Dielectric Strength Notes
Note 2

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Pulse Breakdown of Transformer Oil

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The accompanying Table I gives the data from 20 sets of "experiments" on oil breakdown performed over the past 9 months with different voltage generators and monitoring systems by various members of our motley crew here. We have held a number of views of what the results meant as time and the accumulation progressed and the present endeavour to relate all the data and give an interpretation of it is not easy and not necessarily final. We trust you will view it with the utmost suspicion!

On the left of the table are the measurements made, which are of the area of electrode stressed, (in the case of balls or cylinders this is the area on which the field is at least 90% of the maximum), the electrode gap, the breakdown field or peak field if breakdown occurs after peak, and the effective time, measured as that for which the field is greater than 63% of its maximum. On the right hand side are a succession of derived quantities in terms of which the results can hopefully be described. (Each data point referred to in the end column is a separate firing; the applied voltage will vary throughout one set of experiments, but the spacing is constant, or nearly constant, in each.) The values quoted for F and t are typical values; the derived quantities are calculated for each firing and averaged for the experiment as a whole.

In attempting such a description we try to relate the breakdown field F to three variables; the time of application of the pulse, the gap, and the area. Ideally, we should hold two of these constant at a time and vary the third, but little of our data can be so conveniently grouped, and the analysis I am going to describe proceeds by supplementing this approach by guesswork and backtracking.

First, the time dependence. An approximate calculation based on measurements of streamer velocity from needles suggested that $F^{3/2}$ t should be nearly constant and equal to about 0.2 independent of gap d. The results (1)-(5) for ball bearings in the table seem consistent with this, spanning an order of magnitude in time. Result (1) was obtained using output waveforms from one of our fast pulse generators; the rest used a slower transformer. (Unfortunately, scatter prevents one from getting a good measure of time dependence from one experiment alone, varying only the peak amplitude of the pulse applied. In one experiment, number (13), relentless grouping of many data points can be made to yield $Ft^{.35}$ = constant, but little significance can be attached to this). A similar comparison between Nos. (8), (13) and (14) indicates a much poorer fit with $F^{3/2}$ t and $Ft^{1/2}$ is more nearly constant. Exact comparisons are made difficult because the gaps and areas are not quite constant in either case, but we tentatively adopt $Ft^{1/2}$ as a tool for further analysis.

One next finds indications (Nos. (10), (11), (12) and (13), (14), (15)) that $Ft^{1/2}$ increases with increasing gap d; elsewhere ((2), (3), (4), (5) and (17), (18)) this effect is not visible. Assume for want of anything better that $K = Ft^{1/2} d^{-1/4}$ is constant; Graph A then plots them against area. Three points emerge. First, the ball bearings are not distinguishable from the plates and cylinder, which are of copper foil or sheet; the change in surface finish appears not to be important. Secondly, the slope of the log-log plot is about $-.12$, which is the same as that of a previously obtained plot of the breaking stress of polythene (in that case time independent) against volume stressed. Now the slope of the line relates to the standard deviation of the results at any point; in the case of polythene this is 12% at all points, and in the case of the oil, the standard deviations over all the data average out at about 14%, which is the same number, and hence we would expect the slopes to be approximately equal. This provides some slight justification for taking $-1/4$ for the exponent of d, for the slope becomes greater the larger we make the exponent, owing to the fact that it tends to increase throughout the data as the area increases. However, $d^{-1/3}$ would do equally well.

Lastly, using the slope obtained it is possible to write a value K_A for each experiment which is K corrected back to 1 cm^2. This can then be used to look again at the time dependence deduced from fast pulse data and in the main table the ball bearing results suggest that K_A decreases as t increases, so that we might choose a larger exponent for t; however, the subgroup 8 - 14 for plates indicates the opposite, so $Ft^{1/2}$ remains our best guess in this respect. It seems possible, though, that this is really a smaller exponent, with a finite threshold.

The average value of K_A, weighting each experiment equally, is .48; the departure of many results from this is no greater than would be expected on the basis of a 14% standard deviation for each measurement, of which often only a few were made, together with errors of the order of 0.2 centimetres in measuring and setting gaps, which in some cases amount to quite a large error. A further source of error is the different monitoring systems used, which have occasionally been found 10% in error. There are three results which, it seems to me, are clearly more than 2 standard errors away from the mean, and these are (13), (14), and (16), whereas in 20 cases one would expect only one. Of the three, (13) and (16) were performed in succession with the same method of assembly, and it is possible that the gap was really larger than 0.8 cm.

The conclusions above are by no means as strongly supported by the data as we would like, although we believe they are, broadly speaking, a good guide for prediction. We intend to plan specific experiments to elucidate what remain sensitive or obscure areas; for example, to try to establish more firmly the exponent of d, which still could conceivably not exist at all. A plot is in fact shown of $Ft^{1/2}$ versus area which could be regarded as satisfactory; it has a lower slope. It is tempting, however, to draw the separate dotted lines grouping gaps of 0.5 and 1.0 cms approximately, and these return to the larger slope.

We have been largely unsuccessful in changing the strength of oil either for better or worse by external means. Carbon in the oil and moderately pitted electrodes - so long as no serious projection exists - do not seem to lower the strength except on the smallest areas; it requires a knife edge projecting .05 cm to produce much degradation. Small bubbles on either electrode seem also to us to have little effect and a D.C. field of 1000 V/cm only lowers the strength. Increasing the temperature of the oil from ambient to 60°C has no effect. However, after an electrode assembly has been undisturbed for 10 hours or more (e.g. overnight) a field some 20% larger may be held off for one shot only. An effect of similar magnitude occurs if the electrodes are covered with a plastic film, for example, a coat of polythene paint or a sheet of melinex. A breakdown punctures the film, of course, but does not destroy the effect, which is rather erratic, however. The most spectacular change in strength we have witnessed occurred after a pair of oil immersed plates of area 100 cm^2 had been left under oil overnight in a vacuum system, the oil outgassing steadily. This produced a value of $Ft^{1/2}$, double that normally observed, but alas the effect had utterly disappeared on the second firing. We have, I may add, no firm views on the mechanism which starts the streamer off.

		A Area, cm^2	d gap, cm	(Mean Values)		$F^{3/2}t$	$Ft^{1/2}$	$Ft^{1/2}d^{-1/4}$ = K	K_A	N No. of data points, i.e. firings
				F Field MV/cm	t time, µsec					
	Balls									
^{x}Fast Pulse→	(1)^x	.10	.15	2.7	.02	.11	.37	.60	.44	6
	(2)	.05	.14	1.8	.06	.14	.44	.72	.43	4
	(3)	.10	.11	1.6	.06	.11	.37	.63	.47	3
	(4)	.07	.20	1.0	.15	.12	.33	.50	.35	3
	(5)	.30	.4	1.0	.15	.12	.37	.47	.41	3
	Cylinders									
	(6)	.8	.42	.80	.20	.15	.40	.50	.46	8
	(7)	3.0	.45	.72	.25	.15	.36	.44	.49	2
	Plates									
^{x}Fast Pulse→	(8)^x	160	.42	1.25	.013	.02	.15	.19	.38	5
	(9)	6	.45	.60	.08	.08	.28	.34	.43	3
	(10)	25	.60	.75	.13	.11	.30	.34	.51	2
	(11)	25	.20	.65	.08	.04	.18	.27	.41	2
	(12)	25	.30	.70	.11	.06	.72	.30	.40	3
	(13)	110	.63	.55	.15	.056	.20	.23	.43	47
	(14)	110	.95	.50	.25	.093	.24	.25	.46	9
	(15)	100	.80	.80	.20	.16	.38	.40	.73	2
	(16)	380	1.0	.73	.15	.09	.28	.28	.60	8
	(17)	380	2.0	.65	.15	.07	.25	.21	.44	1
	(18)	630	.8	.67	.22	.12	.32	.34	.75	3
	(19)	1,500	.90	.42	.23	.06	.20	.21	.55	10
	(20)	100,000	4.5	.25	.45	.05	.16	.11	.48	4

TABLE I