High-Voltage Notes
Note 2

16 March 1971

Fast Pulse Vacuum Flashover

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SSWA/JCM/713/157

The recent visit of Dave Hammer from NRL gave me occasion to analyse roughly the available small sample flashover data and I thought the results might be of minor interest to others. This re-analysis has been directed towards the region of interest to tube designers and concentrated on perspex (ie lucite) at about 45°, ie the region where it withstands the maximum gradient. The results from different experimentalists are in reasonable agreement, after manipulation, and in agreement with the performance of the best tube designs.

A few general comments are worth making before a brief resumé of the available data. The first point concerns the value of t_{eff} . As is shown below, a $t^{1/6}$ power appears to apply reasonably well and as such the relevant fudge to convert an odd shaped waveform into an approximately rectangular pulse is the full width at 89% of full height. As with all fudges, this is only approximately correct but it is in the right ball park. Unfortunately it is not always clear from the reports how the quoted pulse times are in fact measured and some judgment has had to be used in estimating t_{eff} . However, as this is raised to the 1/6th power, errors are not strongly reflected in the final results.

The second point concerns the long pulse (of the order of 1 μsec) data, where the spread of results is considerably greater. This is, I think, because there is a greater dependency on the surface finish, etc. of the cones. In addition there appears to be a weak dependence of the breakdown field on the length of the sample. There may well be a residual effect for short pulses (of the order of tens of ns) apart from any area effect, but from Ian's results it would appear to be small. An additional piece of evidence is that for diaphragm tubes (ie ones with straight sheets of perspex orthogonal to the axis) the breakdown strength is very close to that estimated from the cone data, despite the fact that there are no intervening grading rings across the long surface. Fortunately the short pulse data is the most interesting from the tube designer's point of view and here the data appears to be only weakly dependent on surface finish, fit and shape, near the triple points, oiling, etc., when these are reasonably done.

I D Smith(1). The samples had various lengths but in general were 1" long and had areas of the order of 40 cm^2. Ian used as a criterion of breakdown the voltage at which the sample broke at the end of the pulse, as it passed through zero volts. This had the advantage of being very well defined but is perhaps a little less useful than taking the voltage at which the surface flashed over at peak volts. The easiest voltage to measure is the one on a linear ramp but I think this leans rather heavily on the t_{eff} fudge. Because of Ian's convention for the breakdown field, I have multiplied his results by 1.1 to get peak breakdown, probably a slightly conservative factor. The scatter was observed to be of the order of ± 10% per shot and the effect of oiling with MS F704 silicone oil small. The breakdown fields were 200 kV/cm for a t_{eff} of about 30 ns and 115 kV/cm for about 300 ns.

Watson and Shannon(2) tested glass and lexan. Unfortunately the lexan curve is incomplete and I have had to extrapolate it to give a very approximate value of 200 kV/cm for 70 ns at 45°. For long pulses, lexan behaves like perspex (see Ref. 4) but its comparison with perspex can be questioned; however I feel it is probably rather similar. The area of the samples was of the order of 10 cm^2.

Glock and Linke(3) looked at perspex in some detail and in addition imposed a magnetic field on the sample with no significant effect. Their samples were about 25 cm^2 in surface area and they obtained 290, 200 and 114 kV/cm for times of 3, 30 and 300 ns approximately. At the shortest time they found the optimum breakdown gradient was obtained at an angle of about 30°, but I have used their value for 45° to be consistent. They also quote a scatter of ± 10% in single shot data.

O. Milton(4) has performed an extensive series of tests with a 5 μsec pulse with different materials and also quotes results for a short pulse for perspex. His samples were probably rather better finished and seated than others and it appears he found a rather larger conditioning effect than others found for the short pulses. The question of what effective time to use is particularly difficult in this report. The pulse is quoted as 5 μsec for the long pulse tests, but the t_{eff} measured from a record given in the report is of order 0.6 μsec. If this is a typical record then the samples were broken on the faster rising front of the waveforms and the t_{effs} I have assumed apply. The area of the samples was of the order of 14 cm^2 and the mean breakdown fields were 304 kV/cm and 196 kV/cm for effective times of the order of 20 and 600 ns.

In analysing the above data I have assumed an $A^{1/10}$ effect (based on the + 10% scatter of single shot results) and I have also used a $t^{1/6}$ power. This appears to be a reasonable first approximation to what is likely to be a fairly complicated situation and may only apply to the range 10 ns < t_{eff} < 200 ns. However, various real life tubes have shown a time dependency of this sort out to a hundred ns or so and in one test a diaphragm tube broke at a few microseconds on the slow Marx charging waveform at a time which fitted this power closely. However, for exactness the breakdown relation obtained really only applies to short pulses and should not be extrapolated to times over a couple of hundred ns, except in desperation.

Table I summarises the data and includes the lengths of typical samples. The luxury of a third significant figure is obviously not justified in either this or the next table and I apologise. Table II gives the values of $Ft^{1/6}A^{1/10}$ using the values given in Table I.

TABLE I

ALL VALUES AFTER CONDITIONING

	Area (cm^2)	Length (cm)	Breakdown Field (kV/cm)	t_{eff} (μsec)
I D Smith	40	2.5	220 128	0.03 0.3
Watson (Lexan)	10*	0.95	~200	0.07
Glock	25	1.25	290 200 114	0.003 0.03 0.30
Milton	14	1.27	304 196	0.02 0.6

TABLE II

VALUES OF $Ft^{1/6} A^{1/10}$ (kV/cm, μsec, cm^2)

	Short Pulse $t \sim 0.03$ μsec	Long Pulse $t \sim 0.5$ μsec
Smith	178	154
Watson	154	
Glock	152 153	129
Milton	206	236
Average*	173	~170

*Giving equal weight to each experimentalist

Considering the internal data in each group, the $t^{1/6}$ power seems to be a reasonable average effect, subject to the remarks made above. The data of O Milton is significantly higher but, as was mentioned above, his samples appear to be better made and mounted. For the short pulses, an average value of 173 is within a standard deviation of ± 15% in the individual data. The average for the longer pulses is much more uncertain and it is speculated that the fit of the cone to its electrodes is beginning to have a significant effect. For DC this factor is found to be very important.

However, for short pulses, the factor can be taken to be 175 and it is possible that where great care is taken with the finish and fit at the triple points, this number might increase by about 10%. Another 10% increase may be around for different plastics which are obtainable in large enough blocks to make tubes out of, but of course the material should be tested in sensible sizes. I D Smith at Physics International, has found significant increases in certain samples of lucite made up as tube rings, but the cause of this increase is obscure.

Using a constant typical tube diameter of about 30 cm, the relation can be written as $Fd^{1/10}t^{1/6} = 100$ where the spacing rings are a small proportion of the thickness (~ 10%) and the tube is very well graded overall. This is the relation that we have used at AWRE for some time past. It applies, of course, to a clean tube. For real working conditions this would have to be reduced somewhat. During the P.I. Aurora programme, tests showed that short very well graded tubes achieved this level with overall lengths of 25 cm and using four sections. They also tested a well graded tube of about 83 cm length of 11 sections which went to 6.9 MV for a 100 ns pulse, giving a value of 90 for the constant. It should be repeated that this relation applies for tubes with an inside diameter of the order of 20 to 40 cm, and also the tube has to be well graded overall in order to reach this level.

Concluding, it may be objected that even the short pulse data in Table II is not very consistent, but in view of the different conditions such as surface finish, thinness of the cone's edges, seating against the electrodes, voltage calibration and wave shape monitoring errors, etc, I think the agreement is rather good. This is confirmed by the fact that both axial and diaphragm tubes, when well designed and clean, closely approach the gradients predicted by the very small scale test results which have been obtained in considerably different geometries.

REFERENCES

(1) I D Smith. Proceedings of the 1st International Symposium on Insulation of High Voltages in Vacuum. p.261, Oct. 64.

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(2) A Watson and I Shannon. Proceedings of the 2nd International Symposium on Insulation of High Voltages in Vacuum. p.245, Sept. 66.

(3) W Glock and S Lenke. Pulsed High Voltage Flashover of Vacuum Dielectric Interfaces. Cornell Lab. of Plasma Studies, August 1969.

(4) O Milton. Pulsed Flashover of Insulators in Vacuum. SC-DC-70-5459.