Dielectric Strength Notes
Note 14

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Pulse Breakdown of Large Volumes of Mylar in Thin Sheets

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This work follows that reported by Ian Smith in the notes: "Revision of Breakdown Data concerning Mylar" (SSWA/IDS/6610/102)[1] and "D.C. and Pulse Breakdown of Thin Plastic Films" (SSWA/IDS/6610/105).[2] These notes were concerned with fairly small volumes of mylar but also suggested that stacks of thin foils might have a significantly greater breakdown strength than thicker single films. This possibility was mentioned in the original note on the "Volume Effect of the Pulse Breakdown Voltage of Plastics", where it was suggested that for very large areas of thin foil, the intrinsic breakdown field might become independent of the volume since the defects could not be greater in length than the thickness of the foil. Owing to the encouragement (both moral and material) of Dr. Alan Kolb and his group at the Naval Research Group it was decided to investigate the breakdown field of large volumes of mylar to see if there was any sign of this happening. N.R.L. very kindly provided two large rolls of mylar, one of ten thou. and the other of 1/4 thou. thickness, with which the tests were done.

The material was laid out in a large shallow perspex tank, about 10 x 3 1/2 x 1/2 foot in size. The material was sandsiched between two or more 5 thou. copper sheets whose edges had been bent over. These electrodes stressed an area of 56 x 282 cms per layer and it was checked that the breakdowns (except where noted for the 1/4 thou. tests) occurred at random over the electrodes. Flashover was prevented by using dilute copper sulphate solution with a resistivity of about 5 kilohm cm to give a grading length which was about 1 cm for the 10 thou. tests. Handling of the 1/4 thou. presented very considerable difficulties and after much confusion and helpful advice from everyone within range, it was found possible to guide the mylar out from the roll with perspex rods and then let surface tension pull it down onto the wetted surface of the layer previously deposited. To wet this the copper sulphate solution had to have detergent added to it and a fairly critical quantity did this without foaming too badly. After every 6 or 8 layers, the mass was debubbled by fairly gentle prodding and smoothing with the hands. Initially this process took a day to achieve 50 layers but practice speeded it up a bit. However, the very small quantity of data on the 1/4 thou. reflects on the tediousness of handling this material. After the mylar was wetted and copper electrodes were added and debubbled, polythene faced sheets of perspex weighted with lead were used to force the water out. Even in the case of 50 layers of mylar the fraction of the final thickness which was water was less than 25%. This, taken in conjunction with the fact that the water is rather conducting, means that better than 99% of the pulse voltage was applied across the plastic.

The voltage calibration of the system was carried out by two different methods which were within 1% of each other and the calibrations were repeated near the end of the measurements

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1. Dielectric Strength Note 5 2. Dielectric Strength Note 8

with results again within 1% of the previous determination. I consider the relative voltage measurements to be better than 2%, while the absolute values should be within 3% of the true ones.

As a check against values obtained a couple of years ago, twleve litres of polythene in the form of single sheets of 61 thou. average thickness was tested in the new set up. The mean breakdown field of 1.02 MV/cm obtained was slightly above the value given by the old curve of 0.85 MV/cm. The standard deviation deduced from four shots was 14% per shot. The difference between the two values is on the borderline of the statistics but it may reflect a change in quality of material. It is certainly now true that the polythene is much more uniform in thickness than it used to be.

The thickness of the ten thou. was remarkably constant and after a series of measurements which gave a value of 10.15 thou. with a standard deviation of .05 thou., most of which was estimated to be measurement error, the thickness measurement was stopped. It failed to register when halfway through the roll the mylar was spliced but later it was found that the inner mylar was 9.7 thou., again with a very constant thickness. The results have been corrected for the different thicknesses used in each test but the somewhat unusual variation between and within sets of tests was purely accidental and follows no pattern.

Table II gives the results for the 10 thou. material and the results are discussed below in the order given in the table.

The first set were two sheets in a single layer, the volume stressed being 800 ccs.

The second set comprised four shots, each consisting of 5 layers of two sheets at a time. As these tests used the slightly thinner material mainly, the field quoted is a little larger than given in an earlier note. The ratio of the breakdown values for the two volumes (including those given in test 5) is 0.92 ± .03, whereas a standard deviation of 4% per shot would have been expected to give a ratio of 0.94. Using the standard deviations of all the tests a better value of 5% per shot might be a better choice and the agreement is then even better.

As is usual if the breakdown occurs at the mean voltage or lower, only one break is usually seen in the sheet, but when the breakdown voltage is rather above average, several breaks occur. These don't happen on the rising wave form but occur during the ringing after the first breakdown. The most spectacular example of this was during test 4, where a pair of sheets went to 201 MV before breaking and this resulted in a total of 13 breaks which carried very roughly equal currents. This effect gives a measure of how far over the mean any of a small number of shots are, since an excess of multi-breakdown shots shows that, for this set of measurements, the mean will be above the real average.

Test 3 was a very rough shot at the life of the material at a reduced voltage. The actual lives observed were 7, 2, 17, 1, averaging a mean life of about 9 after allowance is made for the fact that the applied waveform was a slightly damped oscillatory one and hence each test voltage application corresponds roughly to 1 1/3 pulses. Using a life power of 16 rather than 8, gives better agreement for both this test and that described in test 6. While I still do not have a direct relation between the standard deviation of the breakdown fields and the life power, it seems reasonable that the smaller the deviation, the higher the power in the life relation.

These results suggested that the volume effect is rapidly flattening out for the 10 thou. material and that the original curves were pessimistic for large volumes. It also suggested that the life might be significantly greater at any working voltage than had originally been predicted. All the tests had been conducted with material that was pulled off the roll into the copper sulphate solution and there had been no time for water to diffuse into the mylar. It was decided to repeat some of the tests with material which had been soaked in the dilute solution. The data for vapour transmission through mylar suggests that only a day or two is needed to staurate mylar to a value given in the literature of rather less than 1% of water. However, it has been suggested that rather longer times than this were needed and also that values of the dielectric constant of 5, after soaking, have been quoted. As a result of this we decided to soak most of the remaining material in 5 kilohm cm solution at an elevated temperature of about 45°C for some 12 days. Care was taken that the temperature couldn't go sailing up, in case embattlement of the material occurred. In order to get the solution into the mylar, two 1" wide bands of 5 thou porous paper were interleaved near either edge of the roll. When the material had been rewound with these spaces in it, it was put vertically into a column of solution, a previous test having shown that nearly all the bubbles would leave the setup in a few hours. Using some data on the temperature dependency of diffusion of gas through a plastic film, it seems possible that this elevated temperature soaking corresponds to 100 to 200 days immersion in room temperature solution.

On unwinding the material, a fairly strong, vaguely alcoholic, smell was obvious. In addition to this, the soaked material is very much more transparent than the dry material. The thickness of the material did not seem to increase by as much as 1% but this measurement was not an exact one. The dielectric constant was measured at 1.6 kc and compared with some dry material. The soaked material had a value only some 4%

higher than the other. Another test with 2 thou. thick material failed to show any significant increase in dielectric constant. We are not very confident about these measurements but, taken in conjunction with the reported take up of water value given in the literature, it does raise the question as to how the dielectric constant can rise as high as 5.

Anyway, on the first shot of the soaked material we got a breakdown value of 85 kV where we had expected 160 kV - panic! However, the break had occurred very near the edge of the copper where the paper spacer had been. While rewinding the material we had taken care that grit did not get into the mylar rolls but we had been less careful about the paper and we suspect a bit of grit got wound in via the spacing paper and had punctured one of the two sheets of mylar. Anyway, in the subsequent ten firings of soaked material values above those expected were obtained. A test was also run with two mylar sheets in which breaks had been intentionally introduced. As expected, the breakdown originated from those in the sheet next to the positive electrode and the breakdown voltage recorded was 89 kV. Thus it is concluded that this shot had a hole in the sheet nearest the positive plate and has been excluded from the analysis. This is the only result to have been so excluded; all the others have been used in the analysis.

Test 4 gave a value significantly above those obtained with dry material. To check this the small remnant of remaining dry material was retested and a value slightly above that obtained in test 1 resulted. In these three tests, the two with the largest breakdown voltages showed considerable multiple breakdowns and this suggests that these were both well above average and hence the mean is likely to be above the true value. However, the difference between test 1 and test 5 results in 0.2 MV/cm and has an error of ± 0.15 MV/cm and thus is not too big to be chance. The weighted mean of the two tests has been used in the analysis - this is 3.21 MV/cm.

The difference between the dry and soaked material is 10%, with an error of ± 3%. Thus it is probable that soaking has slightly increased the strength of the material. It does not seem that this is unreasonable since presumably the water might have a small effect, if it is preferentially absorbed near to the defects, by reducing the field locally. We wouldn't go bail on the increased strength of soaked material but there might be another reason for pre-soaking, since it was found quite a bit easier to get bubbles out of the layers when the material had been soaked. The mylar also slides about more easily and also shows less tendency to float up to the surface when it has been pre-soaked. All in all, it is easier to handle, but neither of these reasons for pre-soaking is a strong one.

The final test on the 10 thou. material was a very rough life test. This was initially undertaken at the same voltage as was used in test 4, but the increased strength plus the fact that the thickness was 4 1/2% less in the earlier tests meant that no breakdowns were observed in 25, 25, and 16 shots on three samples of soaked material at a field of 2.65 MV/cm. The same material (after being left out overnight damp, but not under water) was retested at a mean field of 3.00 MV/cm. The life obtained then was 6, 1 and 2 shots. Using the 16th Power Law, the earlier testing is estimated to have added 6, 6, and 4 shots. Using a multiplying factor of 1 1/3 to allow for pulse ringing, the life at breakdown is estimated to be about 16, 8 and 8, with an average life of about 11. The expected life on a 16th power law is 11, an agreement which is obviously fortuitous. However, even without the second lot of high voltage life tests, 2,400 ccs had a life greater than 20 at 2.65 MV/cm.

The conclusions of these tests were that accelerated soaking has, if anything, made an improvement on breakdown strength and that the life relation again looks very roughly like a 16th power.

The 1/4 thou. mylar caused edge difficulty because the sheets adjacent to the electrodes showed a strong tendency to billow up and wrap themselves at least in part around the edge of the electrode. This reduced the copper sulphate solution to a very thin film and also caused larger voltages to appear across the raised bits of the thin mylar. Either of these effects ruins the grading of the solution and caused breakdowns to occur at or just outside the edge of the electrodes. A soultion to this was found in small volume tests by masking the edges of the copper electrodes with two extra sheets of thicker mylar which only reached a couple of cms inside the electrode edges. On the small volume tests the breakdown occurred other than near the edges and also gave breakdown voltages with a satisfactorily small standard deviation. These are the values given in Test No. 1 of Table III. However, when the same technique was tried on a much larger volume, the breakdown occurred at the edges of the extra mylar that extended a couple of cms inside the electrodes. Several breaks occurred in each of the two tests, but all were round the edge of the masking mylar and hence the values obtained of 5.1 and 4.7 MV/cm are only lower limits. Unfortunately time and patience were both at an end and it was decided that there was no chance to develop a yet further improved edge field control, especially as it appeared that this would have to be done with the large area samples, each of which would take a great deal of effort, and so the experiments were discontinued. However, it is considered that the tests with 1/4 thou. had established that very thin foils of mylar could stand fields considerably above those that the ten thou. could support and that there was some indication that, as with ten thou., the field became largely independent of volume over some critical value.

It should be pointed out that in the 1/4 thou. tests the time taken to assemble the mylar was probably longer than the estimated time for the material to absorb 1% of water. In the case of all the previous tests with thicker material this was probably not so and while the ten thou. tests had not proved that soaking raised the breakdown strength, they had made such an effect very likely. It is probably rather an academic point since any attempt in quantity to use very thin mylar under water will mean that the material is fully soaked but it might well be that the 1/4 thou. data is not strictly comparable with the rest of the data now to hand. This effect has not been allowed for in plotting Graph I because the magnitude as well as the effect itself is largely unknown.

The section that follows is highly speculative and is included more in the hope that someone will be stung to prove it wrong rather than as a claim to being factual. Certainly the experimental evidence which is relevant is very sketchy.

Graph I replots the data listed in the table in "Revision of Breakdown Data concerning Mylar" and the present note. In this graph the data has been clumped into four groups of mean thicknesses .0006, .005, .025 and .10 cms. The point given in the table for 50 ccs at 3 thou. has been omitted for no very good reason except that the mode of testing used in this case was to roll a cylindrical specimen containing several test volumes. This differs drastically from the other tests and the value obtained may have been affected by the mode of testing. If the bald assumption is made that the large thickness breakdown-volume relation lies parallel to that of polythene, the curves shown for mylar can be drawn without doing too much violence to the data. An interesting question is whether polythene might show the same effect. Nearly all the breakdown data on polythene has been obtained with samples many times thicker than that used in the mylar tests because of the danger of mechanical damage to thin foils of this plastic. However, Ian Smith obtained some data for a stack of 4 one thou. sheets which gave a value well above the curve and the value he obtained was a breakdown field of 2.75 MV/cm for 4.4 cc. On Graph I the polythene curve for thick polythene is given as well as this one thou. point. If the mylar curves are used to extrapolate from this one point for polythene, it suggests that for 60 thou. samples the curve should flatten for volumes above 10 litres.

The fact that there is a critical thickness below which the volume dependency largely disappears does not prove that the initial defect size is the same as this thickness, unfortunarely, since it may merely mean that the length associated with some portion of the breakdown process is equal to this thickness. For instance, the initiating defect might still be some hundreds of atoms long but if a multiplying process (similar to the Townsend avalanche length) has to intervene before a full streamer can be formed, the breakdown might still cease to be volume dependent for a thickness less than or equal to this pseudo avalanche length. If this is the case, then the curves suggested in Graph I might well depend on the presence and nature of the liquid layer. If the thin sheets of plastic were to be wrung together very well so as to exclude effectively all the liquid or air, the avalanche process might well carry on as if the plastic were a monolithic block and the volume dependency come back with a vengeance.

From a purely practical point of view, however, mylar in the form of thin sheets has the greatest field strength, energy transmission and energy storage for reasonable quantities of electric energy that we know about and it would be very desirable for its properties to be investigated further than we have been able to so far.

This work was done by G. Herbert, D. Wilcox and J. C. Martin and we would like to repeat our thanks to N.R.L. for their encouragement and support in it.

TABLE I
Results for Polythene

No. of shots	Thickness (cms)	Volume (ccs)	Mean BD (kV)	Field (MV/cm)	Life or S.D.
4	0.156	12000	159	1.02	± 14% per shot

TABLE II
Results for 10 thou. Mylar

Test No.	No. of Shots	Thickness (cms)	Volume (ccs)	Soaked or Dry	Mean BD (kV)	Field (MV/cm)	Life or S.D.
1	6	.0514	800	D	161	3.14 ±.055	± 4% per shot
2	4	.0492	4000	D	145	2.95 ±.06	± 4% per shot
3	4	.0492	800	D	135 (test volts)	2.75	9
4	7	.0514	800	S	181	3.52 ±.09	± 7% per shot
5	3	.0492	800	D	163	3.34 ±.135	± 7% per shot
6	3	.0514	800	S	154 (test volts)	3.00	11 corrected

For Life data expectation on 16th power law is 11 for both tests 3 and 6.
Difference between tests 1 and 5 is 0.2 MV/cm ± 0.15 MV/cm.
Weighted mean for dry 800 ccs is 3.21 ± .06 MV/cm.
Increase on presoaking is 10% ± 3%.
Volume effect: Expected ratio 0.94 (based on 4% per shot)
Observed ratio 0.92 ± 0.03.
Errors are derived from the spread of data and do not include absolute errors.

TABLE III
Results for 1/4 thou. Mylar

Test No.	No.of Shots	Thickness (cms)	Volume (ccs)	Mean BD (kV)	Field (MV/cm)	Life or S.D.
1	3	.0127	1.3	79	6.2	~1% per shot
2	2	.0317	250	≥154	≥4.9	-