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P. M. BARNES
K. HARRIES
T. E. JAMES
J. PHILLPOTT

Culham Laboratory
Abingdon Berkshire

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P.M. BARNES
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ABSTRACT

Problems arising during the development and operation of a 100 kV multiple arc solid dielectric closing switch for use in fast low inductance switching applications are discussed. The switch has been operated at peak currents of up to 2.0 MA and for a pulse length of 70 μsec. The arc voltage is about 200 V and the switch inductance is 5 nH. Breakdown is achieved at any voltage using a high current triggering system to rupture the main insulation in a time of 1.4 μsec with a standard deviation of 0.15 μsec. A theoretical model of the breakdown process based on an electromagnetically driven shock wave passing through the main insulation is proposed which gives good agreement between theory and experiment. Tests on a similar 40 kV switch suggest that the maximum performance can probably be extended to about 8.0 MA for short pulse times and up to 1000 C at lower currents.

U.K.A.E.A. Research Group,
Culham Laboratory,
Abingdon,
Berks.

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CONTENTS

1. INTRODUCTION

100 kV low inductance capacitor banks, used for fast magnetic compression experiments in plasma physics and controlled thermonuclear research, typically require a switching system capable of passing a peak current of 1 to 2 MA having an inductance of about 5 nH and a voltage drop of only a few hundred volts. A multiple arc solid dielectric switch has been developed to meet this duty, based on the principles used in the single arc switches already described(1,2).

The switch is used either for clamp duty(3) to short-circuit a 50 nH single-turn 'theta-pinch' coil at peak current and zero voltage and so maintain the current for about 70 μsec, or as a diversion switch when it is operated at any required voltage after one half-period of current to reduce the current thereafter to about ± 10% of its peak value. A multiple arc switch proved necessary to give a low inductance and to minimise the arc voltage and electrode erosion. It consists of two large parallel plate electrodes separated by a thin sheet of polythene insulation which is replaced manually each time the switch has been operated. Multiple arc triggering is achieved by supplying a peak current of 135 kA to each of the four breakdown points which physically ruptures the 1.0 mm main insulation at each point.

Other methods have been used to switch these large pulsed currents such as parallel spark gaps(4,5,6,7), multiple arc spark gaps(8), or metal-to-metal solid dielectric switches(9,10,11). One solid dielectric switch can in general replace about 10 or more spark gaps so that its use results in a simpler switching system with a 100% voltage range. However, because of the need to replace the insulation between shots the repetition rate is limited to about one operation every 5 minutes when manual insulation replacement is used. The recently developed metal-to-metal switches have the advantage of a negligible voltage drop though their replaceable insulation assembly is more complex and their jitter in breakdown time more subject to electrode deformation than in the arc solid dielectric switches described below.

2. GENERAL DESIGN

The multiple arc switch forms an integral assembly with the single turn coil and another single arc solid dielectric start switch as shown in Fig.1. The latter connects a 100 kJ capacitor bank to the coil by means of low inductance parallel plate transmission lines under oil. The vertical clamp switch plates (42 cm × 40 cm) are separated by 1.0 mm of replaceable polythene main insulation and are connected across the horizontally mounted transmission line. To prevent surface flash-over between the upper portion of the switch plates in air, the edges of the plates are shaped (to grade the electric stress along the polythene insulation surface) and moulded in silicone rubber. Removable electrodes are placed in the centre of the switch plates with a 15.0 cm × 1.2 cm horizontal slot through the H.T. electrode to release the large gas pressures built up at high currents. It also enables the combustion and erosion products to be transferred via an insulated duct to a large sound-proof container maintained below atmospheric pressure to prevent contamination of the coil and permanent insulation. The H.T. plate is hinged at its base by means of a 0.4 mm phosphor bronze current-carrying foil and is opened about 2 cm between operations to enable the polythene insulation assembly to be changed manually.

3. TRIGGERING

Breakdown is achieved by means of a high current auxiliary trigger arc at the insulation surface[1,12,13] the main insulation being ruptured by the high magnetic and thermal pressures produced by this trigger arc.

An alternative method of triggering has been used which electrically overstresses the main insulation by applying a fast rising voltage pulse to a centrally placed trigger foil[16]. This method produces breakdown in a few nanoseconds though it has a limited voltage range and requires a very fast high voltage trigger system.

The electrode configuration and insulation details near the breakdown points are given in Fig.2(a). The trigger arc is established in 0.33 mm diameter holes initially placed at each of four breakdown points in an additional 0.25 mm polythene sheet, referred to as the trigger insulation.

The trigger current is fed into each breakdown point through separate 0.05 mm copper foils (trigger foils in Fig.2(a), from a 5 kJ 35 kV capacitor and 3/1 step-down low inductance strip-wound transformer by means of pressure contacts which pass through the earthed electrode (Fig.1). A peak trigger current of 540 kA (135 kA per breakdown point) at 140 kHz is achieved. In clamp (or crowbar) switches which have to withstand a rapidly rising pulsed voltage the impedance of the trigger circuit must be kept sufficiently low to avoid arcing between the trigger foils (due to their capacitance to the main electrodes), otherwise premature breakdowns will occur[13].

An investigation into the breakdown mechanism and the effect of various parameters including insulation thickness, trigger current and frequency have been made using the electrode configuration shown in Fig.2(b) and will be discussed in Section 5 below. It should be noted that with this configuration the trigger insulation is placed between two equal sheets of main insulation, and the breakdown point is positioned in the centre of a 2.5 cm diameter hole and recess in the electrodes to avoid erosion of the flat surfaces of the electrodes. This arrangement, which was originally used in a single arc start switch[1,2], has the further advantage that the breakdown time is halved for a given total insulation thickness compared with the asymmetrical arrangement in Fig.2(a). However, when the first insulation sheet breaks down during triggering a high electric field exists at the edge of the centrally placed trigger foils, initially held at mid-potential, which can cause breakdown between the foils and the other main switch plate at the edge of the moulded insulation portion of the switch plates and cause extensive damage to this insulation. For this reason the asymmetrical configuration in Fig.2(a) has now been adopted for both single arc and multiple arc 100 kV switches, the increase in breakdown time being minimised by using a higher energy trigger circuit. It was also found necessary to attach a 0.9 mm copper backing plate to the side of the insulation assembly adjacent to the solid electrode. This avoids the electrode becoming so eroded that the explosive pressures generated by the trigger arc are not adequately contained which would lead to increased breakdown time and jitter. At the peak trigger current of 135 kA per breakdown point the breakdown time is 1.4 μsec for 1 mm thickness of main insulation with a standard deviation of 0.15 μsec at switch voltages to 10 kV. At or near zero voltage an increase in breakdown time of about 15% was noted.

Consistent multiple arc triggering is achieved by using a separate trigger foil and pressure contact for each breakdown point. The pressure contacts are connected in parallel about 15 cm away from the breakdown points at the output of the trigger circuit transformer. Previous experiments(2) have shown that to obtain good main circuit current sharing points a 0.02 mm aluminium foil should be placed on the insulation assembly adjacent to the H.T. electrode. This ensures a connection to the main circuit as soon as the insulation is punctured, in spite of variations in the placing of the trigger hole or erosion of the H.T. electrode.

4. SWITCH PARAMETERS

4.1 Inductance and arc voltage

The switch has been used to short circuit a 50 nH theta-pinch coil carrying a peak current of 1.3 MA rising in 2.0 μsec. The coil and switch current waveforms are given in Fig.3 when the multiple arc switch is (a) not operated (b) operated at peak current (clamp or crowbar duty) and (c) operated after one half period of coil current (diversion duty). Analysis of these waveforms gives 7 nH for the clamp or diversion circuit inductance, of which it is estimated the switch contributes 5 nH. It should therefore be possible to design 40 kV switches of this type with an inductance of about half this value.

It has been shown that to minimise the arc voltage the arc length must be kept short(14) and for this reason the breakdown point is positioned opposite the solid portion of the H.T. electrode (Fig.2(a) but near the edge of the 1.2 cm slot to maintain the advantages of an open electrode configuration as discussed in Section 2. If the breakdown point is positioned in the centre of the 1.2 cm wide slot then at a peak coil current of 1.0 MA the arc voltage is about 600 V higher than the value obtained with the breakdown point positioned on the edge of the slot. This has been deduced from the decay of coil current which gives the total voltage drop of coil, transmission lines and clamp switch. It is estimated that the switch arc voltages are 200 and 800 V for the two conditions.

4.2 Peak Current and Coulombs

In the 100 kV theta-pinch application the peak switch current is 1.8 MA, the coulombs per shot being 100 on clamp duty. The electrode surfaces need machining flat after about 500 to 1000 shots to remove the effects of erosion of the H.T. electrode and deformation of the earth electrode. Although the backing plate prevents erosion of the latter the high magnetic pressures deform the electrode surface into a shallow trough. If this deformation is allowed to become too deep the backing plate will not be supported adequately and may be ruptured and bent by the magnetic forces. This will result in increased erosion of the permanent electrode, increased jitter in breakdown time and difficulty in removing the insulation assembly.

The single arc solid dielectric start switch (Fig.1) passes a peak current of 1.3 MA through its single breakdown point when the circuit is clamped (Fig.3(b)) though the pulse length is only 5 μsec. However when the circuit is diverted (Fig.3(c)) the peak current of both start and clamp switch is 2.0 MA though the coulombs per shot are only 10. The start switch insulation assembly is similar to that shown in Fig.2(a) but its single breakdown point is placed in the centre of a 2.5 cm diameter hole in the H.T. electrode (heavy alloy), since a low arc drop is not required for start switch duty. The H.T.

electrode has been in service for over 2000 shots without requiring maintenance because the arc is confined to the surface of the hole and no erosion occurs on the electrode surface facing the insulation. However the very high magnetic pressure of, say, 64,000 atmospheres (assuming a 2 mm diameter arc carrying a current of 2 MA) deforms the solid earth electrode appreciably so that re-machining is required about every 100 shots. It should be noted that the electrode life at these high currents does not depend on the coulombs passed but on factors that depend on peak current.

4.3 Maximum performance

It is interesting to consider the maximum performance which might be obtained from a switch of this type. This will be limited by the factors given in Table I, which estimates the maximum performance that appears possible in an enclosed 4-breakdown point switch based on present experience, although the maximum value of all parameters may not be obtainable if they occur together in a given application.

TABLE I

Estimated maximum switch performance	
Peak Current	8.0 MA (estimated)
Resistive energy	300 kJ (tested)
Magnetic forces (effective)	250 tons (tested)

The peak current of 8.0 MA is based on the value of 2.0 MA per point already achieved in the 100 kV start switch (configuration Fig.2(b)). This could be exceeded as far as the breakdown region is concerned, but other problems arise such as high current densities in the hinged joint and elsewhere if the switch plates are to be limited in size. At such high currents there is not yet much experimental evidence available on which to assess the maximum coulombs that can be passed per shot though it will be mainly dependent on the amount of electrode maintenance that is acceptable.

Tests on a prototype 40 kV switch with one breakdown point up to 1.7 MA peak current have shown that an energy of 300 kJ can be adequately contained if the sound-proof steel container is sufficiently large and mounted directly on the open electrode[2,14]. This means that if the arc coltage is 300 V and the resistive energy that can be contained is 300 kJ, then the pulse length at a peak current of 2.0 MA would be 0.5 msec to give 1000 C. Current sharing between two arcs over such a long pulse length has been shown to be within 20% on the above prototype assembly[14].

The development and operation of a 40 kV, 1.0 MA, 2000 C clamp switch with two breakdown points have been reported[15]. The insulation configuration is similar to that in Fig.2(b), the two copper foils being isolated from the earth electrode although they are maintained at earth potential. The maximum life of the electrodes used in this application has not yet been ascertained though no maintenance proved necessary for 50 shots. Thus the performance of this switch appears consistent with the maximum performance proposed above.

5. BREAKDOWN MECHANISM

5.1 Theoretical principles

It is considered that breakdown occurs because the trigger arc and its associated magnetic field give rise to an electromagnetically driven shock wave through the main insulation. The magnetic pressure due to the trigger current compresses the trigger arc plasma against the inner surface of the main insulation (Fig.4(c)) and displaces the latter outwards until it is ruptured and breakdown occurs.

The breakdown process has been studied theoretically and experimentally assuming the symmetrical electrode and insulation configuration in Fig.2(b). The details of an actual insulation assembly near the breakdown point are shown in Fig.4(a) before breakdown and Fig.4(c) after breakdown if the switch has passed no main current. Fig.4(b) gives a qualitative picture of the displaced main insulation during the breakdown process. It has been shown[1] that the breakdown time t_b can be predicted theoretically if it is assumed that the mass of the displaced insulation at any time is proportional to its mean effective displacement x (i.e. a 'snowplough' model) and that the insulation is ruptured when it has been displaced a distance equal to the insulation thickness X. A summary of this analysis is given in the Appendix which gives the following breakdown criterion for a sinusoidal trigger current $i = I \sin \omega t$ if breakdown occurs in the first half-cycle:

$$\frac{I/\omega}{K_T X} \left[\frac{2(\omega t_b)^2 + \cos 2\omega t_b - 1}{8} \right]^{\frac{1}{2}} = \text{a constant} \qquad \ldots (1)$$

K_T is a non-dimensional thickness factor to account for the increased radius of the displaced insulation as the insulation thickness X increases, as discussed in the Appendix.

5.2 Measurements of Breakdown Time

The above discussion and the breakdown criterion in Eq.(1) suggest that the important factors affecting breakdown time are the trigger current, insulation thickness X and trigger circuit frequency. It will also be noted from Eq.(3) in the Appendix that the hole diameter $2r_o$ in the trigger insulation is important since it influences the magnetic force on the insulation.

The influence of the above parameters on the breakdown time t_b has been measured at a switch voltage of 40 kV by varying the peak trigger current I from 50 to 300 kA, the insulation thickness X from 0.25 to 2 mm, the frequency $\omega/2\pi$ from 340 to 560 kHz and the trigger insulation hole size $2r_o$ from 0.12 to 1.0 mm. The measured breakdown time is given as a function of total insulation thickness $2X$ in Fig.5 and as a function of the hole diameter $2r_o$ in Fig.6. The standard deviation in breakdown time is generally about 10% of the breakdown time. Thus for $I = 100$ kA and $X = 1.0$ mm the breakdown time is 1.1 μsec ± 0.1 μsec. The shortest breakdown time that has been achieved is 0.25 μsec for $X = 0.5$ mm and $I = 300$ kA. The effect of variation of trigger current and frequency will be discussed below.

5.3 Comparison of Experimental and Theoretical Results

The variation in breakdown as a function of insulation thickness X in Fig.5 shows that t_b increases very significantly at higher values of X. This would be expected from the discussion in the Appendix where it is suggested that the effective radius and mass of the polythene displaced by the shock wave will increase by an amount proportional to X^2 as the insulation thickness X gets larger.

The value of the thickness factor K_T of $(1+X^2/4)$ deduced from the experimental results (Appendix 9.2) confirms that this is so. The large difference between the calculated values of t_b for this value of K_T and for K_T equals 1.0, plotted in Fig.5, shows the importance of this effect.

The relationship between the breakdown time t_b (expressed as a proportion of the half period $\omega t_b/\pi$) and the trigger current. I, insulation thickness X and frequency $\omega/2\pi$ (combined in the expression $\frac{I/\omega}{K_T X}$) as predicted Eq.(1) and as obtained experimentally are given in Fig.7. Agreement between theory and experiment is within 30% over a wide range of parameters which suggests that the breakdown criterion in Eq.(1) accounts correctly for the physical phenomena involved. Since the experimental results in Figs.5 and 6 have been used to deduce the constants in Eq.(1) this does not necessarily demonstrate conclusively that the displacement of the insulation is mainly due to the electromagnetic forces exerted on the trigger arc plasma. However, it is considered that this is so firstly, these forces are adequate to displace sufficient insulation during the breakdown time (Appendix 9.2), and secondly, because the experimental results in Figs.6 and 7 confirm that the accelerating forces are proportional to $(i)^2$ and vary logarithmically with r_0 as do the magnetic forces.

If the rupturing process is produced only by the vaporisation of the trigger foils and the thermal energy of the resulting plasma it would be expected that changes in the geometry of the foils and trigger insulation would affect the breakdown time appreciably, whereas if the process depends mainly on the magnetic forces the breakdown time would not be affected by these changes. Further experiments[1] were carried out with trigger foil thicknesses from 0.025 to 0.25 mm, trigger insulation thicknesses from 0.25 to 1.5 mm, holes in the trigger foils from 0.33 to 3.0 mm (but with a constant 0.33 mm hole in the trigger insulation), and with a 0.06 mm diameter wire placed in the hole in the trigger insulation, but no significant change in the breakdown time occurred. These results therefore further confirm the proposed model of the breakdown process based on an electromagnetically driven shockwave.

6. CONCLUSIONS

The 100 kV multiple arc solid dielectric switch described has operated successfully at peak currents up to 2 MA without electrode maintenance for about 500 shots. Its inductance is 5 nH and it can be triggered with a breakdown time of 1.4 μsec and a deviation of 0.15 μsec. Consistent multiple arc breakdowns are achieved by feeding a trigger current of 135 kA to each of the four breakdown points from a 5 kJ capacitor and so physically rupturing the main insulation. A breakdown mechanism is proposed from which breakdown times can be calculated in close agreement with experimental results.

Based on present experience it appears that the performance of such switches could be increased to a peak current approaching 8.0 MA in fast low coulomb applications and that for longer pulse times a peak current of 2.0 MA and 2000 C per pulse should be possible provided the most favourable electrode configuration is used.

7. ACKNOWLEDGMENTS

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9. APPENDIX

9.1 Analysis of Breakdown Process

In the model previously proposed(1) for the breakdown process it is assumed that the insulation displaced by the shock wave (shaded portion in Fig.4(b)) can be effectively represented as a cylindrical 'plug' of radius r_m and length x where x is the effective distance moved by the displaced insulation in a time t. It is further assumed that the rupturing force is due to the magnetic pressure exerted on the trigger arc plasma though the analysis applies to any mechanism which results in a pressure which is proportional to (current/radius)^2. If the magnetic pressure is exerted between an effective radius r_p and the trigger insulation hole radius r_o (Fig.4(b)) the outward magnetic force on the insulation is $10^{-7}\ i^2 \log_e r_p/r_o$ where i is the trigger arc current per breakdown point.

Equating the accelerating forces at any time t for insulation of density ρ gives:

$$10^{-7}\ i^2 \log_e r_p/r_o = \pi\rho r_m^2\ {}^{d}/_{dt}(x\,{}^{dx}/_{dt}) \qquad \ldots (2)$$

The polythene will be ruptured when the cylindrical 'plug' is displaced a distance equal to the insulating thickness X and, therefore, integrating Eq.(2) twice over the breakdown time t_b and distance X gives the breakdown criterion:

$$\frac{\int_0^{t_b}\int_0^{t_b} i^2\ dt\ dt}{r_m^2\ X^2} = \frac{\pi\rho}{2.10^{-7}\ \log_e r_p/r_o} \qquad \ldots (3)$$

The magnetic pressure falls off rapidly with increasing radius and therefore the choice of r_p is not critical at low values of x

and r_o where it can be assumed to equal the effective mass radius r_m. The effective mass radius r_m increases with insulation thickness X from a minimum value r_1 for thin insulation sheets where $X < r_p$ and a plane shock results. At higher values of X where $X > r_p$ and a more spherical shock is produced it would be expected that the increase in r_m will be proportional to X^2. This analysis is of course not rigorous, since our model (Eq.(2)) assumes a constant r_m, whereas in practice the value would change during the triggering process but this approximation is justified by the good agreement between theory and experiment given in Section 5.3. It is therefore convenient to let $r_m = K_T r_1$ where K_T is a non-dimensional thickness factor and is a function of X. For a sinusoidal trigger current $i = I \sin \omega t$ and where breakdown occurs in the first half cycle the above breakdown criterion then becomes:

$$\frac{I/\omega}{K_T X}\left[\frac{2(\omega t_b)^2 \quad \cos 2\omega t_b - 1}{8}\right]^{1/2} = \text{a constant} \qquad \ldots (4)$$

9.2 Evaluation of Constants from Experimental Results

The variation in breakdown time t_b as a function of insulation thickness X enables the thickness factor K_T to be evaluated. Agreement with the experimental results within 15% is obtained with $K_T = (1 + \frac{X^2}{4})$ as shown by the chain-dotted curve in Fig.5. The value of the constant on the right hand side of Eqs.(1) and (4) can now be deduced using this value of K_T and is found to be 0.042 A.S/mm for the configuration in Fig.2(b) with $2r_o = 0.33$ mm. For other values of r_o the constant has different values (since it includes $\log_e r_o$ in Eq.(3)), which can be deduced from the results in Fig.6. These constants include r_m and r_p, the effective mass radius and the radius inside which the magnetic pressure in exerted respectively (Fig.3(b)), which can therefore now be determined. The theoretical values of breakdown time given in Fig.6 (dotted curve) have been calculated with values of $r_m = 0.5$ mm, and $r_p = 0.6$ mm for $X = 1$ mm. Since $r_m = K_T r_1$ it follows that the minimum value of the effective mass radius r_1 is 0.4 mm which applies when X is small and K_T is 1.0.

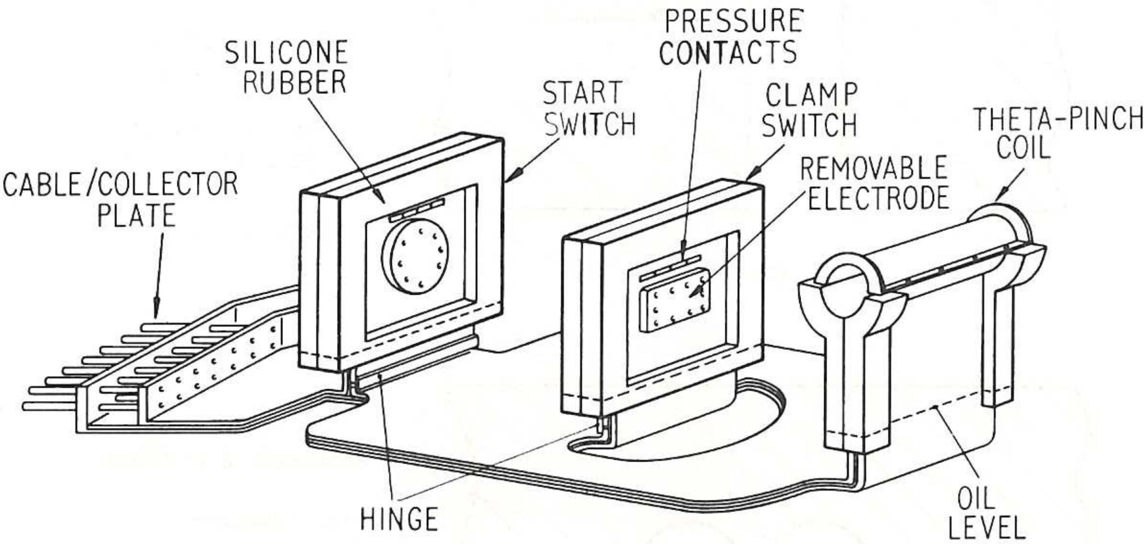

Fig.1 100 kV collector plate, single arc start switch, multiple arc clamp switch and coil assembly. CLM-P209

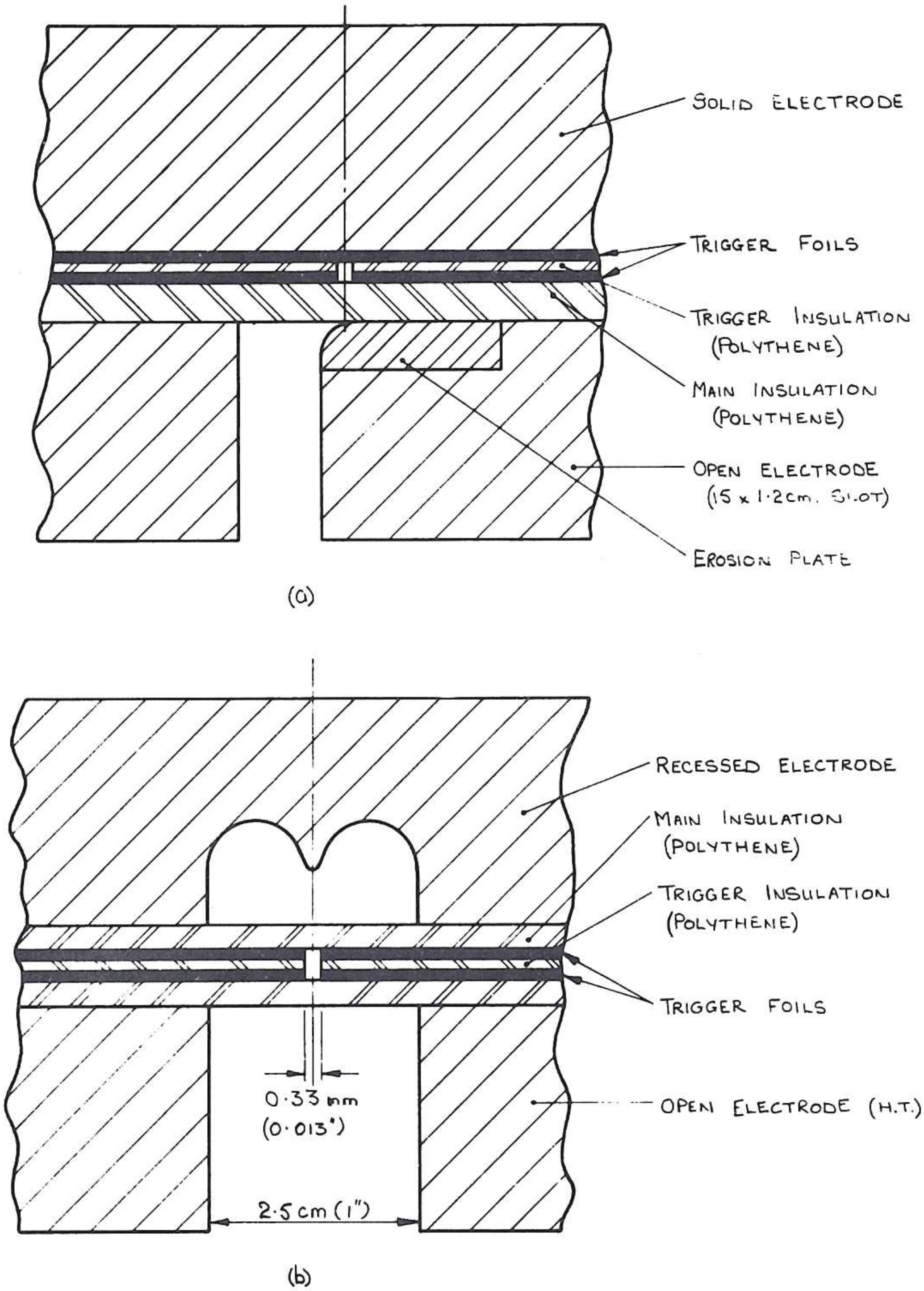

Fig.2 Removable electrode and insulation configurations:

(a) Asymmetrical arrangement.

(b) Symmetrical arrangement.

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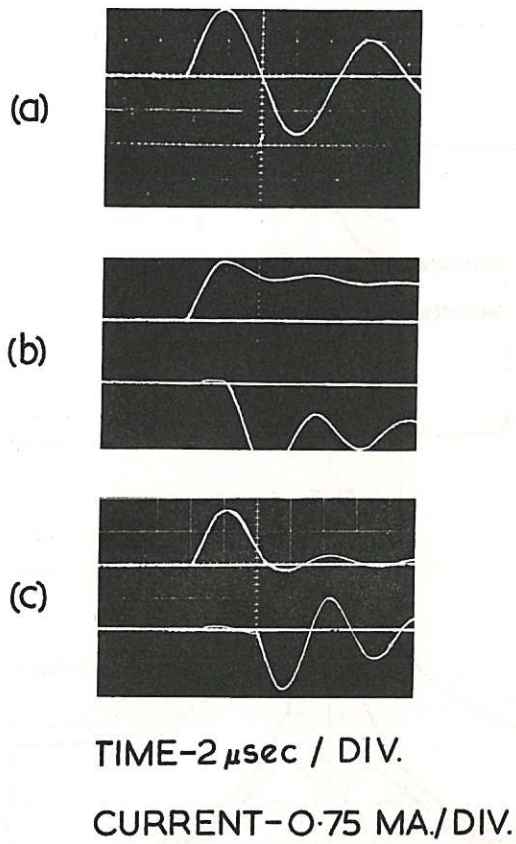

Fig.3 Coil and multiple arc switch current waveforms (2 μsec per division).

Upper trace - coil current

Lower trace - switch current

(a) Unclamped

(b) Clamped

(c) Diverted

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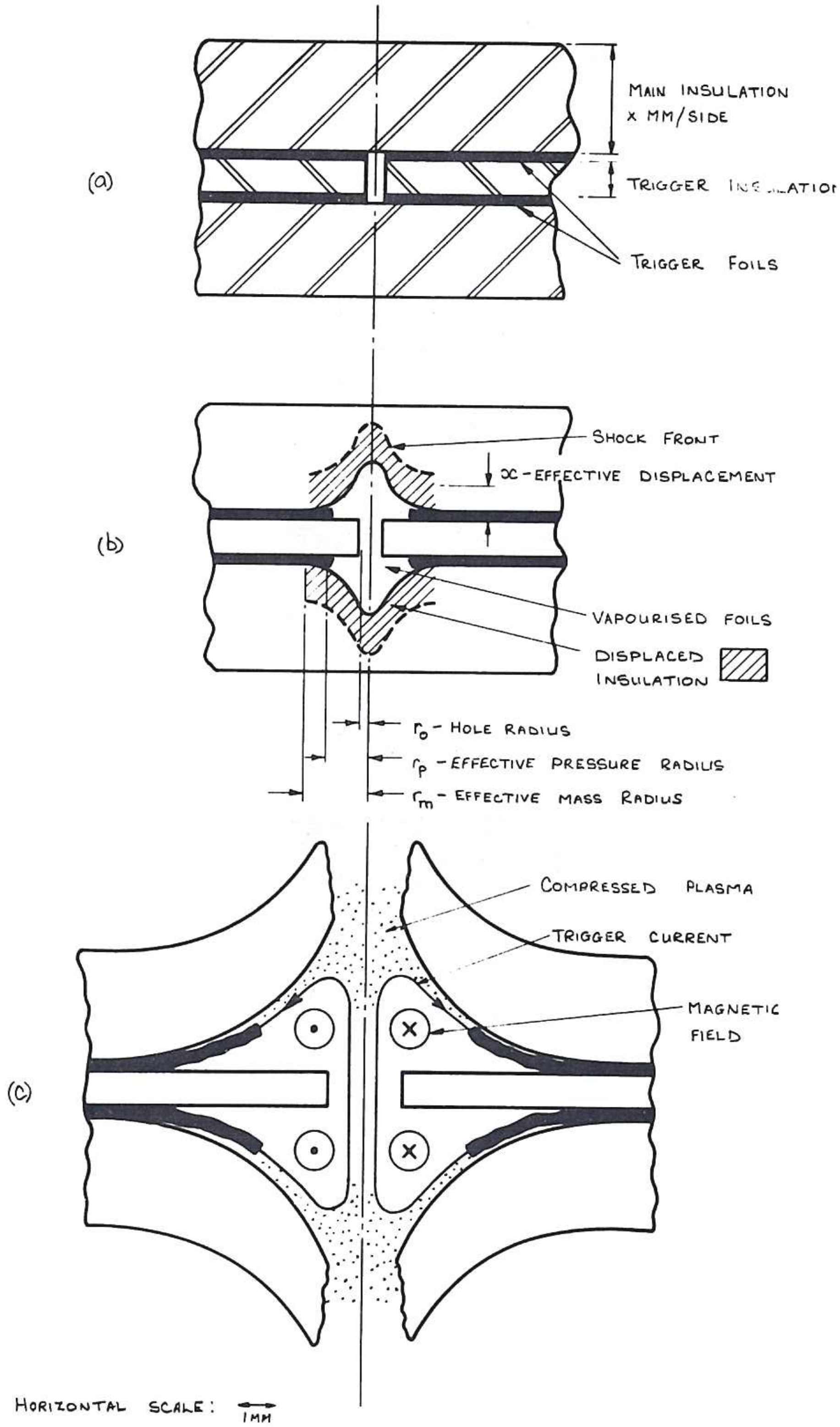

Fig.4 Stages in the breakdown process -

(a) Before triggering

(b) During breakdown

(b) Actual insulation assembly after breakdown (trigger current only).

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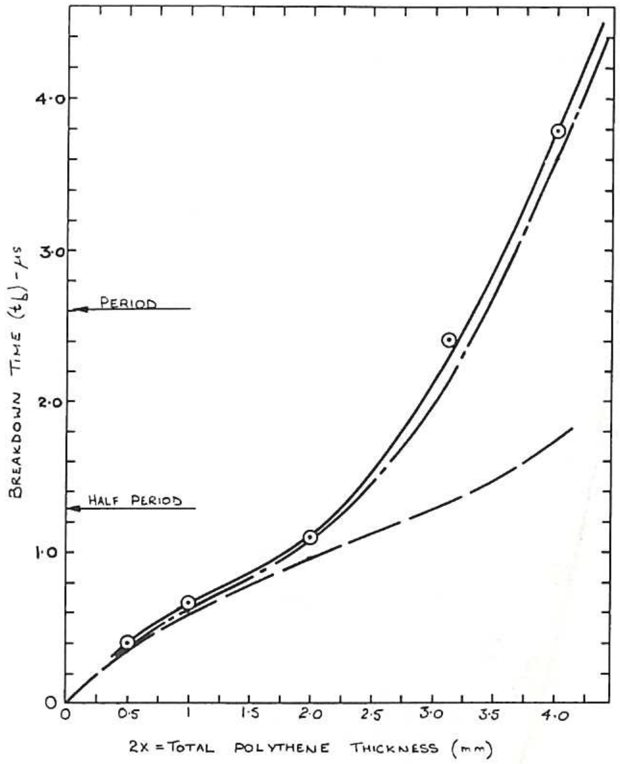

Fig.5 Variation of breakdown time (t_b) as a function of main insulation thickness (2X).

—⊙— Test results — — Calculated with $K_T = 1.0$
— - — Calculated with $K_T = (1 + X^2/4)$

Peak trigger current 100 kA at 390 kHz. Hole diameter ($2r_o$) in trigger insulation 0.33 mm.

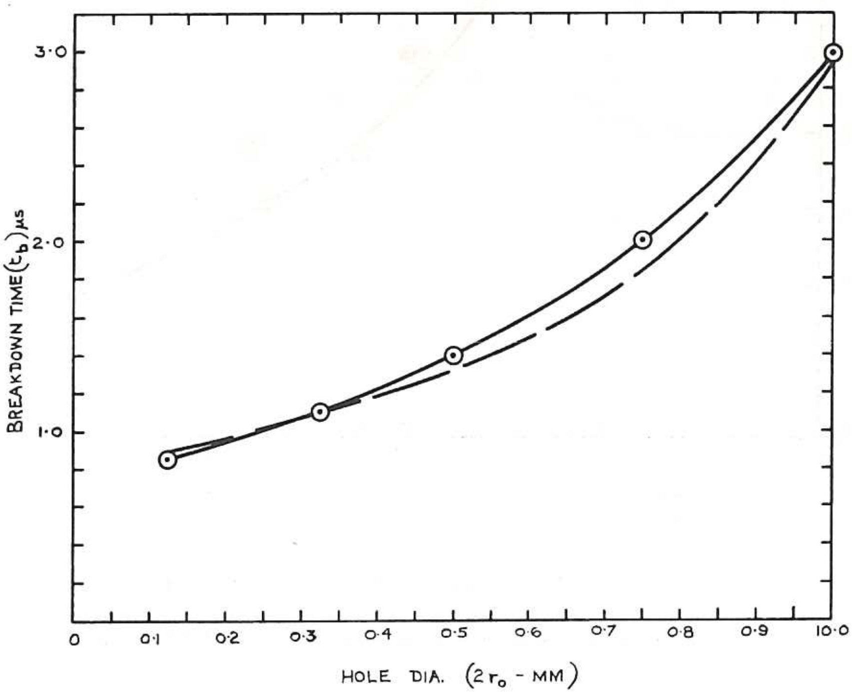

Fig.6 Variation of breakdown time (t_b) with hole diameter ($2r_o$) in the trigger insulation. Peak trigger current 100 kA at 390 kHz.

—⊙— Test results — — Calculated from Eq.(3) (r_p = 0.6 mm, r_m = 0.5 mm).

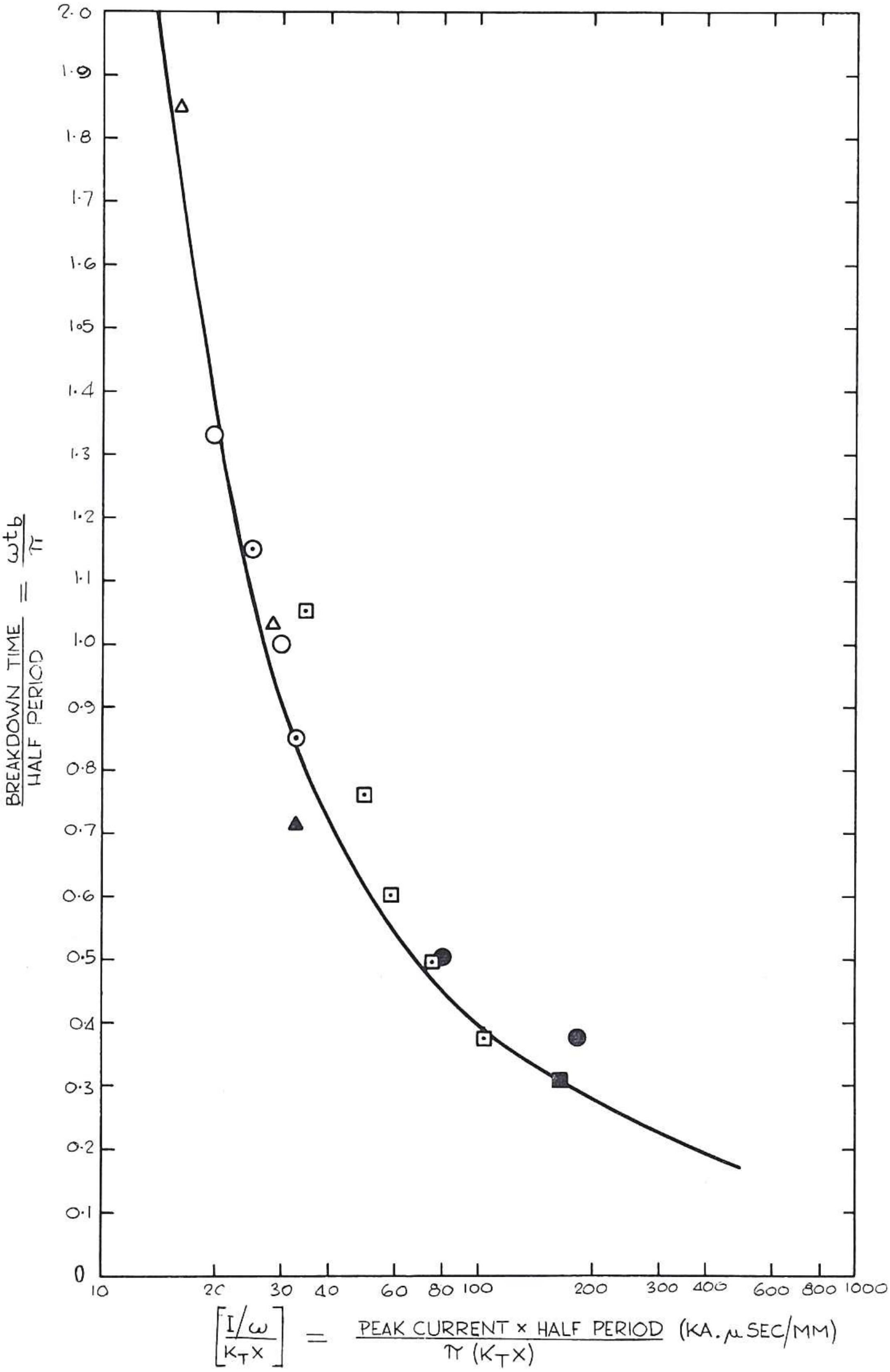

Fig.7 Comparison of theoretical and experimental breakdown times

——————— Calculated from Eq.(1).

Test results:

X = 1.0 mm	○	560 kHz	trigger
	⊙	390 kHz	
	⊡	340 kHz	
X = 2.0 mm	▲		
X = 1.59 mm	△		
X = 0.5 mm	●		
X = 0.25 mm	■		

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