Weibull Statistics in Short-term Dielectric Breakdown of Thin Polyethylene Films

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ABSTRACT

A Weibull statistical analysis of breakdown voltages of thin polyethylene-insulated power cable slices is performed on large populations. Computation of confidence intervals implies that the statistically correct description is a three-parameter Weibull distribution, *i.e.* with a non-zero location parameter. It is shown that a data set described by a two-parameter Weibull distribution contains additional statistical dispersion factors which may or may not yield information on the insulation itself. In other words, a zero-location parameter always results from inhomogeneities in the sampling. These may be due to uncontrolled experimental parameters or to defects of various origins; but aging is also a source of dispersion of the electrical properties of dielectrics. To discriminate between the two, we proceed by comparative testing. When obtained under carefully controlled experimental conditions, the location parameter value can be considered a true quality factor of the system under test. The possible physical meaning of the so-called threshold may be envisaged once the breakdown mechanism at work under the conditions of the test is known. The statistical analysis of data collected in routine breakdown tests provides a very sensitive tool to investigate small changes in electrical insulation when performed on extensive data sets.

1. INTRODUCTION

When testing several identical samples in the same way, the breakdown voltages (or time-to-failure) scatter over a wide range. Of the several possible statistical descriptions of such tests, the Weibull distribution [1] has come to be preferred, and is widely used by insulation system designers [2]. Initially, the Weibull equation was based purely on empirical grounds. But it is one of the extreme value functions [3], and hence could be related to general features of the system and its breakdown mechanism. A theoretical background has been proposed for the use of this particular statistical form [4]. According to this model, the Weibull statistical parameters have a direct physical meaning. A recent publication reviewed the theoretical basis for the statistics of dielectric breakdown [5].

The most controversial use of the Weibull statistic concerns the so-called threshold problem. The cumulative probability of failure for the Weibull distribution can be written in its general form as

$$P(x) = \begin{cases} 1 - \exp - \left[\frac{(x - x_s)}{x_0}\right]^\beta & x_s < x < +\infty \\ 0 & x < x_s \end{cases} \quad (1)$$

where x is either the time-to-failure or the breakdown voltage, depending on whether the test is conducted at a constant electrical stress or if it is a ramp test with a linear increasing voltage dV/dt, x_s is the location parameter, or the threshold, while x_0 and β are the scale and shape parameters.

The location parameter x_s is frequently assumed to be zero. A non-zero value implies a threshold voltage in a ramp test, or a threshold time to breakdown in a constant stress experiment. The objective of this paper is to deal with the threshold problem in a ramp test. The main difficulty in this matter is that, in order to analyze the statistics with any degree of confidence, extensive data sets are needed for the analysis. Furthermore, the portion of the distribution that is important for assessing the material quality is the region where the cumulative failure probability is low and the statistical error the largest. But the very breakdown process in a sample of bulk dielectric makes the sample unsuitable for further examination. This explains why the sample populations in measured data sets are generally limited. In order to perform reliable statistical analysis, we have carried out routine breakdown experiments on a large number of specimen types, each type containing a population of 80 to 100 samples.

In Section 3 of this paper, we discuss the results of several trials performed on very homogeneous and well characterized polyethylene samples. A rigorous statistical analysis shows that the correct description is a three-parameter Weibull distribution.

In the Section 1, we show that the threshold character of a given population can be altered either by a poor control of the experimental conditions during the test, or by sample aging.

In Section 5, the breakdown process at work under routine test conditions is discussed. It is concluded that the location parameter must be considered as a true quality factor of the system under study.

2. EXPERIMENTAL PROCEDURE

2.1 SAMPLE CONDITIONING

The samples are crosslinked polyethylene slices, 200 μm thick and 40×40 mm^2 in section, cut from the insulation of a power cable using a microtome. They were outgassed for 48 h at 80°C, and then kept under a primary vacuum at room temperature. It has been verified by infrared spectroscopy that the decomposition byproducts of the crosslinking reaction are swept away during this treatment. The scatter in the slice thicknesses is ±20 μm *i.e.* 10%. The tested populations are therefore very homogeneous, both in composition and in geometry. The thickness used in computing the electric field is the average of four different measurements taken in the vicinity of the breakdown path. Each population contains typically 80 specimens.

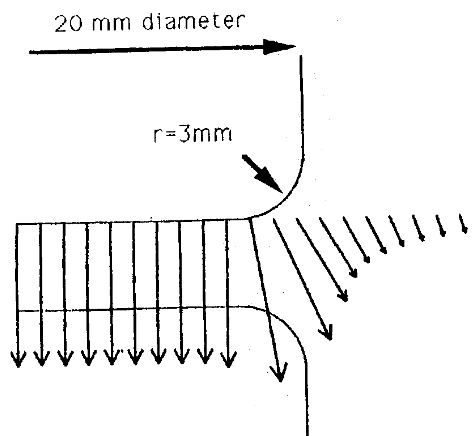

Figure 1.

Field variation along the sample surface showing the stress intensification factor at electrode edges

2.2 ELECTRODE CONFIGURATION AND TEST CONDITIONS

The electrode systems used are designed with the specific intent not to measure intrinsic breakdown, but rather to provide the information necessary to assess any changes from normal characteristics resulting from certain processing variables, aging conditions, or other manufacturing or environmental situations. The tests were performed using common parallel-plane electrode geometry with circular electrodes of equal diameters, made of stainless steel, 20 mm in diameter and with edges rounded to a 3 mm radius. Electrodes with a constant field profile were not used in these routine tests. The equal-diameter electrode configuration has the decisive advantage, over the unequal diameter arrangement, of providing a lower stress intensification factor at the edges. Figure 1 shows the field variation along the sample surface. The field intensification factor at the edge, which depends on the radius of curvature at the electrode edges, is ~ 1.2 in the actual configuration. The electrode surface was not polished to

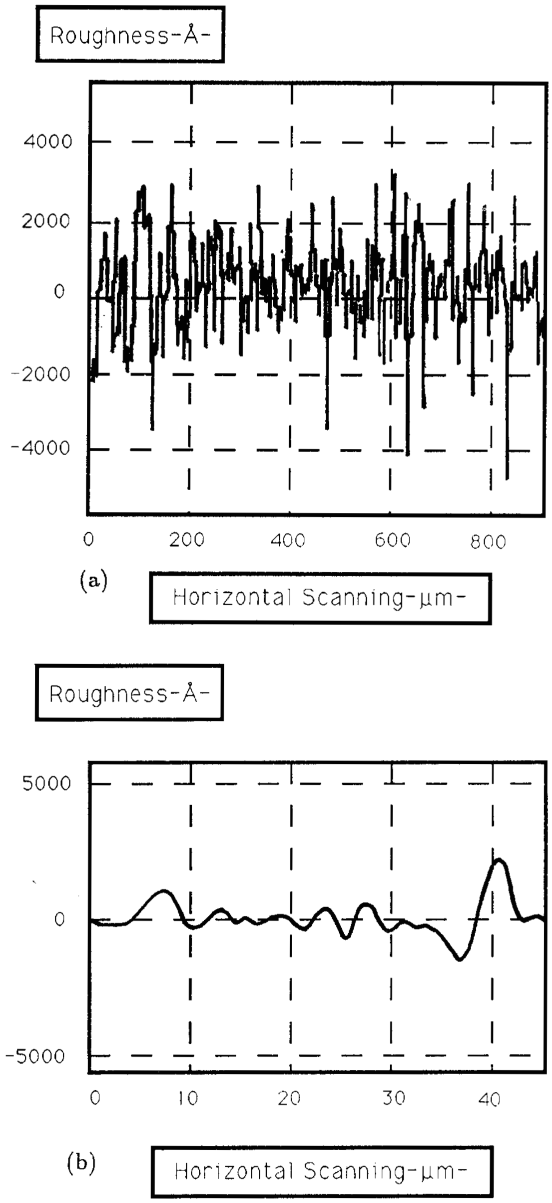

Figure 2.

Surface roughness profile of the test electrodes and the polyethylene samples. (a) Electrode surface roughness, (b) polyethylene surface roughness.

an optical finish. Typical surface roughness is given in Figure 2 together with the roughness of the polyethylene films resulting from microtome cutting.

A slight force of ~ 2 N is applied to the specimen by a spring, pressing the electrodes to the specimen. Ten twin electrode systems are used during a given test, which means that each of them sustains 8 breakdown events during the test of a single population. The samples are individually connected to the supply and tested one by one, *i.e.* one given sample does not see any voltage surges due to the breakdown of the others. The breakdown current is limited to 1 mA by a series resistor and a current-sensitive circuit breaker, in order to prevent any major degradation of the electrodes. Their surfaces did not degrade, at least not on a macroscopic scale, during the whole procedure. The setup is immersed in an oil bath to prevent discharges in the ambient around the electrode edges. The oil was dimethylpolysiloxane, with very good dielectric properties and thermal stability. A 10 min rest was imposed between sample installation and the breakdown test. A 50 Hz ac linear ramp voltage with a slope of 4 kV/min was used for the results presented here.

3. EXPERIMENTAL RESULTS

We studied nine different populations, each of them consisting of 80 samples of a particular kind of crosslinked power cable insulation, electrically aged and unaged. Our aim in this paper is not to correlate the Weibull parameters to the cable's parameters, but rather to investigate the breakdown statistics. To do so, we present uncensored data, and report all the experimental results.

3.1 TWO-PARAMETER WEIBULL DISTRIBUTION

The experimental data are first plotted according to a two-parameter Weibull distribution, stating a zero location parameter. The cumulative failure probability is therefore

$$P(E) = 1 - \exp\left[\frac{-E}{E_0}\right]^{\beta} \tag{2}$$

where E is the electric field obtained by dividing the breakdown voltage by the thickness of the sample, and E_0 is the nominal field, *i.e.* the field corresponding to a 63.2% breakdown cumulative probability.

The experimental plot must be a straight line in a coordinate system

$$X = \log E$$
$$Y = \log\left[\ln\frac{1}{1-P}\right] \tag{3}$$

if a simple two-parameter Weibull distribution is a correct description. How well the experimental data fit a straight line is the subject of controversy. To get around this problem and follow an exact procedure, we computed the tolerance bounds on percentiles of the Weibull distribution, using an exact approach [6–8]. By definition, these bounds quantify the uncertainty due to inherent statistical variation of a Weibull distribution and the limited numbers of specimens tested. We present the current results as a plot of the experimental data with the two-sided tolerance bounds at a 90% confidence level. We therefore chose a risk of 10% to find an experimental point belonging to the true Weibull distribution outside the tolerance bounds. This value of the risk is reasonable from a statistical point of view.

Among the nine populations tested, we discerned three cases with different probabilities of occurrence.

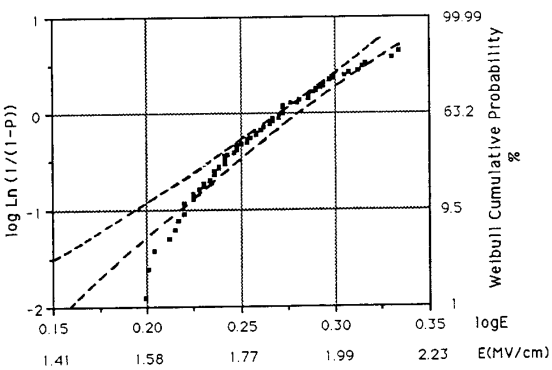

Figure 3.

Type 1 plot of breakdown data in a two-parameter Weibull distribution and 90% confidence bounds.

Type 1 is depicted in Figure 3 and corresponds to a high probability of occurrence, since five of the populations have these characteristics, *i.e.* a regular concave downward shape, with a few data points lying outside the tolerance bounds of the two-parameter Weibull distribution. This is clearly the demonstration that a statistical description of breakdown data fails in such a representation.

Type 2 can be considered as a particular case of type 1: the regular downward shape is broken by a single point which corresponds to the lowest cumulative probability of failure (see Figure 4). One population behaved like this. We will discuss this topic later on.

In Type 3 population, all the experimental data lie inside the tolerance bounds, and a two-parameter Weibull distribution can be considered as an acceptable description, even if a slight curvature is discernible 'by eye' on the plot (see Figure 5).

It is noticeable on each portion of the plots corresponding to the lowest and highest probabilities of failure that

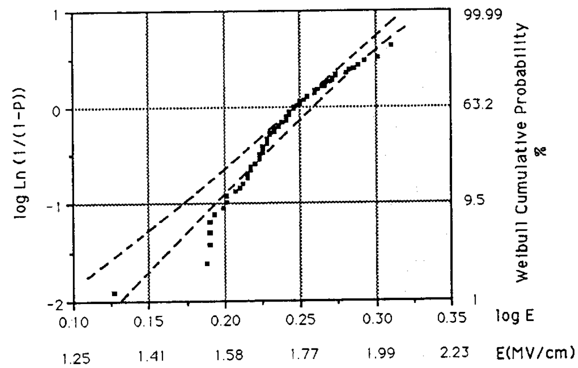

Figure 4.

Type 2 plot of breakdown data in a two-parameter Weibull distribution and 90% confidence bounds.

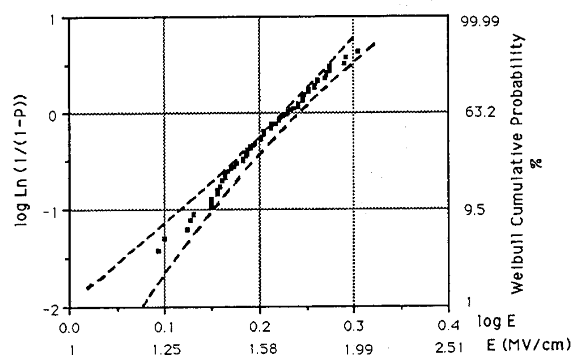

Figure 5.

Type 3 plot of breakdown data in a two-parameter Weibull distribution and 90% confidence bounds.

the tolerance bounds become increasingly wider. This is a general feature of these bounds, which depends on the number of trials, and on the probability of failure. The uncertainty is greatest for the extreme values of the distribution.

We computed the 95% and 99% confidence bounds for the same populations. In spite of an increasing bound at a given percentile as a function of a decreasing risk (respectively 5% and 1%), the conclusions are the same: a two-parameter Weibull distribution does not fit the data in the general case.

3.2 THREE-PARAMETER WEIBULL DISTRIBUTION

We then look at a possible fit of the data in a three-parameter Weibull distribution, according to the expression

$$P(E) = 1 - \exp\left[-\frac{E - E_s}{E_0 - E_s}\right]^{\beta} \qquad (4)$$

E_s being the threshold field. The data must fit a straight line in the coordinate system

$$X_s = \log(E - E_s)$$
$$Y_s = \log\left[\ln\frac{1}{1 - P}\right] \qquad (5)$$

The computation procedure consists in finding the best fit between the data and a straight line. The selected Weibull parameter values correspond to the one that minimizes the scatter between the experimental points and the theoretical representation. Both the least squares and the maximum likelihood methods have been used to quantify the scatter, and therefore to infer the threshold. The Weibull distribution parameters derived from the two methods are compared in Table 1 for the three populations under study. The nominal field (scale parameter) is insensitive to the computation method, but the threshold taken together with the slope may be different. It is worth noting that for five populations out of nine, the two methods lead to identical Weibull distribution parameters. Since the unweighted least-squares regression is strictly valid for non-skewed distributions, which is not the case for the Weibull, the maximum likelihood estimates of the distributions will be considered in the following.

Table 1.

Comparison between Weibull parameters obtained from least-squares regression and maximum likelihood method for the three populations under study.

Weibull parameters → / ↓ population	Nominal field (MV/cm)		Threshold field (MV/cm)		Shape parameter	
	least squares regression	maximum likelihood	least squares regression	maximum likelihood	least squares regression	maximum likelihood
type I	1.88	1.86	1.51	1.54	2.6	1.5
type II	1.77	1.78	0.79	1.21	8.9	4.7
type III	1.70	1.70	0.55	1.06	6.6	3.6

Figure 6 shows the 'Type 1' plot. The best linear fit of the equation

$$Y_s = 2.43X_s + 1.21 \qquad (6)$$

is obtained for a threshold value $E_s = 1.5$ MV/cm. To evaluate the goodness of the fitting procedure, we computed the 90% tolerance bounds of the three-parameter Weibull distribution obtained by assuming that the threshold is not a statistical parameter, but a true constant. All the data lie inside these tolerance bounds.

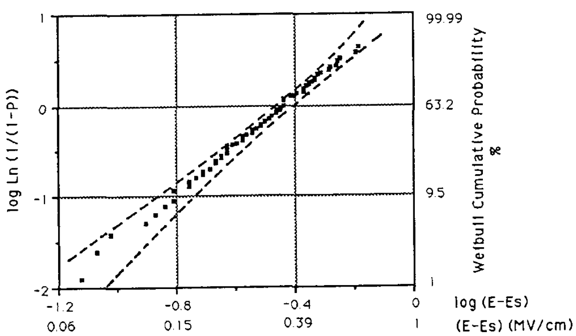

Figure 6.

Type 1 plot of breakdown data in a three-parameter Weibull distribution and 90% confidence bounds. *90% confidence level on the parameters:* Nominal field E_0. (MV/cm): $1.83 < E_0 = 1.86 < 1.94$. Shape parameter β: $2.35 < \beta = 2.76 < 3.14$.

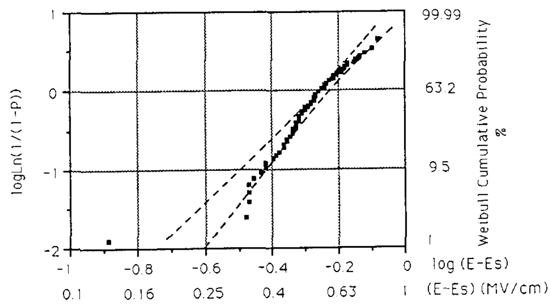

Figure 7.

Type 2 plot of breakdown data in a three-parameter Weibull distribution and 90% confidence bounds.

The 'Type 2' plot is displayed in Figure 7. The best linear fit is obtained for a threshold value of 1.24 MV/cm, but it is apparent that the data cannot be represented by a Weibull distribution. This population appears to be very strange, but further considerations show that this odd behavior is only due to the extreme and quite isolated point corresponding to a cumulative probability of 1%. Just to check, we suppressed this one point and computed the new three-parameter Weibull distribution (see Figure 8). It appears that the best linear fit of equation

$$Y_s = 2.27X_s + 1.25 \qquad (7)$$

is obtained for a threshold $E_s = 1.5$ MV/cm. This time, the distribution satisfactorily describes the experimental data. It therefore seems reasonable to discard the isolated point lying outside the distribution. The 'new' Type 2 population can therefore be considered as a Type 1 population.

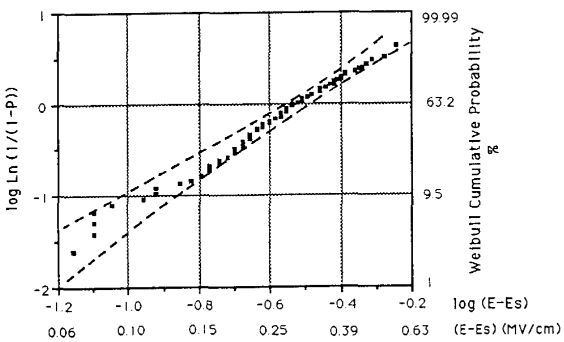

Figure 8.

Type 2 plot of breakdown data in a threeparameter Weibull distribution and 90% confidence bounds, with the lower probability data discarded. 90% confidence level on the parameters: Nominal field E_0 (MV/cm): $1.74 < E_0 = 1.77 < 1.79$. Shape parameter β: $2.11 < \beta = 2.27 < 2.82$.

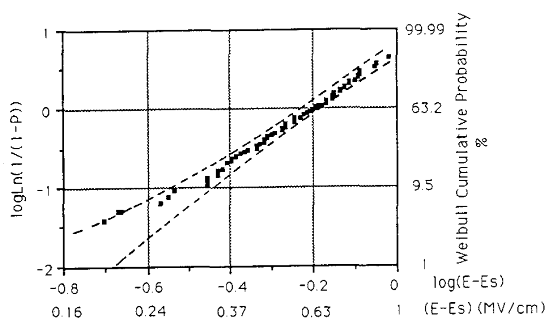

Figure 9.

Type 3 plot of breakdown data in a threeparameter Weibull distribution and 90% confidence bounds. 90% confidence level on the parameters: Nominal field E_0 (MV/cm): $1.64 < E_0 = 1.68 < 1.71$. Shape parameter β: $3.03 < \beta = 3.6 < 4.12$.

The 'Type 3' plot is displayed in Figure 9 in spite of the fact that all the breakdown data lie within the 90% confidence bounds of the two-parameter Weibull distribution. The best linear fit of equation

$$Y_s = 3.59X_s + 0.73 \tag{8}$$

is obtained in a three-parameter distribution for a threshold field $E_s = 1.06$ MV/cm.

3.3 CONFIDENCE ESTIMATION ON THE THRESHOLD FIELD

A truly objective interpretation of the threshold would bring in the concept of a confidence interval on the value derived from the curve-fitting procedure. Up to now, no correct method has been proposed for such an evaluation.

Table 2.

Experimental and theoretical χ^2 values obtained on the two- and three-parameter Weibull representation of the experimental data for the different populations under consideration.

χ^2_{test} ↓ / statistical population →		Type 1	Type 2 all data	Type 2 lowest point discarded	Type 3
$\chi^2_{exp.}$	two-parameter	8.33	12.81	13.97	6.75
	three-parameter	0.73	6.79	3.47	1.04
$\chi^2_{theo.}$	at a 20 % confidence level	3.82			

As an alternative, we evaluated the match between our experimental data and its representation in a threeparameter Weibull distribution by a χ^2 test. As can be seen in Table 2, the tests are very favorable at a confidence level of 20% (*i.e.* by taking an 80% risk of wrongly rejecting the statistical model), except for the uncensored 'Type 2' population. This is another indication of the 'strange' origin of the lowest probability point. In fact, the model passes a much more severe test: the result is still positive for Type 1 and 3 populations at a confidence level of 0.5%.

Even if this test cannot be used to evaluate the degree of confidence in the value of the threshold, as pointed out previously, it does give an indication of how good the fit is between the experimental data and the model under consideration: applied to a two-parameter Weibull description, the χ^2 test at a 60% confidence level is unfavorable for the three populations.

At this point, we have demonstrated that a statistical description of our breakdown data calls for a threeparameter Weibull model. In the following Section, we discuss the possible meaning of the threshold on the basis of other experimental results. The nominal field (scale parameter) values are known with a very good confidence level, since they result from the treatment of dense populations. For reasons given above, the threshold values derived from the curve-fitting procedure must be handled with care. Consequently, the discussion is based on the evolution of these thresholds as a function of experimental parameters, and not on their precise numerical value.

4. INFLUENCE OF EXPERIMENTAL PARAMETERS ON THE DISTRIBUTION

THE existence of a threshold E_s could be very important to the design of insulation systems, since if the design stress is $< E_s$, by definition electric breakdown will never occur. Unfortunately, the real picture is far less simple: the threshold field depends on the test conditions, as does the nominal field. In the following Section, we will not discuss in detail the effects of the numerous different parameters which can affect the threshold, but rather just give some examples of such a dependence, while distinguishing between the effect of the electrical stress parameters used during the data gathering process; the effect of the electrode parameters; and the effect of the sample parameters (*e.g.* electrical aging). We will then summarize the results and discuss the possible physical meaning of the threshold.

Table 3.
Weibull parameters for three identical populations of high density polyethylene samples, 200 μm thick, tested with different voltage ramp rates. Each population contains 50 samples. All the populations obey a three-parameter Weibull model.

Voltage ramp rate (kV/s)	Weibull parameters		
	Nominal field (MV/cm)	Threshold field (MV/cm)	Shape parameter
4	1.40	1	3.8
10	1.81	1.3	3.8
30	2.11	1.6	3

4.1 ELECTRICAL STRESS PARAMETERS

The Weibull parameters of three identical populations of high density polyethylene tested at different voltage ramp rates, are given in Table 3. An increase in the nominal field is accompanied by a corresponding increase in the threshold. The variation of the nominal field as a function of the voltage ramp rate is a well-known result in the breakdown theory. It denotes the very strong dependence of the breakdown process *vs.* time. The first step in defining a procedure for comparative testing of materials under ac voltage must be devoted to the mode of application of the electrical stress.

Table 4.
Weibull parameters for high density polyethylene samples, 200 μm thick, tested with different electrode materials, for a voltage ramp rate as specified. Each population contains 50 samples (4 kV/s rate experiments) or 90 samples (10 kV/s rate experiments). All the populations obey a three-parameter Weibull model, except the undefined threshold population.

	Electrode material	Nominal field (MV/cm)	Threshold field (MV/cm)	Shape parameter
4 kV/s rate	stainless steel	1.40	1	3.8
4 kV/s rate	Al coating	1.40	1	3.8
10 kV/s rate	stainless steel -see figure 10-a-	1.81	1.5	3.8
10 kV/s rate	stainless steel covered with silicone conducting grease -see figure 10-b-	1.82	undefined	

4.2 ELECTRODE PARAMETERS

More interesting are the results summarized in Table 4. These demonstrate that the threshold can be decoupled from a variation of the nominal field. Four populations of similar high-density polyethylene samples were tested using either a 4 or a 10 kV/s voltage ramp rate. The aluminum coating was deposited by evaporation of a 100 nm thick layer of this metal on both sides of each sample. The population tested with the conductive grease was prepared by spreading the silicone grease on the electrode system.

The aluminum coating does not change the value of the Weibull distribution parameters, which denotes the low sensitivity of the experiment *vs.* electrode material. This result will be confirmed later on when looking at the effect of electrode surface roughness. This can be understood by considering that a thin layer of oil exists at the interface between the metal and the dielectric. Another interesting result concerns the stainless steel electrode experiments with and without a thin layer of conductive grease. The two-parameter Weibull representations are displayed in Figure 10(a) and (b) for the standard test and for the test with conductive grease, respectively. It is

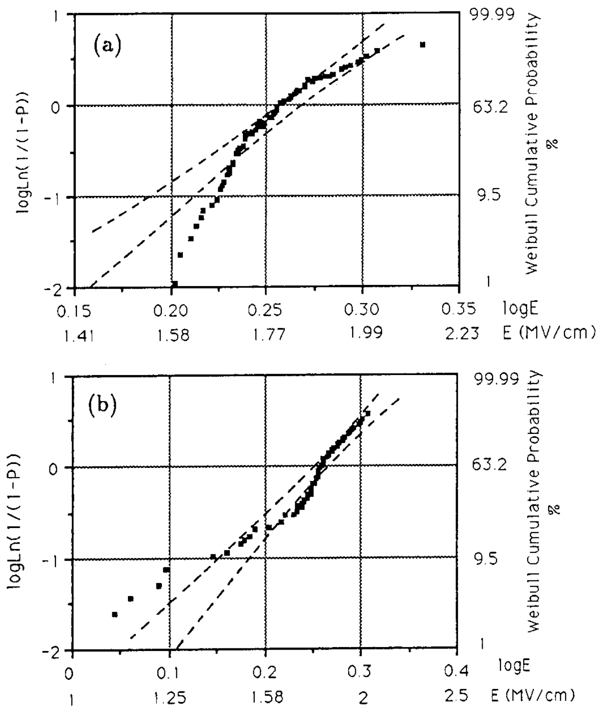

Figure 10.

Weibull plots for high-density polyethylene tested with stainless steel electrodes: (a) without (E_0 = 1.84 MV/cm); and (b) with a thin layer of conductive grease (E_0 = 1.82 MV/cm)

clear that a two-parameter plot fails to represent the data in both cases, since some of the experimental points lie outside the 90% confidence bounds. In the standard test without grease, a three-parameter representation yields a threshold value of 1.5 MV/cm. No threshold was found that would linearize the data obtained with a layer of conducting grease. This population does not obey a simple Weibull distribution, since it is impossible to define a threshold which keeps the data inside the 90% tolerance bounds. However, a field of 1.82 MV/cm is obtained at a 63.2% breakdown cumulative probability, implying that the data in the center of the distribution are not affected. This behavior can be understood qualitatively by noting the upward curvature of the plot due to the lower data. The 'S' shape of the curve denotes the existence of a new distribution of weak spots, probably due in this case to the uncontrolled interface factors introduced by the layer of grease. These extrinsic defects overwhelm the true breakdown voltage distribution, which characterizes the samples under better controlled conditions.

This result should be compared to Type 2 population discussed in the previous Section. What we have called

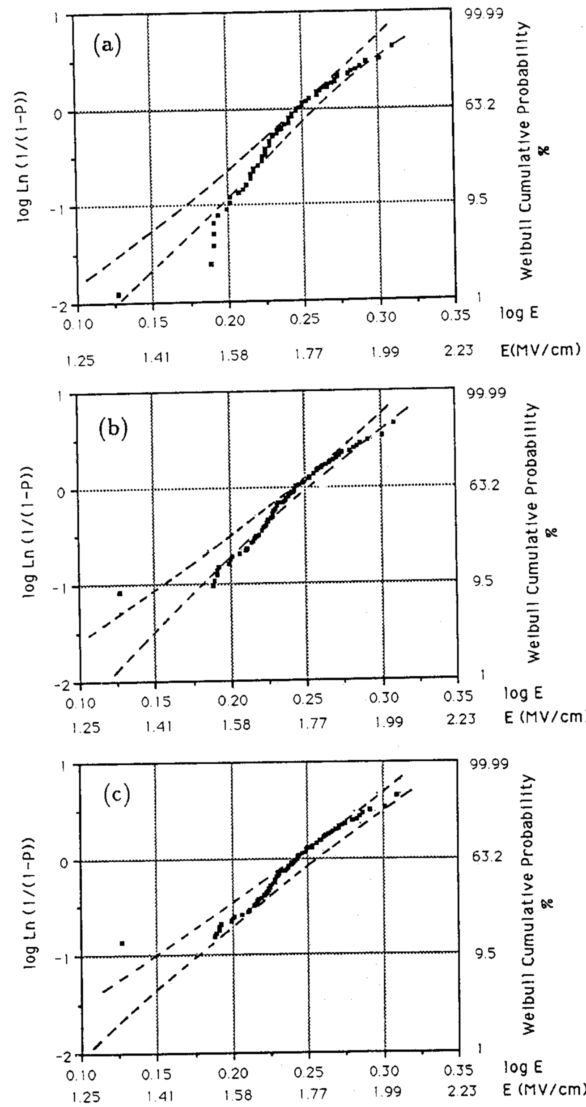

Figure 11.

Weibull plots of the 'Type 2' population obtained by statistically weighting the lowest point. (a) Statistical weight: 1, (b) statistical weight: 7, (c) statistical weight: 11.

the 'odd lowest point' (see Figure 4) is due to a breakdown event at an extrinsic defect. It confers an 'S' shape to the Weibull plot and makes the whole population unconventional. By statistically weighting this lowest experimental point (see Table 5), the shape of the Weibull plot gradually changes (see Figure 11). As a matter of fact, none of these examples can be satisfactorily represented by a single Weibull distribution, since they consist of two distinct populations.

Table 5.
Best Weibull distribution parameter of 'Type 2' population as a function of the statistical weight of the lowest point.

Type 2 population	Nominal field (MV/cm)	Threshold field (MV/cm)	Shape parameter	Statistical description
lowest point discarded	1.77	1.5	2.1	3-parameter Weibull
all data (see fig.11-a)	1.78	1.2	4.6	impossible using Weibull law
statistical weight of the lowest point: X7 (fig. 11-b)	1.77	1	5	impossible using Weibull law
statistical weight of the lowest point: X11 (fig. 11-c)	1.76	0.7	6.6	impossible using Weibull law

Table 6.
Surface roughness parameters of the electrodes.

Roughness parameters → / Electrode reference ↓	Difference between min and max values of the roughness (Å)	Average (Å)
R1	1340	114
R2	7482	872
R3	33660	2700

4.3 SAMPLE PARAMETERS: AGING

Another remarkable result is the influence of electrical aging on the threshold character of a given population. The samples of crosslinked polyethylene tested with a 4 kV/s voltage ramp rate after aging in water environment are described as an example in Figure 12 and 13. The two-parameter Weibull description of the reference population (unaged samples) is given in Figure 12(a). Curve fitting in a three-parameter plot gives a threshold value of 1.3 MV/cm (see Figure 12(b)). The material was aged at 0.2 MV/cm and 50 Hz for 750 h, each sample being in contact with a 0.5 mol/l NaCl water solution on one side. The two-parameter Weibull distribution of the aged population is displayed in Figure 13(a) with its 90% confidence bounds. All the data lie inside the bounds, and a curve-fitting technique gives a zero value for the threshold. The Weibull plots for the aged and unaged populations are given in Figure 13(b) in a three-parameter distribution. The two curves appear to

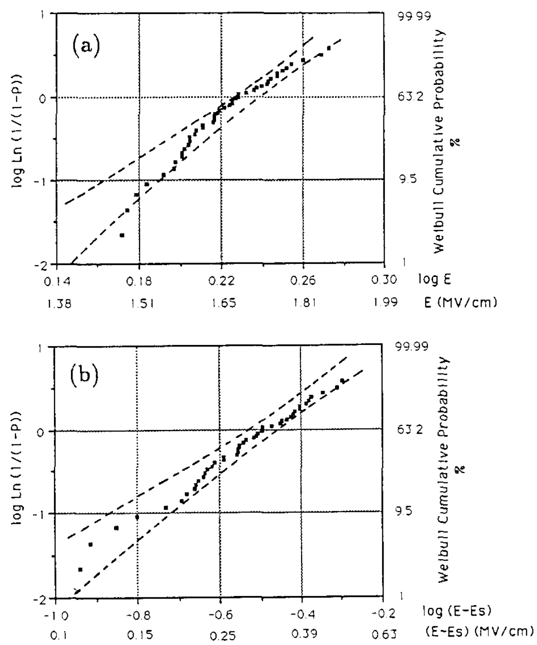

Figure 12.
Weibull plots with 90% confidence bounds for the unaged crosslinked polyethylene population (50 samples tested): (a) two-parameter Weibull plot, (b) three-parameter Weibull plot.

be parallel in such a plot, meaning the controlling parameter is $(E - E_s)$.

The aging effect has to be discussed in greater depth. From Figure 13(a), it is apparent that the aged population scatters over a wider range than the reference population: one finds 1 MV/cm for the scatter of the aged population, compared with 0.4 MV/cm for the reference population. This is obviously connected to the downward curvature of the plot, *i.e.* to the value of the threshold. In other words, aging tends to increase the scatter of a given population. This can be understood by considering the fact that electrical aging starts at local sites of the sample's structure. In the presence of water, the degradation appears as water trees. These defects have no reason to develop at the same time and with the same dynamic from one sample to the next, because of the local fluctuations. They introduce a new scattering factor.

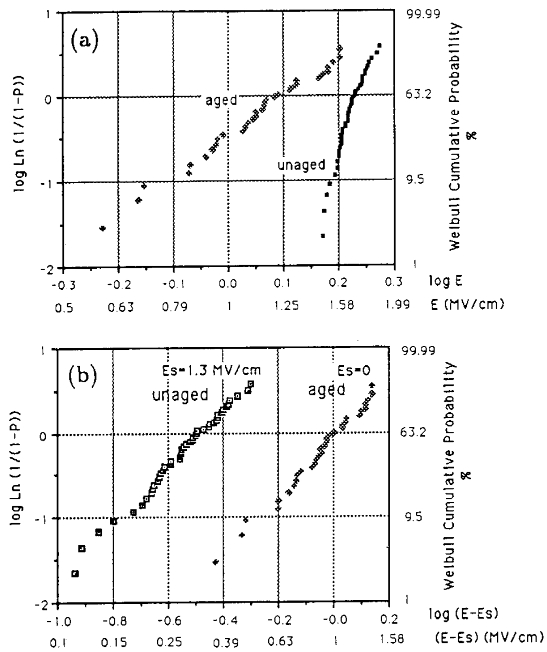

Figure 13.

Weibull plots for the aged population: (a) two-parameter Weibull plot, (b) three-parameter Weibull plot.

5. DISCUSSION

5.1 WEIBULL STATISTICS AND SHORT-TERM DIELECTRIC BREAKDOWN

THE results presented in this paper yield the following picture: the statistics of short-term dielectric breakdown derived from a given test procedure, *i.e.* all the parameters of the electrical stress being tested, depend on both the insulation and the electrode system. The most complete characterization encompasses all the parameters of the Weibull distribution, including the location parameter. Uncontrolled sample or electrode parameters may result in a complete loss of the information for the population being studied.

When the sampling is very homogeneous and the other experimental parameters are well under control, the plot in a two-parameter Weibull representation exhibits a regular downward curvature. This is the indication of a threshold that is a true characteristic of the population.

The same initial sampling, when the experimental parameters are poorly controlled, can eradicate the threshold, or disturb the statistics as a whole. If the disturbance is large, the two-parameter Weibull plot may be S shaped, with a downward curvature for the high breakdown probability, and an upward curvature for the low breakdown probability. In such a case, all the information on the insulation itself is lost and a simple Weibull distribution cannot describe the results. A compound distribution may be considered, but this is only acceptable if it is proven that two independent processes are at work in the system, both of which are individually represented by a Weibull distribution. This information is not generally known, and the analysis is made more difficult by the limited number of data points in the low probability region.

It is thus of prime importance to control the experimental conditions carefully during the test of each specimen. If this is done, there is still another stray factor: the scattering in the geometrical parameters of the samples. In our study, the scatter in the sample thickness was ±10%. Results obtained with an equivalent number of specimens, but with a 30% scatter in thickness, lead to a much lower location parameter.

When the whole procedure is under control, the threshold value is a true characteristic of the insulation under test, and its physical meaning can be discussed.

5.2 BREAKDOWN MECHANISM

The search for a possible physical meaning of the threshold is of course of importance. In order to tackle this problem, we must first consider the breakdown mechanism taking place in our samples. The controlling parameter may vary greatly for each failure process. Under ramped voltages, and for relatively thin specimens, inception dominates propagation, which is more likely to control the breakdown in thick insulation tested under constant stress. It is often assumed that the breakdown of insulating films tested with bare metallic electrodes in oil is due to the corona that may occur in the medium surrounding the electrodes, eventually causing breakdown outside the electrode active surface. In order to estimate the relevance of this breakdown mechanism during our tests, we studied the localization of the breakdown paths *vs.* the electrode area in a test on a population containing 30 samples. Three areas were distinguished. Area 1: breakdown is located somewhere in the contact area between the electrodes and the sample, area 2: breakdown is located near the electrode edges, and area 3: breakdown is outside the contact area between the electrodes and the sample.

It appears that 65% of the breakdown paths are in area 2, 20% in area 1, and the remaining 15% in area 3.

No correlation was found between the cumulative probability or the breakdown voltage of each sample and the localization of the breakdown path (*e.g.* the low cumulative probabilities, or the highest breakdown voltages do not correspond to a specific localization of the breakdown paths). The conclusions that can be drawn from the results are twofold.

Partial discharges in oil do not seem to control the breakdown process of the solid during our tests. This is further substantiated by the observation of the sample surfaces which does not show any evidence of surface deterioration.

The field intensification factor at the electrode edges localizes the breakdown at the periphery of the electrode system.

It is often assumed that metal electrodes embedded in epoxy resin provide a better evaluation of the properties of the dielectric material than bare metal electrodes directly immersed in oil. In these composite systems, the epoxy prevents any partial discharges that might occur in the oil between the electrode edges and the sample surface prior to breakdown. An increase of $\sim$ 100% in the nominal field was reported when embedded electrodes where used instead of bare ones in the test of polyethylene sheets [9]. We carried out statistical tests using such composite electrodes on 80 polyethylene samples. Contrary to what was reported elsewhere, the use of these composite electrodes introduces new problems. The results can be summarized as follows.

1. The distribution does not obey a simple two or three-parameter Weibull probability law.

2. The breakdown field at a cumulative probability of 63.2% is 15% higher than the nominal field obtained by testing a similar population with bare electrodes.

3. 68% of the breakdown occurs in area 1, the remaining 32% near the electrode edges.

After several breakdown tests, the visual examination of the composite electrodes denotes local surface deteriorations of the resin near the electrode edges. This is probably why the data cannot be fitted with a simple Weibull distribution. The scatter is much more important than the one obtained with bare electrodes, an experimental fact that was noted by de Toureil *et al.* a long time ago [9]. Moreover, the relatively small increase of the 63.2% breakdown probability that we obtained with the composite system confirms that discharges in the surrounding medium outside the active electrode surface are not an important factor in the breakdown of samples tested with the bare electrodes. The quality of the oil used during the test is of course of importance because it determines the probability of occurrence of such discharge phenomena. In addition, the contact between the electrodes and the sample involves a thin layer of oil which diffuses between the two surfaces. Charge transport in the oil is consequently an important step toward breakdown initiation. This fact is confirmed by the relative insensitivity of the experiment to the electrode surface roughness. As described in Section 2, both the electrode and the sample surfaces are rough. We performed statistical tests on three identical populations, of 80 samples each, using electrodes with different surface roughnesses. The surface parameters are reported in Table 6. Populations R1 and R2 were strictly identical from a statistical point of view (superposition of the 90% confidence limits for the two populations), while population R3 has a confidence limit domain shifted toward the lower field and distinct from those of R1 or R2. The surface roughness effect becomes noticeable for very rough electrode surfaces, which is an indication of the importance of the thin oil layer. Some other information on the breakdown mechanism can be obtained by comparison of the failure statistic obtained in this study and the statistical models describing various breakdown processes and summarized by Dissado [5]. Initiation processes tend to exhibit thresholds both in time and in field. The apparent value obtained for the Weibull time exponent a is less than unity. According to these data, tree initiation is described by a three-parameter Weibull distribution, with a time dispersion parameter $a < 1$. For constant stress experiments, a is just the slope of the Weibull line. Its value can be deduced from ramped voltage experiments if different ramp rates are used. From the data reported in Table 3, $a \approx 0.9$ is obtained for the Weibull exponent. This is in accordance with an initiation dominated breakdown process in our experimental conditions, contrary to the common assumption that ramped tests are dominated by breakdown at randomly distributed contaminants. This could be the case, as we have shown in the previous Sections, when experimental conditions are badly controlled, or when the sampling is very inhomogeneous.

6. CONCLUSION

BREAKDOWN voltage distributions obtained on dense, very homogeneous populations of HV cable insulation slices, and subjected to a ramp test, have been analyzed according to the Weibull statistics. The tolerance bounds as computed by an exact method show that a correct description of the data imply a three-parameter Weibull model, *i.e.* with a non-zero location parameter. A zero location parameter always results from inhomogeneities in the sampling. This may be due to uncontrolled experimental parameters or to defects of various origins, but aging is also a source of scattering. These possibilities can be discriminated by comparative testing.

This routine breakdown test is easy to run and has limited sensitivity to electrode surface roughness. It provides a very efficient way to assess any changes from normal characteristics resulting from certain processing variables, aging conditions, or other manufacturing or environmental situations. In a carefully controlled experiment, the threshold must be considered as a quality factor of the system under test.

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