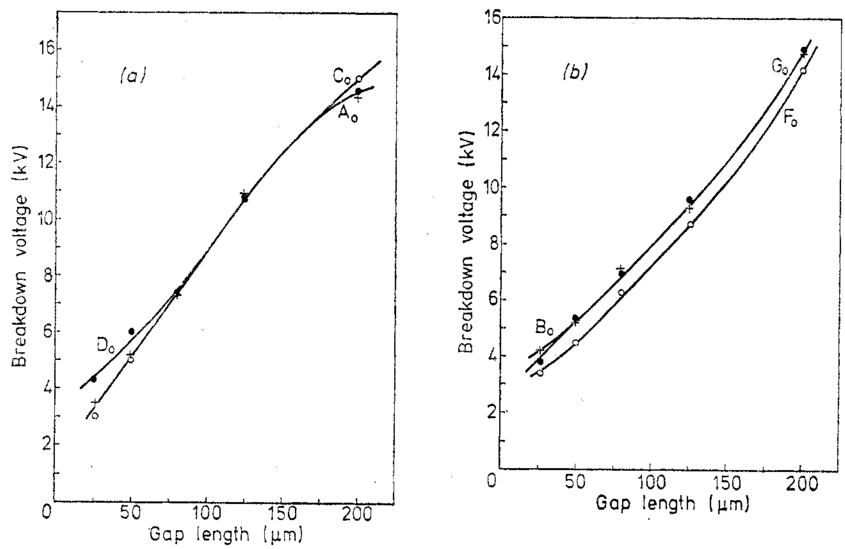


Figure 1. Breakdown voltage versus gap length for various electrode combinations (see text table) in degassed oil. (*a*) +, case A; △, case B; ○, case C; ●, case D. (*b*) Cases E, F and G. (*c*) Cases H and I.

The results of a polarity reversal test using stainless steel and anodized aluminium electrodes (cases H and I) are given in figure 1(*c*). The characteristics indicate the presence of a crossover point corresponding to a critical gap length of about 135 μm. At larger gaps the breakdown voltage with an anodized aluminium anode (curve I) was significantly higher than that with a stainless steel anode (curve H).

3.2. Oil saturated with oxygen

The breakdown voltage against gap length characteristics for cases A_0, C_0 and D_0 are shown in figure 2(*a*). By comparing these characteristics with the corresponding ones in the degassed oil (figure 1(*a*)), it can be seen that the presence of oxygen increased the breakdown level of all the characteristics and that the greatest increase occurred in case C_0. Comparison of cases D and D_0 shows that in the latter case the increase in the breakdown voltage is accompanied by a change in the shape of the lower portion of the characteristic from concave to convex with respect to the gap axis.



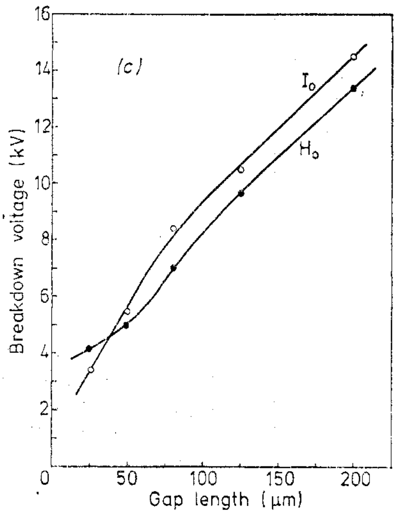


Figure 2. Breakdown voltage versus gap length for various electrode combination (see text table) in oil saturated with oxygen. (*a*) +, case A_o; ○, case C_o; ●, case D_o. (*b*) +, case B_o; ○, case E_o; ●, case G_o. (*c*) Cases F_o and G_o.

Figure 2(*b*) shows the results obtained for cases B_o, F_o and G_o. Comparison of these characteristics with the corresponding ones for degassed oil shows that for cases B_o and G_o the presence of oxygen increased the breakdown level over the whole range of gap lengths examined.

Figure 2(*c*) shows the results obtained from polarity reversal tests using stainless steel and anodized aluminium electrodes (cases H_o and I_o). The presence of oxygen produced a considerable reduction in the critical gap length from about 135 μm for the degassed case to about 35 μm. Comparison between cases H_o and H shows that, as for cases D_o and D, the presence of oxygen produced a marked change in the shape of the lower portion of the characteristics.

Figure 3 shows a comparison between the characteristics obtained with anodized aluminium electrodes for degassed oil (curve I) and oil saturated with oxygen (curve II); there is no significant difference between the two cases.

4. Discussion

The salient features of the present results, which will be discussed in some detail, are: (*a*) the presence of a crossover point in the breakdown voltage against gap length characteristics obtained from polarity reversal tests, and (*b*) the dependence of the shape of these characteristics on the state of the electrode surfaces.

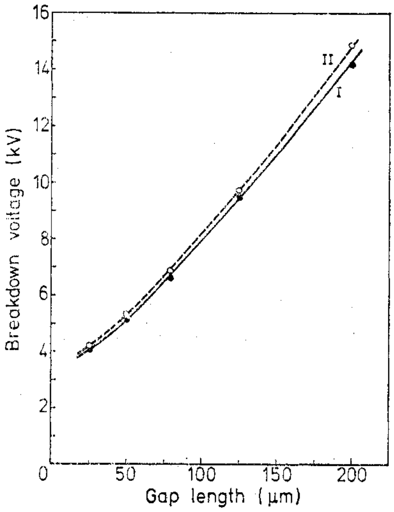


Figure 3. Breakdown voltage versus gap length for two anodized aluminium (AA) electrodes: I, degassed oil; II oxygen-saturated oil.

4.1. Polarity reversal tests

The characteristics obtained from polarity reversal tests in which one of the electrodes had a thick blocking oxide film (anodized aluminium) and the other electrode had a thin oxide film (etched aluminium or stainless steel) indicate the presence of a crossover point. This point corresponds to a critical gap length at which the breakdown voltage for both polarities is the same (figure 1(*b*), cases F and G; figure 1(*c*), cases H and I). It is significant to note that the existence of such a crossover point was also found for the characteristics obtained from polarity reversal tests using a point-to-sphere electrode geometry (Angerer 1965, Zaky *et al* 1976a, b).

Asperities, unavoidably present on electrode surfaces, would act as local high field sites when present on electrodes with thin oxide films. The preparation of an electrode surface by mechanical polishing, as with the stainless steel electrodes, and by etching, as with the etched aluminium, would lead to the presence of a relatively large number of such asperities. Anodization, however, would give a more uniform oxide film which would tend to smooth out the existing asperities.

It has been suggested from experiments on the effects of electrode area (Sharbaugh *et al* 1955, Brignell and Metzmacher 1971) that the events leading to breakdown are initiated at asperities on the cathode. The striking similarity between the polarity reversal characteristics for non-uniform fields (Zaky *et al* 1976b) and those obtained in the present work indicates that breakdown is initiated at local asperities on the electrode surfaces. Thus when a breakdown channel is initiated at some local asperity, this channel will propagate a short distance into the gap and will act as a point electrode. Under these conditions, the explanation for the existence of a crossover point in the present results will be similar to that already put forward by the present authors for non-uniform field geometries (Zaky *et al* 1976b). The fact that the presence of dissolved oxygen produced a marked reduction in the critical gap length, both in the present work and in the non-uniform field case, lends strong support to the above argument.

Tests with both electrodes anodized (figure 1(*b*), case E) were found to give higher breakdown voltages than those obtained with only one of the electrodes anodized. This is attributed to the fact that anodization of both electrodes would reduce the effect of asperities, thereby increasing the breakdown voltage. When both electrodes are anodized, the neutralization of negative charge carriers at the anode would be difficult, irrespective of whether these charge carriers are formed by electrons attached to liquid molecules or trapped by oxygen molecules. Hence the breakdown voltage of the liquid would be insensitive to the presence of oxygen (figure 3).

4.2. Shape of the V–d characteristics

The results show that the shape of the *V–d* characteristics depends on the material of the electrodes. Thus when both electrodes are aluminium the characteristics are convex with respect to the gap axis, whereas when one or both of the electrodes is stainless steel the characteristics are in general concave with respect to the gap axis.

The different shapes of the *V–d* characteristics are illustrated schematically in figure 4. Curve I is typical of the results obtained when one or both of the electrodes is stainless steel, whereas curves II and III correspond to those obtained when both electrodes are aluminium. It is significant to note that of the *V–d* characteristics reported by Gosling and Tropper (1964) for different electrode materials with degassed oil, the only convex characteristic (of type II) was that obtained with aluminium electrodes; all other electrode materials used (iron, nickel, copper, brass) gave concave characteristics (of type I).

When one or both of the electrodes is stainless steel the *V–d* characteristics (type I) will result in an average dielectric strength (V/d) which decreases monotonically with

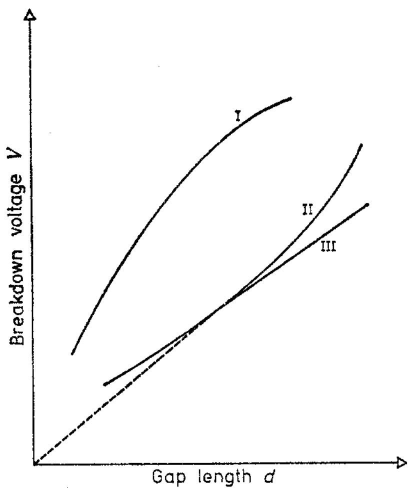


Figure 4. Schematic diagram showing the different shapes of the *V–d* characteristics: I, shape with one or both electrodes stainless steel; II and III, shape with both electrodes aluminium.

gap length. Such a decrease may be attributed to the increased electrode area subjected to high stresses at large gaps (Sharbaugh *et al* 1955). On the other hand, when both electrodes are aluminium the *V–d* characteristics will result either in a dielectric strength which decreases to a constant value as the gap is increased (type III characteristic), or in a strength which has a minimum value at a certain gap length (type II characteristic). In the latter instance, this gap length will be that at which the tangent to the *V–d* characteristic passes through the origin. The possibility of the existence of a minimum in the breakdown strength against gap length for electrodes having a strongly blocking oxide film has not been reported before; it is a very interesting but intriguing result which deserves further investigation before any definite conclusions can be drawn.

It is significant to note that the shape of the lower portion of the *V–d* characteristics will determine the apparent zero-gap intercept obtained when the characteristics are extrapolated to zero gap. Thus a concave characteristic will lead to a low intercept, whereas a convex one will result in a high intercept. A detailed discussion of the effect of surface oxide films and dissolved oxygen on the intercept phenomenon has been given recently (Zaky *et al* 1977). The present results show that in cases D_0 and H_0 the presence of oxygen changed the shape of the lower portion of the characteristics from concave to convex with respect to the gap axis. Since in both these cases an aluminium electrode was used as the cathode, it may be inferred that in the presence of oxygen it is the cathode material which determines the shape of the lower portion of the characteristics.

References

Angerer L 1965 *Proc. IEE* **112** 1025–34
Brignell J E and Metzmacher K D 1971 *J. Phys. D: Appl. Phys.* **4** 253–8
British Standards Institution 1959 BS 148
Evangelou C, Zaky A A and Megahed I Y 1975 *Proc. IEE* **122** 225–6
Gallagher T J 1975 *Simple Dielectric Liquids* (Oxford: Clarendon Press)
Gosling C H and Tropper H 1964 *Conference on Dielectric and Insulating Materials* (London: IEE)
Sharbaugh A H, Cox E D, Crowe R W and Auer P L 1955 *Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena: US Natn Res. Coun. Publ. No.* 396, p 16–20
Zaky A A and Hawley R 1973 *Conduction and Breakdown in Mineral Oil* (London: Peter Peregrinus)
Zaky A A, Nosseir A and Megahed I Y 1977 *J. Phys. D: Appl. Phys.* **10** L43–5
Zaky AA, Nosseir A, Megahed I Y und Evangelou C 1976a *J. Phys. D: Appl. Phys.* **9** L77–9
—— 1976b *J. Phys. D: Appl. Phys.* **9** 2287–93