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Impulse Breakdown Characteristics of Polymers Immersed in Insulating Oil

Mark P. Wilson, Member, IEEE, Martin J. Given, Member, IEEE, Igor V. Timoshkin, Member, IEEE, Scott J. MacGregor, Member, IEEE, Mark A. Sinclair, Member, IEEE, Ken J. Thomas, Member, IEEE, and Jane M. Lehr, Fellow, IEEE

Abstract—Surface discharges along oil-immersed solids used as insulators and supports in high-voltage, pulsed-power equipment can lead to catastrophic system failures. To achieve reliable compact pulsed-power systems it is important to quantify the electrical fields at which surface flashover, or other types of breakdown event, will occur for different dielectric materials.

This paper reports the observed behaviour of samples of: polypropylene; low-density polyethylene; ultra-high molecular weight polyethylene; Rexolite; and Torlon; which were subjected to impulse voltages of peak amplitude 350 kV and rise-time 1 µs. The cylindrical samples were located between pairs of electrodes immersed in insulating oil. Breakdown events were studied under both non-uniform and uniform field conditions, with sample lengths being chosen so that the breakdown events occurred on the rising edge of the impulse. Ultra-high molecular weight polyethylene showed the highest average breakdown field 645 kV/cm in uniform fields, and the corresponding breakdown field was reduced to ~400 kV/cm in non-uniform fields. Weibull plots of the various sets of results are presented, providing comparative data for system designers for the appropriate choice of dielectric materials to act as insulators for high-voltage, pulsed-power machines.

Index Terms—Dielectric breakdown, flashover, oil insulation, plastic insulation, pulse power systems.

I. Introduction

Composite liquid-solid dielectric systems are required to insulate sub-sections of multi-megavolt pulsed-power machines, with the incorporation of the solid into the liquid bulk being necessary to provide mechanical support. Unwanted breakdown of such liquid-solid systems means the loss of the output data relating to the shot and can result in catastrophic failure, leading to costly system downtime as oil-immersed sub-systems are drained and disassembled to facilitate the location and replacement of damaged dielectric components. Three different types of breakdown event can occur: bulk breakdown of the liquid dielectric; bulk breakdown of the solid dielectric; or interfacial surface flashover.

The self-healing properties of liquids usually results in the bulk breakdown of the liquid dielectric as being the least damaging to a system. The liquid will have ample time to recover its insulating properties between impulse applications in industrial-scale facilities that are operated in the single-shot regime, with the number of applied impulses achievable in any testing day usually amounting to single figures. It is established that the impulse breakdown voltage increases with shorter pulse duration, and Lehr et al. [1] showed that breakdown fields as high as 11 MV/cm can be achieved under uniform-field conditions in Shell Diala oil AX. The applied impulses had rise-time 130 ps and full-width at half-maximum pulse duration 300 ps. However, studies by Top and Lesaint [2,3] in a "semi-uniform geometry" in insulating oil, where a 100-µm-diameter wire was fed through a 200-µm-diameter hole in the high-voltage electrode to mimic the effect of a protrusion on the electrode surface, have shown that a threshold "inception mean field" value of 50 kV/cm caused filamentary, positive streamers to propagate to the point of breakdown, highlighting the adverse effect that electrode surface defects can have on the breakdown voltages of oil. A review of the form and propagation of streamers in liquid dielectrics can be found in [4].

Bulk breakdown of thin-film polymer samples immersed in silicone oil has been extensively researched, particularly for use in high-voltage coaxial cables. Contrary to liquid breakdown where the applied electrical fields required for breakdown can greatly exceed those for dc voltages, the impulse breakdown voltages for solids is lower than that for the application of dc voltages. Several studies in the 1960's [5-7] showed that the impulse breakdown strength of polythene was only 80% of the dc breakdown strength. Kitani and Arii [8] conducted a study of bulk breakdown of 30-µm thick low-density polyethylene (LDPE) films, and found uniform-field breakdown strengths of 5.8 MV/cm for dc voltages, and 4.9 MV/cm for square-wave impulse voltages of 1 ns rise-time and 100 ns pulse duration. Improvements in impulse breakdown strength are achieved by pre-stressing with dc voltages opposite in polarity to the impulse voltage, and a review of work in this field can be found in [9], with a review of the statistics of breakdown of polymers found in [10].

Requirements of the power industry have meant that the pre-breakdown and breakdown behaviour of composite gaps

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M. P. Wilson, M. J. Given, I. V. Timoshkin, and S. J. Macgregor are with the Dept. Electronic & Electrical Engineering, University of Strathclyde, 204 George Street, Glasgow G1 1XW, UK (e-mail: m.wilson@eee.strath.ac.uk).

M. A. Sinclair, and K. J. Thomas are with the Pulsed Power Group, AWE Aldermaston, Reading RG7 4PR, UK.

J. M. Lehr is with Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185, USA.

consisting of pressboard immersed in insulating oil have frequently been investigated to facilitate proper transformer design. The authors of [11], for example, performed experiments in an oil-solid configuration, designed to replicate the dielectric interfaces in the diverter switches of on-load tap changers, with two electrodes positioned perpendicularly at either side of a rod-shaped solid insulator. The authors compared the breakdown and flashover behaviour of the gap with five different types of solid rod in highly-divergent fields. Polyethylene, which has a relative permittivity closest to that of the oil, showed the highest breakdown voltages. The higher the permittivity mismatch between the solid and the liquid, the greater the distortion of the electric field and bending of the field lines towards the solid surface, creating high-field regions and leading to flashover; hence the lower breakdown voltages recorded for the other four materials with higher relative permittivity.

Katahoire et al. [12] investigated the breakdown properties of cross-linked polyethylene (XLPE) immersed in silicone oil, with electrode profiles chosen to replicate the interfaces found within high-voltage coaxial cable terminations. For the application of positive-polarity lightning impulses (1.2/50 μs), the breakdown voltages were slightly lower with the inclusion of an XLPE spacer in the oil gap than for a gap consisting only of silicone oil. The impulse breakdown field varied from 540 kV/cm for a 2.5 mm oil gap to 380 kV/cm for a 7.5 mm oil gap with no solid, and from 500 kV/cm for a 2.5 mm spacer/oil gap to 350 kV/cm for a 7.5 mm spacer/oil gap.

Studies of surface discharges driven by fast-rising (nanosecond regime) impulses in insulating oil have included measurements of the surface-discharge-field for materials such as nylon and PMMA under uniform-field conditions. Wang et al [13] found that the breakdown field of cylindrical PMMA samples held between plane-parallel electrodes increased 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. On investigation of the sample thickness as a variable parameter, it was found that the breakdown field was unaffected over the range 1-3 mm. The impulses applied were ~40 ns-wide, with peak amplitude 50-200 kV. In another study by Guangjie et al [14], the breakdown voltage associated with a single surface flashover event across 102 individual PMMA spacers was found to vary by up to 180 kV for the same experimental conditions. The inter-electrode gap length was 2 mm in this study (shortest distance between Rogowski profile electrodes), and peak voltages of up to 300 kV were applied, rising in ~10 ns.

The purpose of the present work was to undertake a comparative study of the breakdown fields for oil gaps bridged with five different types of polymer, with applied wave-shapes and levels of electrical fields comparable to those found in industrial machines, in order to facilitate the design of dielectric components to be deployed as insulators in sub-sections of these machines. As well as studying uniform-fields, non-uniform field geometries were also investigated, in order to provide data for the likely reduction in breakdown field due to the presence of protrusions on the surface of the electrodes, or due to the presence of conducting particles present in the oil in the vicinity of the electrodes and solid surface.

II. Experimental Methods

In the present work, impulse voltages of peak amplitude 350 kV were applied to cylindrical samples of:

Polypropylene (PP);
Low-density polyethylene (LDPE);
Ultra-high molecular weight polyethylene (UHMWPE);
Rexolite (cross-linked polystyrene); and
Torlon (polyamide-imide).

Breakdown events were studied with samples located between a pair of electrodes immersed in insulating oil. Different sample and electrode topologies, leading to non-uniform and quasi-uniform field distributions, were investigated to determine the effect on the average surface-discharge/breakdown field. The rise-time of the applied impulses was 1 μs, and the sample lengths were chosen such that breakdown events occurred on the rising edge. Previous results for faster-rising (100 ns) impulses, where breakdown generally occurred on the falling edge after a variable delay time, indicated that PP displayed the highest applied field 630 kV/cm prior to breakdown under uniform-field conditions [15].

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. 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. An 800 Ω aqueous copper sulphate ($CuSO_4$) wave-tail resistor and a 1.6 kΩ $CuSO_4$ wave-front resistor were utilised as wave-shaping components. A wave-front capacitance of 200 pF was also connected in parallel with the test-cell load. The impulse rise-time was 1 μs, with a fall-time to half peak value of 6.5 μs, as shown in Fig. 1a.

The test cell consists of a pair of aluminium 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: for the type A electrode, a 3-mm-long, 1-mm-diameter, tungsten pin protrudes perpendicular to the surface, at a radial distance of 12.5 mm from the electrode centre; while for the type B electrode, a 25-mm-diameter, aluminium collar protrudes perpendicular to the surface at the centre of the plane. 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. L10B insulating oil.

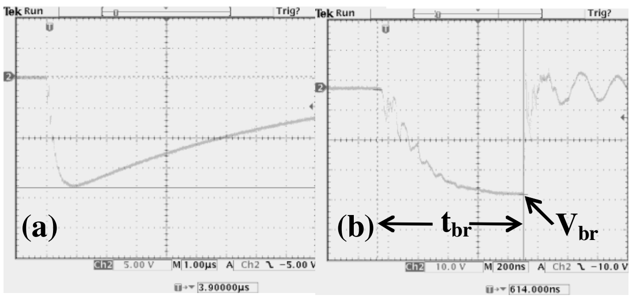

Fig. 1. Fig. 1a: Full voltage waveform with no breakdown event (1 μs/div.). Fig. 1b: Typical voltage waveform for surface flashover of a dielectric sample, with a breakdown voltage (V_{br}) of 350 kV, and a time to breakdown (t_{br}) of 976 ns (200 ns/div.).

Three different types of sample (types I, II, and III) 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 types of sample used for testing is shown in Fig. 2, and a sketch of the various combinations of electrode geometry and sample used for testing can be found in [15]. A 3-mm-long, 1-mm-wide recess 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 ("shoulder") machined to a reduced diameter of 24 mm at the end to be in contact with the high-voltage electrode, allowing them to be used with both type A and type B electrodes. The type III samples have no modifications, and can be used with the type B and type C high-voltage electrodes.

Prior to treatment, all samples were rinsed in warm water with a little detergent to remove any surface grease, and then rinsed in isopropyl 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.

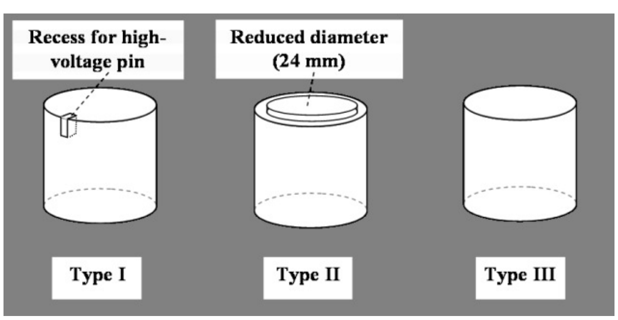

Fig. 2. Sketch of the different types of sample used.

The impulse voltage waveforms were monitored using a Tektronix P6015A 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 ration of 10,000:1. The voltage waveforms were viewed and recorded on a Tektronix TDS3032 digitizing oscilloscope, a typical example at breakdown being shown in Fig. 1b.

Five test series were conducted with different combinations of electrodes and sample geometries. Each test series consisted of subjecting a sample to a number of impulses and recording the breakdown voltages. The electrodes were removed and polished between test sequences.

Sample lengths were chosen such that breakdown events would occur on the rising edge of every applied impulse: for non-uniform field measurements, the samples were 11.5 mm long, giving an inter-electrode gap of 8.5 mm; and for uniform-field measurements (plane-parallel electrodes), the sample/inter-electrode gap length was 4 mm.

III. Experimental Results

A. 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. For each test series, the sample was subjected to 35 impulses.

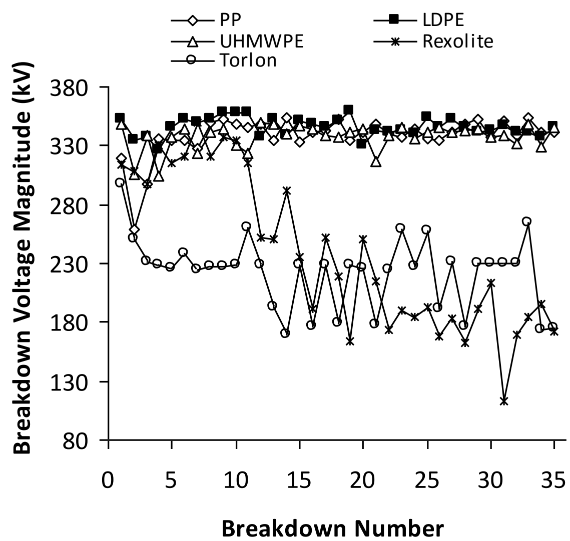

Fig. 3. Breakdown voltage magnitude versus breakdown number for type I samples (recess) tested with high-voltage electrode type A (pin).

Fig. 3 shows how the magnitude of the breakdown voltage varied over the course of the test for type I (recess) samples tested with high-voltage electrode type A (pin). LDPE showed a relatively flat curve in this configuration, with breakdown voltages consistently in the range 330-350 kV, corresponding with breakdown occurring around the peak of the impulse. PP and UHMWPE exhibited some initial variation in breakdown voltage, but settled at around the same level as LDPE towards the end of the test. Rexolite and Torlon both exhibited a significant drop in breakdown voltage after a few discharges, ending up at around half the voltage of the other materials, and a wide variation in breakdown voltage was observed after breakdown number 10 with these materials.

Fig. 4 shows Weibull plots of the breakdown voltage for these experimental conditions. It can be seen that the plots for

PP, LDPE and UHMWPE all follow a reasonably linear behaviour. The plots for Rexolite and Torlon deviate markedly from the behaviour expected from flashovers following a process modeled by the Weibull distribution.

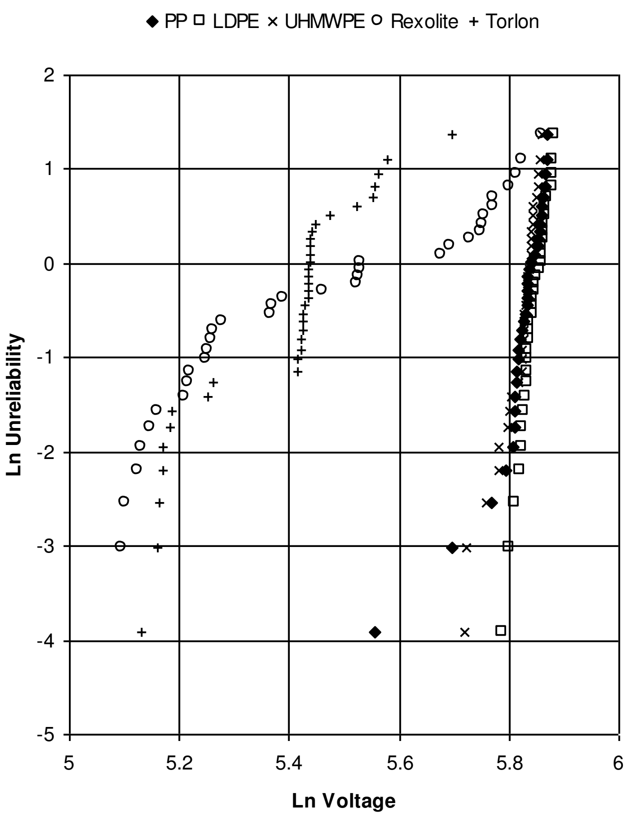

Fig. 4. Weibull plots of voltage magnitude versus breakdown number for type I samples (recess) tested with high-voltage electrode type A (pin).

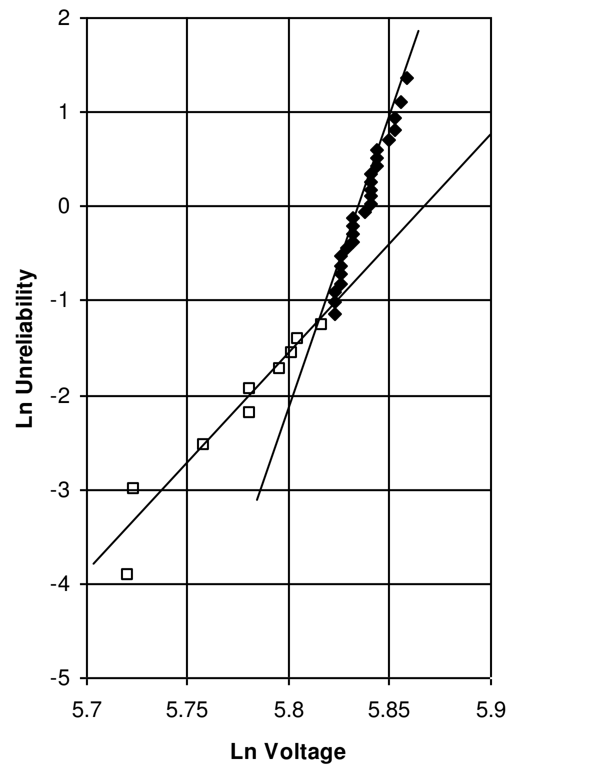

Fig. 5. Weibull plot for UHMWPE type I sample (recess) tested with high-voltage electrode type A (pin).

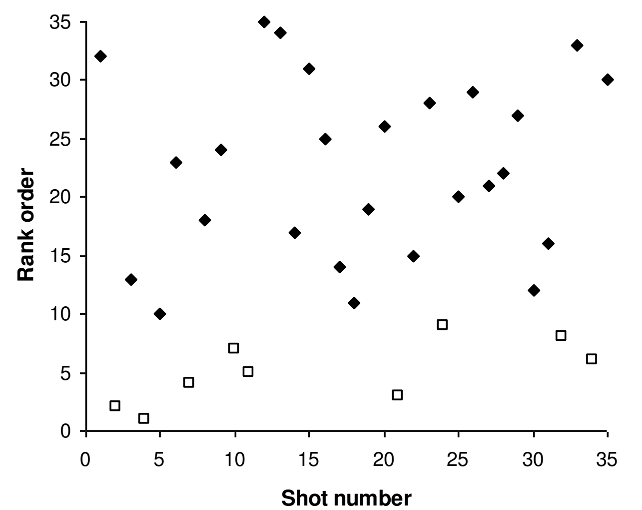

Fig. 6. Plot of breakdown voltage rank versus shot number for UHMWPE type I sample (recess) tested with high-voltage electrode type A (pin). Open squares correspond to points plotted with open squares in Fig. 5.

Fig. 5 shows the Weibull plot obtained for the breakdown data for UHMWPE using a type I sample (recess) and a type A electrode (pin). It can be seen on this plot that there seems to be two distinct regions for the behaviour of the breakdown. The change in gradient observed for breakdowns that occur at lower voltages cannot be explained in terms of a three parameter Weibull distribution, where it would be expected that the points would follow a curve. In addition, the value of the offset parameter would have to be negative to bring the points onto a single line, which is physically unrealistic under these conditions. The plot therefore suggests that there are two different processes occurring during the sequence of breakdown tests. To determine if the observed change in breakdown behaviour was as a result of damage or ageing of the insulator surface the plot of breakdown rank versus breakdown number shown in Fig. 6 was examined.

From Fig. 6 it can be seen that there is no correlation between shot number and the corresponding rank of the breakdown voltage. For the UHMWPE, PP and LDPE samples there was no evidence of bulk breakdown events having occurred in the samples.

The behaviour of the Weibull plot for Rexolite (Fig. 7) shows a more complicated structure, with two broadly straight line regions and a shoulder. The corresponding plot of voltage breakdown rank versus shot number (Fig. 8) shows two regions, an initial region for low shot numbers where the breakdown voltage is constant or perhaps rising slightly, plotted using the solid diamonds in Figs. 7 & 8, followed by a region where the breakdown voltage is decreasing as the sample is repeatedly broken down, plotted as open squares on Figs. 7 & 8. The behaviour for Rexolite suggests that some ageing process is occurring in the system as the sample is repeatedly broken down. A similar behaviour is observed for Torlon although there is a greater drop in breakdown voltage observed between the two straight line regions.

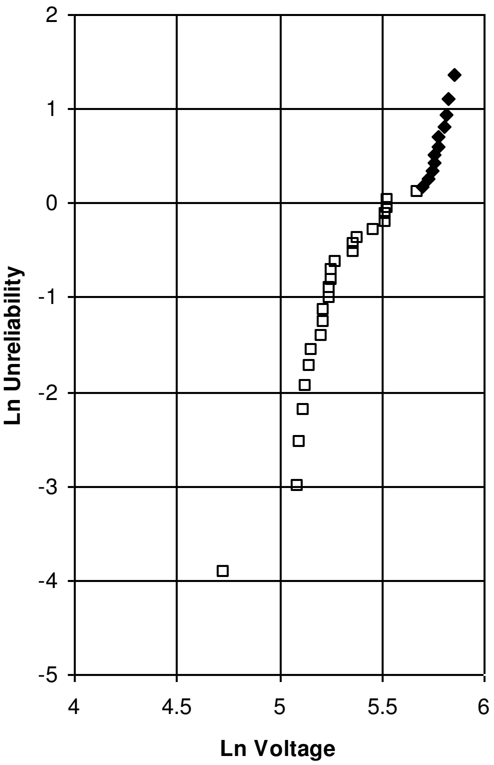

Fig. 7. Weibull plot for Rexolite type I sample (recess) tested with high-voltage electrode type A (pin).

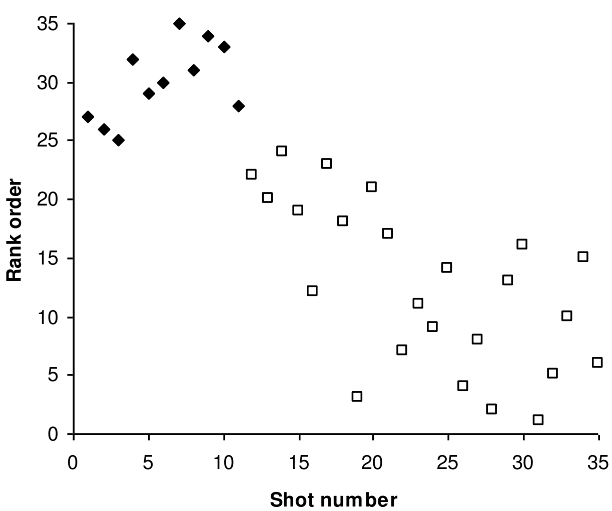

Fig. 8. Plot of breakdown voltage rank versus shot number for Rexolite type I sample (recess) tested with high-voltage electrode type A (pin). Open squares correspond to points plotted with open squares in Fig. 7.

The traces in Fig. 9 represent the breakdown voltages for type II (shoulder) samples tested with high-voltage electrode type A (pin). PP, LDPE, and UHMWPE again exhibited relatively flat traces, corresponding with breakdown events occurring around the peak of the impulse. The breakdown voltage for Rexolite initially fell, and levelled out at around 270 kV for breakdown numbers 29-35. Torlon exhibited the lowest breakdown voltages, varying between 180-230 kV for most of the test. It is expected that the lower breakdown voltages (at around 180 kV) correspond with bulk solid breakdown events.

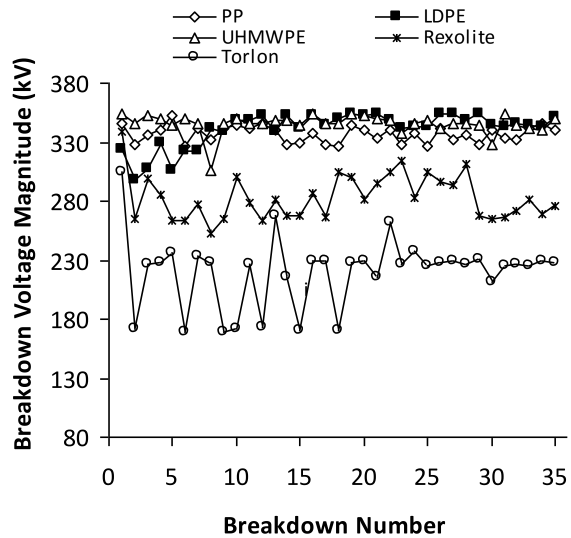

Fig. 9. Breakdown voltage magnitude versus breakdown number for type II samples (shoulder) tested with high-voltage electrode type A (pin).

Fig. 10 shows the corresponding Weibull plots for the breakdown data for the type II samples (shoulder) tested with the type A (pin) electrode. The Weibull plots are broadly similar to those for the type I (recess) samples observed with the type A (pin) electrode, with the data for PP falling close to a straight line, UHMWPE and LDPE showing plots with two straight line regions, and Rexolite and Torlon showing a behaviour with two straight line regions separated by a shoulder.

Displayed in Fig. 11 are traces for type II (shoulder) samples tested with high-voltage electrode type B (collar). LDPE showed the most stable performance initially (breakdown numbers 1-17), although the breakdown voltage varies between 300-350 kV from breakdown number 18 onwards. The average breakdown voltage for PP was lower than that for LDPE and UHMWPE in this configuration, and the breakdown voltage for UHMWPE varied considerably throughout the course of the test. Both Rexolite and Torlon again reflected a significant drop in breakdown voltage after a few discharges, with the breakdown voltage for these materials ending up significantly lower than that of the other three materials. The Weibull plots of this data (Fig. 12) again shows a broadly similar behaviour in the forms of the traces when compared with the data associated with pin electrode geometries. However, there is a much clearer separation in the behaviour associated with the PP, LDPE and UHMWPE data under these conditions.

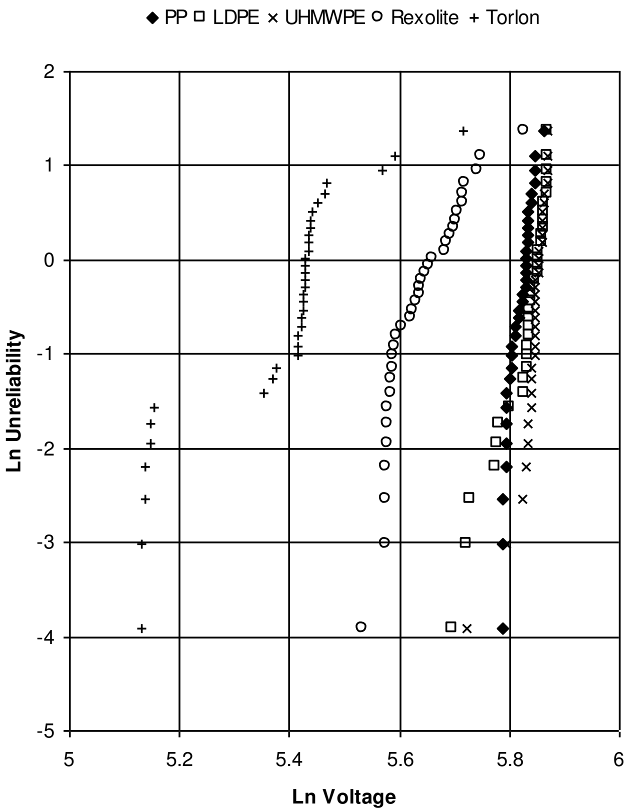

Fig. 10. Weibull plots of voltage magnitude versus breakdown number for type II samples (shoulder) tested with high-voltage electrode type A (pin).

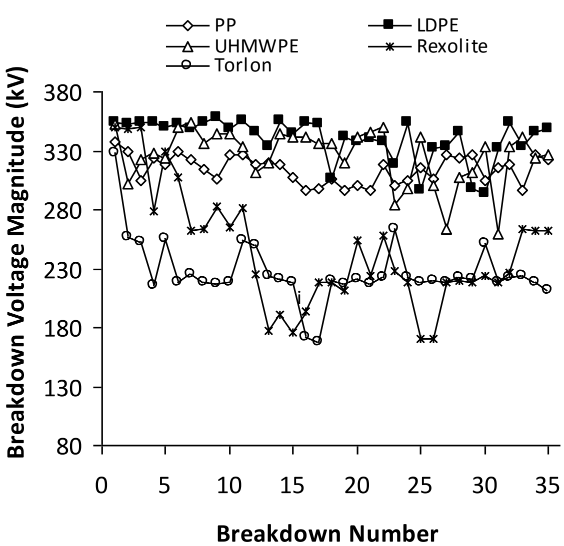

Fig. 11. Breakdown voltage magnitude versus breakdown number for type II samples (shoulder) tested with high-voltage electrode type B (collar).

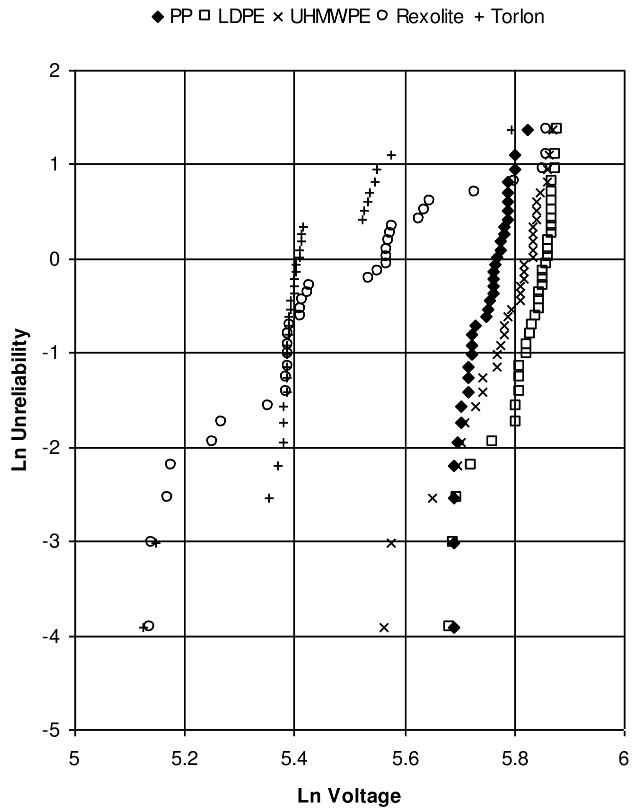

Fig. 12. Weibull plots of voltage magnitude versus breakdown number for type II samples (shoulder) tested with high-voltage electrode type B (collar).

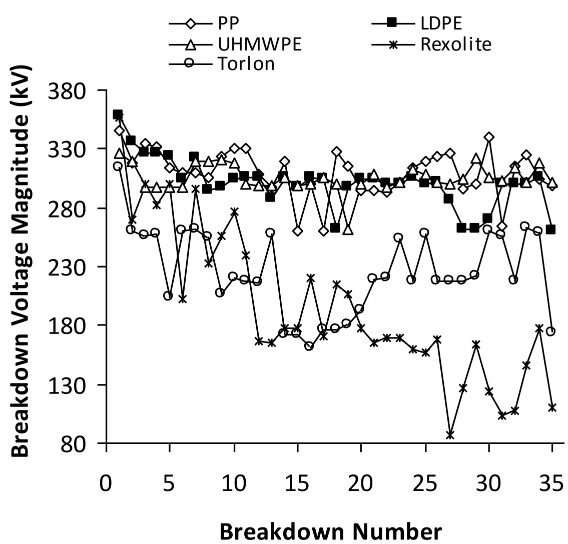

Fig. 13. Breakdown voltage magnitude versus breakdown number for type III samples (no modifications) tested with high-voltage electrode type B (collar).

Type III (no modifications) samples were also tested with high-voltage electrode type B (collar), and the results are displayed in Fig. 13. It is apparent that a drop in the average breakdown voltages was witnessed in this regime when compared with the results in Fig. 11, and most breakdown events occurred before the impulse peak. The breakdown voltage for PP, LDPE, and UHMWPE was rarely higher than

330 kV in this configuration. The breakdown voltage for Rexolite fell steadily from breakdown number 1, with voltages as low as 85 kV being recorded towards the end of the test (breakdown number 27). The breakdown voltage for Torlon also fell from breakdown number 1, and varied between 170-260 kV for breakdown numbers 2-35.

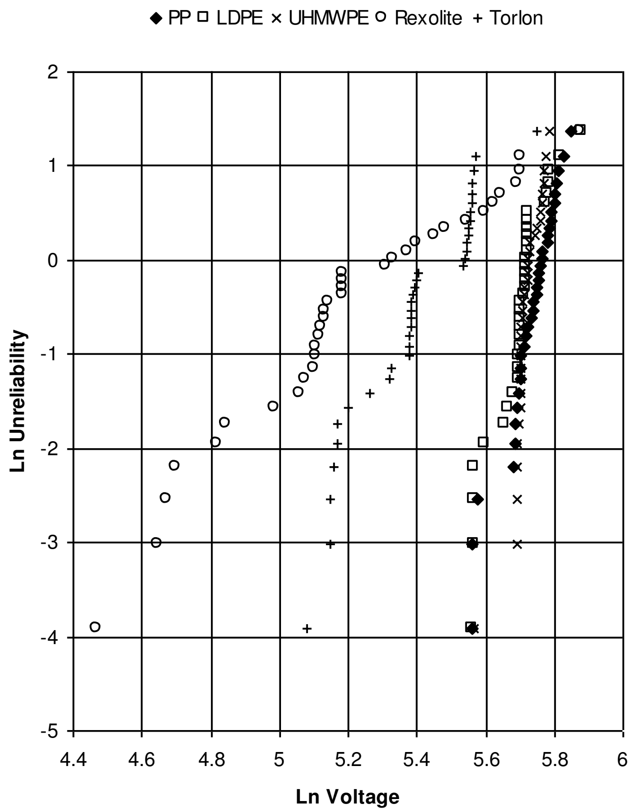

Fig. 14. Weibull plots of voltage magnitude versus breakdown number for type III samples (shoulder) tested with high-voltage electrode type B (collar).

The results in Fig. 14 show the Weibull plots of the data displayed in Fig. 13. The behaviour of the plots for PP, LDPE and UHMWPE is similar for the higher ranked breakdowns. As the breakdown rank decreases, the separation of the plots increases. Unlike in the other geometries where frequently the lower ranked breakdowns for LDPE and UHMWPE file on a line with a lower gradient than that for the higher ranked breakdowns, the opposite effect is observed here. The behaviour for Rexolite and Torlon shows similarities to the other geometries in the form of the Weibull plots, but a more significant shift in the breakdown voltage is observed as the breakdown rank decreases.

Fig. 15 shows the Weibull plots for UHMWPE for the various sample/electrode geometries used. It can be seen that for the highest ranked breakdowns, the breakdown voltages for the type I (recess) / type A (pin), type II (shoulder) / type A (pin), and type II (shoulder) / type B (collar) sample/electrode configurations are similar in value. It appears that the breakdown voltages associated with the type A (pin) electrode are slightly higher than those for the type B (collar) electrode.

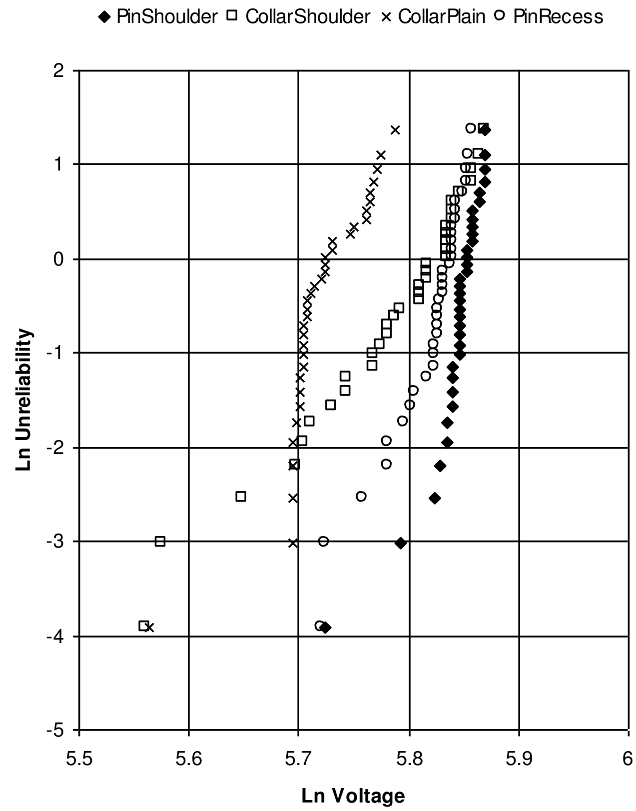

Fig. 15. Weibull plots of voltage magnitude versus breakdown number for UHMWPE for the different experimental geometries.

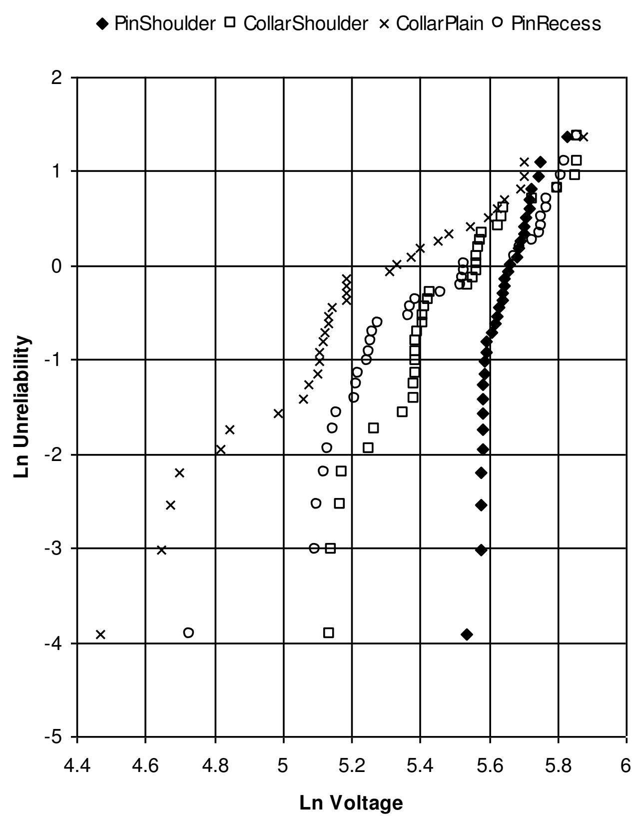

Fig. 16. Weibull plots of voltage magnitude versus breakdown number for Rexolite for the different experimental geometries.

The breakdown voltage for the combination of a type III (no modifications) sample with a type B (collar) electrode is distinctly lower than those for the other sample/electrode combinations. A much clearer separation in the breakdown behaviour at lower ranked breakdowns can be observed, with higher values of breakdown voltage generally being observed for the pin geometries. The difference in the change of gradient for the lower ranked breakdowns for the type III (no modifications) sample / type B (collar) electrode is distinct. A similar behaviour is observed in the Weibull plots for LDPE.

Fig. 16 shows the Weibull plots obtained for the experimental data for the four experimental geometries for Rexolite samples. It can be seen that there is a larger spread in the plots compared to those observed in UHMWPE. For the higher ranked breakdowns it is not possible to separate the behaviour of the different geometries consistently. For the lower ranked breakdowns, the plots are more separated. Unlike the results for UHMWPE, the sample type is more significant, with the data for the type II (shoulder) samples being associated with higher breakdown voltages. Again the combination of a type III (no modifications) sample and type B (collar) electrode leads to the lowest values for breakdown voltage in this regime.

Average values have been calculated for the breakdown voltage for the different experimental geometries and materials, and these are shown in Table 1. This data suggests that when using the type A (pin) high-voltage electrode, the breakdown voltage is higher than that observed using the type B (collar) electrode. It also appears that in general for the type A electrode (excepting LDPE), the value of the breakdown voltage is higher for the type I (recess) samples than for the type II (shoulder) samples. Comparing the average data for breakdowns measured using the type B (collar) electrode, it can be seen that in general the breakdown voltages for the type III (no modifications) samples are lower than those observed for the type II (shoulder) samples. However, it should be noted that the calculated values for the standard deviation of the breakdown voltage are relatively large. The average values of the breakdown voltage indicate a generally similar performance for the PP, LDPE and UHMWPE samples for all experimental geometries. The Rexolite and Torlon samples perform relatively poorly with significantly lower values of average breakdown voltage.

TABLE 1
AVERAGE BREAKDOWN VOLTAGES

Sample Geometry	Type I (Recess)	Type II (Shoulder)	Type II (Shoulder)	Type III (No mods.)
Electrode Geometry	Type A (Pin)	Type A (Pin)	Type B (Collar)	Type B (Collar)
PP	310±17	337±7	314±12	310±20
LDPE	346±8	341±14	340±18	301±21
UHMWPE	338±11	356±9	326±23	305±12
Rexolite	238±66	283±19	244±50	195±65
Torlon	222±20	220±30	227±27	225±36

Figures quoted in kV
± indicates standard deviation of values

B. Uniform Fields

Type III (no modifications) samples of each material were tested with high-voltage electrode type C (plane) to provide uniform field conditions, and the results are displayed in Fig. 17. The breakdown voltage for LDPE steadily dropped from breakdown number five onwards as bulk solid breakdown behaviour began to dominate, characterised by shorter times to breakdown and corresponding lower breakdown voltages. The flashover behaviour in general was difficult to determine in this regime due to the occurrence of bulk solid breakdown events at an early stage in the tests. The breakdown voltage for the other materials varied significantly over the first five breakdown events, and then appeared to level out over breakdown numbers 6-10 as the sample surfaces became 'conditioned'. UHMWPE clearly had the highest breakdown voltages based on the data for breakdown numbers 6-10, and the average breakdown field over all ten breakdown events was 645±50 kV/cm for this material, the highest of the five tested materials. This is around 1.5-times higher than the highest average breakdown field for UHMWPE in non-uniform field tests.

Bulk breakdown damage was observed on all samples, and as there was a change in the breakdown mechanism, with bulk breakdowns occurring after a relatively low number of shots under these conditions, no attempt has been made to produce Weibull plots of the data.

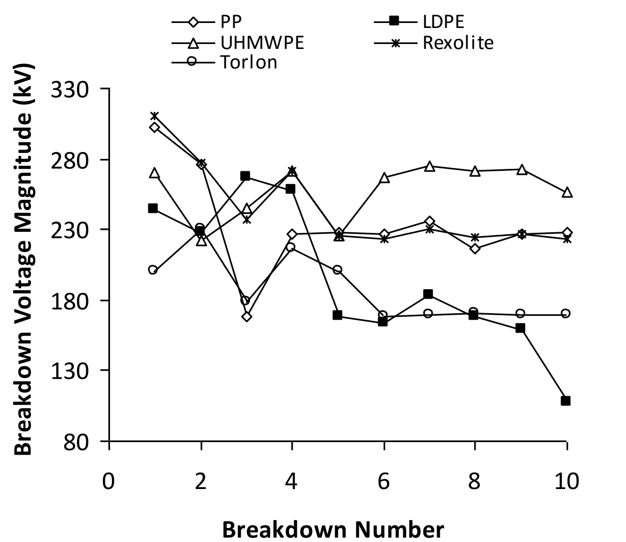

Fig. 17. Breakdown voltage magnitude versus breakdown number for type III samples (no modifications) tested with high-voltage electrode type C (plane).

IV. DISCUSSION AND CONCLUSIONS

The breakdown voltages associated with surface flashover of five different types of dielectric material have been investigated in non-uniform and uniform field conditions under impulse voltages. The experimental conditions were designed in order that breakdown events occurred on the leading edge of the impulse. A Weibull analysis of the voltage breakdown data has been performed for the data under non-uniform fields. The behaviour of the Weibull plots in general do not follow a simple straight line behaviour associated with a two-parameter Weibull distribution, or the curved behaviour that would be expected for a three parameter Weibull distribution. The plots instead show several straight line sections. It was initially assumed that this could suggest that some change in breakdown mechanism was occurring as the samples were repeatedly broken down. However, this was not supported by further analysis of the experimental data where it was observed that the lower ranked breakdowns for PP, LDPE and UHWPE did not occur towards the end of the experimental sequence. The difference could not be attributed to a surface breakdown versus a bulk breakdown mechanism, as no bulk breakdowns were observed using these materials. There is the possibility that for these materials, two competing processes are occurring on the surface of the samples: an ageing process were the surface is damaged, leading to a reduction in the breakdown strength and a possible change in the breakdown mechanism; and a conditioning process were the previously damaged surface is modified by a subsequent discharge.

Some solid breakdown behaviour was also apparent, giving rise to the wide variation in breakdown voltage observed for all materials under uniform-field conditions, and also consistently witnessed for Rexolite and Torlon samples in non-uniform fields. This behaviour is reflected by the wide variation in breakdown voltage for both of these materials, as streamers propagate with varying time delays either over the solid/liquid interface, or directly through the bulk of the solid dielectric.

Comparing the results with those obtained when breakdown was allowed to occur on the falling edge of the impulse [15], some differences in the effects of the electrode/sample geometry can be observed. The breakdown voltages reported here appear to be consistently higher for the type A (pin) electrode geometry as compared with the type B (collar) geometry. The results reported in [15] show that in general the type B (collar) geometry lead to higher average breakdown voltages than that for the type A (pin) geometry. As was observed in the present paper, the breakdown voltages using the type B (collar) electrodes reported in [15] appear to be larger for the type II (shoulder) samples as compared with the type III (no modifications) samples.

PP, LDPE, and UHMWPE all exhibited desirable properties for use as oil-immersed insulators, with high breakdown voltages/fields in non-uniform field measurements. UHMWPE reflected the highest average breakdown voltages in uniform fields. Rexolite and Torlon appear to be poor choices to act as oil-immersed insulators for the conditions investigated, with the effects of bulk solid discharges as well as surface flashover events combining to remove large parts of material from the discharge sites – this could lead to mechanical instability if undiscovered in large-scale industrial machines which are fully immersed in oil.

Although some field enhancement will occur in the ‘uniform-field’ geometries employed here, particularly at the liquid/solid/electrode triple points, the effects are considered to be minimal, with the combination of plane-parallel electrode configuration and non-modified cylindrical solid sample providing a reasonable approximation of uniform-field conditions. The results indicate that the average breakdown field for a given material in non-uniform fields can be 1.5-2 times lower than that seen in uniform fields, and this reduction in breakdown strength could be useful to predict the effect of protrusions on the surface of electrodes [2,3], or of conducting material present either on or around the surface of the solid dielectric from previous breakdown events.

Future work will include the application of impulses at lower electrical field levels, with the results to be used in conjunction with Weibull statistical analysis of the data presented here, to determine if there are field levels below which surface flashover (or other breakdown events) will not occur, even after the application of multiple impulses. The intention is to provide system designers with confidence intervals for which a given electrical field can be applied without resulting in a breakdown event.

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Mark P. Wilson (M’10) was born in Stranraer, Scotland, in 1982. He received the B.Eng. (Hons.) degree (2004) and the M.Phil. degree (2007) in Electronic & Electrical Engineering from the University of Strathclyde, Glasgow, U.K. He is presently studying for the Ph.D. degree at the University of Strathclyde, working on a project to analyze the surface flashover properties of dielectric materials used in pulsed power research. He is a member of the IEEE and IET.

Martin J. Given (M’99) is currently a Senior Lecturer in the Department of Electronic and Electrical Engineering at the University of Strathclyde. He received a degree in physics from the University of Sussex in 1981 and a PhD in electronic and electrical engineering from the University of Strathclyde in 1996. His research interests include, ageing processes and condition monitoring in solid and liquid insulation systems, high speed switching and pulse power applications.

Igor V. Timoshkin (M’07) received a degree in physics from the Moscow State University and the Ph.D. degree from the Imperial College of Science, Technology and Medicine, London, U.K., in 1992 and 2001, respectively. He joined the Department of Electronic and Electrical Engineering of the University of Strathclyde (Glasgow, U.K) in 2001, where he became a Research Fellow in 2002 and a Lecturer in 2006. His research interests include properties of solid and liquid dielectric materials; electronics of plasma discharges in condensed media; practical applications of electrohydraulic and high-power ultrasound pulses produced by spark discharges, effects of electric fields on biological objects.

Scott J. MacGregor (M’95) received the B.Sc. and Ph.D. degrees from the University of Strathclyde, Glasgow, U.K., in 1982 and 1986, respectively. He became a Pulsed Power Research Fellow in 1986 and a Lecturer in pulsed-power technology in 1989. In 1994, he became a Senior Lecturer, with a promotion to Reader and Professor of High Voltage Engineering, in 1999 and 2001, respectively. His research interests include high-voltage pulse generation, high-frequency diagnostics, high-power repetitive switching, high-speed switching, electronic methods for food pasteurization and sterilization, generation of high-power ultrasound (HPU), plasma channel drilling, pulsed-plasma cleaning of pipes, and stimulation of oil wells with HPU.

Mark Sinclair (M’03) received the B.Sc. degree from the Victoria University of Manchester, UK, in 1990 and then went to St. Andrews and Strathclyde Universities in Scotland to receive an MSc in Laser Engineering and Pulsed Power Technology. In 1992 he joined the Pulsed Power Group at AWE. Initially he worked on the E Minor machine moving on to Mogul E which was optimised for radiography of dense objects. Currently he is the technical lead and Team Leader for Pulsed Power at AWE running a number of programmes to develop fundamental knowledge and skills, to develop new x-ray sources and to use Pulsed Power for Hydrodynamic simulation.

Kenneth J. Thomas (M’05) was born in Carmarthen, South Wales in 1958. He received the B.Sc degree in physics from Imperial College, London in 1979. He completed the Ph.D. degree in Laser Physics, also at Imperial College, in 1983 and joined the Pulsed Power Group at AWE. Since then he has been involved in the design and construction of multi-MegaVolt pulsed power machines for flash radiography and supporting research, particularly the application of Induction Voltage Adder technology to the next generation of accelerators. He is a C. Phys. and a member of the IET and IoP.

Jane Lehr (S’91-M’96-SM’02-F’08) received the B.Eng. degree from the Stevens Institute of Technology, Hoboken, NJ, and the Ph.D. degree in electro physics from Polytechnic University, New York, NY. Since 2002, she has been a Member of the Technical Staff with the Exploratory Pulsed Power Technologies Branch, Sandia National Laboratories, Albuquerque, NM. Prior to joining Sandia National Laboratories, she was with the Directed Energy Directorate, Air Force Research Laboratory. Dr. Lehr is currently the President of the IEEE Nuclear and Plasma Sciences Society.