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1989 J. Phys.: Condens. Matter 1 3041

(http://iopscience.iop.org/0953-8984/1/18/011)

J. Phys.: Condens. Matter 1 (1989) 3041–3045. Printed in the UK

LETTER TO THE EDITOR

Dielectric breakdown in metal-loaded polyethylene

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Received 6 January 1989, in final form 22 February 1989

Abstract. The failure statistics of polyethylene plaques loaded with a know volume fraction of metallic particles of fixed size distribution have been determined. The results are compared with the predictions of the percolation breakdown model. It is shown that the large decrease observed in characteristic strengths at low defect loadings obeys the theoretical expression derived for the model. However, the type of breakdown statistic could not be determined unambiguously.

In a series of papers Duxbury and co-workers have discussed the breakdown features of a bond percolation model (Duxbury *et al* 1986, 1987, Duxbury and Leath 1987). It has been suggested that this model is applicable to dielectric breakdown in insulators loaded with conducting contaminants (Beale and Duxbury 1988). Here we present the results of dielectric failure measurements obtained for polyethylene plaques containing a known volume fraction of aluminium particles. Each plaque was compression moulded to a disc of thickness 0.7 mm with a depressed inner region of diameter 54 mm, with a Ragowski profile—this was to ensure that the applied field was uniform. The particles were of indeterminate shape (figure 1(*a*)) but had a well defined size range (53–75 μm), and appeared to be randomly distributed within the polyethylene (figure 1(*b*)). Breakdown statistics were obtained by stressing the metal-loaded plaques under a uniform AC field (50 Hz) and ramping the field amplitude at a fixed rate until failure occurred.

In the first instance the data were analysed using Weibull statistics (Gumbel 1958) which is standard practice. Thus it was assumed that the probability of failure P_F had the form

$$P_F = 1 - \exp[-(E/E_c)^\beta] \qquad (1)$$

where E is the applied field and E_c and β are constants. This type of statistic gives a straight line on a plot of $\log[-\ln(1 - P_F)]$ against $\log E$, with a gradient of β. These plots are shown in figure 2 and exhibit straight lines with good regression values (typically $R^2 \simeq 0.95$). The maximum liklihood values of β and the characteristic value of E, E_c, are quoted in table 1. Note that the control is a polyethylene plaque prepared from super-clean material into which no conducting particles were intentionally added. This does not mean that the material was defect-free.

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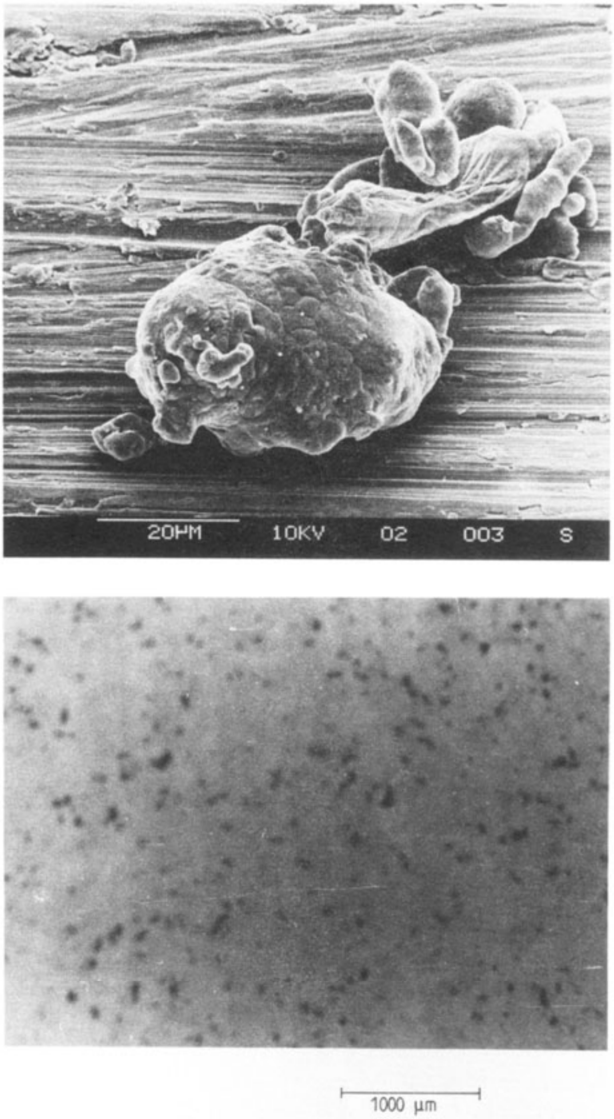

Figure 1. (*a*) A SEM of a typical aluminium particle. (*b*) An optical micrograph of the particle dispersion in the plaque centre for a typical specimen with $p = 5 \times 10^{-4}$.

These results show qualitatively the trend predicted by the percolation model (Beale and Duxbury 1988), i.e. a reduction in the characteristic value of E and a tendency to large values of β with increasing particle volume fraction, p. In detail, this model predicts that E_c has the form (Duxbury *et al* (1986), equation (3))

$$E_c(p) \propto (p_c - p)^t/(1 - \alpha(\Omega)/\ln(p)) \tag{2}$$

where p_c is the percolation limit and Ω the system volume. The exponent t is equal to the correlation length exponent ν for the lattice model and $\nu + 1$ for the continuum model (Chakrabarti *et al* 1988).

Failure in the percolation model is the result of a deterministic sequence of bond breaking originating with the most severe conducting cluster. The expression for $E_c(p)$

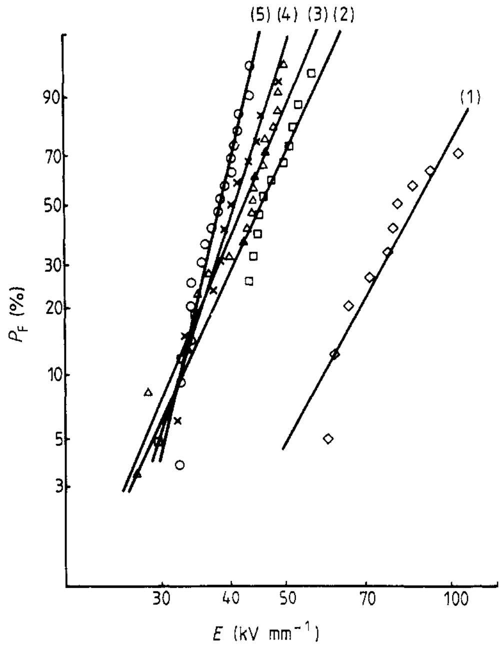

Figure 2. The probability of failure, P_F, against applied field from equation (1) for various concentrations of conducting defects. The symbols are as defined in table 1.

Table 1. Parameters taken from data presented in figures 2 and 4 for five volume fractions of conducting particles, p.

Sample set (figures 2 and 4)		p	Weibull distribution (equation (1)) E_c (kV mm^{-1})	β	IAEV distribution (equation (4)) E_c (kV mm^{-1})
1	◇	0	93	5	340
2	□	1.7×10^{-5}	48	6	460
3	△	5.0×10^{-5}	44	7	500
4	×	1.7×10^{-4}	42	9	340
5	○	5.0×10^{-4}	39	12	390

is derived from the field enhancement of the characteristic cluster with the numerator originating with its size and the denominator with its length-to-breadth ratio (Duxbury *et al* 1986). In the low-loading limit equation (2) takes the form

$$E_c(p) \simeq E_c(0)/(1 - \alpha(\Omega)/\ln(p)) \qquad p \ll p_c \tag{3}$$

and thus small concentrations of defects can have a significant effect upon the characteristic breakdown strength. Even a single conducting defect will reduce $E_c(0)$ to $\frac{1}{4}E_c(0)\pi$ (Beale and Duxbury 1988). The percolation limit for metal spheres is $p_c \simeq 0.27$ (see Giraud *et al* 1983) and whatever the system it is not likely to be less than 0.2 (Stauffer 1979). Thus the volume concentrations used here clearly lie in the low-loading limit for which equation (3) applies. That this is indeed so is illustrated in figure 3 where we have shown that $E_c(0)/E_c(p)$ is a linear function of $1/\ln(p)$ whose intercept on the y axis ($1/\ln(p) = 0$) is unity as required by equation (3). To the best of the authors' knowledge

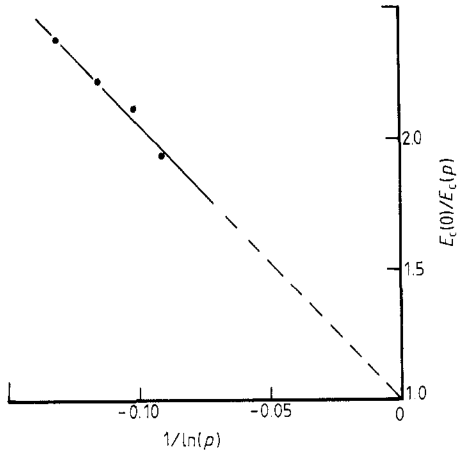

Figure 3. A plot of $E_c(0)/E_c(p)$ as a function of $1/\ln(p)$, with the characteristic fields taken from column 3 of table 1.

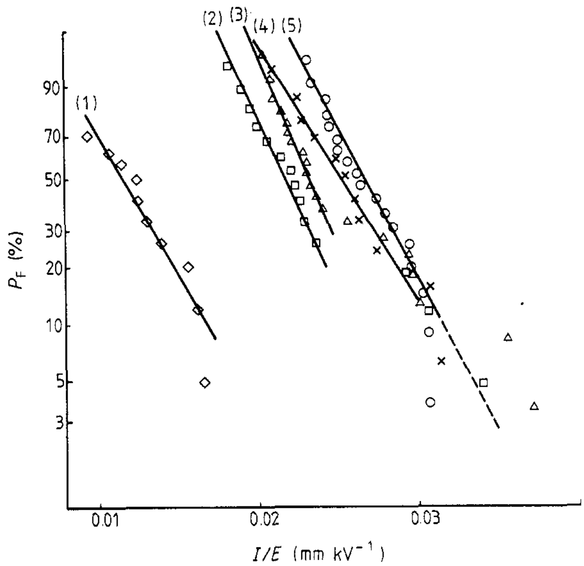

Figure 4. The probability of failure, P_F, against the reciprocal of the applied field from equation (4) for various concentrations of defects. The symbols are as defined in table 1.

this is the first time that a theoretical expression relating the breakdown strength of contaminated insulation to that of defect-free material has been verified. It can therefore be expected that equation (3) will form the basis for a tolerance limit on the concentration of conducting defects in cable insulation.

Since the most severe cluster is essentially the largest in a sample, the failure statistic of the percolation model is based on the probability of a given size being the extreme selection from the cluster size distribution. As long as p is not close to p_c the cluster size distribution is exponential, and P_F is given by the first asymptote extreme value (1AEV) distribution (Gumbel 1958),

$$P_F = 1 - \exp[-c\Omega \exp(-E_c/E)] \qquad (4)$$

where c is a constant weakly dependent upon p (Beale and Duxbury 1988). This expression for P_F gives a straight line of gradient $-E_c \log(e)$ if $\log[-\ln(1 - P_F)]$ is plotted against $1/E$ as in figure 4. Here we can see that the large-defect-concentration data give a fairly reasonable straight line, but no better than that found in the Weibull plot of figure 2. Lower concentrations appear to give results lying on this same line for the low-field failures and then cross over to plots roughly parallel to the original for the higher-field failures. The values obtained for E_c in this case, which are given in table 1, are essentially constant within the error of estimation and lie close to the uniform field breakdown strength of polyethylene (500–800 kV mm^{-1}). It therefore appears that in this statistic the parameter c contains all the dependence on p that was found for the characteristic breakdown strength (equation (3)) and shape parameter, β, in the Weibull case (figure 2). This suggests that only at the highest-concentration or lowest-field breakdowns is the failure statistic governed by the cluster size distribution. At lower concentrations it seems that the distribution of largest clusters remains unchanged and the survival probability is determined by the number density with a field-enhancing shape ($\propto c$).

The choice of statistic is of major importance in assessing the reliability of insulation materials since it is usually necessary to extrapolate from high to working stresses. Under these circumstances a difference appears in the predictions from expression (1) and (4) (Duxbury *et al* 1987). No such choice can be made on the basis of the data we have obtained, since in all cases the straight-line fits to equation (4) were no better than those for the Weibull function (equation (1)). In order to differentiate between the two statistics 1000 failures would be required (Duxbury *et al* 1987) rather than the sample sets of 10 to 20 used here. It should be noted, however, that these are actually large sample sets for this type of test, and it is unlikely that sufficiently large numbers could be obtained experimentally except in the case of metal-loaded thin capacitor films.

In summary therefore this work has demonstrated the validity of the percolation model expression for the characteristic breakdown strength in the low-loading limit, and shown that the IAEV failure statistic predicted is at least as valid as the more commonly used Weibull statistic. More data and far larger loadings are required to test the theory in greater depth; however, the substantial reduction in breakdown strength already realised may make this a rather difficult undertaking.

The authors express thanks to the Directors of STC Technology Ltd, Harlow, IKO A/B Grimsas and STK A/S Oslo for permission to publish this Letter. RWC also acknowledges support from these companies and the SERC. The authors thank the referee for drawing their attention to the low-loading limit.

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