

LARGE AREA DIELECTRIC BREAKDOWN UNDER PULSED CONDITIONS

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Abstract

Dielectric materials are a critical component of pulsed power systems. Often times these materials are the limiting factor in system design and operation. To aid in the understanding and prediction of the breakdown of polypropylene under pulsed operating conditions experimental evaluation and analysis of large area 50.8 cm×121.9 cm (20"×48") sheets of 1.59 mm (1/16 in). polypropylene material between aluminum plates were explored. Accelerated lifetime tests in the thousands of shots range were made with various types of coating on the aluminum electrodes and with bare electrodes. The aluminum and polypropylene were assembled under vacuum and sealed along the plate edges. Testing was conducted utilizing pulses with two different damped ringing shapes. This paper describes the testing configuration and process, followed by a discussion of the breakdown data and how it relates to historical test results.

I. INTRODUCTION

Solid dielectric performance is a critical aspect of the design and performance of low impedance pulsed power systems enabling operation at higher electric field levels than liquid or gas dielectrics. However, pulsed power system designs using solid dielectrics should include lifetime considerations to ensure design and operational cost effectiveness. Many nuances must be considered including [1]:

- the type of dielectric,
- the ability to purchase the dielectric in homogeneous and continuous large area samples,
- surface treatments for the transmission line plates,
- how to implement high current penetrations,
- how to mitigate tracking at the edges of the transmission line plates,
- as well as lifetime and reliability.

Materials considered for large area lifetime analysis included: Polycarbonate, Silicon, Polypropylene, high density polyethylene, G10, G11, and CPVC. Limited testing was conducted with most of these. There is a particular result from the testing of Polycarbonate that should be mentioned. A pulsed test, utilizing

Polycarbonate and paint coated transmission line plates, was demonstrated to last 1893 pulses with a 100 kV peak. The same configuration tested with DC fields (50 kV – 9mins, 60 kV – 9mins, 75 kV-7mins, 90 kV-6mins, 120 kV – 10mins) did not fail. Ten minutes equates to 20 million 30 μs pulses indicating that the dynamic nature of the pulse accelerates the failure of the dielectric. It is unclear if it is the rising edge of the first pulse or the rapidly changing fields in the later portion of the waveform that impacts failure the greatest.

Of the sheet materials, polypropylene demonstrated the most promising performance. For this reason the results included in this paper are based on polypropylene. Overcoming manufacturing limitations in surface area was approached by developing the ability to assemble smaller sections of dielectrics together forming seams that are capable of maintaining voltage hold off [2]. Transmission line surface treatments were considered as techniques to increase voltage hold off and dielectric lifetime. Both coated and uncoated plates were tested with some uncoated plates achieving lifetime results that were similar to coated plates. High current penetrations through the dielectric were developed and verified at currents up to 80 kA in test fixtures and Protogen [2]. Tracking around the edges of the dielectrics was addressed with a number of different techniques including increasing tracking distance, reducing corona formation through the use of graded impedances, and the elimination of corona formation through a combination of transmission line geometry selection at the edges and a potting process. Lifetime of seamless polypropylene dielectric sheets separating 50.8 cm×121.9 cm (20"×48") coated transmission line plates with potted edges is discussed and followed by results dating back to the 1960s.

II. EXPERIMENTAL SETUP

Voltage waveforms were generated using a two stage Marx generator capable of outputting a 200 kV pulse into an inductor that was in parallel with the transmission line plates. The pulser control was automated to allow for unmanned operation around the clock. The voltage waveform, see Figure 1, chosen for the experiment was based on a typical ringing shape that would be observed

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in an under damped low impedance system. Figure 2 contains a picture of the transmission line plates connected to high voltage cables from the pulser. The edges of the transmission line plates have been assembled to eliminate tracking. Additional damping resistance was added in parallel with the test fixture for some experiments. The resulting waveforms plotted with Matlab [3] and test fixture are provided in Figure 1 and Figure 2. The added damping primarily impacted the high frequency content of the waveform.

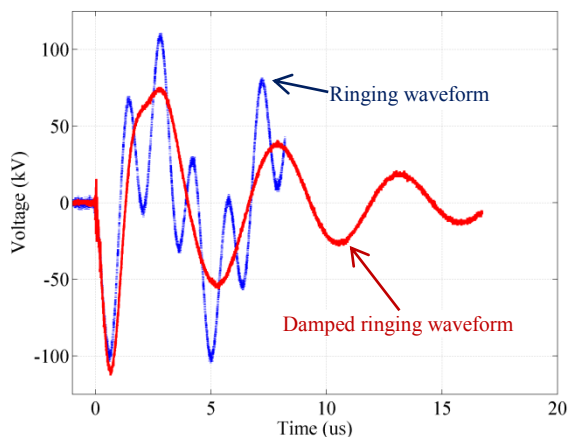


Figure 1. Example measured test voltage waveforms.

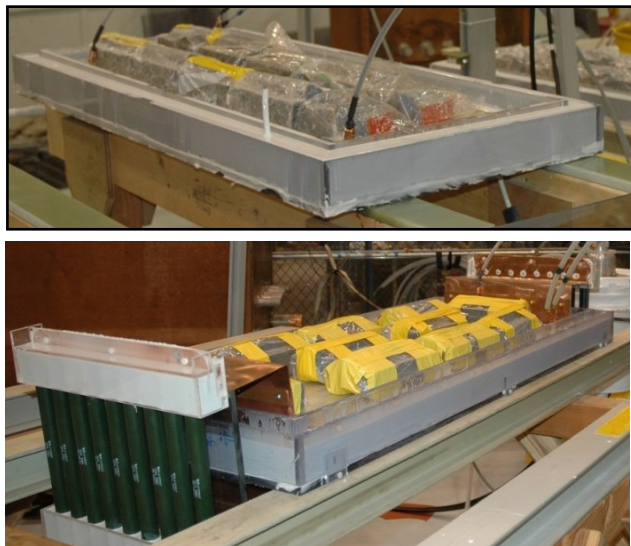


Figure 2. Test fixtures with/without damping resistors.

III. ANALYSIS

Table 1 summarizes analyses of the results of all tests of 50.8 cm × 121.9 cm × 1.59 mm (1/16 in) polypropylene (pp) except for tests with paint coated electrodes. The results are for coatings described as Powder coating and Super Corona Dope (SCD) manufactured by MG Chemicals [4] on aluminum electrodes, and for bare electrodes. Each line of Table 1 identifies a group of tests with a specified electrode coating that were performed in the specific time period

stated, either with a ringing waveform (R) or a damped ringing waveform (D). Average coating thickness and the number of individual samples N in each group are stated. Each sample was tested at a fixed electric field E , repeatedly until breakdown established the life L for that sample. The field E_k that corresponds to a life of 1000 shots is calculated for each sample based on the assumption $L \propto E^{-n}$ where $n = 9$, and the mean 1000-shot life \bar{E}_k is given. The standard deviation of the N values of E_k is given a percentage of \bar{E}_k . The geometric mean life for the group is stated; this corresponds to averaging the N values of $\ln L$ and taking the exponential of this mean. The comments on each line are discussed in the following line-by-line discussion.

The Powder-coated samples, see Table 1, were all tested with ringing waveforms that consisted of voltage excursions of approximately equal magnitude and opposite sign; excursions of opposite sign followed at about 75% of the magnitude of the first pair; and then excursions of still lower amplitude. The stresses for each test were calculated from the maximum voltage, the sum of the pp thickness (1.59 mm) and the average coating thickness (which was in the 0.38-1.02 mm range). The life exponent n in the assumed equation $L \propto E^{-n}$ was estimated by calculating the stress E_k corresponding to 1000 shot life assuming different values of n to find the value that minimized the standard deviation of the 12 E_k values. This value of n was near to 9, and this value was used to calculate an average stress \bar{E}_k (555 kV/cm) for the 12 samples; the value of the standard deviation σ was 11%.

This analysis for the Powder coated samples appeared reasonable because there was a significant number of samples (12) and a range of test fields. For most of the other lines in Table 1 there is a small range of test fields, so that no value of n can be estimated. For the group SCD (B), there is a range of fields, but because of the small number of tests (3) scatter masks any correlation between E and L . For SCD (E) there is a range of fields and the data from four tests suggests $n = 9$ or 10.

The value of $n = 9$ has been used throughout Table 1 to calculate \bar{E}_k and σ . Since the geometric mean lives for the groups other than Powder are not very different from 1000 shots and the adjustment in stress using $n = 9$ is not great, errors if $n \neq 9$ may not be large.

The coating SCD, see Table 1, was also tested with the ringing waveform and line 2 of the table shows a value of \bar{E}_k of 595 kV/cm, about 7% higher than for the Powder. One test with a coating of only 254 μm instead of the typical 508 μm shown on line 3 has been excluded from line 2; it has a higher \bar{E}_k , which might be expected for the thinner coating. If it is included then SCD gives an \bar{E}_k value 10% higher than the Powder (line 4). The differences between Powder and SCD are probably significant.

Table 1. Results of Life Tests on Polypropylene.¹

Coating	Group	Date tested (month/year)	waveform	Average Coating thickness (μm)	N	\bar{E}_k (kV/cm)	σ (%)	Geom Mean Life (k-shots)	Comment
1. Powder		8/10-1/11	R	381→1016	12	555	11	1.58	Has E-range; n = 9 indicated
2. SCD	B	11/10-1/11	R	508	3	595	3.3	1.48	Has E-range, but n is masked by scatter
3. SCD	B	1/11	R	254	1	646	--	1.0	No E-range
4. All SCD	B	11/10-1/11	R		4	608	5.0		Has E-range
5. SCD	C	2/11-3/11	D	508	3	735	3.5	1.38	No E-range
6. SCD	D	6/11-7/11	D	508	4	600	6.7	1.47	No E-range
7. SCD	E	5/12-9/12	D	508	4	618	10.3	1.09	Has E-range; n = 9 or 10 indicated
8. Bare	A	6/11-7/11	D		2	720	5.6	0.83	No E-range
9. Bare	B	1/12-1/12	D		3	763	9.1	1.68	No E-range
10. Bare	C	6/12-7/12	D		2	726	3.3	1.17	No E-range
11. Bare	D	9/12-9/12	D		2	615	10	2.52	No E-range

¹ R: ringing waveform; D: damped ringing waveform; \bar{E}_k : mean field for a 1000 shot lifetime; σ : standard deviation as a percentage of \bar{E}_k ; Geometric mean life of the sample set at the test field; E-range: the samples were tested over a range of field levels; No E-range, all samples were tested at the same field level.

Next, SCD coatings, see Table 1, were tested with a damped waveform in which successive excursions reduce by a factor of about 1.5. The first group of tests with the damped waveform (line 5) was done in the same period as the ringing tests and show \bar{E}_k to be 735 kV/cm, higher by ~20% than for the ringing waveform. But when this test was repeated three and seven months later (lines 6 and 7), in neither case was this increase seen. The difference between line 5 and lines 6 and 7 is greater than is likely from statistical variations, and is due to a change in either coating quality or variations from lot to lot of polypropylene. If an average of lines 5-7 is taken the value of \bar{E}_k is about 8% higher with the damped waveform than with the ringing.

All tests with the bare plates, see Table 1, were done with the damped waveform. The first group of these tests (line 8) was done in the same time period as lines 6 and 7 and therefore the ~18% increase of \bar{E}_k from an average of 609 to 720 kV/cm is probably significant. Subsequent tests with bare electrodes were done at three separate times and averaged 701 kV/cm, essentially the same \bar{E}_k value, though there were considerable differences between them (lines 9-11).

Conclusions are that the coatings tested lower on the electric field stress that corresponds to 1000 shot life by 10-15% from the value for bare plates; and that SCD lowers the stress slightly less than Powder. SCD also has the advantage that it can be applied with a more consistent thickness.

The relation of these results to other experience with polypropylene will be discussed in the following section.

IV. HISTORICAL RESULTS

The experience with solid dielectrics in general and polypropylene (pp) in particular described below was mostly gained at the Atomic Weapons Research Establishment (AWRE) from 1965 to 1967, with some later experience at Physics International. Some of the AWRE work appears in the book "J.C. Martin on Pulsed Power" [5] and in the Air Force Weapons Laboratory (AFWL) Dielectric Note series. The unpublished work is from notes made by one of the authors (Smith) at AWRE and his experience at Physics International (PI).

In an impulse breakdown test, of a substantial thickness, of solid dielectric the breakdown strength is not necessarily determined by the solid itself if the medium in which the solid is immersed is stressed above its breakdown strength. If the immersion medium is oil, for example, breakdowns typically initiate first in the oil and penetrate the solid. If the medium is air the breakdown of air may not have enough energy to penetrate the solid--but for thick plastics high voltage tracking at the electrode edges will prevent fields reaching the breakdown strength of the solid. In most AWRE tests that measured the breakdown strength of solids the solids were immersed in deionized water, where the field in the water is lowered below its breakdown level by the high permittivity of water (~80). Often instead of water, dilute Cu SO₄

solution was used, which lowered the field further by conduction. This reduced the fields at the edges of thin electrodes, which are convenient to use for large area tests, below breakdown. The importance of the immersion medium is not always stressed in AWRE publications.

Layers of inferior dielectrics (liquid or solid) between the electrodes and the dielectric under test, or between layers of this dielectric—even layers thin compared to the dielectric—have the same effect, developing breakdowns that rapidly propagate through the high-quality dielectric. This is illustrated in the case of Mylar by AWRE results obtained by Smith and shown in Table 2. Layers of higher permittivity develop lower fields and reduce the breakdown field less.

Table 2. Pulsed breakdown voltage of two layers of 254 μm (0.01") Mylar with thin layers of different substances in between.

	Breakdown Voltage (kV)	Permittivity
Water	260	81
Glycerine	210	45
Ethylene Glycol	250	40
Hardener 951	205	12
Araldite Unpolymerised	230	9
Castor Oil	165	4.7
Tensol Cement (liquid)	205	~3
Tensol Cement (solid)	155	3

While Table 2 is for layers between the Mylar sheets, the results were similar for layers between the Mylar (or another plastic) and the electrodes. An exception to this is the case of a layer on the negative side of polyethylene or polypropylene. These plastics (both hydrocarbons) have a large polarity effect, and resist breakdown from field enhancements on the negative side. This polarity effect is mentioned in the case of “stabbed” polyethylene switches in [5], p. 62. In stabbed switches the breakdown due to the field-enhancement at the tip of the ionized stab occurs at a voltage that is 2.4 times higher when the stab is negative than when it is positive, at least in the time-range 100 to 1000 ns where the breakdown voltages are essentially time-independent; at shorter times this factor rises even higher, because breakdown from a negative field-enhancement is slow to propagate. Results for stabbed pp were similar to those for polyethylene. The polarity effect was also very apparent when breakdown was initiated from a thin (≤ 1 mil) negative trigger electrode in a liquid layer between sheets of plastic. For most plastics breakdown immediately occurred through the plastic, and this was used at AWRE in nanosecond-jitter triggered switches. But with polyethylene or pp a streamer propagated some distance through the liquid

layer, and only penetrated the plastic when because of its length it had developed a much greater field-enhancement than existed at the metal edge.

In AWRE tests that identified the breakdown strength of the solid dielectric itself in uniform fields, a number of solid dielectrics were found to have mean single-shot breakdown strengths F proportional to v^{-n} where v is the volume of dielectric and the exponent n is a constant. For a number of dielectrics n was found to be about 0.12. In decreasing order of electric strengths, for 1 cc volumes, these dielectrics were: Perspex (an acrylic), 4.0 MV/cm; polypropylene (pp), 3.0 MV/cm; polyethylene (pe), 2.6 MV/cm; and an epoxy (Araldite), 2.0 MV/cm. Data on the first three are plotted in Figure 3, taken from [6]. Volumes tested approach 10 ℓ for pe, 1 ℓ for Perspex and epoxy, and 100 cc for pp. Samples from Table 1 were of 983 cc volumes but were not tested for single shot breakdown.

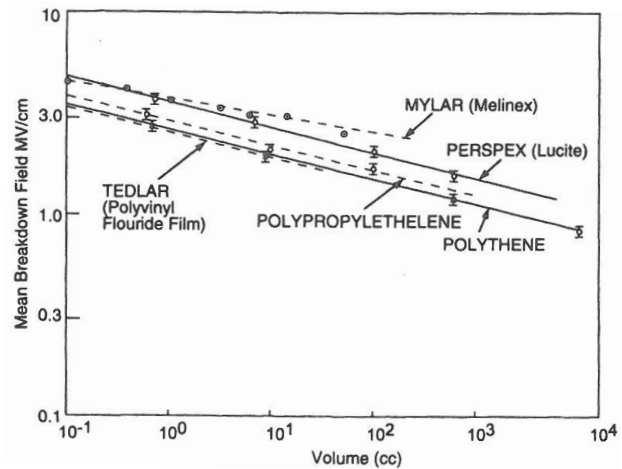


Figure 3. Volume effect for single shot breakdown of plastics.

The breakdown strengths were independent of the pulse duration or risetime in the tens to hundreds of ns range, never occurred after the peak of the voltage pulse, and where the DC strength could be checked in the case of small samples, it was essentially the same as the impulse value. The breakdown processes were therefore considered time-independent.

The recognition that the average breakdown strengths of dielectric samples must decrease with increasing sample size if there is any scatter in their values was due to J.C. Martin, and is very important for estimating breakdown in both solids and liquids in the field of pulsed power. The proportionality of F to v^{-n} , shown as the linear dependence when $\ln F$ is plotted against $\ln v$ in Figure 3, was inferred by the AWRE group to result from the probability distribution for the breakdown strengths of samples of equal volume, expressed as fractions of their mean, having a form such that the probability distribution of the strengths of groups of samples, which is the lowest strength in the group, has the same distribution when

expressed as fractions of *their* mean. The standard deviation σ of single-shot breakdown fields expressed as a fraction of the mean μ will therefore also be independent of sample size, or volume.

Martin approximated this probability distribution by a graphical method. Later at PI, Smith and Creedon [7] showed that the probability that the sample survives a field F is of the form

$$p(F/\mu) = \exp[-a(F/\mu)^{1/m}] \quad (1)$$

where a is a constant; and that when σ/μ is small the result $\sigma = 0.12 \mu$ holds approximately. For the dielectrics listed in Table 1, therefore, $\sigma \approx 0.14 \mu$, and that is what AWRE found.

Note that the dielectrics in Figure 3 are in the form of sheets 254 to 3175 μm thick. When AWRE tested Mylar in sheets less than 25.4 μm thick [8] higher breakdown strengths were found. Later a PI group under the author tested pp in stacks of 6.35 μm sheets; the breakdown strength was found to be much higher than that of thicker sheets of the same volume, and moreover the standard deviation was only a few percent, so the dependence on volume was much weaker. The construction was used by PI in reliable, long-life 3MV pulse-charged capacitors. ([5] wrongly reports that the PI work was with Mylar.)

At AWRE Martin investigated the dependence of the life of Mylar on the electric field as a fraction f of the single-shot breakdown value. [9] applies dc to 127 μm -thick Mylar in air and then rings the voltage with 92% reversal. The important dielectric stresses in this work were found to be the peak stresses of each polarity and not the peak-to-peak values, which in fact greatly exceeded the single-shot strengths of the samples. Peak-to-peak stresses are important in capacitors where dc fields are annealed by charge transfer into the liquid impregnant from the sharp edges of thin metal foils of the windings, and the voltage swing on capacitor discharge then generates pulsed fields in the impregnant that are proportional to the magnitude of the voltage swing.

In [9] Martin found that the life of Mylar samples was proportional to $t^{7.5}$, and in fact that the mean life is $(V_{\text{break}}/V_{\text{test}})^{7.5}$, though in other tests of 254 μm Mylar underwater he reported finding the exponent to be 16. These results are similar to the exponent $n = 9$ reported here. For an exponent 7.5 Martin asserted that in a train of pulses or an oscillation each peak voltage V_i can be considered to represent a fraction $(V_i/V_0)^{7.5}$ of one pulse with the magnitude V_0 of the largest pulse (usually the first pulse). On this view, and with $n = 9$, the ringing pulse used in the tests reported here is essentially equivalent to two pulses of the maximum amplitude, and the damped pulse to a single pulse; successive pulses 75% or less of the first pulse add up to the order of 0.1 pulse, and are equivalent to a 1% increase in field, which is negligible here. In the results on pp reported in this paper we therefore consider peak fields and not peak-to-peak values. On the view that the ringing waveform has two excursions and the damped waveform only one, the lives

under the two waveforms might be expected to differ by a factor of $2^{1/9} \sim 8\%$; this is consistent with the difference calculated in the previous section for the coating SCD using an average of all values obtained with the damped waveform, but this might be considered fortuitous.

The breakdown strength for the bare plates can be compared with the value expected from AWRE single-shot results. The volume of the 20 in. x 48 in. x 0.062 in. samples is about 983 cc., and the results in Figure 3 and [6] predict the mean single-shot strength to be $3 \times 975^{-0.12}$ or 1.3 MV/cm. The AWRE results for pp in Figure 3 extend only to 100 cc; but the linearity of the plot of $(\ln E)$ against $(\ln v)$ appears to be holding at this volume, so the extrapolation should be reasonably accurate. The field for 100 shot life is estimated by dividing by $(1000)^{1/9}$, giving 603 kV/cm. The mean of lines 7 to 10 in Table 1 is about 710 kV/cm. The difference is not great, but could be explained by our polypropylene being slightly superior to that used by AWRE almost 50 years ago. Alternatively, we do not know the exponent 9 accurately; a value of 11 would bring results essentially into line.

The standard deviation of the results for the Powder coating in Table 1 is 11%. The standard deviation of pp breakdown data at AWRE averaged 14%, as implied by the 0.12 exponent of the volume effect. The difference could be regarded as barely significant; but the weighted average of all the other sample groups in Table 1 is 6 or 7 %; it is 6.0% for SCD and 7.2% for bare electrodes. While any one σ value is very inaccurate because of the small sample size the lower average is probably significantly different from 14%. It should be noted that σ may be larger for Powder than for SCD because the Powder coating thickness varied more across each individual sample (this could also explain why the mean breakdown strength E_k is lower). Therefore a value $\sigma \sim 6$ or 7% might also apply to a uniform Powder coat.

Several possibilities exist for why the standard deviation seen here is less than the AWRE value: the larger pp volume (unlikely because linearity of the AWRE plot of $(\ln E)$ against $(\ln v)$ appears to be holding at 100 cc); the pp being better quality than that tested at AWRE (plausible, though many different pp orders or types were tested at AWRE and all results fitted the same pattern); or the stress for 1000-shot life being more consistent than the single-shot stress. In the cases of Powder and SCD the breakdown could be initiated in the coatings, and the coating strengths could be more consistent than that of the pp; but the mean $\sigma = 7.2\%$ for bare electrodes would still require explanation.

The fact reported here that the coatings lower the breakdown strengths, at least for 1000-shot lives, may be considered consistent with the AWRE results described above in which thin, electrically weaker coatings initiate breakdowns. As illustrated in Table 2, the extent to which the strength would be lowered would depend on the coating permittivity, which is not known for either of the coatings used here. The permittivity of polypropylene

(2.3) is lower than that of almost any other solid; the only instance of a lower permittivity solid known to one of the authors (Smith) is a value of just under two reported for radiation-aged polyethylene. However, the situation is different from that in Table 2, because the coatings here have thicknesses that are not negligible compared to that of the pp; as a result, a higher permittivity coating will lower the breakdown strength of the composite independent of whether the coating breaks down, because it will raise the field in the pp above the average field, which is what is used in the analyses. The SCD coatings always totaled about one third of the pp thickness, and a coating permittivity of just over 3 would increase the field in the pp to about 10% above the average, which would be consistent with the reduction in breakdown strength seen. The Powder coatings tended to be thicker, which with the same coating permittivity would increase the pp field more. However, as noted earlier, the lower breakdown field with Powder could also be due to the variation of coating thickness over each sample from the mean value that is used to calculate the electric field. Also, a correlation would be expected between E_k and the average Powder thickness, which was quite variable from sample to sample, but no such correlation was found. Furthermore, coating quality from sample to sample likely had some variation in how effectively the total metal surface was covered. Enhanced application processes may improve the effectiveness of the coatings.

Another difference from the AWRE tests is that here vacuum may have been present between the coatings and the pp. However, it seems likely that the intimate contact between coating and pp would still result in coating breakdowns, at least ones on the positive electrode, propagating into the pp and through the opposite coating. A final comment is that because of the polarity effect described earlier, breakdown of a coating on the *negative* electrode would probably *not* lead to pp breakdown. Therefore if the breakdowns initiate in the coating, the fact that the values of E_k are lower for the ringing waveform is due to the two equal and opposite voltage peaks causing effective breakdowns in both coating layers rather than just one, and statistically finding a weaker region.

V. CONCLUSION

Dielectrics are a critical component of pulsed power systems. They enable low impedance designs but at a risk of greater manufacturing and operational costs. For these reasons understanding the lifetime and reliability of solid dielectrics is critical. Tests of more than forty polypropylene plates, each almost a liter in volume, for an average of 2500 shots, provided a good basis for predicting satisfactory reliability of a system that includes tens of these plates. The results are generally consistent, with minor deviations, to experience with solid dielectric breakdown at AWRE Aldermaston.

VI. ACKNOWLEDGEMENTS

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