Dielectric Strength Notes
Note 11

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Pulse Life of Mylar

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This work was performed by A. MacAulay and the author and stemmed out of an experimental setup where a series of sheets of mylar which had been Evostuck together broke at a very low mean field after a short number of oscillatory discharges. This led to some simple experiments aimed at roughly determining the life voltage relation for single sheets and multiple sheets, stuck and unstuck.

It had been assumed for a long time that, in common with condenser data, the life could be expressed as a power law of the ratio of the single pulse breakdown voltage to the working voltage. For the ICSE condenser the power was known to be about 8 and this had been used liberally in various other situations to provide a guess as to the likely life. In impregnated paper condensers (such as the ICSE condenser) the life is a function of the peak to peak voltage swing. Simple theories exist to account for this where breakdown occurs in small gas-filled voids which progressively elongate over many pulses. However, for lives of 10 to 100 reversals these theories are not very applicable. In the case of polythene, charge annealing of the defects occurs and if a sample is stressed close to its DC breakdown (which is about 20% greater than the pulse value) and then pulsed through zero volts to the opposite voltage, the polythene will break at a voltage of only 20% of the unidirection pulse voltage strength. Thus in polythene (and possibly some other plastics) there is good reason to consider that it is still the peak to peak voltage that is relevant for life determinations. Mylar fortunately shows very little, if any, tendency to follow suit and the DC and pulse strengths seem quite similar, also a sheet DC charged near to breakdown can be rung through several reversals before it breaks, the reduced breakdown voltage in the case of a reasonably undamped ringing circuit being attributable solely to the fact that the mylar has had a number of test pulses at one go and therefore would be expected to have a slightly reduced breakdown strength.

A small digression might be in order to give a tentative explanation of a somewhat puzzling phenomenon which has been observed on a number of occasions where a mylar sheet is broken at a voltage (DC or pulse) above the mean value for the volume stressed. It is then observed that several breakdown sites exist. For pulsed voltage it can easily be shown that unless the test pulse has a rise time of a few nanoseconds, there is a negligible chance of two sites' breakdown independently in the sheet; yet the phenomenon can be displayed with microsecond rise time pulses. Also such an explanation cannot account for DC or very slowly rising pulses at all.

If the sheet is highly stressed and by chance the voltage on it goes to a value above the mean when the primary break occurs, the capacity of the test plates ring via the inductance of the solid dielectric breakdown channel. In a case encountered in the work referred to in this note, the capacity was about 5×10^{-8} F and the inductance can be estimated as 5×10^{-10} H. Thus the $\sqrt{LC}$ is 5 ns and as the gradient in the mylar before closure of the channel in the solid was more than 3 MV/cm the resistive phase is about 2 ns. Thus the damping of the oscillations is not great and the circuit, if it were composed of lumped components, would ring to about 90% and carry on ringing with very little damping. Because the spark channel is within the capacitor plates, not all the volume of plastic will experience the 90% reversal, but the voltage drop across the inductance occurs largely with a few mms of the spark channel and the greater part of the volume of the plastic reverses the full amount. This ringing has been observed after sheets of mylar and polythene have been broken in pulse voltage tests as a high frequency, lightly damped oscillation after the break. If the sheet does not break on the subsequent many reversals of voltage the waveform remains simple. If, however, the plastic sheet breaks at a field above the mean for the volume stressed, subsequent breaks are quite likely and the waveform can be seen to get more complicated as they occur. Sheets have been seen to have at least six breaks that have carried reasonable currents, although it is usually easy to tell which is the original break because of the larger hole blown. By considering the number of cycles of reversal and the voltage on the sheet when it broke, it is possible to make a statistical estimate of the number of channels likely in any given situation. Equally, the fact that a mylar sheet that breaks at only a little below the mean field will have only one break in it shows that there is not likely to be any charge storage annealing, as is shown by polythene.

Returning to the main object of the experiments, the test circuit was designed to produce a lightly damped oscillation and in determining the life for single pulses it is desirable to estimate a multiplying factor (M.F.) to turn the number of oscillating waveforms into an equivalent number of single unidirectional pulses for estimating the life. For a waveform that reverses to about 92% per half cycle, an M.F. of 3 was taken. This can be approximately substantiated by raising the waveform to the 7 1/2th power, when the chain can be seen to be effectively about 3 reversals long. Thus the use of a reasonably high Q circuit (a) reverses the polarity many times, which is the worse case to be considered; (b) it increases the effective number of pulses by a small factor. The circuit chosen was an inductance of about 10^{-4}H, a constant capacity of 10^{-8} F and a series spark gap. The test mylar sheets were placed across the condenser, the waveform applied being largely controlled by the lumped constant circuit and except in the case of the largest area tested, it had a frequency of 160 kc.

The method of applying the voltage to the plastic is all important and over the past five years various techniques have been developed for both pulse and DC work. In this application it was required that the mylar start with a DC stress on it and then undergo a series of voltage reversals. Earlier work had shown that values equally or even slightly higher than the pulse ones could be obtained by leaving air in the thin space between the thin copper sheet electrodes and the sample. The air space is at most a few mils thick and can hold neither DC nor pulse volts to any significant extent. Tracking at the edge of the metal is of course the limitation to this simple technique and this is largely overcome by surrounding the sharp edges of the metal sheet by a strip of porous blotting paper lightly stuck to a backing sheet of plastic. Two such electrodes systems are sandwiched together with the sample between them under lead blocks, the localised forces of which are spread by a sheet of rigid plastic or wood with sponge rubber under it. In order to stop tracking it is essential that outside the blotting paper edge the plastic films are firmly pushed together, reducing any air films to very small dimensions. With this simple demountable system voltages up to about 60 kV can be held across a 5 mil sheet without tracking round edges located 3 inches away from the end of the electrodes. When a breakdown occurs the copper sheet electrodes (which are typically 10 mil thick) are dished in slightly and many breakdowns can take place between the electrodes before their scrofulous appearance eventually compels replacement.

DC Breakdown Values

Data from these experiments and those of Ian Smith quoted in his *"Note on DC and Pulse Breakdown of Thin Plastic Films" are given in Table I and compared with the pulse values given in Ian's note: **"Revision of Breakdown Data concerning Mylar".

TABLE I

Thickness mils.	Area cm^2	Vol. cc	B.D. Voltage kV	Field D.C. MV/cm	Pulse Value MV/a
2.1	20	0.11	23.2	4.4	4.4
2.1	180	0.95	17.2	3.25	3.7
5.5*	220	3	55	3.8	3.4
10.5	180	4.9	102	3.8	3.3
5	3,000	35	38	3.05	2.8
5.5*	3,000	38	44	3.1	2.8

*Two sheets, the rest being single sheets.

* Ref. SSWA/IDS/6610/105, Dielectric Strength Note 8
** Ref. SSWA/IDS/6610/102, Dielectric Strength Note 5

It is not considered that the difference between the pulse and DC values are really significant since the combined experimental errors are several percent and pulse values scatter about the line by about 10% as well. Thus it is taken that slope of the mean breakdown field against volume is the same for DC as for pulse and this is consistent with the standard deviation of about 8% which was observed.

Life Measurements

These were carried out for three different areas of mylar, 52 cm^2, 220 cm^2, and 3,000 cm^2. In the case of the first area, six separate test areas were laid side by side and the same test oscillatory voltage discharge applied to each when the spark gap broke down. When a sample broke, the number of spark gap firings was noted and the sample of mylar blanked off with a 10 mil sheet and the tests continued until all the samples in one 36 inch wide sheet had broken. For the other two larger areas, tests were conducted only one at a time. For these two systems the damping was slight and a multiplying factor of 3 was used to turn the number of applications of the ringing waveform into an equivalent single pulse life. For the array of six small areas, the damping was heavier and an MF of 2 was used for these results. The data is shown on the left hand side of Figure 1 and indicates that over the range investigated the mean single pulse life is the 7 1/2 power of the ratio of the mean breakdown voltage to the operating voltage. The single pulse breakdown value for the 52 cm^2 area is a value estimated from Table I, because tracking made it difficult to get an experimental value.

After a large number of pulses, faint signs of erosion round the edges of the electrodes could be seen on the mylar test sheets. This is caused by the corona sparks flowing under the blotting paper surface during the oscillatory discharge. However, there was no tendency for the mylar to break on or outside the edge of the electrode. As there was no sign of erosion at all under the electrodes in the area where the vast majority of the breakdowns occurred, this is taken as evidence that chemical erosion and mechanical shock from coronaring was not causing degradation of the mylar. The discharges took place at the rate of about one every two seconds and in view of the very high volume resistance of mylar, heating is not considered to have affected the results; certainly at the end of several hundred discharges the mylar did not feel even faintly warm to the touch, although the system should have reached thermal equilibrium after 100 shots or so.

The next investigation was the effect of the method of sticking mylar sheets together on the life. Double sided Evo tape was tried but this reduced the D.C. breakdown strength from 4.4 MV/cm to under 1.7 MV/cm, the latter value ignoring the thickness of the double sided sticky tape. Evostick was then tried and after a period of some uncertainty, it was established that providing the Evostick film was not fluid, the thickness has little effect on the life at a given applied field. Again, the field is calculated as if the Evostick layer was not there; certainly for the D.C. breakdown it is very unlikely that the Evostick can have anything like the resistance of the mylar and hence the volts will be across the mylar. The D.C. breakdown was shown to be essentially the same as that of the unstuck sheets.

The life of the stuck sheets is given on the right hand side of Figure 1 for different thicknesses of Evostick for the smallest area, and a couple of determinations for the largest area. There is a slight indication that for values of the field only 20-30% lower than the single shot breakdown field, the life of the Evostuck sheets is reduced on occasions to a single shot, but this is an area of no great practical interest, so this suspicion was not investigated further. It was, however, shown that the presence of liquid or near liquid puddles of Evostick produced by sealing the sheets together too soon can lead to great reductions in life. The original occurrence which gave rise to the investigations had a breakdown at just such a liquid lens. In order to get a good life with transmission lines that have to be stuck together, it is very desirable to form a thin, uniform layer of Evostick on both surfaces, wait until it is just dry and then stick them together. This process sounds delightfully simple but in my opinion requires considerable care and practice. It is considered that if the Evostick is fluid enough (guessed to have a viscosity less than one million or thereabouts) a streamer can form in it and punch through the mylar sheets.

Distribution of Lives for a Constant Applied DC Voltage

Experiments to obtain the distribution of lives at a constant pulse voltage, or applied DC volts as in these experiments, are tedious and quite tricky to carry out: consequently the results should be treated with care. Ian Smith determined the distribution for a pulse voltage chosen so that the mean life was a little under three shots. The results tended to suggest a simple radioactive decay type probability. An alternative possible form for the life distribution with a maximum differential probability situated near the mean life can be calculated from the distribution derived in "Volume Effect of the Pulse Breakdown Voltage of Plastics" (ref. SSWA/JCM/6511/A)[1] by the author. This curve, for a standard deviation of 8% is shown in Figure 2. The life relation found above has been used to obtain this curve and the life is given in terms of the mean life and the area under the curve has been normalised to unity.

1. Dielectric Strength Note 3

The life varies on this theory simply because each sample has a breakdown voltage for a single pulse which has a distribution of values and this reflects directly into a life distribution.

The experimental values were obtained for two systems, one using 220 cm of two sheets totalling a mean thickness of 5.5 mils and the other for 52 cm of a single sheet of 5 mils thickness. Thirty-three samples were used in the first set and 36 in the second; all the observed values were included in the analysis. Care had to be taken that the spark gap did not vary its mean breakdown voltage because a 2% shift of this leads to a 16% change in the mean life. The same ratio applies to any variation of thickness of the mylar sheets. In fact, both sets of sheets varied by up to ± 3% and after the breakdown had happened, the thickness of the sheet near the breakdown site was measured and the sets of results nominalized to a constant thickness of sheet. This had the effect of sharpening the distributions slightly but not by more than 20%. It also brought the means of sets of results into line with scatter to be expected from the standard deviation of the results in each subset. The agreement between the two sets of results and the calculated curve is gratifyingly good and I consider that the experimental results differ from the exponential type probability by many times the standard deviations of the statistical errors in the results, when the combined results are taken.

Summarizing, given the standard deviation per shot of 8%, the mean breakdown voltage and distribution of such voltages can be calculated for DC or pulse breakdown for a given volume. With the addition of the life power law, the life can be calculated and the distribution of observed lives in a series of shots for any volume of mylar obtained. It is my personal belief that, given the standard deviation of single shot voltage breakdown values and the form of this distribution, it should be possible to obtain the power law deductively. If the probability destruction had been the radio decay type, a simple argument can be used to obtain the power in the life relation, this value being a power of 12, which would of course have been incorrect. It is already interesting that, given the standard deviation for a set of measurements and the life law power, the life and distribution lives for a large range of volumes and test pulse amplitudes can be predicted with reasonable accuracy. It would be even better if the second piece of information was unnecessary.

It is probably worth repeating that this and all the other notes in these series are written to enable estimates to be made of the breakdown voltage life, etc. of various solid, liquid and gaseous insulators under various fairly ideal but experimentally realisable conditions. No great accuracy is claimed for the data and the estimates obtained by the methods outlined should be used with caution and checked experimentally as soon as possible. It is also always possible to do a lot worse than the values given by the simplified treatments if the experimental setup contains stress enhancements or serious tracking or multiple breakdown paths. It should also be mentioned that there is some experimental data on mylar condensers which seems to give values quite significantly higher than those obtained by applying the methods given in this note. A possible explanation might be that multiple very thin films are employed and that the effect occurs because either multiple foils have an advantage or because the individual foils are too thin to contain a defect greater than the foil thickness. In the latter case, the scatter of the breakdown of individual samples should be smaller than 8% and hence the volume effect on the breakdown voltage would be less.

With regard to the effect of multiple foils, Ian Smith has shown that for polythene the breakdown field of stacks of foils is greater than that of a single foil of equivalent thickness.

Some caution should be observed in interpreting these results, since there are sample to sample variations in polythene strength, but the effect seems to be too big to be accounted for by any likely variation of the properties of the plastic. Another way in which very different answers may occur is when the breakdown process is not an "intrinsic" volume process but something such as tracking at an edge. In this case a quite definite life with a very much smaller standard deviation than those reported here may occur. Such cases can usually be diagnosed because of the pattern in space of breakdowns which occur.

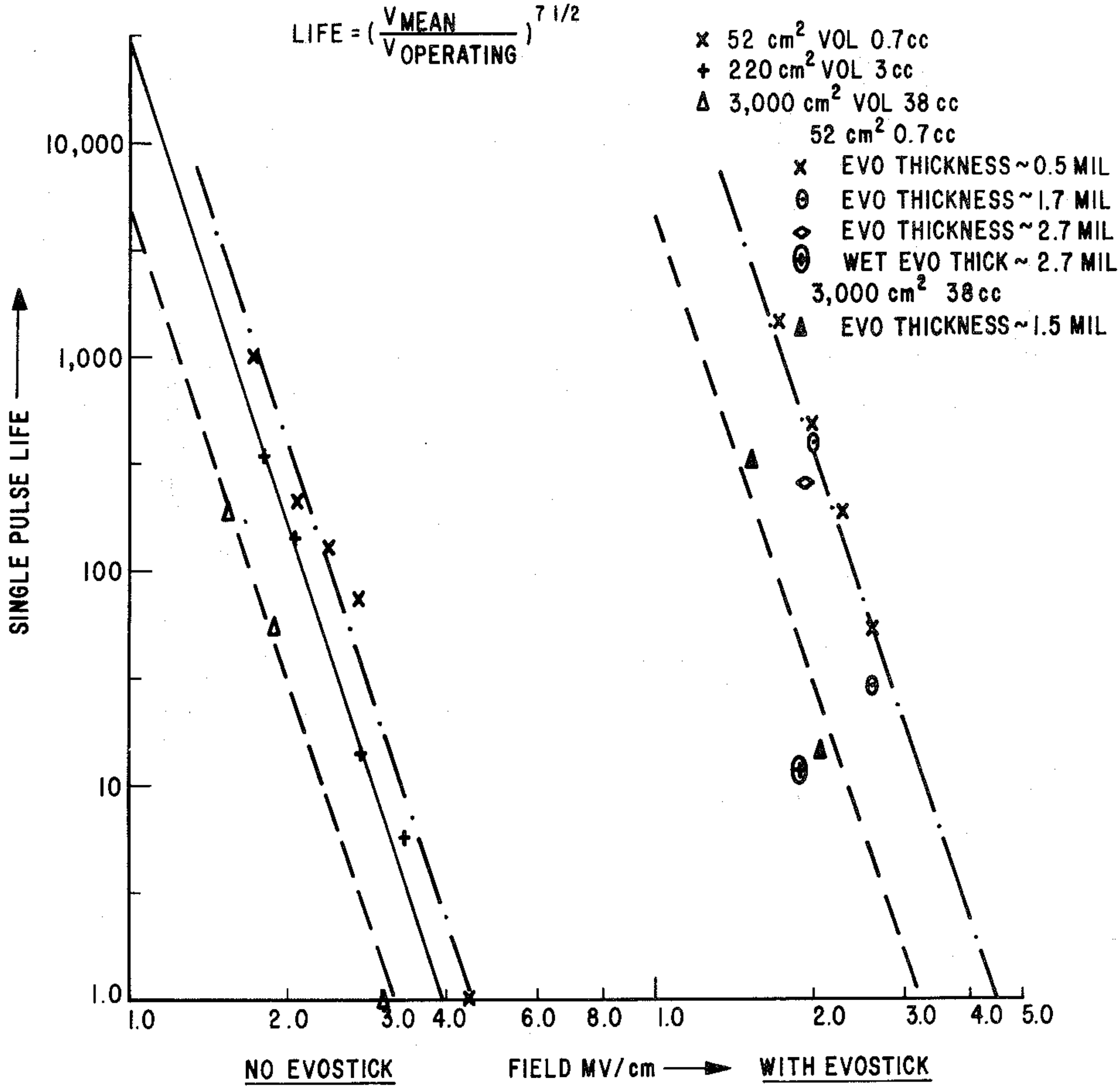

FIG. 1 LIFE AGAINST PULSE VOLTS

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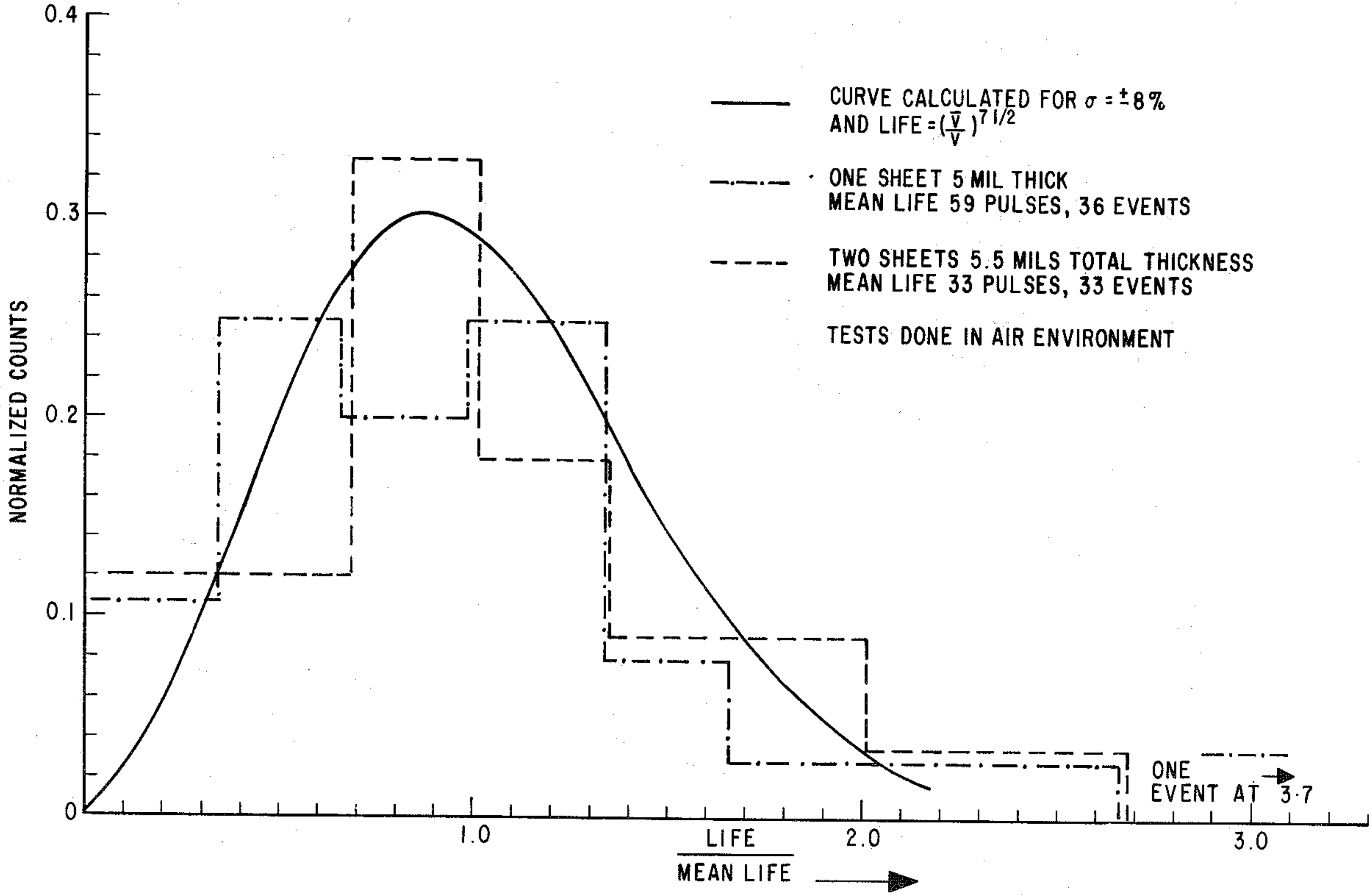

FIG. 2 LIFE DISTRIBUTION MYLAR