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Surface Flashover of Oil-immersed Dielectric Materials in Uniform and Non-uniform Fields

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ABSTRACT

The applied electrical fields required to initiate surface flashover of different types of dielectric material immersed in insulating oil have been investigated, by applying impulses of increasing peak voltage until surface flashover occurred. The behavior of the materials in repeatedly over-volted gaps was also analyzed in terms of breakdown mode (some bulk sample breakdown behaviour was witnessed in this regime), time to breakdown, and breakdown voltage. Cylindrical samples of polypropylene, low-density polyethylene, ultra-high molecular weight polyethylene, and Rexolite, were held between two electrodes immersed in insulating oil, and subjected to average applied electrical fields up to 870 kV/cm. Tests were performed in both uniform- and non-uniform-fields, and with different sample topologies. In applied field measurements, polypropylene required the highest levels of average applied field to initiate flashover in all electrode configurations tested, settling at ~600 kV/cm in uniform fields, and ~325 kV/cm in non-uniform fields. In over-volted point-plane gaps, ultra-high molecular weight polyethylene exhibited the longest pre-breakdown delay times. The results will provide comparative data for system designers for the appropriate choice of dielectric materials to act as insulators for high-voltage, pulsed-power machines.

Index Terms — **Flashover, surface discharges, dielectric materials, dielectric breakdown, oil insulation, plastics.**

1 INTRODUCTION

SURFACE discharges along dielectric components are a limiting factor in the attainment of stable operation of pulsed-power machines operating in increasingly higher-voltage and higher-current regimes. Under conditions with impulse rise-times in the nanosecond regime and associated high rates-of-change of electrical field, selection procedures for insulating materials are not well defined. Of particular concern in pulsed-power systems is the flashover performance of solid dielectric materials – used to form insulating component legs/ supports/ stand-offs, high-voltage lead-through, etc. – that are immersed in fluids such as insulating oil and water, and in pressurized gases.

It is established that both gases and liquids can withstand higher electrical stresses as the pulse duration is reduced, and breakdown fields as high as 11 MV/cm have been measured in [1], when Shell Diala Oil AX was subjected to single-shot impulses with a rise-time of 130 ps, and a pulse duration of 300 ps full width at half maximum (FWHM) in uniform fields.

Research into the physical mechanisms leading to the electrical breakdown of liquids has been ongoing for many years. The advent of fast digitizing oscilloscopes and optical detection systems has led to recent research showing that streamer activity occurs in liquids prior to breakdown, and that these streamers have a similar structure to those observed in gases and solids. A review

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of the understanding of streamer propagation in liquids can be found in [2].

Butcher et al [3] describe a 3-stage conduction process observed prior to dc breakdown for point-plane electrode configurations in insulating oil. A low resistive current phase is initially witnessed at low fields (stage 1). When the applied field is increased, a rapid rise in the injection current is observed as the effective energy barrier at the metal/oil interface is lowered, and a "tunneling" mechanism begins (stage 2). With further increase of the field, the current reaches space-charge saturation in stage 3, leading to breakdown.

Under impulse conditions, Top and Lesaint [4, 5] carried out experiments in a "semi-uniform geometry" in insulating oil, feeding a 100 µm diameter wire through a 200 µm diameter hole in the high-voltage electrode to mimic the effect of a protrusion on the electrode surface. It was shown through a combination of experiments and calculations that the local fields required to initiate streamers were very similar to those determined for point-plane geometry. With such a semi-uniform geometry (6 mm inter-electrode gap), a threshold "inception mean field" value of 50 kV/cm was found to cause filamentary, positive streamers to propagate to the point of breakdown.

Studies of impulse-driven surface discharges in insulating oil to-date have included measurements of the surface-discharge-field for one or two materials under uniform-field conditions [6, 7]. The parameters investigated include the thickness (length) of the samples, the shape of the samples, and the rate-of-rise of the applied impulse voltage.

For example, Wang et al have investigated dielectric surface discharges in insulating oil [6]. The authors applied ~40 ns wide, 50-200 kV pulses to trapezoidal samples of nylon 6 and PMMA held between plane-plane electrodes. Samples of both materials showed the highest hold-off voltages when the angle between the electrode and the sample surface was 45°. The breakdown field of cylindrical PMMA samples was found to increase from 450 kV/cm to 700 kV/cm when the rate-of-rise of voltage was raised from 11 kV/ns to 22 kV/ns, but was not affected by the thickness of the samples (1-3 mm).

The effect of applying similarly narrow pulses, with a rise-time of ~10 ns, and peak voltages of up to 300 kV, on PMMA spacers immersed in insulating oil was investigated by Guangjie et al [7]. The authors subjected 102 individual samples to a single surface flashover event, and found that the breakdown voltage varied by up to 180 kV for the same experimental conditions.

In the present work, the applied electrical fields required to initiate surface flashover of samples of four different polymers immersed in insulating oil have been investigated in both uniform and non-uniform fields. Investigations of the breakdown mode, pre-breakdown delay time, and breakdown voltage were also made in repeatedly over-volted gaps. The materials examined were:

- polypropylene (PP);
- low-density polyethylene (LDPE);
- ultra-high molecular weight polyethylene (UHMWPE); and
- Rexolite (a cross-linked polystyrene).

The results presented will provide comparative data for system designers for the appropriate choice of dielectric materials to act as insulators for high-voltage, pulsed-power machines.

2 EXPERIMENTAL ARRANGEMENT

The experimental system comprised a high voltage impulse generator, an adaptable 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 (~1 MV if immersed in oil). 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. A 200 Ω aqueous copper sulphate ($CuSO_4$) wavetail resistor provides an alternative path to earth for the stored energy of the stages, should no breakdown occur in the test cell. The output resistance is 600 Ω, in the form of a second $CuSO_4$ resistor, and the rise-time is ~100 ns with the test-cell load. The fall-time to half peak value is around 700 ns.

The test cell consists of a pair of aluminum electrodes, between which the polymer samples are inserted for testing. The inter-electrode gap is readily adjustable by varying the position of the earth electrode, which consists of a 50-mm-diameter plane. A further three inter-changeable electrodes, also 50 mm in diameter, are used as high-voltage electrodes. Two of these electrodes (types A and B) provide different point-plane configurations, with features designed to initiate discharges in close proximity to the sample surface: a 3-mm-long, 1 mm diameter, tungsten pin protrudes perpendicular to the surface of high-voltage electrode type A, at a radial distance of 12.5 mm from the electrode centre; while a 25 mm diameter, aluminum collar protrudes perpendicular to the surface at the centre of the plane of high-voltage electrode type B. The third type (type C) has no modifications, and is used to provide a plane-parallel configuration. For testing, the cell is immersed in ~20 litres of EOS Ltd. (UK) L10B insulating oil.

Three different types of sample were machined to match the geometries of the different high-voltage electrodes, each type being based on a cylinder of diameter 25 mm. A sketch of the different combinations of electrode geometry and sample used for testing is provided in Figure 1. A 3 mm long, 1 mm wide recess (dashed line in Figure 1a) is cut into the curved surface at one end of the type I samples, to accommodate the pin from high-voltage electrode type A. The type II samples have a 3-mm-long section machined to a reduced diameter of 24 mm at the end to be in contact with the high-voltage electrode. The type III samples have no modifications. Prior to treatment, all samples were rinsed in warm water with a little detergent to remove any surface grease, and then rinsed in isopropyl

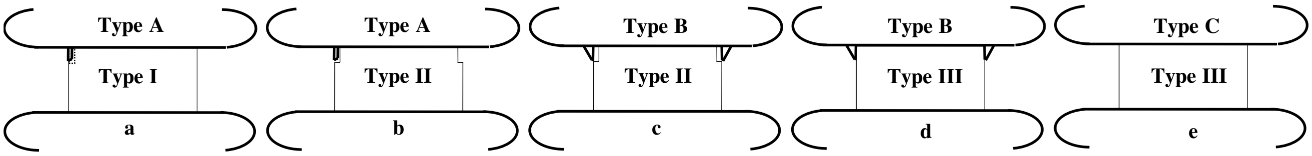

Figure 1. Sketch of the Different Combinations of High-Voltage Electrode and Sample.

alcohol and dried in an oven at 50 °C for one hour to remove surface moisture. Powder-free latex gloves were worn throughout the pre-treatment process to prevent re-contamination of the sample surfaces.

A Samtech Ltd. DE(LRP)-02 $CuSO_4$ resistive voltage divider (10:1 division ratio), with an input impedance of 2 kΩ, was connected in parallel with the test cell to allow the voltage waveform to be monitored. Either a Tektronix P6015A (section 3) or a North Star PVM-2 (section 4) voltage probe (1 000:1 division ratio) was connected between a tap-off point on the divider and ground, such that the total division ratio was 10 000:1. The voltage waveforms were viewed and recorded on a Tektronix TDS3032 digitizing oscilloscope, typical examples being shown in Figure 2.

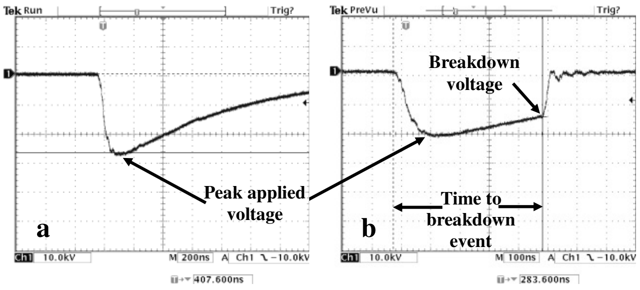

Figure 2. Typical voltage waveforms. Figure 2a: no breakdown event. Figure 2b: surface flashover along a type II PP sample with high-voltage electrode type A; the peak applied voltage is -222 kV; the breakdown voltage is -158 kV; and the time to the breakdown event is 510 ns.

3 FLASHOVER INITIATION RESULTS

Tests were performed to find the average applied electrical fields (defined here as the peak applied voltage divided by the inter-electrode gap length) necessary to initiate surface flashover, by applying impulses of increasing peak voltage until a breakdown event occurred.

Samples of each material were placed between the electrodes and subjected to negative-polarity impulses. For both point-plane gaps, where the electrode separation was 10 mm, a peak voltage of -190 kV was initially applied across the electrodes, and for plane-parallel electrodes, where the electrode separation was 4 mm, the voltage initially applied was -110 kV. No breakdown event was ever found to occur at these levels of applied voltage. The charging voltage was raised in steps of 2 kV and increasingly higher-voltage impulses applied until a breakdown event occurred, upon which the peak applied voltage, the time to the breakdown event, and the breakdown voltage were recorded (see Figure 2). The charging voltage was then reduced to return the peak applied voltage to the appropriate initial value, and the process was repeated until a total of five breakdown events had occurred. The electrodes were removed and polished between samples.

The time to breakdown and breakdown voltage are defined here as the time/voltage at which any breakdown event occurred, whether surface flashover or bulk breakdown. It should be noted that post-test inspection of all treated samples revealed only surface damage, which is discussed later in section 4.1, and no bulk damage. Based on this observation, the breakdown events registered in these measurements can be attributed to surface flashover, and the measured voltages and times are associated with the propagation of discharges along the oil/sample interface, and not propagation through the bulk of either the sample or the oil.

The results of these measurements are summarized in Tables 1 and 2, which contain data for the average applied field (Table 1), and for the time to breakdown and breakdown voltage (Table 2), for all five surface flashover events for each of the materials and electrode/sample combinations. Three samples of each material were treated for every data point,

Table 1. Mean Average Applied Fields (E_{ap} (av.)) for Flashover Initiation Measurements (all data is for the treatment of 3 samples for each material and electrode/sample combination).

		HV Electrode Type A/ Sample Type I (Figure 1a)	HV Electrode Type B/ Sample Type III (Figure 1d)	HV Electrode Type C/ Sample Type III (Figure 1e)
		E_{ap} (av.) (kV/cm)	E_{ap} (av.) (kV/cm)	E_{ap} (av.) (kV/cm)
PP	1	325±83	391±27	637±58
	2	293±107	345±48	594±68
	3	287±69	328±60	677±167
	4	285±41	324±73	617±130
	5	303±25	316±53	592±29
LDPE	1	325±34	337±25	631±146
	2	284±27	281±18	638±260
	3	253±34	275±18	456±30
	4	266±21	262±14	528±131
	5	265±57	275±28	474±23
UHMWPE	1	305±32	353±27	483±64
	2	250±5	277±43	327±60
	3	257±45	267±35	386±88
	4	265±88	261±26	338±17
	5	282±39	279±40	374±73
Rexolite	1	284±26	346±24	503±70
	2	257±18	266±12	431±2
	3	281±20	244±7	444±25
	4	294±2	250±36	442±17
	5	299±10	241±44	385±47

Table 2. Mean Times to Breakdown (t_{br} (av.)) and Mean Breakdown Voltages (V_{br} (av.)) for Flashover Initiation Measurements (all data is for the treatment of 3 samples for each material and electrode/sample combination).

		HV Electrode Type A/ Sample Type I (Figure 1a)		HV Electrode Type B/ Sample Type III (Figure 1d)		HV Electrode Type C/ Sample Type III (Figure 1e)	
		t_{br} (av.) (ns)	V_{br} (av.) (kV)	t_{br} (av.) (ns)	V_{br} (av.) (kV)	t_{br} (av.) (ns)	V_{br} (av.) (kV)
PP	1	392±91	257±27	235±74	377±21	388±74	211±34
	2	355±174	258±138	229±228	312±23	419±233	190±57
	3	417±35	232±60	445±315	254±58	289±87	251±85
	4	480±45	214±30	318±109	292±37	360±98	214±52
	5	471±57	229±12	347±105	279±68	417±217	189±36
LDPE	1	832±223	165±60	269±153	308±51	548±313	189±50
	2	533±286	202±45	361±149	247±53	289±174	229±54
	3	343±181	215±32	493±130	204±23	316±194	176±44
	4	521±194	187±37	252±150	247±33	297±187	199±52
	5	464±205	198±2	248±60	266±25	193±70	203±34
HMWPE	1	463±212	239±78	619±161	223±25	611±162	161±50
	2	174±99	243±8	319±150	246±24	341±251	135±13
	3	351±198	211±5	411±155	215±14	311±157	176±50
	4	403±196	203±33	325±86	233±7	445±170	134±18
	5	509±237	203±59	224±25	277±43	547±38	133±29
Rexolite	1	333±62	254±28	284±169	314±41	323±85	223±41
	2	516±177	187±49	196±70	261±19	335±51	192±9
	3	509±133	209±46	231±83	235±17	397±95	185±12
	4	460±96	226±22	232±83	240±45	384±80	190±21
	5	616±91	183±19	177±54	239±46	433±125	154±24

and the data contained in Tables 1 and 2, as well as the data points shown in Figures 3-5, represent the mean values from the three samples. The ± values quoted correspond to the standard deviation. As can be seen from Table 2, the times to breakdown were all of the order of hundreds of nanoseconds, corresponding with breakdown occurring on the falling edge.

3.1 NON-UNIFORM FIELDS

Type I samples of each of the materials were tested with high-voltage electrode type A (see Figure 1a). The samples were 13 mm long, such that the point-plane inter-electrode gap was 10 mm. Figure 3 shows how the average applied field required to initiate flashover varied over five surface flashover events for each of the materials. With this electrode arrangement, PP (325±83 kV/cm) and LDPE (325±34 kV/cm) jointly exhibited the highest average applied field to initiate the first surface flashover. The applied field fell to a minimum of 285±41 kV/cm for PP (fourth flashover), and to a minimum of 253±34 kV/cm for LDPE (third flashover). The applied field for both UHMWPE and Rexolite initially fell, and then gradually increased over flashovers three to five. Low-density polyethylene had the longest time to first flashover of 832±223 ns in this configuration, followed by UHMWPE at 463±212 ns.

The results are clearer in Figure 4, which shows how the average applied field required to initiate flashover varied over five surface flashover events for type III samples tested with high-voltage electrode type B (see Figure 1d). The samples were again 13 mm long, such that the inter-electrode gap was 10 mm. The average applied fields required to initiate the first flashover for each material were higher than with high-voltage electrode type A (Figure 3), suggesting that the field enhancement provided by the pin is greater than that for the collar. The average applied field required to initiate flashover generally decreased with an increasing number of flashover events. Higher applied fields were clearly required to cause flashover of the PP surface compared with the other materials; the peak applied field started at 391±27 kV/cm, and fell to 316±53 kV/cm by the fifth flashover. The applied field to initiate flashover of Rexolite fell from 346±24 kV/cm for the first flashover to 241±44 kV/cm for the fifth flashover. Ultra-high molecular weight polyethylene had the longest time to first breakdown of 619±161 ns.

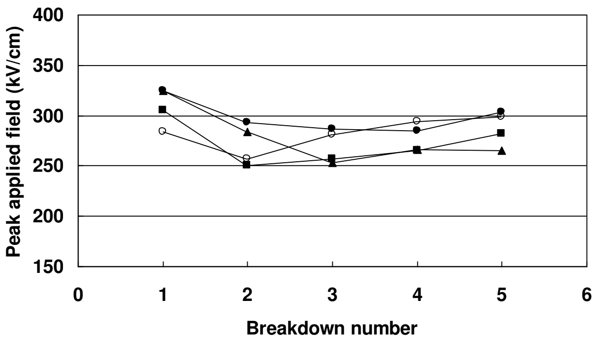

Figure 3. Average applied fields to cause surface flashover across type I dielectric samples with high-voltage electrode type A (Figure 1a). Closed circles PP; closed triangles LDPE; closed squares UHMWPE; open circles Rexolite. Each data point represents the mean value from 3 samples.

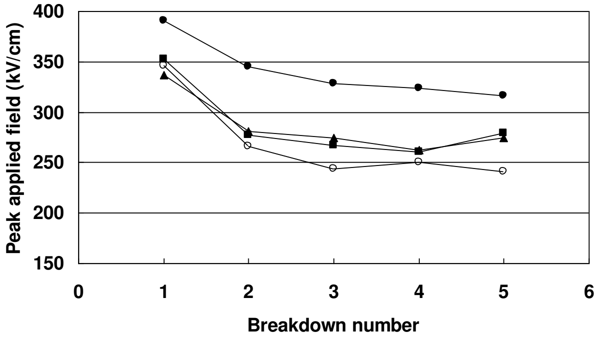

Figure 4. Average applied fields to cause surface flashover across type III dielectric samples with high-voltage electrode type B (Figure 1d). Closed circles PP; closed triangles LDPE; closed squares UHMWPE; open circles Rexolite. Each data point represents the mean value from 3

3.2 UNIFORM FIELDS

Type III samples of each material were tested with plane-parallel electrodes (see Figure 1e) to provide uniform-field conditions. The sample length, and hence the inter-electrode gap length, was 4 mm. The variation in the average applied field required to initiate five flashover events is shown in Figure 5.

As with both point-plane gaps, the applied fields required to cause surface flashover were generally higher for PP than for the other materials. With the exception of the third breakdown, which showed the highest average applied field of 677±167 kV/cm, the applied field for breakdown of PP was around 600-630 kV/cm. Low-density polyethylene showed the widest variation in average applied field over the five flashovers, beginning at a similar level to PP, but falling to 450-530 kV/cm for flashovers three to five. The applied fields for surface flashover of Rexolite and UHMWPE were in the region of 450 kV/cm and 350 kV/cm, respectively. The maximum individual average applied field recorded was 870 kV/cm for the third flashover across the second PP sample. The longest times to first breakdown were reflected by UHMWPE (611±162 ns) and LDPE (548±313 ns).

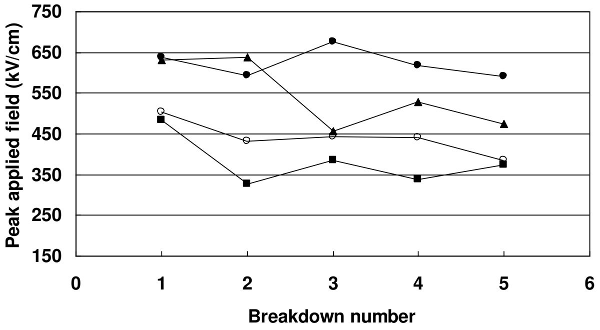

Figure 5. Average applied fields to cause surface flashover across type III dielectric samples with high-voltage electrode type C (Figure 1e). Closed circles PP; closed triangles LDPE; closed squares UHMWPE; open circles Rexolite. Each data point represents the mean value from 3 samples.

4 OVER-VOLTED GAP RESULTS

After analyzing the applied electrical fields required to initiate surface flashover, tests were performed in repeatedly over-volted gaps in order to determine the effect of consecutive applied impulses on the behavior of the different materials, particularly relating to the breakdown mode (surface flashover or bulk sample breakdown), the time to breakdown, and the breakdown voltage. Unlike the results presented in section 3 where only surface flashover was observed, repeated over-volting of the gap in this manner caused bulk breakdown damage to some of the samples, and it should be noted that the voltage and time values in Table 3 are an average of all breakdown events, whether surface flashover or bulk sample breakdown. The ± values quoted correspond to the standard deviation.

4.1 NON-UNIFORM FIELDS

Type I and type II samples of each material were tested with high-voltage electrode type A, and type II and type III samples were tested with high-voltage electrode type B. All samples were 11.5 mm in length, such that the inter-electrode gap was 8.5 mm. For each test sequence, the sample was subjected to 35 negative-polarity impulses, in order to determine the effect of damage caused by previous discharges on subsequent breakdown events. The peak applied voltage for each shot was -400 kV, resulting in either a surface flashover event or bulk breakdown of the dielectric sample for every applied pulse. Both the high-voltage electrode and the earth electrode were removed and polished between test sequences.

The majority of waveforms took the form of that shown in Figure 2b, where despite initially holding off the peak applied voltage of -400 kV (rising in ~100 ns), surface discharges occurred at lower voltages, after a variable time delay, on the falling edge of the pulse. The remainder of the breakdowns occurred on the rising edge of the pulse. The time to breakdown and breakdown voltage, as indicated in Figure 2b, were recorded for each discharge. Despite the damage caused by each discharge, it was found that the time to breakdown and/or the breakdown voltage did not always fall with increasing breakdown number, and hence the mean time to breakdown and mean breakdown voltage over the 35 shots were considered to be of value. This information is provided in Table 3, along with the standard deviation.

Figure 6 shows how the magnitude of the breakdown voltage varied with an increasing number of shots for high-voltage electrode type A and sample type I (see Figure 1a). The effect of damage from previous discharges can be clearly seen for Rexolite, with the breakdown voltage falling steadily from 318 kV for shot 25 to 150 kV for shot 31, with breakdown beginning to occur on the rising edge of the pulse. This is reflected by the short mean time to breakdown in Table 3. Low-density polyethylene showed a different behavior, with the highest mean breakdown voltage of 327±23 kV, and with some of the highest breakdown voltages being recorded in the last five shots. The mean time to

Table 3. Mean Times to Breakdown (t_{br} (av.)) and Mean Breakdown Voltages (V_{br} (av.)) Over 35 Shots for Over-Volted Point-Plane Gaps.

	HV Electrode Type A/ Sample Type I (Figure 1a)		HV Electrode Type A/ Sample Type II (Figure 1b)		HV Electrode Type B/ Sample Type II (Figure 1c)		HV Electrode Type B/ Sample Type III (Figure 1d)	
	t_{br} (av.) (ns)	V_{br} (av.) (kV)	t_{br} (av.) (ns)	V_{br} (av.) (kV)	t_{br} (av.) (ns)	V_{br} (av.) (kV)	t_{br} (av.) (ns)	V_{br} (av.) (kV)
PP	107±86	287±31	112±57	298±27	105±36	311±27	88±29	277±43
LDPE	154±35	327±23	175±29	304±14	105±42	305±34	112±37	306±17
UHMWPE	303±80	258±24	165±94	298±25	115±72	311±27	184±60	283±20
Rexolite	96±56	263±60	144±165	253±57	89±20	308±32	113±91	250±38

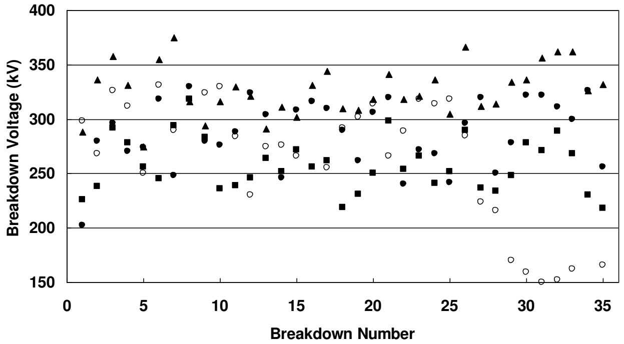

Figure 6. Breakdown voltage magnitude versus shot number for high-voltage electrode type A and sample type I (Figure 1a). Closed circles PP; closed triangles LDPE; closed squares UHMWPE; open circles Rexolite.

breakdown was 154±35 ns. In terms of predictability, LDPE also exhibited the least variation between the maximum and minimum breakdown voltages, jointly with UHMWPE, with a difference of 100 kV. Ultra-high molecular weight polyethylene exhibited the lowest mean breakdown voltage of 258±24 kV, but reflected the longest mean time to breakdown of 303±80 ns. Rexolite had a mean breakdown voltage of 263±60 kV, with the shortest time to breakdown (96±56 ns), and the widest difference of 187 kV between the maximum and minimum breakdown voltages.

From Figure 7, it can be observed that the breakdown voltage for Rexolite fell to below 200 kV for the majority of the last ten shots, for testing with high-voltage electrode type A and sample type II (see Figure 1b). The breakdown voltage for the other three materials was generally in the range 250-350 kV. Low-density polyethylene again exhibited the highest mean breakdown voltage of 304±14 kV, and the least variation of 62 kV between the maximum and minimum breakdown voltages. Rexolite had both the lowest mean breakdown voltage of 253±57 kV, and the widest variation of 201 kV between maximum and minimum breakdown voltages. Low-density polyethylene and UHMWPE exhibited the longest mean times to breakdown of 175±29 ns and 165±94 ns, respectively.

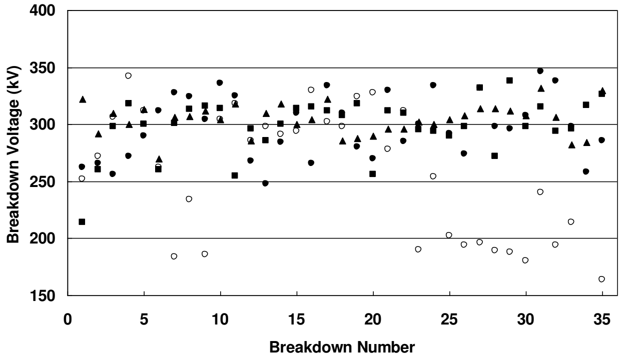

Figure 7. Breakdown voltage magnitude versus shot number for high-voltage electrode type A and sample type II (Figure 1b). Closed circles PP; closed triangles LDPE; closed squares UHMWPE; open circles

With high-voltage electrode type B and sample type II (see Figure 1c), none of the materials tested displayed a particular drop in breakdown voltage due to accumulated surface/bulk sample damage towards the end of the test, as can be seen in Figure 8. Polypropylene and UHMWPE jointly exhibited the highest mean breakdown voltage of 311 kV (±27 kV in both cases), followed closely by Rexolite at 308±32 kV, and LDPE at 305±34 kV. Polypropylene had the least variation of 108 kV between maximum and minimum breakdown voltages, and Rexolite the widest at 178 kV. The times to breakdown were similar for all of the materials, but ultra-high molecular weight polyethylene again had the longest mean time to breakdown of 115±72 ns. All of the materials exhibited a shorter mean time to breakdown for high-voltage electrode type B than with high-voltage electrode type A for the same sample type, and the mean breakdown voltage was higher with high-voltage electrode type B for all of the materials.

For high-voltage electrode type B and sample type III (see Figure 1d), both Rexolite and PP had a significant number of breakdowns at a voltage below 250 kV, particularly from shot 20 onwards, as shown in Figure 9. Low-density polyethylene again exhibited the highest mean breakdown voltage of 306±17 kV (t_{br}(av) = 112±37 ns), and showed the

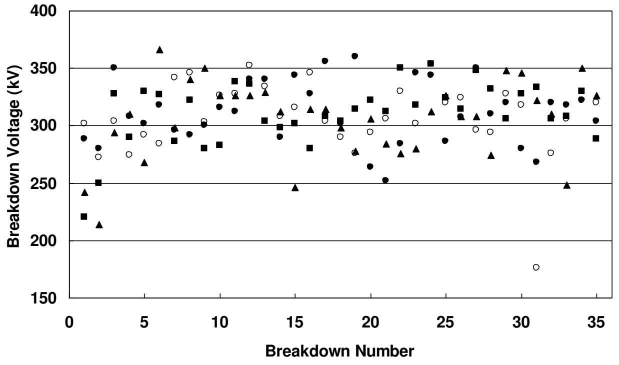

Figure 8. Breakdown voltage magnitude versus shot number for high-voltage electrode type B and sample type II (Figure 1c). Closed circles PP; closed triangles LDPE; closed squares UHMWPE; open circles

least variation of 80 kV between maximum and minimum voltages. Ultra-high molecular weight polyethylene also showed a relatively low variation of 100 kV, and the mean breakdown voltage was 283±20 kV. Rexolite had the lowest mean breakdown voltage of 250±38 kV (t_{br}(av) = 113±91 ns). Ultra-high molecular weight polyethylene again had the longest mean time to breakdown of 184±60 ns. The mean breakdown voltage was marginally lower than that with high-voltage electrode type A and sample type I for all of the materials except UHMWPE in this configuration. The times to breakdown were generally shorter when compared with those for high-voltage electrode type A and sample type I.

Comparing the results in Table 3 for the type II and type III samples, treated using high-voltage electrode type B, shows that the mean breakdown voltage is increased by: 23% for Rexolite; 12% for PP; and 10% for UHMWPE; through the introduction of the shoulder in the type II samples. The only material that does not show an increase is LDPE, where the mean breakdown voltage is similar for both sample types.

In terms of time to breakdown, UHMWPE has the longest mean time in three of the four point-plane cases, indicating that this material could hold off breakdown for longer than the other materials for the same level of peak applied voltage.

With high voltage electrode type A, the type II samples have a longer mean time to breakdown than the type I samples for all materials except UHMWPE. For high-voltage electrode type B, the type III samples have a longer mean time than the type II samples for all materials except PP.

Post-test inspection revealed clear visible surface-discharge damage on all of the samples. This damage was restricted to one location around the circumference of the sample, dictated by the position of the pin, for samples tested with high-voltage electrode type A. Despite being initiated from the same point however, the discharges did not all follow an identical path from the tip of the high-voltage pin to the earth plane. Damage was found in at least two different locations around the circumference of each of the samples tested with high voltage electrode type B, indicating that subsequent surface discharges did not all follow the path established by the first discharge. It is anticipated that each different path followed by the discharge would result in a different time to breakdown, and hence a different breakdown voltage, contributing to the variations in breakdown voltage observed in Figures 6-9.

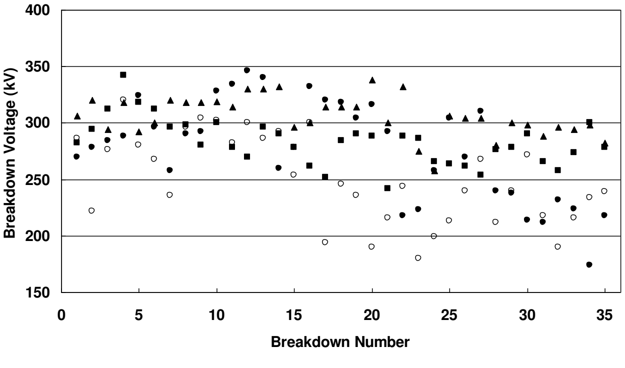

Figure 9. Breakdown voltage magnitude versus shot number for high-voltage electrode type B and sample type III (Figure 1d). Closed circles PP; closed triangles LDPE; closed squares UHMWPE; open circles

For PP, LDPE, and UHMWPE, damage took the form of surface traces (see Figure 10), where it appears that the discharges cause penetration of the top layer of the sample surface, most likely through melting, and ablate material from the discharge channel. The visible surface damage was more severe on the PP samples (see Figure 11a) when compared with the LDPE and UHMWPE samples. Pinhole puncture marks were visible at both ends of several of the samples, indicating that some bulk sample breakdowns had also taken place (see Figure 11b). Such damage was apparent on three of the four PP samples, and the only material that did not suffer bulk breakdown damage in at least one of the tests was LDPE. The Rexolite samples were found to be more severely damaged, with large parts of material removed from the surface-discharge locations. This resulted in all four Rexolite samples being split into two main sections through the bulk of the material. The occurrence of bulk breakdown events is likely to have shortened some of the average times to breakdown in Table 3, compared to if only surface flashover had occurred (as with the LDPE samples), as discussed in section 4.2 and section 5.

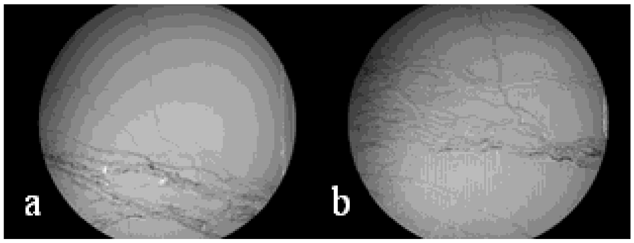

Figure 10. Photographs of surface damage to type II LDPE sample after testing with high-voltage electrode type B (see Figure 1c). Both photographs show different parts of the sample surface located perpendicular to the electrodes; each photograph corresponding to a different discharge site (both x20 magnification).

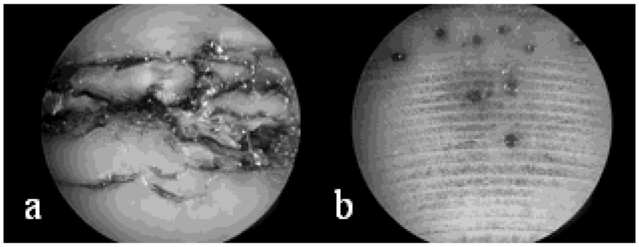

Figure 11. Photographs of damage to type I PP sample after testing with high-voltage electrode type A (see Figure 1a). Figure 11a (x20 magnification) shows surface damage on the surface perpendicular to the electrodes, and Figure 11b (x40 magnification) shows pinhole puncture marks on the sample surface in contact with the earthed electrode, due to bulk breakdown events

4.2 UNIFORM FIELDS

Type III samples of each material were tested with a plane-parallel electrode configuration (see Figure 1e). The electrodes were again removed and polished between samples. The samples were 8 mm long, and each was initially subjected to five shots with a peak applied voltage of -400 kV. The breakdown voltages over the five shots are shown in Figure 12. With this electrode configuration, Rexolite showed the highest mean breakdown voltage of 266±69 kV, with a variation of 150 kV between the maximum and minimum recorded voltages. Ultra-high molecular weight polyethylene had the second highest mean breakdown voltage of 248±36 kV, and the least variation of 94 kV.

Bulk sample breakdowns were more commonly observed in this geometry than with the point-plane geometries, where the pin or collar on the high-voltage electrode will tend to guide the initial discharges along the surface of the sample. This discharge behavior has previously been reported for cylindrical solids held between plane-parallel electrodes in insulating oil [6]. Bulk sample breakdown events were characterized by much shorter times to breakdown compared to those for surface flashover. The pattern generally observed was for the time to breakdown to be in the range 300-500 ns for one or two shots, before dropping to below 80 ns for the remaining shots as bulk breakdown behavior began to dominate. Unlike the measurements reported in section 4.1, once a bulk breakdown occurred under uniform-field conditions, the time to breakdown would never recover, and the tests were hence generally stopped after the occurrence of five breakdown events.

The exception to this was Rexolite, where the first two shots showed times to breakdown of 628 ns and 742 ns respectively, followed by three shots with a time to breakdown in the relatively narrow range 150-200 ns. This test was therefore extended, and six more breakdowns with a time to breakdown of 150-200 ns were observed, before the time to breakdown fell to less than 80 ns for three consecutive shots (14 shots in total), and the test was terminated. The breakdown voltage remained relatively constant over shots three to nine, varying by only 22 kV over the range 314 kV to 336 kV. Post-test inspection of the samples revealed both surface flashover and bulk breakdown damage to all samples.

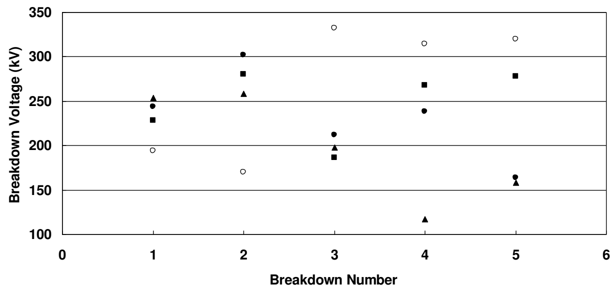

Figure 12. Breakdown voltage magnitude versus shot number for high-voltage electrode type C and sample type III (Figure 1e). Closed circles PP; closed triangles LDPE; closed squares UHMWPE; open circles

5 DISCUSSION & CONCLUSIONS

Two different types of measurement were performed to provide preliminary data for the selection of dielectric materials to be deployed as oil-immersed insulators in high-voltage, pulsed-power machines.

Measurements of the average applied fields required to initiate surface flashover of four different materials revealed that the applied field threshold necessary to cause flashover was lowered by the first flashover event. With particular reference to Figure 4, the field to initiate the first flashover was higher than that for subsequent flashovers, and the gradient of the curves became shallower with increasing flashover number. This suggests that the surface conditioning caused by the first flashover is more damaging to the sample integrity than cumulative damage from subsequent discharges. From a design perspective, the measurements associated with the latter flashover events, when the applied field begins to level out, should be consulted in preference to the measurements associated with the first flashover. Polypropylene has shown the highest levels of average applied field necessary to initiate flashover in all electrode configurations tested, settling at ~600 kV/cm in uniform fields, and ~325 kV/cm in non-uniform fields. The reduction in the applied fields necessary to cause flashover in point-plane gaps when compared with plane-parallel gaps may be useful for predicting the effect of pollution on the electrode/insulator surface [4, 5], for example due to debris present in the bulk of the oil from previous discharges.

For over-volted point-plane gaps, LDPE showed a relatively narrow variation in breakdown voltage/time, and this was the only material not to suffer any bulk (sample) breakdown damage in point-plane gaps despite repeated over-volting. Data on the time to breakdown is important in determining the shape of impulse that can be applied to a given length of insulator without inducing a breakdown event, and the longer times to breakdown shown by UHMWPE in both types of measurement could be significant for the application of shorter-duration impulses, where the energy would be diverted away from the oil/insulator interface before an unwanted surface flashover event could occur. The major damage to the Rexolite samples suggests that this material is not an appropriate choice to act as insulation under the conditions studied.

Visual observation of the samples post-test, and analysis of the pre-breakdown time delays, showed that surface flashover was the only breakdown mode for the initiation measurements reported in section 3, and the primary breakdown mode for the over-volted point-plane gap measurements reported in section 4.1. Although one or two surface flashover events were initially observed, repeated measurements in over-volted plane-parallel gaps were restricted by the occurrence of bulk sample breakdown events, characterized by a sharp drop in the time to breakdown from several hundred nanoseconds to below 80 ns.

When designing a high-voltage system, the length of the insulator should be chosen using information on the known maximum operating voltage of the system, such that the maximum electric field stress would not exceed a value significantly lower than the mean average applied field threshold for breakdown (dependent upon the statistics of breakdown). This could lead to a reduction in downtime for multi-megavolt systems. Cumulative failure distributions based on a Weibull approach may provide information to designers regarding confidence intervals for which a given electrical field can be applied to different materials without inducing surface flashover. While the present work has focused on an experimental approach towards providing results to characterize breakdown events in a solid/liquid system, Weibull statistical analysis of breakdown events in solid/liquid systems will form the basis of a subsequent paper.

Future work will also include the application of pulses with a longer rise-time, in order to analyze breakdown occurring on the rising edge of the pulse.

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