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FAST PULSE BREAKDOWN OF NON-UNIFORM FIELD PRESSURISED AIR SPARK GAPS

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FAST PULSE BREAKDOWN OF NON-UNIFORM FIELD PRESSURISED AIR SPARK GAPS

by

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A B S T R A C T

Pulse breakdown data in the nanosecond range, is given for 3 to 5 mm non-uniform field air spark gaps, at a pressure of 1 to 6 atmospheres. The three-electrode gap has a central disc trigger electrode having an edge radius of 0·5 mm. A negative voltage pulse, which rises linearly from 1·0 to 10·0 kV/ns, is applied to the trigger electrode with various voltages previously applied to the outer main electrodes. Breakdown is initiated with a very low jitter by field emission from the trigger electrode. Comparison with similar data for pressurised uniform field gaps is made.

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CONTENTS

LIST OF SYMBOLS

L_t Inductance of triggered gap.

Z_t Characteristic impedance of trigger cable.

Z_m Characteristic impedance of diagnostic cable.

V_t Trigger cable voltage.

V_p Pulse voltage.

$\dot{V}_p$ Rate of rise of V_p .

V_b Pulse breakdown voltage.

V_s Static breakdown voltage.

E_b Pulse breakdown electric field.

E_s Static breakdown electric field.

E_f Field emission electric field.

ℓ_g Minimum gap length.

x Distance from centre electrode.

E_x Calculated electric field at x.

t_b Breakdown time.

t_f Formative time.

R Impulse ratio (V_b/V_s).

R_h Minimum impulse ratio at high pressures.

1. INTRODUCTION

Breakdown of spark gaps in a few nanoseconds can be produced by applying a voltage pulse which rises rapidly to a value large compared with the static breakdown voltage. A low variation or jitter in the breakdown time is achieved if the statistical time lag[1] in breakdown is eliminated by either previous irradiation of the gap, or reduced to a negligible value by the field emission of electrons from one of the electrodes[1,2]. In the latter case field emission will most readily be produced if a non-uniform field distribution is used, so that a locally high electric field is produced at the cathode. Data on the fast breakdown of negative point-sphere gaps at atmospheric pressure and below has been given previously[3], though no information appears to be available for pressurised non-uniform field gaps.

The objects of the present experiments were to obtain breakdown data on non-uniform field pressurised air gaps, when subjected to a voltage pulse rising linearly with time without previous irradiation, and to compare the results with those obtained for a uniform field irradiated gap using the same rate of rise of voltage. The formative time lag deduced from these results is also compared with the published data for uniform field gaps[10,11,12], when an almost constant voltage step is used with a rise time of less than 5 ns.

2. EXPERIMENTAL APPARATUS AND TECHNIQUES

2.1 Gap details and Field Configurations

The spark gap used for the non-uniform field (n.u.f.) experiments is a 3-electrode assembly, as shown in Fig.1. The electrode geometry is given in more detail in Figs.2a and 2b, with calculated field configurations obtainable under voltage conditions which apply in fast switching applications. This and similar spark gaps are used extensively for low inductance high current switching and have been described in detail previously[4,5,6]. They are generally referred to as 'field distortion' gaps.

The central disc electrode is placed asymmetrically between the toroidal ring outer main electrodes to give minimum air gaps of 5·1 and 3·4 mm at AB and CD in Fig.2a. The minimum radius of the trigger electrode is 0·5 mm between B and C, and that of the outer electrodes is 6 mm at A and D. The electrodes are of heavy alloy (tungsten/copper/nickel).

Complete breakdown of both halves of the gap normally occurs in 'cascade' as described below in section 4.6. In the present fundamental investigation breakdown of the smaller 3·4 mm gap is achieved by earthing the outer electrodes and applying a negative voltage trigger pulse V_p to the centre or pulsed electrode until breakdown occurs at the breakdown voltage V_b and mean electric field E_b, the field configuration being as in Fig.2a. Breakdown of the longer 5·1 mm gap occurs when the electrodes are initially held at positive D.C. potentials, such that both gaps are equally stressed to 80% of the static breakdown value, and again applying a negative pulse to the centre electrode as shown in Fig.2b for a pressure of 3·7 atmospheres. It should be noted that in the latter case, before the trigger pulse is applied, no appreciable increase in electric field occurs at the edge of the centre electrode above the mean value.

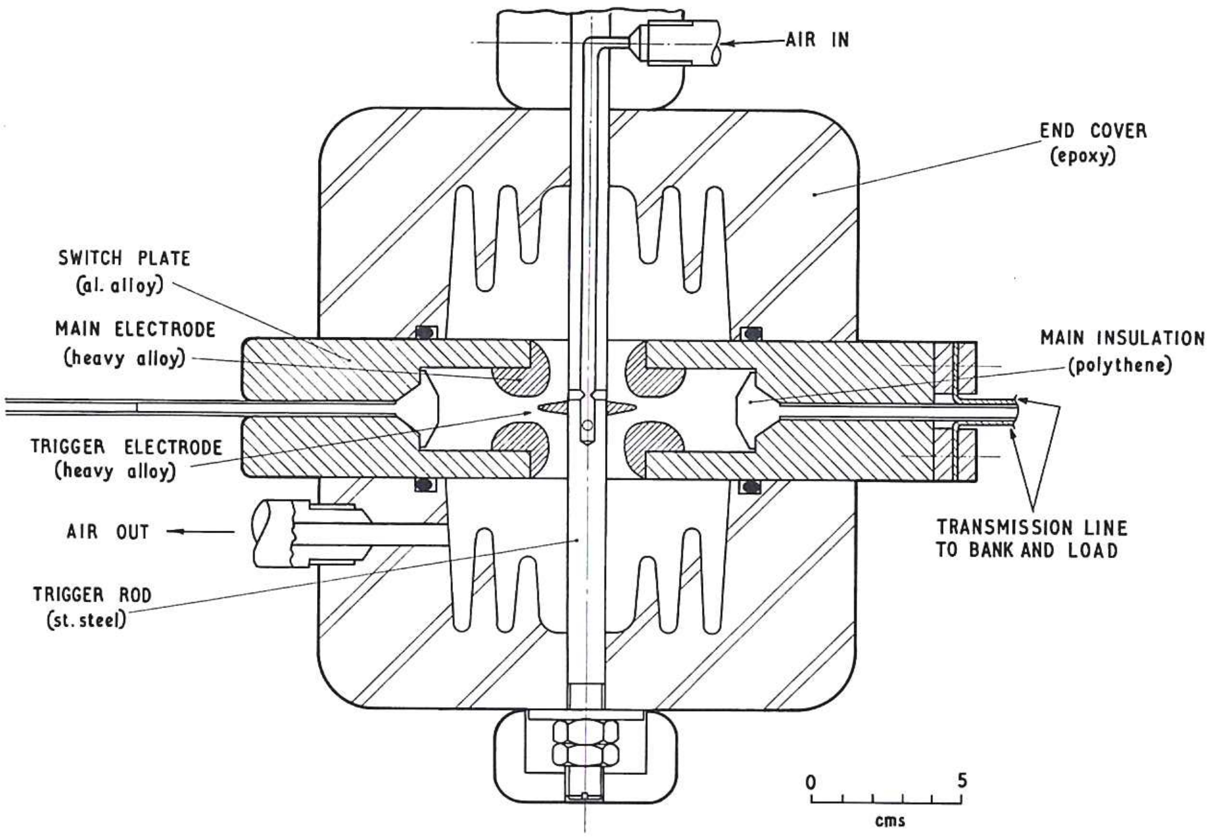


Fig. 1 Three electrode non-uniform field spark gap (CLM-P 171)

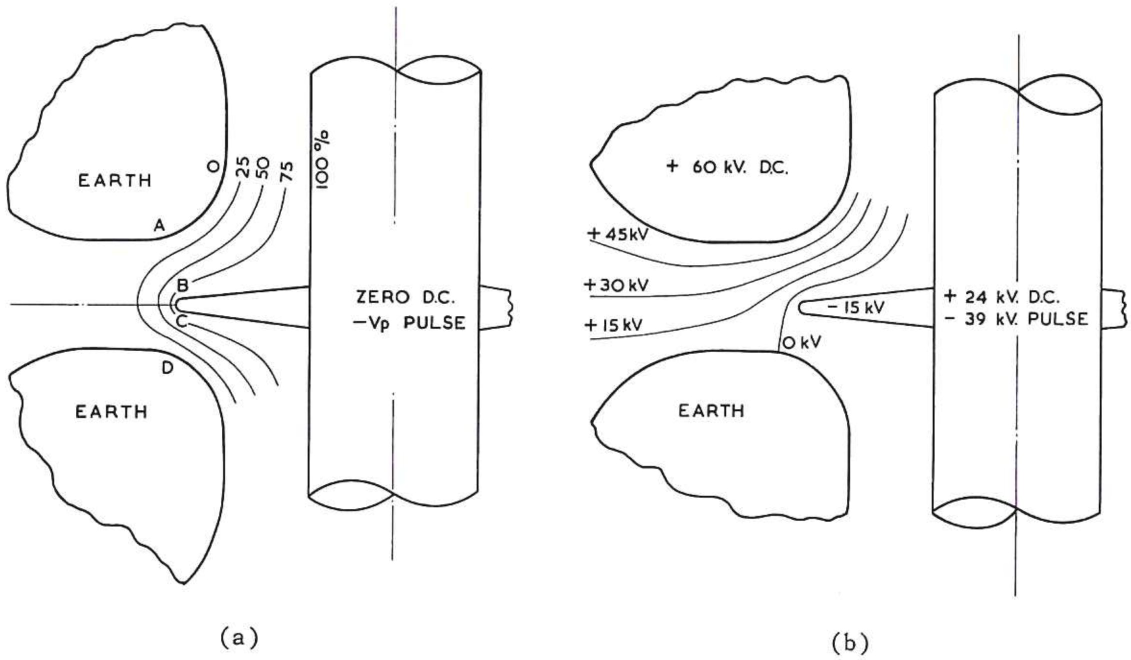


Fig. 2
(CLM-P 171)
Field configurations for pulse breakdown of n.u.f. gaps (a) 3.4 mm gap; (b) 5.1 mm gap at 3.7 atm.

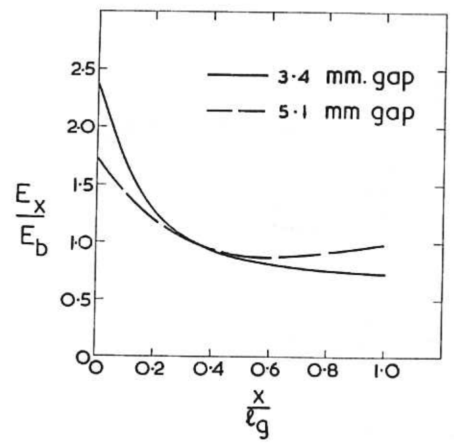


Fig. 3 (CLM-P 171)
Ratio of calculated electric fields Ex/Eb as a function of position for n.u.f. gaps

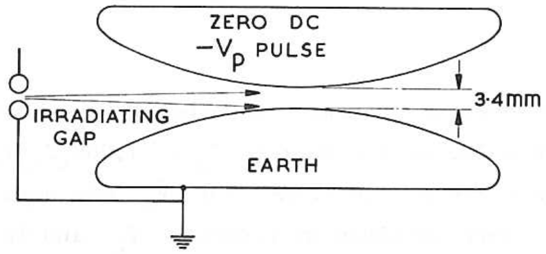


Fig. 4 (CLM-P 171)
Uniform field 3.4 mm irradiated spark gap

The equipotential lines in Figs.2a and 2b refer to typical breakdown conditions for the 3·4 mm and 5·1 mm gaps (at 3·7 atmospheres) respectively, ignoring corona and space charge effects. The ratio of the calculated electric field E_x, at a distance x from the centre electrode, to the mean stress E_b is given in Fig.3 as a function of x/ℓ_g, where ℓ_g is the minimum gap length.

The irradiated uniform field (u.f.) gap shown in Fig.4, has copper electrodes with a spherical surface of 14·0 cm diameter separated by a 3·4 mm air gap. Irradiation is provided by a discharge in an auxiliary spark gap, which was originally initiated by the firing of the triggered gap, such that irradiation of the experimental gap occurred slightly before the application of the voltage pulse V_p. However under these conditions breakdown was not always reproducible and so the auxiliary gap was then connected to a D.C. supply through a high resistance to produce continuous irradiation. This latter method gave consistent results and was therefore used in all the uniform field gap experiments. The auxiliary irradiating gap was positioned 5 cm away from the breakdown region of the experimental gap.

All gaps were pressurised with dry compressed air (-50°C dewpoint). Clean air was passed through the gaps between discharges. The operating pressures given below are absolute values in atmospheres.

2.2 Pulsed Voltage Circuit

A trigger voltage pulse V_p rising linearly with time was used because the data was required for the design of low inductance capacitor banks in which fast switching is achieved using a number of spark gaps connected in parallel. In such systems(6) the low impedance of the trigger cables from the common trigger generator to the individual gaps limits the rate of rise of voltage that can be obtained. Breakdown therefore usually occurs on the linear portion of an exponentially rising voltage pulse.

The pulse forming circuit used in the present experiments is shown in Fig.5. One end of the coaxial trigger cable of 38 ohms impedance (Z_t), having a transit time of 50 ns, was connected to the pulsed and earthed electrode of the experimental gap G_e through a 400 pf blocking capacitor C_t. A triggered spark gap G_t was connected across the other end of the cable which was charged to a voltage V_t up to 60 kV. When the triggered spark gap breaks down a voltage pulse, lasting for 100 ns and having theoretically a maximum value of $2V_t$, is produced at the experimental gap. If the effective inductance of the triggered gap and its connections to the cable is L_t, the voltage pulse rises

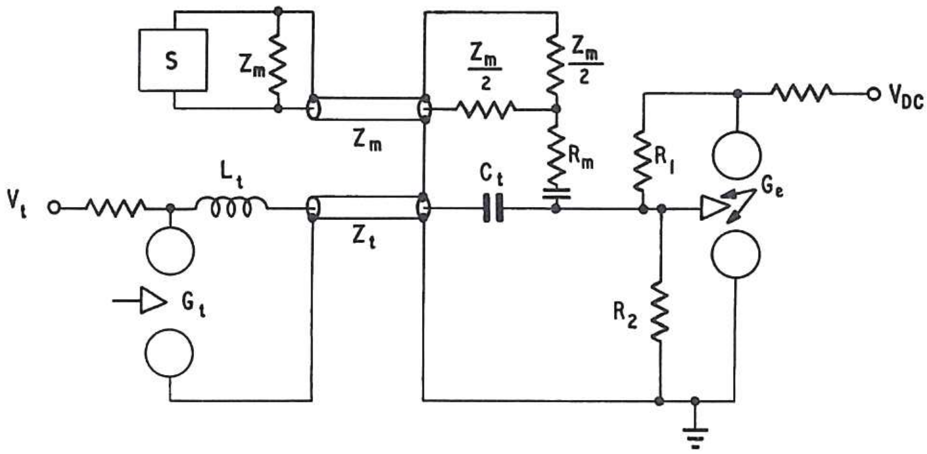


Fig. 5 (CLM-P171)
Schematic circuit diagrams. G_t - triggered gap; G_e - experimental gaps; R_1R_2 - D.C. resistive divider; R_mZ_m - fast pulse divider; S - oscilloscope

exponentially with a time constant L_t/Z_t. During one time constant the voltage V_p rises more or less linearly with time to 63% of the peak value at a mean rate $\dot{V}_p$ of $1.26V_tZ_t/L_t$. L_t could be reduced to 29 nH so that a maximum value of 10 kV/ns for $\dot{V}_p$ was obtainable. Lower values of $\dot{V}_p$ down to 1·0 kV/ns, were obtained by reducing V_t and increasing L_t.

The pulse voltage V_p was measured using a resistive divider R_mZ_m and oscilloscope S having a combined response time of less than 2·5 ns, as in Fig.5.

3. EXPERIMENTAL RESULTS

3.1 Static Breakdown

The static breakdown voltage V_s and corresponding electric field E_s were obtained by applying a slowly increasing negative D.C. voltage to the pulsed electrode. For the 5·1 mm n.u.f. gap the three electrodes were initially held at the same potential as for the pulsed tests.

Curves giving the breakdown field E_s as a function of absolute pressure are given in Fig.6 for the three gaps.

3.2 Pulse Breakdown

The breakdown time t_b is the time taken for V_p to increase from zero to the breakdown voltage V_b at which the gap voltage beings to collapse. The formative time lag[(1)] t_f is defined as the time that elapses while the voltage increases from the static breakdown value V_s (below which breakdown cannot occur) to the breakdown value V_b.

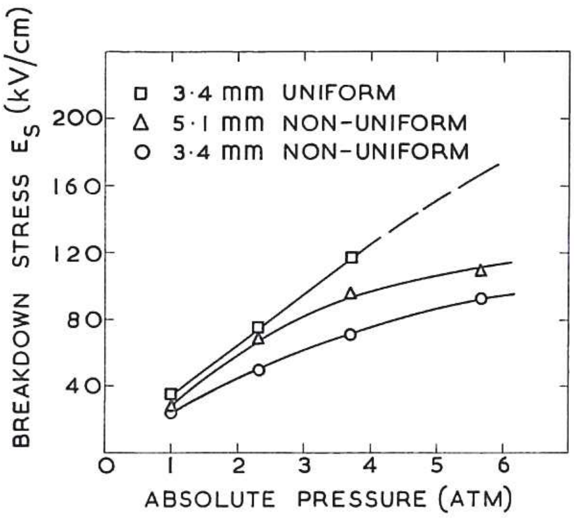
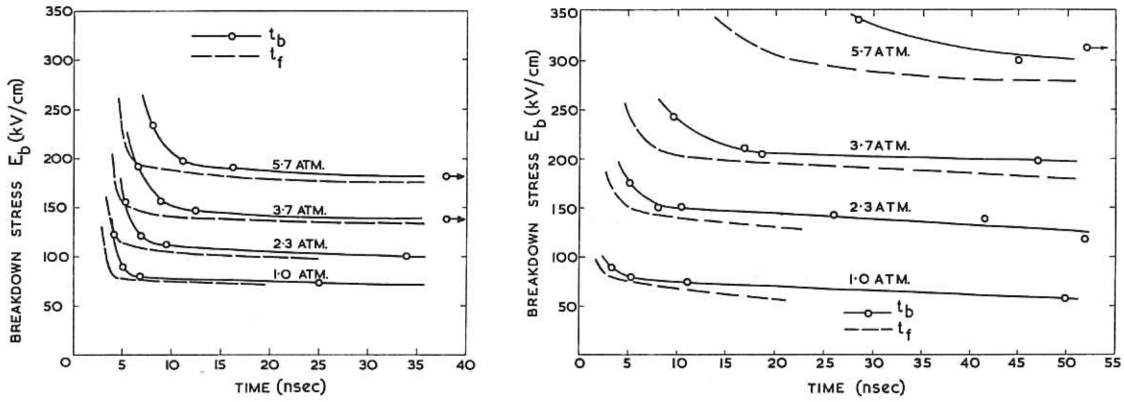


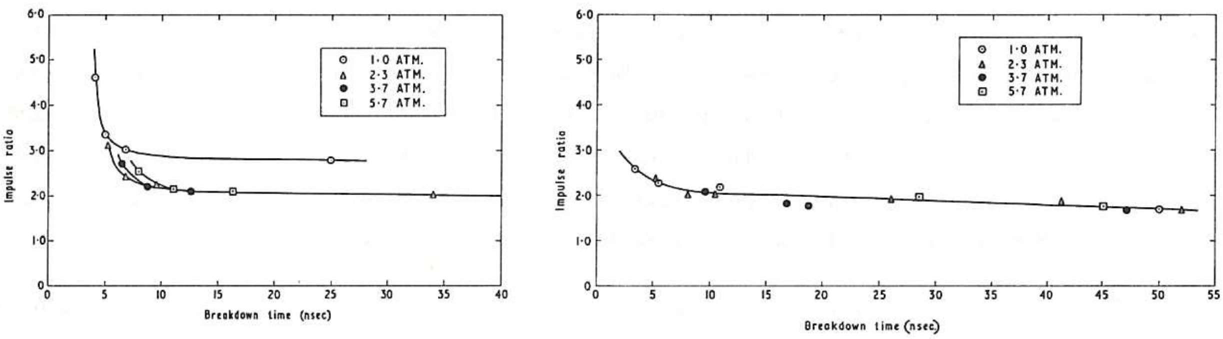
Fig. 6 (CLM-P171)
Static breakdown electric field (E_s) as a function of pressure

Curves relating the breakdown field E_b to the breakdown and formative times t_b and t_f, as $\dot{V}_p$ is varied, are given in Fig.7 for the 3·4 mm n.u.f. gap and u.f. gap. The impulse ratios (V_b/V_s) for these gaps derived from Figs.6 and 7 are as in Fig.8. Comparison of these breakdown times with those for the 5·1 mm n.u.f. gap at 3·7 atm. is given in Fig.9. Each experimental point represents the mean of 5 breakdowns.



(a) (b)

Fig. 7 (CLM-P171)
Pulse breakdown electric field (E_b) as a function of breakdown time (t_b) formative time (t_f) and pressure. (a) 3.4 mm n.u.f. gap; (b) 3.4 mm u.f. gap



(a) (b)

Fig. 8 (CLM-P171)
Impulse ratio (V_b/V_s) as a function of breakdown time (t_b) and pressure (a) 3.4 mm n.u.f. gap; (b) 3.4 mm u.f. gap

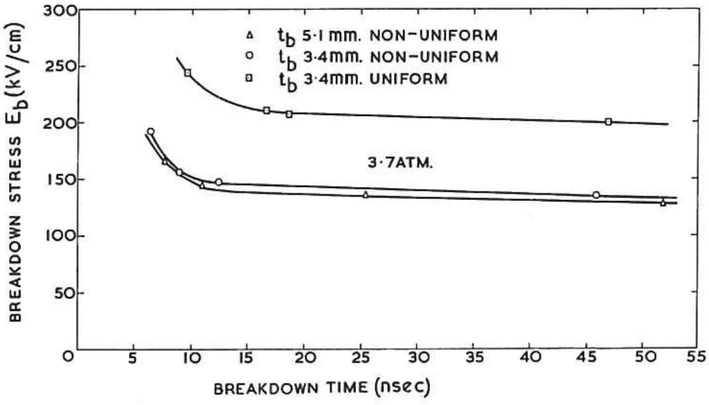


Fig. 9 (CLM-P171)
Breakdown times (t_b) for 3.4 mm n.u.f. gap, 5.1 mm n.u.f. gap and 3.4 mm u.f. gap at pressure of 3.7 atm

3.3 Variation in Breakdown Time

The variation in breakdown voltage V_b and time t_b were investigated for a 4 mm n.u.f. gap, with $\dot{V}_p$ equal to 6·0 kV/ns. The main electrodes were at zero potential, the field configuration being as in Fig.2a. The standard deviation in E_b and t_b are given in Table 1 for 20 breakdowns at each pressure. The total variation or jitter in breakdown time was typically ± 10%, or about ± 1·0 ns, for the conditions in Table 1.

TABLE 1

Pressure	V_b	Std.Dev.(V_b)	t_b	Std.Dev.(t_b)
Atm.	kV	kV	ns	ns
3·7	60	0·9	10	0·15
5·7	72	2·1	12	0·35

4. DISCUSSION OF RESULTS

4.1 Static Breakdown

The static breakdown field E_s (Fig.6) shows the expected dependence on the field configuration. At atmospheric pressure the breakdown field of the 3·4 mm n.u.f. gap is 77% of that of the u.f. gap, which is in qualitative agreement with the breakdown voltages reported previously for negative point-sphere gaps, which have a less uniform field than the present electrode geometry. These latter gaps have a breakdown voltage about 50% of that of a uniform field gap of the same length at atmospheric pressure[1].

The calculated maximum field at breakdown for the n.u.f. gap is 64 kV/cm at atmospheric pressure, which is approximately the same as the corona onset field obtained in a negative point-plane electrode geometry with a point radius of 0·5 mm[7].

4.2 Pulse Breakdown of n.u.f. gap

The breakdown process in non-uniform field gaps, subjected to a time-varying voltage pulse, does not lend itself to theoretical analysis. However the present experimental results can be explained quantitatively if the following assumptions are made:

(i) Breakdown commences in the high field region near the cathode at the static breakdown voltage V_s, provided field emission has already occurred.

(ii) If the minimum gap voltage at which field emission occurs is V_f, then under conditions when V_f exceeds V_s breakdown is delayed by the time interval $(V_f - V_s)\dot{V}_p$.

The experimental data given in Fig.8a shows that the impulse ratio at 2·3 atm. and above is virtually independent of pressure, whereas at atmospheric pressure it is generally about 40% higher. This result would be expected on the basis of the above assumptions since at low pressures V_s will be reduced to a lower value than the fixed voltage V_f necessary to produce field emission.

The impulse ratio R for the 3·4 mm n.u.f. gap reaches a minimum value R_h independent of pressure, as shown in Fig.8(a) at 2·3 atm. and above. If the increase in breakdown time at low pressures (above the value $R_h V_s/\dot{V}_p$ that would be expected using the impulse ratio R_h applicable to the higher pressures) is assumed to be equal to the delay in field emission, then t_b and V_f are given by:

$$t_b = \frac{R_h V_s + V_f - V_s}{\dot{V}_p} \qquad \text{If } V_f \geqslant V_s \qquad \ldots (1)$$

$$V_f = V_s (1 + R - R_h) \qquad \ldots (2)$$

V_f can be deduced from equation (2) and Fig.8(a), and equals 14·0 kV when $\dot{V}_p$ equals 2·0 kV/ns and the value of R corresponds to atmospheric pressure. Since V_f is independent of pressure and $\dot{V}_p$, equation (1) should predict the correct breakdown times for other values of $\dot{V}_p$. The comparison of the calculated and experimental values at atmospheric pressure is given in Table 2, where the agreement is within 10% as $\dot{V}_p$ varies from 1·0 to 10 kV/ns.

TABLE 2

Breakdown times of 3·4 mm n.u.f. gap at atmospheric pressure

$\dot{V}_p$	R_h	t_b measured	t_b equation (1)
kV/ns		ns	ns
1	2·1	25·0	23·8
4	2·7	6·8	7·3
6	3·2	5·1	5·6
10	4·6	4·2	4·6

Another guide to the appropriate value to be chosen for $\dot{V}_f$ is the electric field at the electrode surface since this is the most important factor influencing field emission, the emission current density being proportional to the square of the surface electric field(8). At a voltage V_f of 14·0 kV in the 3·4 mm n.u.f. gap the maximum electric field at the cathode is about 100 kV/cm, a value at which field emission has previously been noted with contaminated electrode surfaces(2). A limitation on the maximum value of V_f is that it must be less than V_s for pressures at which the impulse ratio is the minimum value R_h. This limit is satisfied since at the lowest pressure of 2·3 atm. satisfying these conditions V_s is 17·0 kV.

4.3 Effect of Electric Field Non-uniformity

The comparison of the 3·4 mm and 5·1 mm n.u.f. gaps in Fig.9 shows that the different field configurations (Fig.3) have little effect on the relationship between the breakdown time t_b and the mean electric field E_b. Also the impulse ratio of the 3·4 mm gap is 20% higher than in the 5·1 mm gap, since E_s in the two gaps differs by this amount (Fig.6). A similar result was obtained in previous experiments(6), where it was shown that reducing the edge radius of the pulsed electrode to less than 0·1 mm did not significantly reduce the breakdown time. At the static breakdown voltage in the 5·1 mm gap the electric field at the cathode surface is about 170 kV/cm which is adequate effectively to initiate breakdown by field emission, as discussed above for the 3·4 mm gap. Under these circumstances it appears that the breakdown time is mainly dependent on the mean electric field E_b and the only advantage of reducing the cathode radius to give a more non-uniform field would be to achieve the required electric field to initiate field emission at lower pressures.

The fact that t_b and E_b are not dependent on the non-uniformity of the field is rather surprising since the calculated maximum field and the static breakdown voltage in the two gaps differ by 35% and 25% respectively. However since breakdown could be influenced by other factors, such as the differing air gaps and D.C. potentials applied to the electrodes, it is not possible to give an explanation of the results based only on the effect of field non-uniformity.

4.4 Comparison of 3·4 mm n.u.f. and u.f. gaps

The ratio of the breakdown times in the 3·4 mm n.u.f. and u.f. gaps, as a function of pressure and rate of rise of voltage $\dot{V}_p$, is given in Fig.10. Significant features of the comparison in Fig.10 and that of the impulse ratios in Fig.8a with those in Fig.8b are:-

(i) At high pressures, above 2·3 atm. the n.u.f. gap breakdown time and voltage are about 70% of that of the u.f. gap. The impulse ratios of both gaps are comparable for breakdown times exceeding 8 ns and are virtually independent of pressure.

(ii) At atmospheric pressure the breakdown time is longest in the n.u.f. gap, especially at high values of $\dot{V}_p$. The ratio of breakdown times (Fig.10) increases from 1·1 to 1·35 as $\dot{V}_p$ increases from 1·0 to 10 kV/ns.

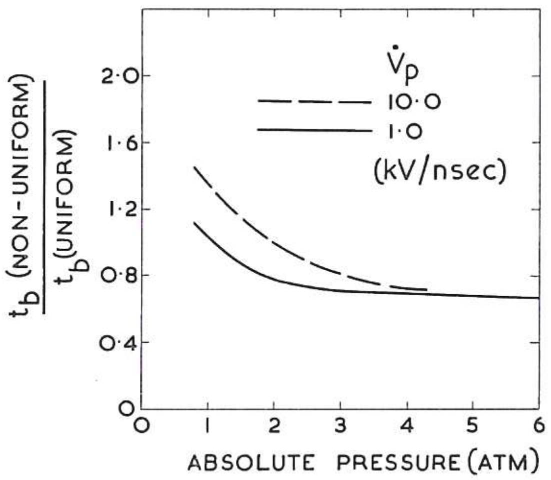


Fig.10 (CLM-P171)
Ratio of breakdown times (t_b) of 3.4 mm n.u.f. and u.f. gaps as a function of pressure and rate of rise of voltage

Shorter breakdown times would normally be expected in the n.u.f. gap because breakdown commences in the high field region near the cathode at a much lower gap voltage than in the u.f. gap. However it has been proposed in Section 4.2 that at atmospheric pressure breakdown of the n.u.f. gap is delayed by a lack of field emission. It is therefore considered that this is also the reason why the breakdown time of the n.u.f. gap is greater than that of the u.f. gap at atmospheric pressure.

There does not appear to be an obvious explanation of why the ratio of the n.u.f. to the u.f. gap breakdown times should become greater as $\dot{V}_p$ is increased. It should however be noted that the shape of the impulse ratio curves in Fig.8a and 8b are very different at high values of $\dot{V}_p$, when the breakdown times are less than 8 ns. In this region the n.u.f. gap tends to approach a minimum breakdown time of 4 ns with an impulse ratio of 4·5, while that of the u.f. gap continues to fall to a value less than 3 ns with an impulse ratio of 2·5.

The results at high pressures show that the static and pulse breakdown voltages in the u.f. gap generally exceed those of the n.u.f. gap by approximately the same amount (40%), resulting in the same impulse ratio for both gaps in spite of the very different field configurations existing in these gaps.

4.5 Effect of Voltage Waveform

Comparison of the formative time lags of the 3·4 mm u.f. gap (Fig.7b) with published data is given in Fig.11 for pressures of 1·0 and 3·7 atmospheres. The breakdown times obtained by applying an almost constant voltage step(10,11) are shorter than those obtained with a linearly rising voltage pulse in the present study, as would be expected. This is especially so at the higher pressure of 3·7 atm.

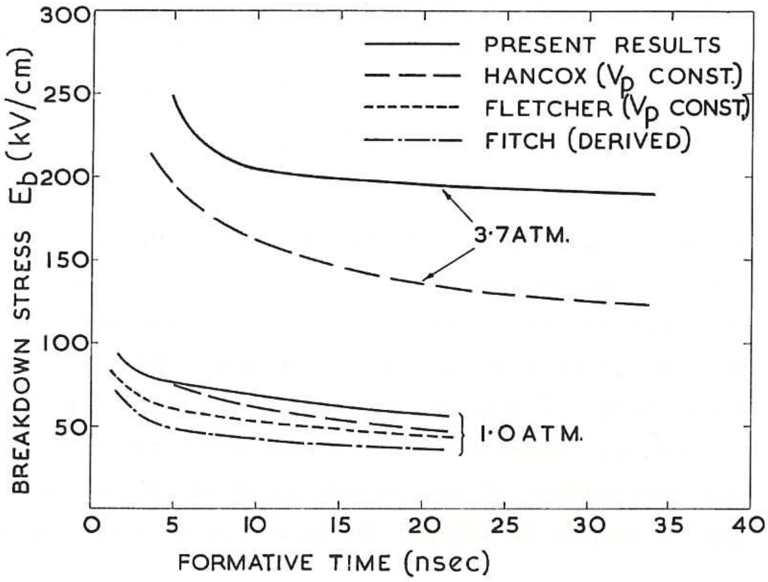


Fig.11 (CLM-P171)
Formative times (t_f) for uniform field gaps with different pulsed voltage waveforms

Formative times have also been derived from previous data for an atmospheric gap, with an irradiating electrode, placed in the centre of one main electrode, but with a linearly rising voltage pulse(12). This arrangement gives shorter formative times than even the results obtained with a constant voltage step. This may be because the presence of the irradiating arc in the main air gap is more effective than external irradiation, or the irradiating arc locally increases the electric field in the main air gap. Unfortunately similar data at higher pressures does not appear to have been reported for comparison with the present results in non-uniform field gaps.

4.6 Application to Fast High Current Switching

The n.u.f. gap shown in Fig.1 was developed for the fast high current switching of 60 kV capacitor banks(6). In such applications the 5·1 mm and 3·4 mm gaps usually break down in 'cascade'(13). After the trigger voltage is applied the field configuration is as in Fig.2b, until breakdown of the 5·1 mm gap occurs. The potential of the centre electrode then approaches 60 kV in a few nanoseconds, and rapidly overvolts the 3·4 mm gap until it in turn breaks down. The overall breakdown time of the gap is 18 ns; 12 ns for the first stage (5·1 mm gap) and 6 ns for the second stage (3·4 mm gap). The overall jitter in breakdown time of one gap (± 2 ns), and the spread in breakdown time between a number of gaps triggered simultaneously, is so low that the gaps can be operated successfully when connected in parallel without the transit time isolation between gaps normally provided by their individual connecting leads(14). Each gap can operate at a peak current of 500 kA and has an inductance of 18 nH.

The same electrode geometry has also been used successfully in a multiple arc spark gap, where six simultaneous arcs are established between the two main electrodes even though the gap voltage decays in 20 ns[15].

5. CONCLUSIONS

A non-uniform field pressurised air spark gap has been described in which fast pulse breakdown, initiated by field emission without previous irradiation, is achieved with a very low jitter in breakdown time. With a voltage pulse rising linearly at 10·0 kV/ns the breakdown time of a 3·4 mm gap is 4 to 8 ns as the pressure is increased from 1·0 to 6·0 atmospheres. When the applied voltage rises more slowly the breakdown voltage does not vary appreciably so that the breakdown time at a given pressure is almost inversely proportional to the rate of rise of voltage.

Though the gap is not irradiated, at pressures greater than 2·3 atm. its breakdown time and voltage are only 70% of that of an irradiated uniform field gap of the same length. At these pressures it is found that the impulse ratio is more or less independent of pressure, whereas at atmospheric pressure the impulse ratio is 40% higher than at pressures exceeding 2·3 atm. and the breakdown time is greater than in the corresponding uniform field gap. These results are consistent with the assumption that unless the electric field at the surface of the cathode is about 100 kV/cm, at the static breakdown voltage of the gap, breakdown is delayed due to a lack of field emission.

This electrode geometry has been used in three-electrode spark gaps in which the trigger pulse initiates breakdown by field distortion of an initially uniform field. The relatively low breakdown voltages of the gap and its low jitter in breakdown time have enabled parallel spark gaps to be operated successfully without any transit time isolation between them. A multiple arc spark gap using the same electrode geometry has also been successfully developed.

6. ACKNOWLEDGEMENTS

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