Breakdown of Mineral Oil:
Effect of Electrode Geometry and Rate of Voltage Rise

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ABSTRACT

Experimental data on the propagation of streamers in mineral oil is important for the design of high-voltage systems in the power and pulsed-power industries. In the present study, breakdown voltages and pre-breakdown delay times were measured for plane-parallel electrodes, and for two non-uniform electrode arrangements. For each geometry, the breakdown characteristics were determined for impulses of rise-time 100 ns, and also rise-time 1 μs. The maximum rate of voltage rise (dV/dt) was 4 MV/μs. For the non-uniform geometries with inter-electrode gap length of 8.5 mm, the time to breakdown was 2.5-3 times longer for impulses of rise-time 1 μs than for 100 ns rise-time. The time-to-breakdown data suggest that streamer propagation velocity increases with higher values of dV/dt. For example, the estimated propagation velocity for pin-plane geometry with a 1 μs rise-time is 10-12 km/s. At 100 ns rise-time for the same electrode geometry, the average propagation velocity exceeds 40 km/s. The results are compared with data previously generated in parallel liquid-solid gaps, and it is concluded that the time to breakdown is longer, and that higher applied fields are required to initiate breakdown, in open oil gaps compared to the case when a solid spacer is present. The results presented are intended to provide reference data for designers of oil-immersed, high-voltage systems such as power transformers and pulsed-power supplies.

Index Terms — **Breakdown voltage, dielectric breakdown, dielectric liquids, oil insulation, power transformers, pulsed power supplies.**

1 INTRODUCTION

EXPERIMENTAL data on the breakdown of mineral oil under different conditions of applied voltage is important for the design of high-voltage systems in the power and pulsed-power industries.

Mineral oil is used as an insulating liquid in pulsed-power systems such as oil-immersed Marx generators. The dielectric properties of mineral oil, including its breakdown characteristics in different problematic electrode topologies, are important for the design and development of pulsed-power

systems and their elements, including pulsed transmission lines and plasma closing switches [1, 2]. In such systems, the insulating liquid can be stressed with high impulsive electric fields of magnitude up to several MV/cm and duration up to hundreds of microseconds. The present work is focused on investigation of the effect of electrode geometry and rate of voltage rise on the breakdown characteristics of mineral oil. Three different electrode topologies were used: pin-plane and collar-plane topologies which generate highly non-uniform electric field; and plane-parallel topology, used as a reference electrode arrangement. These electrode configurations represent typical problematic topologies found in large-scale

pulsed-power systems employed by AWE and Sandia National Laboratories, and it is necessary to examine and understand the dielectric behavior of such electrode systems to enable the reliable operation of high-voltage machines.

The present study formed part of a larger investigation to determine the voltages and pre-breakdown delay times associated with breakdown of different polymer surfaces immersed in mineral oil [3-7]. Described herein are the differences in breakdown voltage, time to breakdown, and implied average streamer propagation velocity in open oil gaps without a solid spacer, for the electrode geometries and voltage rise-times used for surface breakdown measurements in [3-6].

Breakdown voltages and pre-breakdown delay times were measured for plane-parallel electrodes, and for two types of non-uniform arrangement when the oil gap was subjected to over-voltages. For each geometry, the breakdown characteristics were determined for impulses of rise-time 100 ns, and also rise-time 1 μs. The maximum applied voltage level was 400 kV, giving a maximum rate of voltage rise (dV/dt) of 4 MV/μs. In a second set of measurements, termed breakdown-initiation measurements, impulses of increasing peak voltage were applied to oil gaps until breakdown events occurred.

A polarity effect on breakdown was observed in [8] when transformer oil was tested in a point-plane geometry. The breakdown strength was found to be ~50% higher for a negative point than a positive point at short breakdown times (1-2.5 ns). The polarity effect has been explained in [9-12] by an effective reduction in the inter-electrode gap length under positive polarity, as electrons are generated in the liquid and attracted to the positive-point electrode, and the conducting channel formed as a result of ionization of the liquid between the anode and the electron cloud acts as an extension of the needle anode. In the negative impulse regime, a negative volumetric space charge is formed in front of the needle, reducing the field gradient and impeding the injection of further electrons, meaning that higher applied voltages are required to cause breakdown. Impulse voltages of negative polarity were therefore used throughout the present study, corresponding with the polarity used in [3-6].

Both wave-shapes (100/600 ns and 1/6.5 μs) utilized in the study will be of interest to designers of pulsed-power supplies and components. The 1/6.5 μs wave-shape used is similar to a short-tail lightning impulse, meaning that the results may also be of interest to designers of oil-immersed, high-voltage systems such as power transformers.

2 EXPERIMENTAL ARRANGEMENT

The experimental system comprised a high-voltage impulse generator, test cell, and voltage monitoring diagnostics. The impulse generator is a ten-stage, air-insulated, inverting Marx generator, capable of producing output voltages in the region of 500 kV. The erected capacitance of the Marx is 8 nF, and switching is achieved by the depressurization of an in-line spark-column, consisting of ten discrete spark-gap switches, filled with dry air. The storage capacitors are charged by a positive-polarity, 100-kV, Glassman high-voltage dc supply.

The values of the wave-shaping resistors were varied in order to achieve different voltage rise- and fall-times. To generate impulses of rise-time 100 ns (600 ns to half-peak value), a 600 Ω aqueous copper sulphate ($CuSO_4$) wave-front resistor was utilized along with a 200 Ω $CuSO_4$ wave-tail resistor. In a second configuration, an 800 Ω $CuSO_4$ wave-tail resistor and a 1.6 kΩ $CuSO_4$ wave-front resistor were used to achieve a voltage rise-time of ~1 μs (6.5 μs to half-peak value); in this configuration, a wave-front capacitance of 200 pF was also connected in parallel with the test-cell load.

The test cell consists of a pair of 50-mm-diameter aluminium electrodes, immersed in ~20 L of EOS Ltd. L10B reclaimed insulating oil. The insulating oil received from EOS Ltd. was stored in plastic barrels under atmospheric conditions; the water content and purity of this oil were not examined. These conditions are typical for the practical usage of mineral oils in the pulsed-power industry, and therefore it is important to know the dielectric characteristics of this oil "as received" from the supplier.

Three different electrode arrangements were tested, with the earthed electrode consisting of a 50-mm-diameter plane in all three geometries. Three different high-voltage electrodes were utilized, as illustrated in Figure 1. Both the type A and type B electrodes were designed to initiate discharges in close proximity to the surface of cylindrical solids of diameter 25 mm [3-6]. The first type of electrode, type A, had a 3-mm-long, 1-mm-diameter, tungsten-alloy pin protruding from the main body to provide a point-plane electrode geometry. The second type, type B, also provided non-uniform field geometry, with a 25-mm-diameter aluminum collar centered on the electrode body. The collar was machined at an angle of 45°, and the diameter at the tip was again 1 mm. For the voltage levels (up to 400 kV) and inter-electrode gap lengths (minimum of 8.5 mm) studied herein, the estimated peak electric field levels at the tips of the type A and type B electrodes are of the order of 1-4 MV/cm. The third type of high-voltage electrode, type C, was a 50-mm-diameter plane with no modifications, providing plane-parallel electrode geometry.

The impulse voltage wave-forms were monitored using a Tektronix P6015A high-voltage probe connected to a tap-off point on a Samtech Ltd. DE(LRP)-02 $CuSO_4$ voltage divider (10 kΩ input impedance), giving a measurement system with an overall division ratio of 10,000:1. The voltage wave-forms were viewed and recorded on a Tektronix TDS3032 digital storage oscilloscope; typical wave-forms corresponding to those used in the measurements reported here, but associated with surface breakdown events, can be found in [3-6].
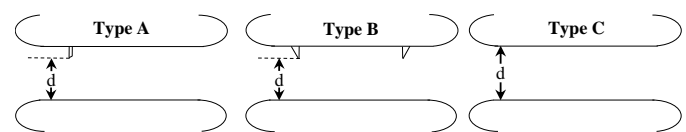

Figure 1. Sketch of the different electrode arrangements used throughout the study. The inter-electrode gap length, *d*, is shown for each geometry.

3 OVER-VOLTAGE TESTS

Oil gaps of each of the geometries shown in Figure 1 were subjected to impulse voltages of negative polarity. For each geometry, five impulses of rise-time 100 ns were first applied across the electrodes. The peak voltage applied to the gap was fixed at −400 kV for these initial measurements, resulting in breakdown of the oil on the falling edge of the impulse. The voltage at breakdown, V_{br}, and the pre-breakdown delay time, t_{br}, was recorded for each breakdown event (see Figure 3).

The voltage rise-time was then increased by an order of magnitude to 1 µs in order to study pre-breakdown delay times associated with breakdown events occurring either on the impulse rising edge or around the peak of the impulse, rather than on the impulse falling edge. A peak voltage of −350 kV was applied across the gap five times, again, for each electrode geometry. The peak voltage magnitude was limited to 350 kV in this configuration due to the voltage rating of the 200-pF wave-front capacitor.

3.1 NON-UNIFORM FIELDS

The values of the voltage at breakdown for the pin and collar high-voltage electrodes (d = 8.5 mm) are listed in Table 1. It is clear that for the 100-ns rise-time, the voltage at breakdown is higher for the pin electrode (average V_{br} 385±11 kV) than for the collar electrode (average V_{br} 307±14 kV). At 1 µs rise-time, the voltage at breakdown is very similar for both the pin-plane (average V_{br} 335±2 kV) and the collar-plane (average V_{br} 336±1 kV) oil gap, and there is only a small variation in the voltage at breakdown over the five shots for either type of gap. The ± values quoted throughout this paper correspond to the standard deviation.

Displayed in Figure 2 are time-to-breakdown data for both non-uniform geometries (d = 8.5 mm) at 100 ns rise-time. It is clear that the times to breakdown are much longer for the collar electrode, and in fact the average pre-breakdown delay time of 499±43 ns over the five shots is over twice that of the average time for the pin electrode (223±15 ns).

It is important to note that although the voltage at breakdown is lower for the collar electrode at 100 ns rise-time, the time to breakdown, as shown in Figure 2, is significantly longer. As breakdown occurred on the falling edge of the impulse, the reduction in the measured voltage at breakdown for the collar electrode is a result of the longer time to breakdown, as illustrated in Figure 3.
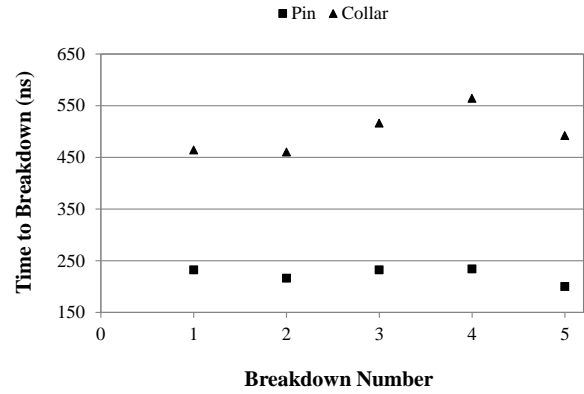

Figure 2. Time to breakdown versus breakdown number (5 individual breakdowns) for non-uniform geometries for rise-time 100 ns.
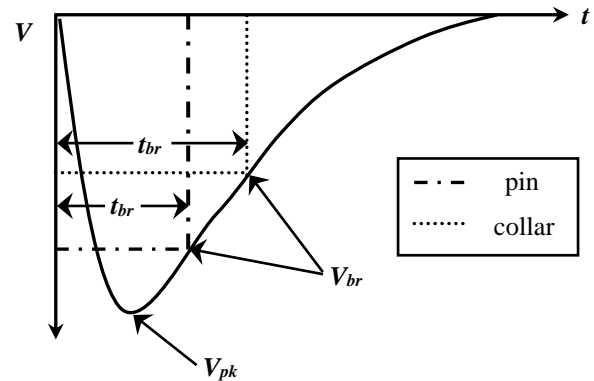

Figure 3. Sketch illustrating the differences in time to breakdown, t_{br}, and hence voltage at breakdown, V_{br}, for impulses of rise-time 100 ns. Also indicated is the peak applied voltage, V_{pk}.

Although the voltage at breakdown for the pin and collar electrodes is very similar for rise-time 1 µs, the pre-breakdown delay times were again longer for the collar electrode. Figure 4 provides a comparison of the breakdown-time data for 1 µs rise-time (d = 8.5 mm). While breakdown events occurred on the rising edge for the pin-plane geometry, it is clear that times to breakdown longer than 1 µs were obtained for collar-plane geometry. As the corresponding breakdown voltage was always within 5% of the peak voltage, the data were accepted in order to provide a comparison with the pin-plane geometry. The average breakdown times are 766±45 ns and 1260±89 ns for the pin-plane and the collar-plane oil gaps, respectively. This behaviour is discussed by way of analysis of the peak electrical field for the pin and collar electrodes in Section 5.

When the data are compared for both rise-times for pin-plane electrode geometry, the time to breakdown is approximately 500 ns shorter for 100 ns rise-time impulses than for impulses of 1 µs rise-time. For the collar high-voltage electrode, again the 100 ns rise-time impulses provide a shorter time to breakdown, this time the difference compared to the 1 µs impulses is around 700 ns.

Table 1. Voltage at Breakdown, V_{br}, for Non-uniform Field Geometries (5 Individual Breakdowns).

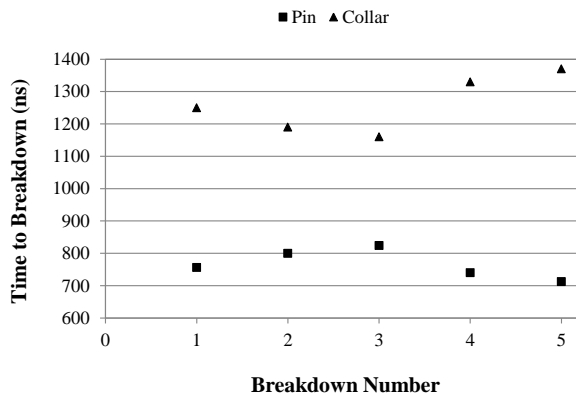| Rise-time		100 ns		1 µs	
High-voltage electrode		Pin	Collar	Pin	Collar
V_{br} (kV)	1	378	318	336	336
	2	394	320	336	336
	3	378	300	338	336
	4	374	286	334	336
	5	400	310	332	334

Figure 4. Time to breakdown versus breakdown number (5 individual breakdowns) for non-uniform geometries for rise-time 1 μs.

At such short time intervals and high *dV/dt*, a streamer mechanism can be assumed to be integral to the breakdown process. Lesaint [13] states that "*the term "streamer" remains widely used in liquids to designate all propagating prebreakdown phenomena*", and it should be noted that the same approach has been taken here. While the actual velocity of the streamer that propagates to the point of breakdown cannot be accurately determined without spatial and temporal imaging of the streamer development, an average streamer velocity, estimated by dividing the inter-electrode gap length by the time to breakdown, can provide a minimum implied velocity of streamer propagation. It is recognized that the propagation velocity will not be constant over the full inter-electrode gap length. Torshin [14] discusses the propagation of *leader* discharges, more commonly discussed in relation to electrical breakdown of air, in mineral oil. Leaders can close the inter-electrode gap, travelling with a higher velocity than in the earlier discharge propagation phases.

The implied average streamer velocities can provide a basis for comparison with the results from other studies, and these are listed in Table 2 for the various non-uniform field tests. Based upon the classification of streamer propagation modes discussed elsewhere [15-18], the data suggest that faster streamer velocities are found under higher *dV/dt*. For example, the propagation velocity for pin-plane geometry with a 1 μs rise-time is 10-12 km/s. At 100 ns rise-time for the same electrode geometry, the average propagation velocity exceeds 40 km/s for the final breakdown.

Table 2. Implied Average Streamer Propagation Velocities Under Non-uniform Field Geometries (5 Individual Breakdowns).

Electrodes (rise-time)	Average Streamer Propagation Velocity (km/s)				
	1	*2*	*3*	*4*	*5*
Pin-plane (100 ns)	37	39	37	36	43
Collar-plane (100 ns)	18	19	17	15	17
Pin-plane (1 μs)	11	11	10	12	12
Collar-plane (1 μs)	7	7	7	6	6

Badent et al [16] studied negative streamers in insulating oil and, according to their classification, *secondary streamers* have average velocity up to 40 km/s, and *tertiary streamers* have velocity exceeding 47 km/s. Massala and Lesaint [17] define *fast streamers* in mineral oil as having a velocity higher than 50 km/s. Duy et al [18] classify streamers simply as *slow* for average velocity 1.5-3 km/s, and *fast* for average velocity 20-200 km/s, although this classification is in relation to the propagation of positive streamers.

3.2 UNIFORM FIELDS

The voltages at breakdown, V_{br}, recorded for the different rise-times for plane-parallel geometry are listed in Table 3 along with the times to breakdown, t_{br}. It must be noted that while the inter-electrode gap length was 8 mm for 100 ns rise-time, it was necessary to reduce the gap length to 4 mm for 1 μs rise-time in order to ensure that breakdown events occurred only on the rising edge of the applied impulse. When an 8-mm gap length was tested under the longer rise-time regime, breakdown events commonly occurred up to several μs after the impulse peak. The main purpose of the results is to provide reference data for comparison with the breakdown characteristics of the various liquid-solid gaps tested in [3-6], and the gap lengths tested herein correspond to the lengths of the solid surfaces subjected to the relevant impulse wave-shape in these papers. The time to breakdown with and without solid spacers is compared and discussed in Section 5.

Table 3. Voltage at Breakdown, V_{br}, and Time to Breakdown, t_{br}, for Over-voltage Measurements with Plane-parallel Electrodes.
(5 Individual Breakdowns).

Rise-time (inter-electrode gap)		V_{br} (kV)	t_{br} (ns)
	1	350	378
	2	340	350
100 ns (*d* = 8 mm)	*3*	356	312
	4	336	376
	5	332	364
	1	284	416
	2	306	480
1 μs (*d* = 4 mm)	*3*	296	472
	4	290	448
	5	280	390

Table 4. Implied Average Streamer Propagation Velocities with Plane-parallel Electrodes (5 Individual Breakdowns).

Electrodes (rise-time)	Average Streamer Propagation Velocity (km/s)				
	1	*2*	*3*	*4*	*5*
Plane-parallel (100 ns)	21	23	26	21	22
Plane-parallel (1 μs)	10	8	9	9	10

Forster and Wong [19] have previously reported on streamers in hydrocarbons under uniform-field conditions similar to those reported herein. The average electric field magnitude in [19] was 300-500 kV/cm, compared to 500-875 kV/cm in this paper. The implied average streamer propagation velocities for plane-parallel electrode geometry

for both impulse wave-shapes applied in the present study are displayed in Table 4.

4 BREAKDOWN-INITIATION TESTS

Using the 100-ns rise-time, oil gaps were then subjected to a test in order to determine the peak applied voltages required to initiate breakdown. This involved subjecting the oil gap to multiple negative-polarity impulses, the majority of which did not result in breakdown, with the following test sequence. For both non-uniform geometries, where the electrode separation, d, was 10 mm, a peak voltage of −200 kV (average applied field (V_{pk}/d) of 200 kV/cm) was initially applied across the electrodes. For uniform plane-parallel geometry, where the electrode separation was 4 mm, the voltage initially applied was −120 kV (average applied field 300 kV/cm). No breakdown events were observed at these levels of applied voltage. For each electrode geometry, the charging voltage was raised in steps of 2 kV (~20 kV increase in output voltage) until a breakdown occurred, upon which the peak applied voltage, the voltage at breakdown, and the delay time to breakdown were recorded (see Figure 3). The charging voltage was then reduced to return the peak applied voltage to −200 kV or −120 kV, depending upon the electrode configuration, and the process was repeated until a total of five breakdowns had occurred. The time between impulse voltage applications was five minutes.

When breakdown-initiation measurements were attempted for the longer rise-time of 1 μs, which was utilized to study rising-edge breakdown events in Section 3, breakdown events generally occurred on the falling edge, with pre-breakdown delay times up to 4 μs, and this type of measurement was not pursued.

4.1 NON-UNIFORM FIELDS

The data plotted in Figure 5 are the average applied field data for both non-uniform geometries (d = 10 mm). The average applied field has been calculated simply by dividing the peak applied voltage inducing breakdown, V_{pk}, by the inter-electrode gap length, d. Higher applied voltages/fields are evidently required to initiate breakdown events using the collar-plane geometry compared to the pin-plane geometry. The difference between the average applied fields for breakdown in the two geometries is around 10%. The general downward trends suggest sample conditioning with an increasing number of applied impulses for these measurements. The decreasing breakdown voltage may be a result of increasing gas content in the oil due to previous breakdown events, although as already mentioned in section 1, the study involved testing the oil "as received", and dissolved gas or water content was not analyzed.

As in the over-voltage measurements, the time to breakdown was generally longer for the collar configuration as compared with the pin geometry. The longer times to breakdown for the collar translate to slower streamer propagation, as summarised in Table 5. Comparing the propagation velocities to those for gaps subjected to over-voltages with 100 ns rise-time

(Table 2), the values are similar for collar-plane geometry. The velocities for pin-plane geometry however, are substantially faster for the over-voltage measurements compared to the velocities obtained from breakdown-initiation measurements.
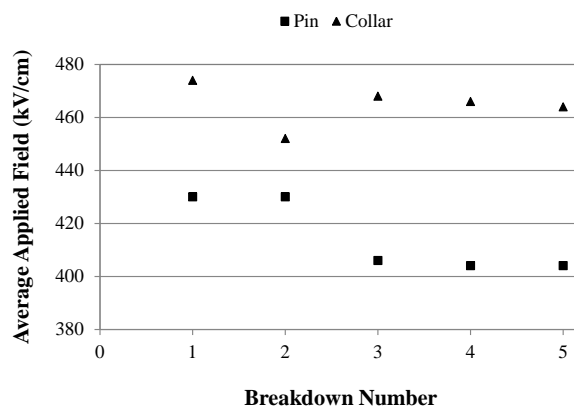

Figure 5. Average applied field (V_{pk}/d) versus breakdown number (5 individual breakdowns) for breakdown-initiation measurements under non-uniform geometries.

Table 5. Implied Average Streamer Propagation Velocities for Breakdown-initiation Measurements under Non-uniform Field Geometries. (5 Individual Breakdowns).

Electrodes	Average Streamer Propagation Velocity (km/s)				
	1	2	3	4	5
Pin-plane	28	18	27	19	21
Collar-plane	17	21	14	15	17

4.2 UNIFORM FIELDS

For a 4-mm open oil gap between plane-parallel electrodes, the highest applied field required to initiate breakdown was 765 kV/cm, as measured for the final breakdown event (V_{pk} = 306 kV). The peak applied voltage inducing breakdown, V_{pk}, is listed in Table 6, along with the voltage at breakdown, V_{br}, and the time to breakdown, t_{br}. The applied field for the other breakdown events was in the range 515 kV/cm to 670 kV/cm. The average breakdown field (calculated by dividing the breakdown voltage, V_{br}, by the inter-electrode gap length) varied form 405 kV/cm up to 750 kV/cm. As expected, the average applied fields necessary to cause breakdown are higher than those obtained in non-uniform geometries.

Table 6. Peak Applied Voltage, V_{pk}, Voltage at Breakdown, V_{br}, and Time to Breakdown, t_{br}, for Breakdown-initiation Measurements with Plane-parallel Electrodes (5 Individual Breakdowns).

Rise-time (inter-electrode gap)		V_{pk} (kV)	V_{br} (kV)	t_{br} (ns)
100 ns (d = 4 mm)	1	226	197	376
	2	268	232	344
	3	229	197	368
	4	206	162	504
	5	306	300	240

As might be expected, the higher the applied field required for breakdown initiation, the shorter the delay time until

breakdown on the falling edge of the impulse. The corresponding implied streamer velocities are displayed in Table 7. The calculated streamer velocities are generally slower than those in non-uniform fields, by up to 2.5 times in collar-plane geometry, and by a maximum of 3.5 times in pin-plane geometry.

Table 7. Implied Average Streamer Propagation Velocities for Breakdown-initiation Measurements with Plane-parallel electrodes. (5 Individual Breakdowns).

Electrodes	Average Streamer Propagation Velocity (km/s)				
	1	*2*	*3*	*4*	*5*
Plane-parallel	11	12	11	8	17

5 DISCUSSION

The breakdown characteristics of open oil gaps have been studied under three different electrode geometries, and with two applied voltage wave-shapes.

In oil gaps subjected to over-voltages, the time to breakdown under collar-plane geometry was longer than that under pin-plane geometry for rise-times of both 100 ns and 1 μs. As would be expected, the pre-breakdown delay times were longer for the 1-μs rise-time for each of these non-uniform geometries.

Despite the shorter breakdown times for the pin electrode under 1-μs rise-time, the breakdown voltages in Table 1 are very similar to those for the collar electrode. This is facilitated by a period of approximately 400 ns around the impulse peak where the rate of voltage change is low.

The times to breakdown are generally much longer for collar-plane geometry than pin-plane geometry, suggesting that the field enhancement provided by the pin is playing a greater role compared with that for the collar.

Only the average electric fields have been discussed thus far, calculated as the ratio of the breakdown voltage and the inter-electrode gap length. In order to estimate the peak field for the non-uniform geometries, these electrode arrangements were modelled using the electrostatic field solver QuickField (Tera Analysis Ltd.). The solver is based on finite element analysis, and produces a rotationally symmetric solution. The applied voltage was 400 kV in all cases. When the pin-plane geometry was modelled using QuickField, the estimated peak fields were ~2.8 MV/cm for $d = 8.5$ mm and ~2.5 MV/cm for $d = 10$ mm. This results in a calculated field enhancement factor (defined here as the maximum field in the gap divided by the average field in the gap) in the range 5.95-6.25 for the pin-plane geometry. The estimated peak field for the collar-plane geometry was ~1.5 MV/cm for $d = 8.5$ mm, and ~1.3 MV/cm for $d = 10$ mm, yielding a field enhancement factor in the range 3.19-3.25.

In analysing hemispherically-capped rod-plane gaps, Qiu [20] states that the field non-uniformity factor, f, can be estimated using the phenomenological equation (1):

$$f = 0.45 \frac{d}{r_p} \frac{\ln(6d/r_p)}{\ln(d/r_p)} \quad (1)$$

when the condition $3 < d/r_p < 500$ is satisfied. The values of d/r_p for the non-uniform geometries investigated in the present study are within this range, and analysis of f using equation (1) yields values of ~14.4 ($d = 10$ mm; $d/r_p = 20$) and ~12.5 ($d = 8.5$ mm; $d/r_p = 17$). According to Torshin [14], "*the leader process forms directly from the electrode at the voltage corresponding to a breakdown probability (1 to 10%)*" for such values of f (from 10 to 15). Torshin states that average field strength of 350-400 kV/cm within a critical volume of oil (~0.04 cm^3) in the vicinity of the high-voltage electrode is required for leader formation, and that "*weak luminous brush-type channels*" develop at speeds of 1.5-40 km/s in the first instance.

In the present study, the pre-breakdown delay times associated with open oil gaps were longer for 1 μs rise-time than for 100 ns rise-time, with fixed inter-electrode gap. The time-to-breakdown data has been used to calculate minimum implied average streamer velocity. The velocity of sound in mineral oil has previously been measured as 1.5 km/s [21], so streamers generated under the conditions investigated here propagate with supersonic velocity in all cases. The maximum calculated velocity was around 40 km/s under pin-plane geometry with rise-time 100 ns (average field ~470 kV/cm; f ~12.5), corresponding with the observations of Torshin [14] on leaders described above. Propagation velocities for collar-plane geometry were similar for both over-voltage and breakdown-initiation measurements, but under pin-plane geometry the velocities were faster when the gap was subjected to over-voltage tests (maximum of 43 km/s) rather than breakdown-initiation tests (minimum of 18 km/s), due to the higher peak voltage. For all geometries, the ratio of propagation velocity is around 2.5-3:1 for 100-ns rise-time impulses (*dV/dt* up to 4 MV/μs) compared to 1 μs rise-time impulses (*dV/dt* up to 350 kV/μs), a direct effect of the shorter times to breakdown discussed above.

Under plane-parallel electrodes, which were used to provide uniform field distribution, the highest average field required to cause breakdown was 765 kV/cm. This field was recorded twice for breakdown of a 4-mm oil gap: first in over-voltage tests with a 1-μs rise-time, and also in breakdown-initiation measurements with rise-time 100 ns.

Comparing the results obtained in breakdown-initiation tests to those previously obtained in liquid-solid gaps for the same type of test [6], the applied field required to initiate breakdown was always lower with a spacer between the electrodes, for both non-uniform geometries. The minimum average applied field (V_{pk}/d) inducing breakdown in an open oil gap was ~405 kV/cm (pin-plane electrodes), and the maximum field was ~390 kV/cm with the inclusion of a polypropylene surface (collar-plane electrodes). In all cases, higher fields were required to initiate breakdown in collar-plane geometry.

The times to breakdown can also be compared with those previously obtained in composite liquid-solid gaps for the same voltage wave-shape, and associated with the breakdown voltages reported in [5]. For the 1/6.5 μs wave-shape, the baseline times to breakdown of the oil were found to be around ~750 ns and ~1250 ns for the pin-plane and collar-plane geometries, respectively (see Figure 4). In terms of surface

breakdown, the closest values to these baseline levels were ~680 ns in pin-plane geometry, and ~715 ns in collar-plane geometry, both with low-density polyethylene (ε_r ~2.2) surfaces. Taking the lower extreme case as an example, the average times to breakdown for Torlon (ε_r ~3.9) were ~225 ns for the pin and ~250 ns for the collar. The corresponding reductions in breakdown time are 3.3 times and 5 times, respectively, when compared to the baseline times for the open oil gap stated above. It should be noted that the calculated standard deviation was always much lower for the open oil gap, suggesting a more consistent breakdown mechanism. It may be the case that the presence of a solid surface acts to promote the conditions required for the initiation of leader discharges (or *fast streamers*), resulting in shorter times to breakdown. This is facilitated by enhanced field in the direction of streamer propagation at the liquid-solid interface, and by restriction of branching of the streamer by the physical presence of the solid [22].

When considering the 100/600 ns wave-shape, the introduction of a solid sample between the electrodes again causes a reduction in the delay time to breakdown. For pin-plane geometry, the baseline pre-breakdown delay time in oil was found to be ~225 ns (see Figure 2). The implied average streamer propagation velocity, calculated by dividing the inter-electrode gap length by the time to breakdown, is 38 km/s. Upon comparing this with the data in [6], it becomes clear that the introduction of a solid spacer between the electrodes generally causes a reduction in this delay time, by ~1.5-2.5 times. This results in implied streamer propagation velocity of greater than 100 km/s in some cases. Generally, the closer the relative permittivity, ε_r, of the solid to that of the surrounding mineral oil (ε_r ~2.2), the longer the pre-breakdown time delay, and polypropylene (ε_r ~2.25) and low-density polyethylene (ε_r ~2.2) offered the best overall performance. In collar-plane geometry in oil, the baseline pre-breakdown delay time was more than double that for pin-plane geometry, at ~500 ns (see Figure 2), corresponding with an average streamer propagation velocity of 17 km/s. In this case, the effect of including a solid spacer between the electrodes is much more pronounced, with a decrease in the pre-breakdown delay time by a factor of five in most cases [6].

The assumption in calculating streamer velocity using information only on the time to breakdown and the inter-electrode gap length is that the statistical time lag will be short at such high electric field and rate of voltage rise, and therefore the major contributor to the time to breakdown will be the formative time lag associated with streamer development and propagation. As discussed in Section 3.1, spatial and temporal imaging of streamer development would be required in order to directly investigate streamer velocity.

In future work, von Laue plots of breakdown time distributions may help to separate the contributions of statistical time lag and formative time lag to the overall time to breakdown, for both liquid breakdown, and interfacial liquid-solid breakdown.

6 CONCLUSIONS

Considering the results on liquid breakdown described herein and the parallel liquid-solid breakdown results reported in [3-6] as a whole, the following general conclusions can be drawn, for breakdown times of the order of hundreds of ns:

- higher applied fields are required to initiate the breakdown process in an open oil gap compared to the case when a solid spacer is present;
- the times to breakdown are longer for open oil gaps compared to oil gaps with solid spacers, showing that the presence of the solid surface acts to decrease pre-breakdown delay times; and
- based upon typical propagation velocities described in [15-18], shorter time to breakdown with fixed inter-electrode gap length suggests propagation of *streamers* (as used to describe all propagating pre-breakdown structures) in faster modes for faster rate of voltage rise. Furthermore, the times to breakdown reported here are consistent with the propagation of *leader* discharges, as discussed in [14].

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