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ABSTRACT

Polythene samples, 0.09 to 0.18 cm thick, with artificial voids, have been subjected to pulses lasting for some 10^{-6} to 10^{-2} seconds, with a wide range of waveforms, at 0.2 to 0.9 MV/cm. It was found that for a given peak stress the life obtained with unidirectional pulses was independent of waveshape; it was independent of the pulse repetition frequency over the range of 1 to 4 pulses per second, but longer lives were obtained at 50 pulses per second. Life was shorter on oscillatory than on unidirectional pulses of the same peak stress, and was not affected by sample thickness.

The results are consistent with life being controlled by the intrinsic electric strength of the polythene, and indicate that a space charge may be set up and decay with a time constant of the order of 10^{-3} seconds.

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1. Introduction

In thermonuclear research it is often necessary to set up a magnetic field rapidly[1]. This necessitates a high rate of rise of current in coils, and therefore a high voltage (since $v = L\frac{di}{dt}$). Were the inductance fixed, the rate of rise of current would be proportional to the voltage. However, if the applied voltage is increased, the insulation clearances must be greater; the stray inductance of the system is therefore increased, and if it becomes comparable with the coil inductance it may limit the attainable $\frac{di}{dt}$. Furthermore, energy is stored in the stray inductance; this energy is wasted and increases the cost of the energy store. Finally, the stray inductance may cause undesirable oscillations. It is necessary therefore to minimise the stray inductance, and in consequence insulation clearances must be small, resulting in high stresses. Fortunately, it is possible to use high stresses, because experimental equipment is only required to have a relatively short life - 10^3-10^6 pulses.

Since the insulation is energised by voltage pulses, breakdown may be due to discharges in voids. Most studies of this mechanism have been made for much longer lives - and therefore lower stresses - and have shown it to consist of two stages[2]. Firstly the discharges erode the insulation, and the void (or part of it) elongates, until the stress at its tip exceeds the electric strength of the solid. The second stage then starts, and the breakdown channel grows due to local electric failure of the solid. The breakdown process during the second stage extends over a number of pulses but is similar to that which operates when puncture of the dielectric is due to a single non-oscillatory short-duration pulse; it is therefore described as intrinsic.

The authors' preliminary experiments on polythene have indicated that at the high stresses used in this work, the distortion of the electric field by a discharge in a void may be sufficient to cause intrinsic breakdown, even if little erosion occurs; life is then controlled by the second, intrinsic-breakdown stage[3]. Data have now been obtained, and will be presented in this paper, on the performance of polythene under a wide range of unidirectional and ringing pulses, and

pulses with superimposed oscillations, at 0.2 to 0.9 MV/cm. These data may be relevant also to the effect of overvoltages on the life of conventional power equipment.

2. Discussion of results

Commercial polythene was used, and samples were made from two sheets; one, which constituted the main insulation, had a nominal thickness of 0.64, 1.01 or 1.59 mm, and the other, into which a 2.5 mm hole had been punched to constitute the void, had a nominal thickness of 0.25 mm. The actual thickness of individual samples was within about 3% of the nominal value. The samples were placed between electrodes designed to give a uniform field over the breakdown region in the absence of the void. A gold or copper electrode was next to the void, but no dependence on electrode material was detected. The pulse repetition frequency was between 0.5 and 5 per second, except for measurements at 50 c/s.

The pulse waveshapes are shown in Fig. 1, and life-stress relationships have been derived as follows. Each experimental point was obtained by applying to a group of at least six samples one of the pulse waveshapes, of fixed amplitude. Preliminary analysis indicated a skew distribution of lives for each group, their arithmetic mean being closer to the shortest than to the longest life. However, the distribution of the logarithms of lives appeared symmetrical, and therefore the life for the group was taken as that corresponding to the arithmetic mean of the logarithms; this equals the geometric mean of the lives themselves. The experimental points shown in Figs. 2 and 3 are therefore the geometric means of the lives of different groups. The spread of lives of individual samples has been indicated by dotted lines in Fig. 2.

For experimental convenience, samples constituting one group were tested at the same voltage, and departures from the nominal thickness resulted in small variations in stress in each sample. The stress for the group was taken as the applied voltage divided by the arithmetic mean of the thicknesses of individual samples.

The discharge inception stress can be estimated by taking the field to be

uniform within the void[4]; the stress is the same as for breakdown between metallic electrodes[5]. With a void 0.25 mm deep, the stress required in the void is 63 kV/cm. Allowing for the dielectric constant of the polythene, this corresponds to about 30 kV/cm as the mean stress in the sample. It will be remembered that the minimum applied stress was 0.2 MV/cm, and this is nearly an order of magnitude greater than the discharge-inception stress.

2.1 Experiments with 1/50 pulses

Fig. 2 contains results obtained with a nominal 1/50 pulse[6]; due to varying circuit conditions, the front ranged from 1.0 to 1.8μS, and the tail from 34 to 45μS. Shorter lives were obtained when the void was at the anode than at the cathode, for the whole stress range of 0.2 to 0.9 MV/cm, and only results with the void at the anode have been entered in Fig. 2. It will be seen that a linear relation has been obtained between the logarithm of life and the stress, from 900 down to 350 kV/cm. It may be that at lower stresses significant erosion is required before intrinsic breakdown occurs, and this would account for the up-curving of the graph.

The data have been obtained in two separate laboratories; in one the pulse repetition frequency was usually 1 per second (blacked-out points), and in the other it was usually between 3 and 5 per second. It will be seen that life is independent of pulse frequency over that range. Fig. 2 shows also that variation in sample thickness from 0.09 to 0.18 cm has no significant effect on life.

2.2 Effects due to pulse waveshape

To illustrate the effect of the pulse waveshape, the curve of Fig. 2 has been redrawn in Fig. 3, together with experimental points obtained using other waveshapes. The void was at the anode for unidirectional pulses, and for the first loops of ringing pulses.

t_1/t_2 waveshapes. The t_1/t_2 waveshape is shown in Fig. 1(a); t_1 ranged from 0.2 to 300μS and t_2 from 0.5 to 1000μS. For $t_1 < 0.5$μS and $t_2 < 10$μS, special circuits were used, and the pulse departed from the usual double

exponential shape; it was, however, free of oscillations. It will be seen that all points lie fairly close to the 1/50 curve. There appears to be no correlation between t_1 or t_2, and the deviation of points from the curve. Life is therefore independent of the front and decay times over the range considered here.

50 c/s. In Fig.3, the point □ shown at 540 kV/cm was obtained with pulses derived by half-wave rectification from the mains voltage. It will be seen that they gave a much longer life than the curve. In order to differentiate between effects due to the rate of change of voltage and the repetition frequency, an experiment was made in which half-cycles of the mains voltage, of the same polarity as before, were applied at the rate of once every two seconds. The resulting point ■ shows that life is much shorter than at the higher repetition frequency; it is rather longer than on the curve, but lies within the scatter of t_1/t_2 results.

Unidirectional pulses with superimposed oscillations. It will be seen that the waveshapes of Figs. 1(b) and (c), with superimposed oscillations of 300 kc/s and 7 Mc/s, gave the same results as simple t_1/t_2 pulses of the same peak voltage.

Oscillatory pulses. All but two of the tests made with the pulse of Fig. 1(d) were at 290 kc/s. The exceptions were at 32 kc/s, with 80 and 95% reversal respectively. The two points obtained at 32 kc/s have been included in Fig. 3, and are within the group shown at about 330 kV/cm. Their proximity to the other points indicate that life is independent of frequency over this range. It will be seen that lives obtained with this high reversal are substantially shorter than with unidirectional pulses. When the reversal decreased to 50% (upward-pointing triangle at 330 kV/cm) life approached the value given by the curve. This is consistent with the fact that with 50% reversal the peak stress falls rapidly on successive half-cycles, and life is very sensitive to decrease in voltage.

The waveshape of Fig. 1(e) was applied to determine the effect of a

single high-amplitude reversal; it yielded a substantially shorter life than the unidirectional pulses.

The waveshape of Fig.1(d) at a frequency of 290 kc/s and 90% reversal was applied to three groups of samples, with nominal thicknesses of 0.09, 0.13 and 0.18 cm. The mean stresses of the three groups were within ± 3% of 340 kV/cm. The lives obtained were 1.6×10^3, 1.8×10^3 and 1.5×10^3 pulses (in the sequence of increasing thickness) and this confirms that life is independent of thickness.

3. The mechanism of breakdown.

Preliminary experiments[3] have indicated that at the high stresses and with the relatively deep voids used in this work, the life of insulation is controlled mainly by its intrinsic breakdown characteristics. This view is supported by three observations. Firstly, the mean stress applied to each sample is only about an order of magnitude less than the intrinsic strength of polythene[7]. If the discharges were looked upon as thin extensions of the electrode, then it is seen that the field intensification which they produce could cause the intrinsic strength to be exceeded. The field intensification decreases with discharge length, and therefore with depth of void, so that life should be longer for samples with a shallow than with a deep void, as has been found by experiment[3].

Secondly, the lives obtained with unidirectional pulses were shorter when the void was at the anode than when it was at the cathode (see Section 2). This is consistent with puncture being controlled by intrinsic breakdown, because experiments on point-plane electrodes[8] have shown that intrinsic breakdown occurs more readily when the point is positive. Previous experiments on discharge breakdown[9,10] have given the reverse polarity effect, i.e. shorter lives were obtained when the discharges occurred at the cathode, and this may have been due to puncture being controlled by erosion.

Thirdly, the fact that life was not affected by superimposing oscillations on unidirectional pulses (see Section 2.2) indicates that puncture was not controlled by erosion, because the erosion per pulse should have been increased

considerably by the oscillations. The effect of oscillations, and the other observations presented here, can be explained in terms of intrinsic breakdown if it is postulated that a space charge is built up ahead of the breakdown channel and persists for some time after the voltage pulse has been removed. When a subsequent pulse of the same polarity is applied, the insulation ahead of the channel is shielded by this space charge and the second pulse does no damage provided that its amplitude is not greater than that of the first pulse. The individual voltage peaks of Figures 1(b) and (c) can be looked upon as a succession of such pulses, and since life was not affected by their presence, it appears that the space charge had a decay time which was large compared to the interval between them, i.e. large compared to 3 microseconds. Again, longer lives were obtained with unidirectional pulses repeated once every 20 milliseconds (50 c/s pulses) than with identical pulses repeated once every 2 seconds, but there was no difference between lives obtained with pulse frequencies of about 1 and 4 per second. This indicates that the decay time for the charge is of the order of milliseconds.

The formation of the space charge is consistent also with the data obtained with the oscillatory pulses of Figs. 1(d) and (e). The space charge set up during the first half-cycle intensifies the stress locally during the second half-cycle, and more intense stress results in greater damage to the insulation, and therefore shorter life, than with unidirectional pulses.

A more precise discussion of the mechanism is not possible because of scarcity of published data on the formation and mobility of space charges in polythene. Mason[8] has suggested that space charges may account for the lowering of breakdown voltage which he observed when he caused breakdown by two pulses of opposite polarity instead of a single pulse. This implies a decay time for the space charge of at least the time interval between pulses, which was several minutes. However, an alternative explanation could be that the pre-breakdown pulse caused permanent structural damage to the polythene; this is quite likely, since the breakdown channel grows with each pulse if the intrinsic strength of the polythene is exceeded, as explained in Section 1. The lowering of breakdown

voltage is not therefore proof of the persistence of space charges. Again, it is well known that charges are sometimes trapped on surfaces for much longer times than milliseconds. However, the stresses associated with these charges must be relatively low; otherwise they would ionise the surrounding air and they would be neutralised. At the high stresses used in this work, much greater charge mobility would be expected.

4. Conclusions

It has been shown that the life of polythene subjected to unidirectional pulses of a given peak value is independent of the presence of superimposed oscillations, and of pulse duration, for pulses lasting from a few microseconds to several milliseconds. Life was the same for ringing pulses of 32 and 290 kc/s; it increased with decrease of percentage reversal, and at 50% reversal it approached the value obtained with unidirectional pulses having the same peak value. For a given stress, life was independent of sample thickness.

Experiments with unidirectional pulses have shown that life is unchanged if the frequency is changed from 1 to about 4 pulses per second, but life increases if this frequency is changed to 50 per second. The experimental observations are consistent with life being controlled by intrinsic breakdown, and suggest that a space charge may be set up and that it may decay with a time constant of the order of 10^{-3} secs.

5. Acknowledgements

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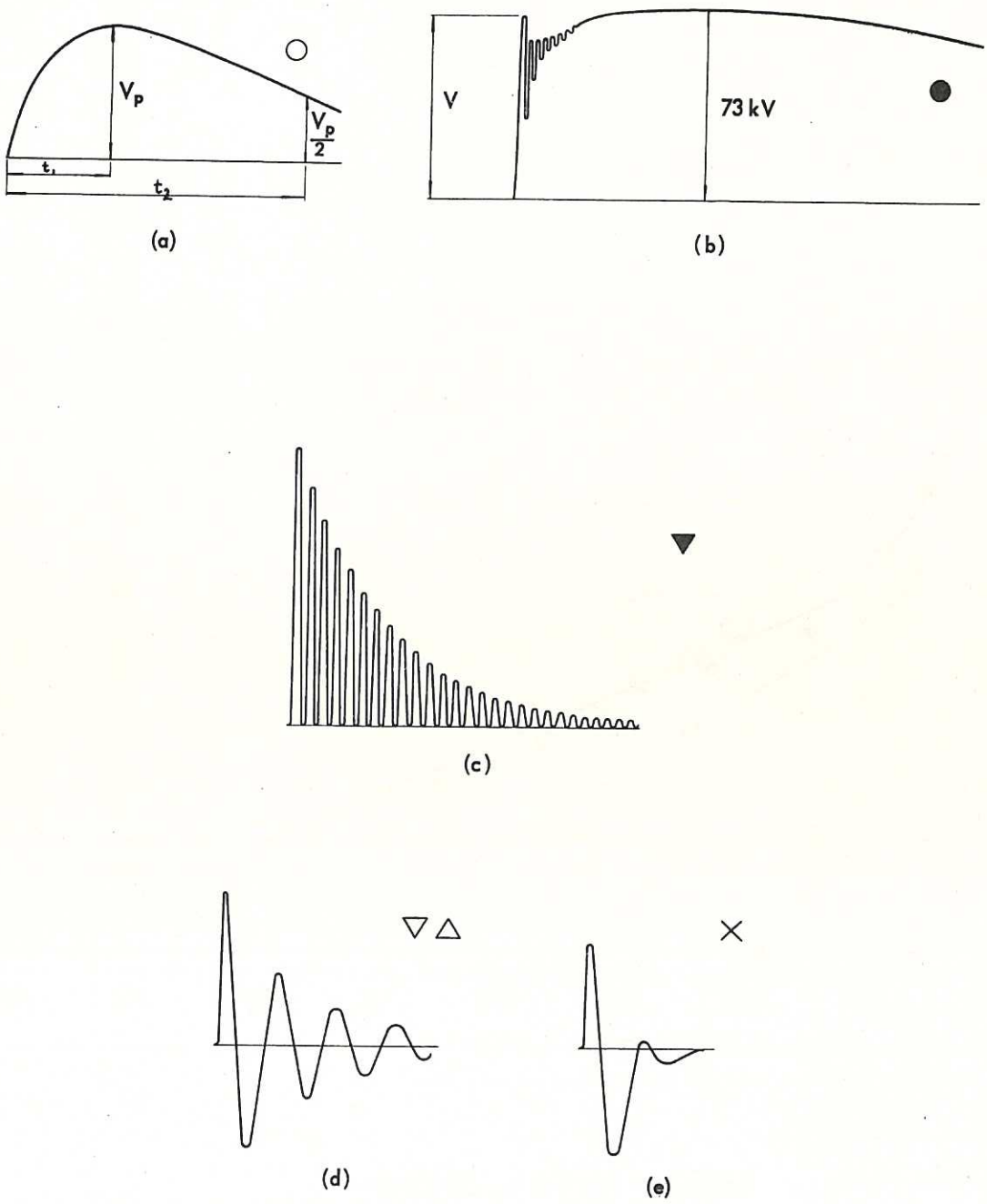


CLM - P 27 Fig. 1

Pulse Waveshapes

The horizontal line corresponding to zero voltage has been shown for each waveshape.

(a) t_1/t_2 waveshape. t_1 ranged from 0.2 to 300 μS and t_2 from 0.5 to 1,000 μS.

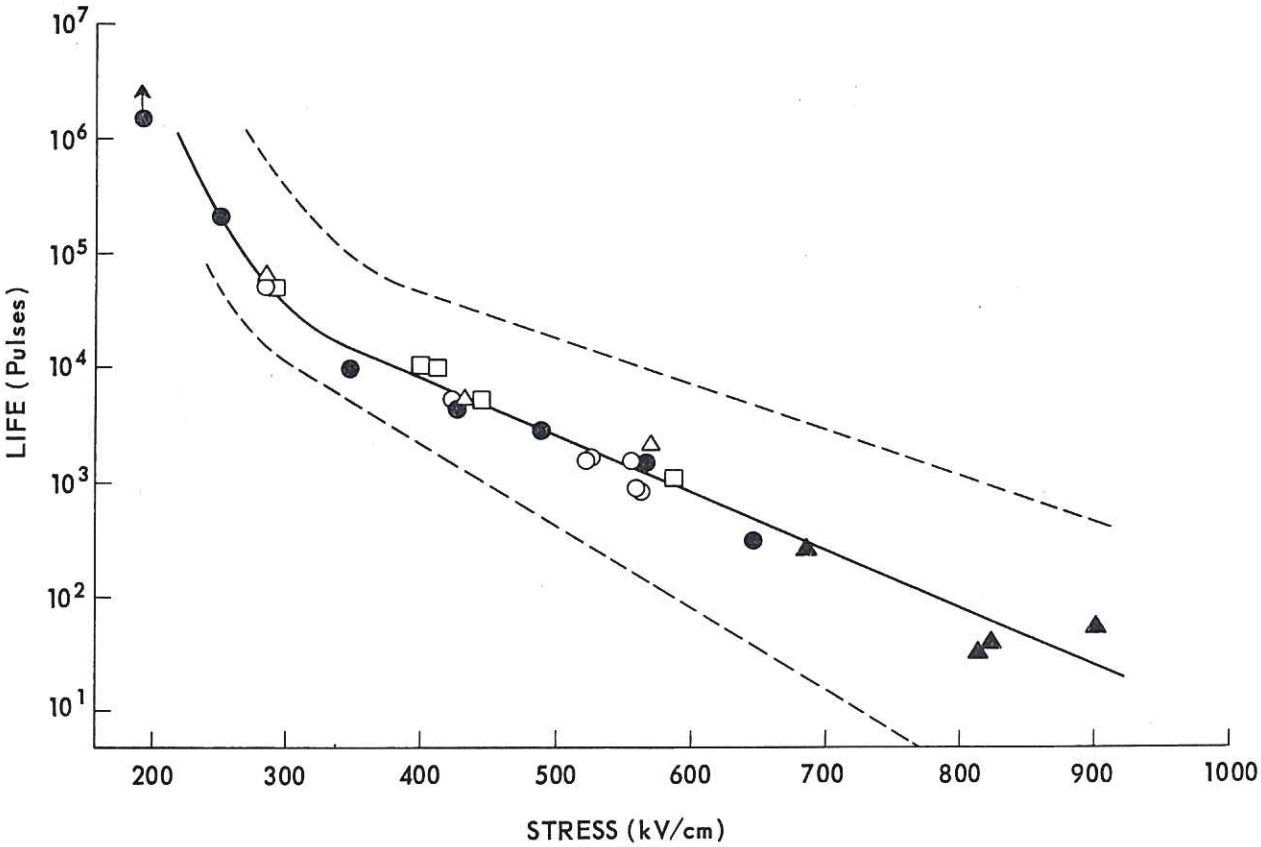
(b) 1/40 waveshape with 7 Mc/s oscillation. This waveshape was traced from an oscillogram for which V was 71 kV. The only other value of V used was 84 kV.

(c) Unidirectional pulse with 300 kc/s oscillation.

(d) Ringing pulses, 32 and 290 kc/s, 50-95% reversal.

(e) Ringing pulse, 30 μS total duration of first two loops.

To facilitate reference, the symbols used for these waveshapes in Fig. 3 are also shown above.



CLM - P27 Fig. 2 Life-stress Relation for 1/50 Pulses

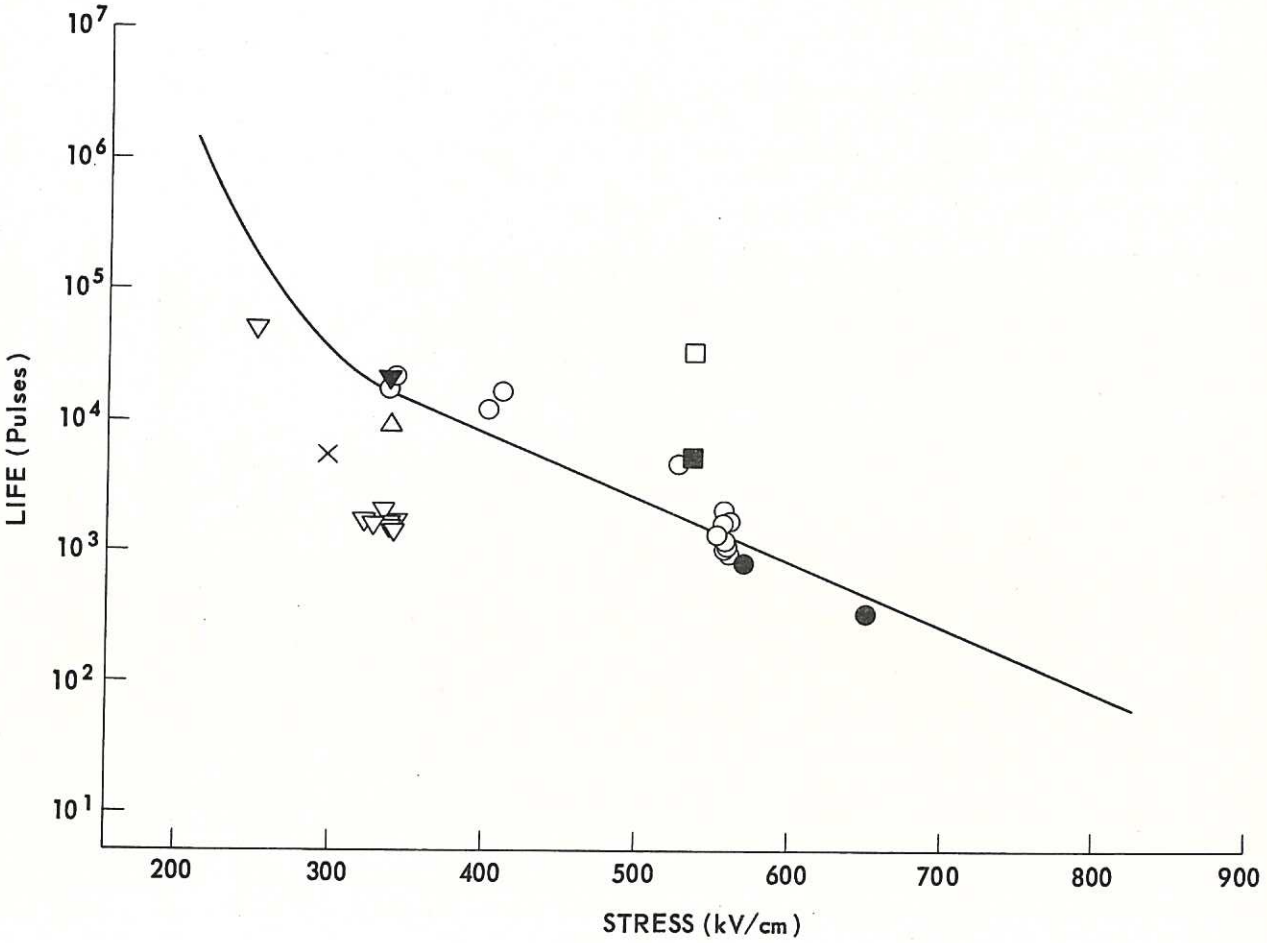
Blacked-out points were obtained in one laboratory and blank points in another.

□ samples 0.18 cm thick

● ○ samples 0.13 cm thick

▲ △ samples 0.09 cm thick

The arrow indicates a test which was stopped before any of the samples punctured.



CLM - P 27 Fig. 3 Life-stress Data for Different Waveshapes

○ t_1/t_2 pulses, Fig. 1(a). The front and tail times of each point, in microsecs, were as follows, in the direction of increasing stress: 0.3/1, 1/25, 0.3/150, 0.2/1, 0.2/5, 0.2/50, 0.2/500, 0.2/300, 0.2/0.5, 300/1000, 5/300, 40/680.
The first four were on 0.18 cm samples and the remainder on 0.13 cm samples.

● 7 Mc/s oscillation on unidirectional pulse, Fig. 1(b). 0.13 cm samples.

▼ 300 kc/s oscillation on unidirectional pulse, Fig. 1(e). 0.18 cm samples.

▽ Ringing pulses, Fig. 1(d). 32 and 290 kc/s, 80 and 95% reversal 0.09 and 0.18 cm samples.

△ Ringing pulses, Fig. 1(d). 290 kc/s, 50% reversal, 0.18 cm samples.

× Ringing pulse, Fig. 1(e). 0.18 cm samples.

□ Rectified 50 c/s. 0.13 cm samples.

■ Half cycles of rectified 50 c/s applied once every 2 seconds. 0.13 cm samples.