Dielectric Strength Notes
Note 3

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Volume Effect of the Pulse Breakdown Voltage of Plastics

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"Intrinsic" Breakdown. This rather ill-defined quantity is practically the largest field that any sample of the material can be made to stand. Typically, the determination is made with D.C. and the applied voltage stresses a few thousandths of an inch thickness of the material. Thicker samples are not used because heating within a thicker sample leads to a runaway condition where the temperature rises: this leads to larger conduction currents causing more heating, etc. This difficulty can, of course, be avoided by using pulse voltages, as can corona-induced surface degradation, chemical reactions, and mechanical instabilities. A further effect that pulse voltage avoids is a sort of stress relieving which conduction currents at near breakdown fields can cause. In this effect a localised defect conducts more readily than its surrounding material and this leads to a field lower than average in its vicinity. Incidentally, if the D.C. voltage is removed rapidly and applied the other way round, a reduction in breakdown voltage is observed, because the stored charge now adds to the field. This effect can raise the D.C. breakdown by up to 20% compared with the pulse values, while the "reversed field" breakdown after D.C. conditioning can fall to well under one half of the pulse value. The time scale of this effect is a few milliseconds.

Work at AWRE has shown that the mean breakdown voltage of a given sample does not depend on the rate of application of voltage when this is reduced from the microsecond range to that of 10 nanoseconds. If some transit time effect were happening (such as is observed in liquids), reducing the time scale by this large factor would produce a large increase in the measured breakdown field. In fact, any observed correction was less than 10%, implying that in the microsecond time scale no transit time effects are occurring. Thus pulse charge methods of determining the "intrinsic" breakdown voltage are to be desired because of the number of interfering effects it avoids. In addition, if pulse voltages are employed, the difficulty of applying the voltage to the sample (which is another major source of error in the normal D.C. methods) can be largely removed by using dilute copper sulphate solution. By selecting the conductivity, the thin film of solution under the flat electrodes ensures that at least 99% of the voltage is across the insulator, while at the same time conduction grading at the edges of the plate electrodes can be used to prevent any field enhancement there. When proper precautions are taken, all the breakdowns can be made to occur at random over the area stressed, with no tendency to cluster at the edges of the electrodes.

Using the above methods, the mean breakdown field for various areas of four plastics were measured. Because pulse voltages were used, it was possible to test large volumes and up to 10 litres of polythene could be stressed in any one test. The results obtained are shown in Figure 1. All the four materials gave values a lot lower than those quoted in the literature for "intrinsic" breakdown and in addition showed a considerable area (or more reasonably volume) effect.

Consideration of this data led to the idea that if the mean breakdown fields, measured for a reasonable number of samples, have a standard deviation which is not a result of purely measuremental errors, then in the region of the measured point there must be a change of mean breakdown field with the volume of the test substance. This can be shown by considering an ideal experiment where the mean breakdown field of a large number of samples is known as well as the intrinsic standard deviation. The samples are then stacked or laid out in sets of ten and the question is asked what the mean breakdown voltages of the sets of ten units are. Obviously in each group the unit with the lowest strength will break as the voltage is applied and the new mean field will correspond to the voltage which broke only 6.5% of the samples when they were tested one at a time. This means that the mean breakdown field must decrease as the volume of the sample increases, providing there is any non-instrumental scatter of measured values of the samples.

It seems a reasonable assumption to make that the probability distribution curve of the breakdown voltages of a set of samples is independent of the number of units in the subsets, at least over a restricted range of number of units. If $\bar{V}$ is the mean breakdown voltage of a set of samples and $p(V/\bar{V}_1)$ is the probability that a given sample will have broken when a voltage V is applied, then $1 - p$ is the probability that it will not have broken. Then, if the samples are taken N at a time, the probability that the group won't have broken is $(1 - p)^N$ and the following relation is required where $\bar{V}_N$ is the mean breakdown voltage of the subgroup of N samples per set:

$$\{1 - p\ (V/\bar{V}_1)\ \}^N = 1 - p\ (V/\bar{V}_N).$$

It is not true that there is only one function p which satisfies this relation, but a function satisfying it can be easily generated by two methods at least, which each lead to the same answer. One is by taking a Gaussian distribution and considering successive sets of, say, 4 samples at a time. After three or four iterations a self-replicating probability curve is obtained. The other method is to take an approximate curve and use the top half of this to generate the bottom portion of the curve for a larger volume sample and the lower half to give that for a smaller volume. Figure 2 shows an integral and differential probability curve which satisfies the requirement that it will self-replicate, which has been generated in this way. For an increase or decrease of a factor of four, the shift of the mean value is 1.18 times the standard deviation of the distribution. Both AWRE and other workers obtain an intrinsic standard deviation of about 11%, when allowance is made for the small number of samples tested, where this applies. Using the observed slope of the breakdown curve of 1.15 for an increase of volume of a factor of 4 gives a calculated standard deviation of 13 1/2, showing a reasonable agreement. If a reasonable number of samples are tested, two pieces of data can be obtained; the mean breakdown field and the slope of the curve of breakdown field against the volume, in the vicinity of the volume of the sample.

Figure 3 shows breakdown data applying to a large range of volumes. It would have been desirable to use only pulse voltage values but these are limited in number and two sets of D.C. data are included, as well as some pulse values showing a volume effect obtained by Cooper et al. The two points obtained by J. Mason should be treated with reserve, as the yield strength of the polythene is close to the electric stress produced by the observed fields and hence the radius may be in doubt. In the case of the stabs and needles the positive breakdown values are quoted, since there is a polarity effect. The interesting feature of Figure 3 is that the slope is apparently constant over a huge range. Indeed, if the curve is taken back to atomic volumes, a reasonable value of 2 eV is obtained for the gradient across a molecule required to break it.

One point that has yet to be mentioned is the evidence that the effect is a volume one and not an area dependence. Two sets of data, one for mylar film 1 to 10 thou. and another for polythene from 1/16" to 3/8", show the expected dependency on thickness and hence volume. The suggested dependency is also made reasonable by consideration of the inherent defects likely to be in the plastic which are either crystals or chain molecules, particularly orientated with regard to the field. For liquids one would expect (and the experimental evidence suggests) an area effect since the discharges are seen to originate on the electrodes.

Additional evidence of the volume dependence of the mean breakdown voltage is provided by some experiments with a thin polythene film over a plane electrode with about 1 cm of water between it and a second electrode. A negative voltage pulse is applied to this electrode, when about half the voltage appears across the 5 thou. polythene film because of the large ratio of dielectric constants. However, when the polythene film first breaks at a voltage of 40 kV across it, the voltage pulse still rises because the slow moving streamer in the water takes several tenths of a microsecond to cross the gap. Thus it is possible to double the applied voltage before the increase of capacity loading and final closure of the water breakdown channels takes the voltage off the system. Using the breakdown against volume curve it is seen that doubling the field will reduce the volume for each break by 1000. In fact, when twice the breakdown field was applied to an area of about 200 cms, over 600 breaks were counted and it is to be expected that self-shielding of some of the breaks will reduce the number below that given by the curve. The same effect has been used in making multichannel solid dielectric switches, where very rapidly rising pulses with rates of increase of 10^{14} volts per second overdrive spark channels, and enable the pulse to continue to rise even though breakdown processes are already under way at the lowest voltage breakdown site. The fact that the pulse overstresses the dielectric enables a number of breakdown channels to be produced (in some systems up to 200) by a single very fast pulse.

The relation between mean breakdown voltage and volume can be used in a number of ways.

One application is to explain why scratches and other surface defects do not cause a sheet of plastic to have a low breakdown strength under single pulse conditions. There is, of course, a field enhancement at the bottom of a fairly bad scratch of, say, 5 thou. depth and radius 1/2 thou. The field at the tip of the scratch will be about 3 times that in the main body of the material but the ratio of the volumes stressed can easily be 10^8 to 1 and this implies a ratio of breakdown fields of 6 to 1. Thus the breakdown will not in general originate at the scratch.

In a case where the stressed volume goes up while the field decreases, say where a ball bearing is pushed into a plastic, as in one of the "intrinsic" breakdown tests, the effective volume stressed can be calculated and the radial distribution of breaks away from the point of maximum field also obtained.

If an additional relation is assumed, the maximum life can be obtained of any volume of polythene used under pulse charging conditions. Table I shows the data on three generators of varying volume of polythene and gives the voltage at which a life of about 40 firings per broken line was obtained.

TABLE I

Generator	kV Charging for 40 Firings per Break	Corresponding Field MV/cm	Volume cc	Field for 1 cc	Mean MV/cm
Dagwood	130 kV	0.42	3×10^4	1.22	)
Polaris	200 kV	0.43	1.3×10^5	1.40	)1.32
SMOG	160 kV	0.34	6×10^5	1.34	)

This value is to be compared with a single shot breakdown voltage of 2.4 MV/cm, thus a life of about 40 shots is obtained for an under voltage of 0.56. For a number of systems (including condensers) the ratio of the mean breakdown voltage to the pulse voltage under consideration raised to the 7th power gives the life roughly and the above relation applies above approximately. Needless to say, the life may be less than this if conditions are unfavourable, such as D.C. charging with pulse reversal.

It should be mentioned that we do not have extensive data on the point at which the volume effect begins to decrease and in the absence of any measurement of the extent of the defect at any volume it is not possible to estimate this. For instance, if the volume were in the form of a very large area of thin foil, then at some critical volume the defect would reach through the foil and from then on the breakdown would become independent of volume. This latter statement only applies to the assumed structural intrinsic mode; it would still be only too easy to have hairs, dust, or indeed a hole right the way through and these mechanical defects would still give a volume effect.

There is also one case where a possibly significantly higher breakdown field has been observed than would have been expected from the curve given in Figure 3. This was with polythene cable, where, even allowing for the fact that the effective stressed volume is considerably smaller than the volume of polythene in the cable, a pulse breakdown strength some 20% to 30% higher than expected was obtained. This may be due to the mode of manufacture of the cable, including rate of coiling and compressional effects of the outer layers on that next to the inner core, where the field strength is greatest and from which the breakdowns originate. However, the experiments have very poor statistics and the effect may well not be a real one.

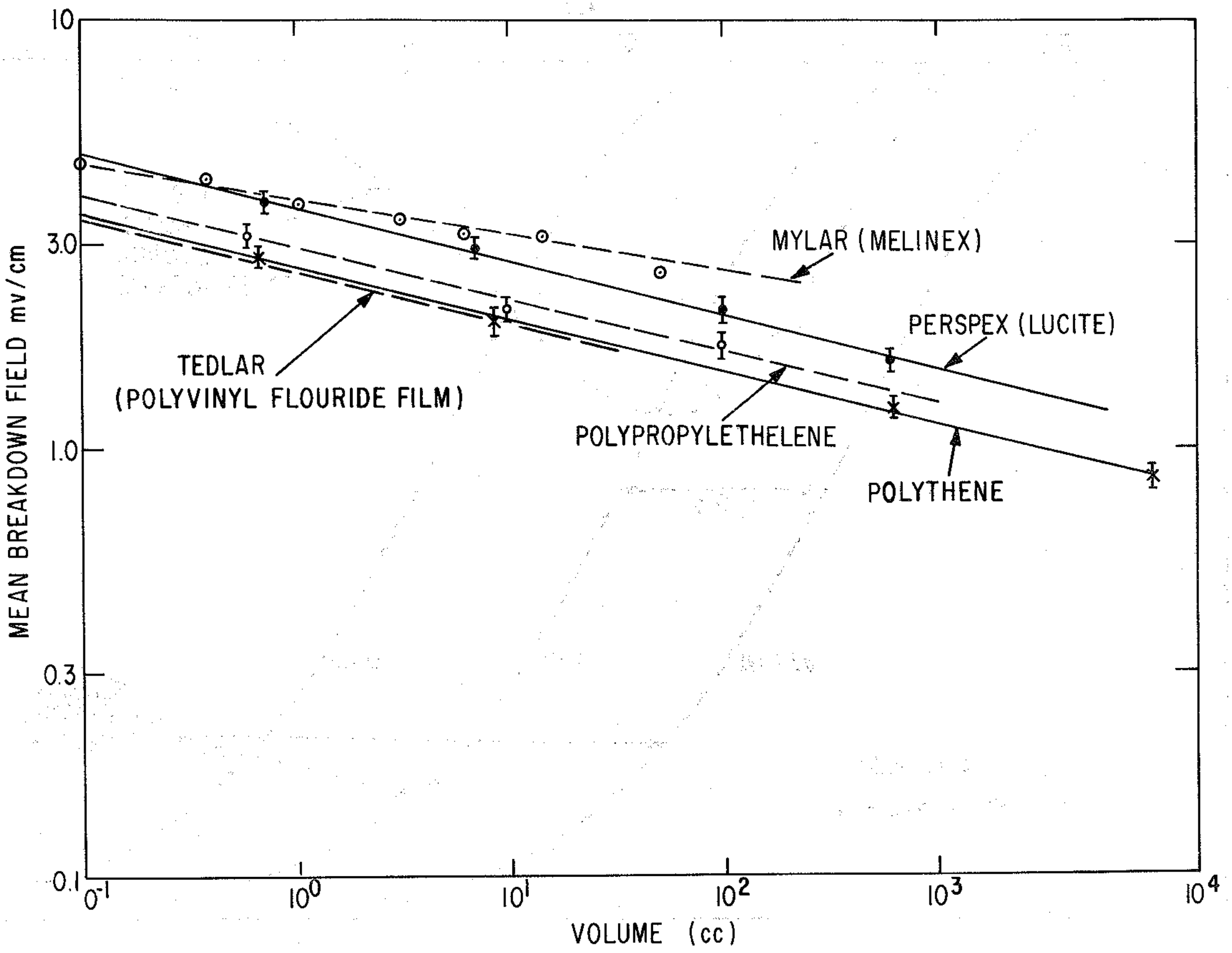
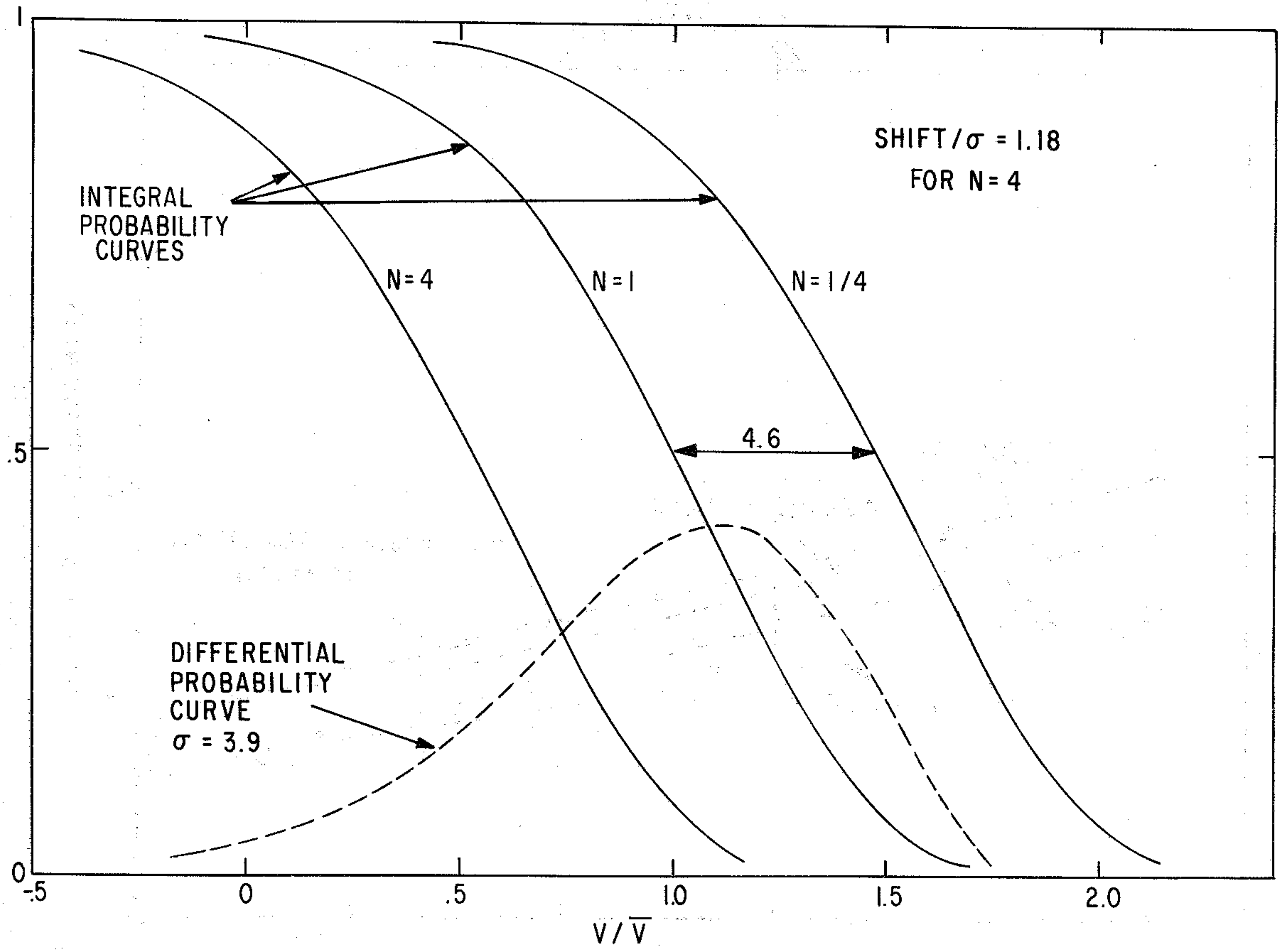


FIG. I PLASTIC BREAKDOWN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FOR N = 4
INTEGRAL
PROBABILITY
CURVES
N = 4
N = 1
N = 1/4
4.6
DIFFERENTIAL
PROBABILITY
CURVE
σ = 3.9
1
.5
0
-.5
0
.5
1.0
1.5
2.0
V / V̄

FIG. 2

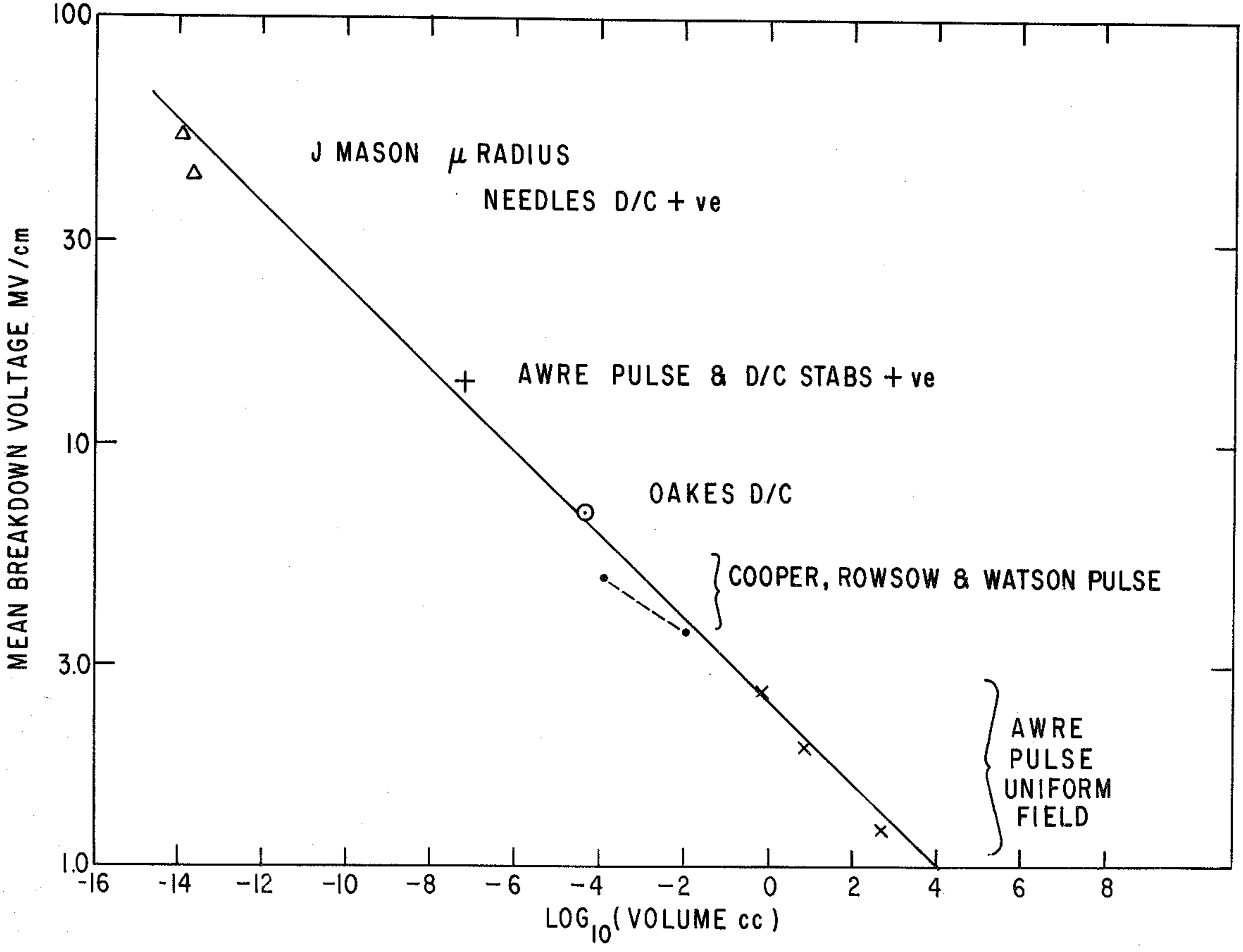

FIG. 3 POLYTHENE BREAKDOWN