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Electrical insulating materials – A.C. voltage endurance evaluation – Introduction

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FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

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- The subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC/TS 61251, which is a technical specification, has been prepared by IEC technical committee 112: Evaluation and qualification of electrical insulating materials and systems.

This second edition cancels and replaces the first edition which was issued in 1993. It constitutes a technical revision.

The main changes with respect to the previous edition are listed below:

- extension of the scope to cover electrical insulating material and insulation systems;
- removal of references to short time dielectric breakdown strength measurements as an indicator of voltage endurance;

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
112/88/DTS	112/95/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

ELECTRICAL INSULATING MATERIALS – A.C. VOLTAGE ENDURANCE EVALUATION – INTRODUCTION

1 Scope

This technical specification explains many of the factors involved in voltage endurance tests on electrical insulating materials and systems. It describes the voltage endurance graph, lists test methods illustrating their limitations and gives guidance for evaluating the a.c. voltage endurance of insulating materials and systems from the results of the tests.

The terminology to be used in voltage endurance is defined and explained. It should be emphasized that where this technical specification is concerned with materials, the results may not be directly applicable to the performance of insulating systems.

Voltage endurance tests are used to compare and evaluate insulating materials with regard to their various applications in electrical systems. Determining the ability of electrical insulating materials and systems to endure a.c. voltage stress is complex. The results of voltage endurance tests are influenced by many factors so this technical specification should only be considered as an attempt to present a unified view of voltage endurance for simplified planning and analysis. Some documents for the various practical cases exist and others are being developed.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60243 (all parts), *Electric strength of insulating materials – Test methods*

IEC 62539, *Guide for the statistical analysis of electrical insulation dielectric breakdown data (IEEE Standard 930:2004)*

3 Terms, definitions and symbols

For the purposes of this document, the following terms, definitions and symbols apply.

3.1 Terms and definitions

3.1.1
voltage endurance
VE
measure of the ability of solid insulating materials to endure voltage

NOTE In this technical specification, only a.c. voltage is considered.

3.1.2
life
time of any technical system until its failure or loss of serviceability

3.1.3
voltage life
time for solid insulating materials to dielectric dielectric breakdown under constant voltage stress

3.1.4
voltage endurance coefficient
VEC
numerical value of the reciprocal of the slope of a straight line log/log VE plot

3.1.5
specimen
representative test object for assessing the value of one or more physical properties

3.1.6
sample
group of nominally identical specimens from the same manufacturing batch

3.2 Symbols

c,c′	constants in the inverse-power model
E	electric stress
E_o	short-time electric strength
E_s	short-time electric strength of prestressed specimens
E_t	electric threshold stress
f	frequency
h, k	constants in the exponential model
L	time to dielectric dielectric breakdown
m	scale parameter in the simple Weibull distribution (one variable)
M	scale parameter in the generalized Weibull distribution (two variables)
n	exponent of stress in the inverse-power model coinciding with the VEC
n_d	differential VEC
n_i	initial VEC
R	dimensional ratio
t	time
t_c	time to dielectric breakdown at constant stress
t_o	time to dielectric breakdown at constant stress E_o
t_p	time to dielectric breakdown with progressive stress
t_{po}	time to dielectric breakdown with progressive stress producing dielectric breakdown at stress E_o
tan δ	dissipation factor
β	shape parameter in the Weibull distribution of times to dielectric breakdown at constant stress
γ	shape parameter of the Weibull distribution of the dielectric breakdown stresses from a progressive stress test
ν	number of dielectric breakdown stress values
ν'	number of dielectric breakdown times

4 Voltage endurance

4.1 Voltage endurance testing

To evaluate the voltage endurance of insulating materials or systems, a number of specimens are subjected to a.c. voltage and their times to dielectric breakdown are measured. In practice, several samples of many specimens are tested at different voltages to reveal the effect of the applied voltage on the time to dielectric breakdown. The mean time to dielectric breakdown of each sample is the average time to dielectric breakdown of all specimens tested at that voltage. The time at which a certain percentage of specimens has broken down is the estimated time to dielectric breakdown with a probability equal to this percentage.

The statistical treatment of the data (either by analytical or graphical methods) allows the extraction of additional data such as other failure percentiles or confidence bounds and, possibly, determination of the distribution (e.g. Gaussian, Weibull, lognormal, etc.).

4.2 Electrical stress

In general, it is advisable to make reference to electrical stress (voltage per unit thickness) instead of voltage. For uniform field, electrical stress is given by the voltage (effective value) divided by the thickness of specimens.

If the electric field is not uniform, the maximum value should be considered.

4.3 Voltage endurance (VE) graph

This is the graph of the time to dielectric breakdown versus the corresponding value of electrical stress. In the VE graph, the electrical stress is plotted as the ordinate with either a linear or logarithmic scale. The times to dielectric breakdown are plotted on the abscissa, usually with a logarithmic scale. The voltage endurance line on this graph gives the final result of the VE tests as it allows clear and complete evaluation of voltage endurance of the specimens under the specified test conditions. For maximum significance, materials or systems should be compared at equal thickness.

An accurate plotting of the line requires many tests at different voltages and some tests are required at voltages which result in long times to dielectric breakdown.

The voltage endurance line may be straight or curved. In the latter case, its trend can often be approximated by a few straight regions, sometimes a first part for short times with a low slope, a middle region (which may extend to long times) with a steeper slope and finally a further trend of the line showing a tendency to become horizontal (see Figure 1, where a general VE line is shown). The shape of the VE graph may change greatly from one material or system to another.

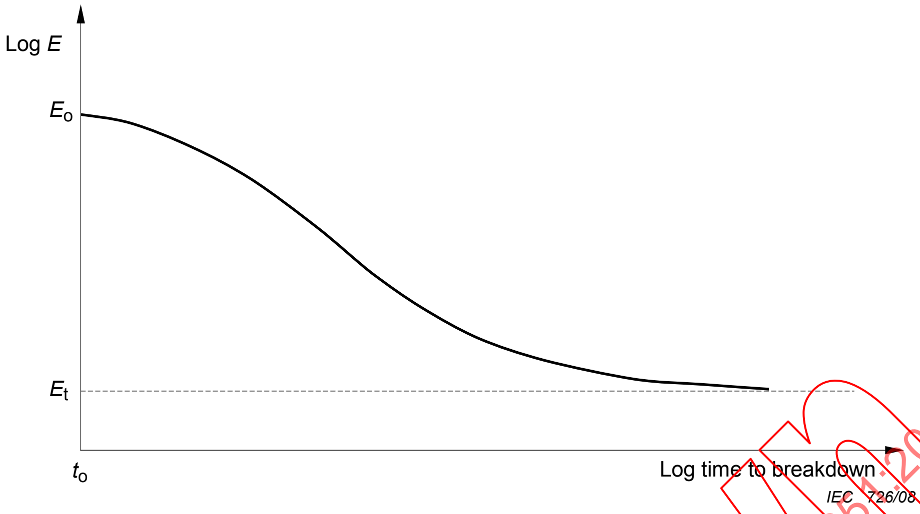

Figure 1 – General voltage endurance line

4.4 Short-time electric strength

The short-time electric strength is generally measured using a linearly increasing voltage. The duration of such a test, as used in this specification, is of the order of some tens of seconds up to some tens of minutes. These short-time electric strength measurements can be used to indicate the degree of ageing of specimens subjected to voltage by comparing the values after voltage exposure with the initial ones.

The results of electric strength tests (or, in general, of tests with increasing voltage) are not reported directly in the VE graph. Instead, a constant voltage test at the same stress as the mean electric strength, E_o (or very close to it, say 0,8 or 0,9E_o), is made to determine the time to dielectric breakdown, t_o, with constant stress. The point (E_o, t_o) is the origin of the VE line. More details on this procedure are given in 5.5. However, when this procedure is used, the following precautions should be taken:

i) The test should be carried out under the same conditions (humidity, temperature, etc.), in the same test cell and with the same procedures as for the voltage endurance tests.

ii) The test specimens and the conditions of the specimen dielectric breakdown should be examined and recorded for future use in the analysis of the results. The latter is to ensure that the mode of failure at high stress is the same as that of the other specimens tested later at lower stress.

4.5 Voltage endurance coefficient (VEC) – *n*

The slope of the VE line is an indicator of the response of a material or system to electrical stress. The parameter n is dimensionless. With a low slope of the VE line, even a small reduction of stress produces a great increase in life. The reciprocal of the slope is taken to be consistent with the numerical value of the exponent n in Equation (1). A large value of the VEC does not necessarily accompany a high electric strength. It may happen that the material with lower VEC has a longer time to dielectric breakdown at the same stress if its short-time electric strength is so high that its poorer endurance is compensated for. The value of n should be associated with a high mean electric strength before attributing a high endurance to the material. What is most significant is the retention of usable electric strength for long periods of time.

4.6 Differential VEC (n_d)

If the VE line is curved in log-log coordinates, its slope may be measured by means of the tangent at any point. For any electrical stress, and thus for any point on the line, the differential voltage endurance coefficient, n_d, can be defined as the numerical value of the reciprocal of the slope of the curve at that point (Figure 2) according to the life model described in Clause 5.

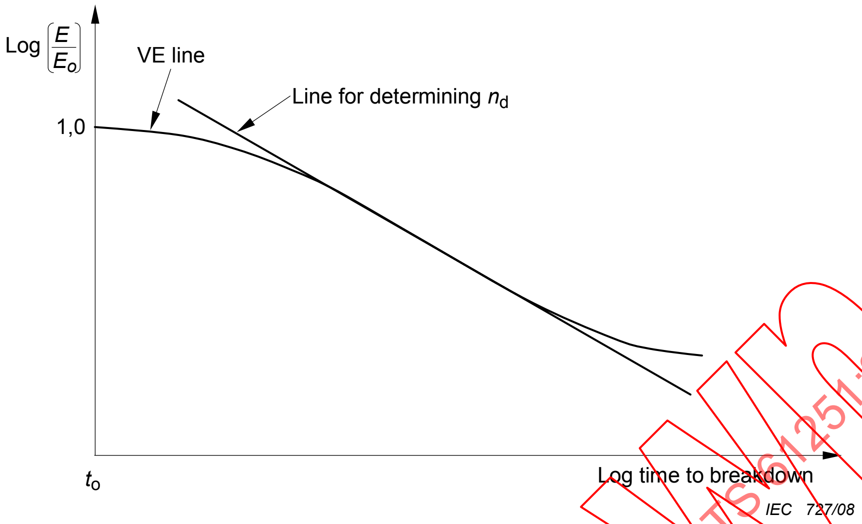

Figure 2 – Determination of the differential VEC n_d at a generic point P of the VE line

4.7 Electrical threshold stress (E_t)

The VE line may tend to become horizontal with decreasing stress, suggesting a limiting stress, E_t, below which electrical ageing becomes negligible. This limit is called the electrical threshold stress. The tendency of the line to become horizontal can sometimes be detected by means of tests of suitable duration. However, the tests do not always succeed in revealing such a trend. Some insulating materials or systems do not show any electrical threshold stress even for very long test times.

4.8 Voltage endurance relationship

The VE relationship is the mathematical model of voltage life, i.e. the equation relating electrical stress and time to dielectric breakdown, whose graphical representation is given by the VE line. If this line is straight on log-log graph paper, the equation is of the type:

$$L = c\, E^{-n} \tag{1}$$

where

L is the time to dielectric breakdown;

E is the electrical stress;

c and n are constants dependent on temperature and other environmental conditions.

Equation (1) constitutes the so-called inverse-power model, which is the voltage-life model often encountered with voltage endurance data on solid electrical insulation. When data are available for time to dielectric breakdown at two voltage stresses, this model may be used to estimate the value of n by using Equation (2):

$$\frac{L_1}{L_2} = \left(\frac{E_1}{E_2}\right)^{-n} \tag{2}$$

If the VE test data do not form a straight line on log-log paper, the use of the inverse-power model is incorrect. If the line approaches an electrical threshold stress, E_t, other models have been proposed, among them:

$$L = c' (E - E_t)^{-n} \tag{3}$$

which becomes the inverse-power model if E_t tends to 0 and is preferably used when the data for short and medium times fit a straight line on log-log coordinates. Alternatively, another model is:

$$L = \frac{k \exp(-h E)}{E - E_t} \tag{4}$$

which derives from the simple exponential model, corresponding to an approximately straight line in semilog coordinates for $E > E_t$ but gives infinite time to dielectric breakdown when E tends to E_t. In Equations (3) and (4), constants c', n, k, h and E_t depend on temperature and other environmental conditions[1].

Equations (3) and (4) can be used to generate two new equations which define the trend of the VE line between any two points, (L_1, E_1) and (L_2, E_2). The following equations are obtained:

$$\frac{L_1}{L_2} = \left(\frac{E_1 - E_t}{E_2 - E_t}\right)^{-n} \tag{5}$$

$$\frac{L_1}{L_2} = \frac{\exp\{-h(E_1 - E_2)\}}{(E_1 - E_t)/(E_2 - E_t)} \tag{6}$$

The equations of the VE line for a straight line or a straight-line segment on log-log plot are (1) and (2). When there is a tendency toward a threshold after an approximately linear trend on log-log or semilog graph paper the Equations are (3), (4), (5) and (6).

By taking the logarithms, the inverse-power model becomes:

$$\ln(L) = \ln(c) - n \ln(E) \tag{7}$$

This is the equation of the straight VE line in log-log coordinates. Its slope is $-1/n$. As the numerical value of the reciprocal of the slope is equal to the VEC, the VEC can also be defined as the exponent n in the inverse-power model.

5 Test methods

5.1 Introductory remark

In this clause, different methods of carrying out the VE test are described. The differences to be discussed concern the way of applying voltage (constant or increasing with time), the frequency (service or higher) and the time at which the test is interrupted (the time to dielectric breakdown or a shorter time at which destructive diagnostic measurements are performed).

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1 Other models have been proposed where (E - E_t) is raised to an exponent ν, dependent on the material or system under consideration.

In general, the type of ageing cell or test object can be the same, whatever the choice of the parameters above. However, with respect to the choice of the frequency of the applied voltage, the amount of heating from either dielectric loss or from partial discharges should be such that the temperature rise from these causes is less than 10 K.

When testing materials, the ageing cell or test object should preferably be such that the applied stress is uniform. This can be achieved by electrodes having a flat surface rounded at the edges. The surface of specimens can be metallized in order to avoid partial discharges at the specimen surface but only within the area of contact of the electrodes. Furthermore, to avoid flashover along the specimen surface, the specimen should extend an appropriate distance beyond the edges of the electrodes. If preliminary tests indicate that this is not enough to avoid flashover after some time, due to deterioration of the specimen surface around the electrodes caused by partial discharges, then the electrodes should be embedded in an appropriate dielectric having permittivity close to that of the material under test.

The form and processing of the specimen will depend on the purpose of the test. For research purposes, internal degradation studies as a function of cavity size and shape have been performed. However, this lies outside the scope of this technical specification. Evaluation and comparison of materials from the point of view of degradation by external discharge are dealt with in IEC 60343.

For insulation systems, the test objects should represent adequately the form taken in service.

5.2 Tests at constant stress

5.2.1 Conventional VE test

In the constant stress test, the magnitude of the voltage applied to each specimen is kept constant during the test. This magnitude is usually selected in such a way that the mean time to dielectric breakdown of the sample is between a few tens to a few thousands of hours. The time to dielectric breakdown of some samples, especially at the lower stresses, may be so long that it is impracticable to wait for dielectric breakdown of all specimens of the sample. In this case, the interruption of the test after dielectric breakdown of the majority of the samples requires the use of statistical procedures for censored data (see IEC 62539).

Usually, three or four different voltages are used, thereby providing three or four points for the voltage endurance line. Four points are often not enough to demonstrate curvature of the line. On the other hand, the amount of data required for tests at more than four voltages may not be economically feasible.

The fit of the data to a straight line may be established through regression analysis (see IEC 62539). If the quality of fit is considered reasonably poor, the VE line can be fitted to a straight line with the negative reciprocal of the slope of the line being the VEC. This is an average of different values of the differential VECs if the line is curved.

For any test voltage, the times to dielectric breakdown can be tested for their fit to various probability functions. If the data fit the Weibull distribution, the experimental data give rise to a straight line (on Weibull paper) whose slope is the shape parameter, β, of the distribution (see Annex A). Proceeding in the same way for every test at different voltages, the constancy of β can be checked.

5.2.2 Diagnostic measurements

Diagnostic quantities such as tan δ or partial discharge activity may be monitored during the test. When tan δ or partial discharge versus time curves obtained at different voltages are compared, a similarity to the VE curve may be found. This may provide a contribution to understanding ageing behaviour and may predict the behaviour of the VE line for other samples. Without such a comparison, a diagnosis of the state of ageing through diagnostic measurements of tan δ or partial discharge is often unreliable.

Short-time electric strength measurements can also be carried out on specimens that remain unfailed, or after a fixed ageing time, in order to evaluate their state of ageing. Thus the short-time electric strength can be a diagnostic quantity to determine the degree of ageing caused by electrical stress.

To investigate the ageing process thoroughly, chemical and microscopic analyses can be employed. The results can often be related to the variation of macroscopic properties such as short-time electric strength, conductivity, tan δ, etc.

5.2.3 Detection of an electrical threshold

The experimental points sometimes show a tendency of the VE line to become horizontal after long exposure times. Moreover, many reports of VE investigations include points indicating much longer times to failures at the lower levels of stress than expected from extrapolation of the trend at higher voltages. These results may indicate the existence of an electrical threshold. It may be desirable to test the data for the presence of such a threshold (E_t).

A check for the threshold voltage may be made by a test at elevated frequency, as illustrated in 5.3. Another method which may permit evaluation of the trend of the VE line at low stresses is described in 5.6. The threshold stress is influenced by temperature, usually decreasing as temperature rises. For temperatures higher than room temperature, the VE line is usually displaced towards the left of the graph and the times to dielectric breakdown are shorter for the same electric stress. The VE test is often carried out at room temperature but tests at higher temperatures may provide information on the shape of VE line and, in particular, on the existence of a threshold and its dependence on temperature.

5.3 Tests at higher frequency

In order to reduce the test times, a procedure sometimes used is to increase the frequency of the applied voltage. The time to dielectric breakdown, L_f, at power frequency f is often derived from the time to dielectric breakdown, L_h, at the test frequency, f_h, by means of the following relationship:

$$L_f = L_h \frac{f_h}{f} \qquad (8)$$

However, the validity of this relationship is not proved, especially if the test frequency is more than 10 times f. Sometimes, acceleration is found to be proportional to the frequency ratio raised to a power different from unity. This may be due to the different stress conditions to which the material is subjected at high frequency. As is well known, permittivity and tan δ depend on frequency and temperature. Hence dielectric heating, proportional to the product of the frequency, permittivity and tan δ may affect the time to dielectric breakdown. Also, partial discharges in micro-voids or defects inside the material and/or on the specimen surface can have a different influence at a different frequency. It would be necessary to perform comparative tests in order to determine the relationship to be used for the various test conditions. This relationship might be different for high and low stresses. Therefore, one should be very cautious in the interpretation of frequency-accelerated experiments.

High-frequency tests at low stresses may provide an indication if a threshold stress exists. If the results of power-frequency tests seem to indicate the possible presence of a threshold, a high frequency test may be made at a voltage very slightly below the voltage of the suspected threshold. If the time to dielectric breakdown at that voltage is considerably longer than it would be expected to be according to the trend of the VE line at higher voltages combined with Equation (5), the presence of the threshold is almost certainly confirmed.

5.4 Progressive stress tests

In the progressive stress test, the magnitude of the stress applied to each specimen increases with time. The rate of the stress rise should be the same for all specimens but must be changed from one sample to another to obtain the VE line with progressive stress (see Figure 3).

The mean, the median or any other percentile of the dielectric breakdown voltage may be used. In this test, all specimens fail. Statistical treatment of the data is particularly useful due to the large quantity of information obtainable at low additional cost. If the data relevant to each sample fit the Weibull distribution, the corresponding points fit a straight line in Weibull paper. The slope of the line is the shape parameter γ of the distribution (see Equations (A.2) and (A.3). Note that if γ is the same at different rates of voltage rise, the VEC can be derived from the ratio of γ to β (see Equation (A.4)). For this reason, in the VE test on materials and systems for which constancy of the VEC is expected in the test voltage range, a good practice is to carry out a progressive stress test in order to determine γ before starting with the constant stress tests. The VEC can then be derived theoretically. This may permit a check of the value of the VEC and thus the likely duration of the test programme.

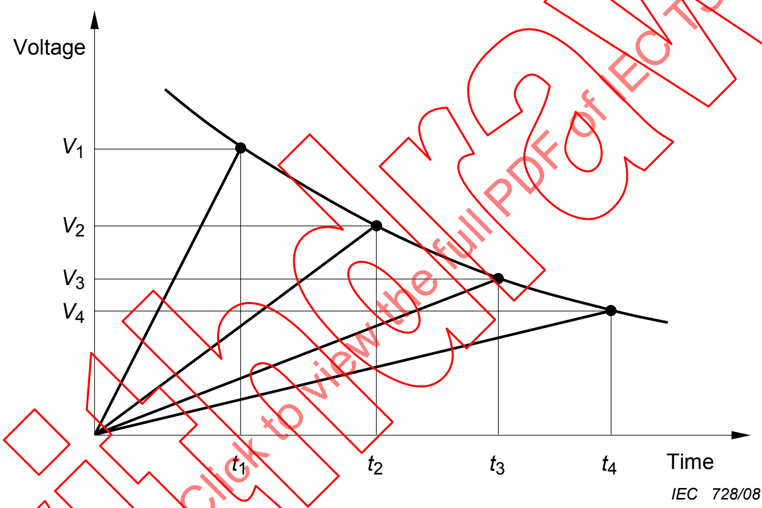

Figure 3 – Plotting the VE line with progressive stress

Knowledge of the value of γ is of great importance when the results have to be reported for specimens of different areas or volumes. The dielectric breakdown probability at the same voltage stress is indeed an increasing function of the dimensions of specimens. In order to refer the data – for instance the dielectric breakdown stress with a given probability – from the specimens for which these data have actually been obtained to elements of different dimensions, it is then necessary to know the relationship between probability, stress and dimensions. In the case of validity of the Weibull distribution, the ratio between two stresses, E_1 and E_2, corresponding to the same dielectric breakdown probability for two elements, 1 and 2, of different dimensions is given by:

$$\frac{E_1}{E_2} = R^{1/\gamma} \tag{9}$$

where R is the dimensional ratio, i.e. the ratio of dimensions (area or volume) of element 2 to those of element 1 (see Equation (A.2)).

The progressive stress test data are usually less scattered than those from constant stress tests. If the VE line is straight on a log-log plot, its slope is also the same for progressive stress. The progressive stress data may be related to those at constant stress by the following formula:

$$t_p = t_c (n + 1) \quad (10)$$

where t_p and t_c are the times to dielectric breakdown at progressive and constant stress, respectively, for the same value of stress and n is the VEC.

Since n is usually in the range 8-15, t_c is much shorter than t_p. The dielectric breakdown times with progressive stress correspond to times with constant stress which are, normally, considerably shorter. Therefore, the progressive stress test is useful only for evaluation of the VEC in the short-times range. If the VEC is not constant, it is not possible to predict time to dielectric breakdown at constant stress starting from progressive stress data. In any case, no information on the long-time behaviour of the test material, let alone on the threshold, is obtainable by progressive stress test.

5.5 Preliminary tests to determine the initial part of the VE line

In certain cases, preliminary tests may be useful to determine the initial high-voltage part of the VE line, as well as an initial estimate for the value of n. These tests provide data for planning the future lower voltage tests. They include:

a) A progressive stress test or a step voltage test similar to a short-time electric strength test. The mean dielectric breakdown voltage from this test is E_o. The failure must not be a flashover and should resemble the dielectric breakdowns obtained at lower voltages and longer times. The time to dielectric breakdown in this test may be longer than the value suggested in IEC 60243.

b) A constant stress test at or near E_o. In the performance of this test, the voltage must be raised to the value of E_o without overshoot and time t_o should be measured from the time the voltage reaches E_o. A zero crossing switch may be used to initiate the test and a counter to count the number of a.c. cycles to dielectric breakdown.

c) Constant stress tests at stresses slightly lower than E_o, for example 0,9 E_o, 0,8 E_o.

According to Equation (10), the theoretical ratio of the mean time to dielectric breakdown with progressive stress, t_p, to the mean time to dielectric breakdown with the constant stress, t_c, is n + 1, from which an estimate of the value of n at the initial part of the VE line may be calculated. Note that the point (E_o, t_o) is on the VE line.

5.6 Suggested test method

In order to characterize insulating materials or systems comprehensively from the point of view of electrical endurance, the following method is suggested.

a) Performance of preliminary tests at high stress, as mentioned in 5.4.

b) Constant stress tests at lower stresses. Sufficient tests at different stresses should be performed to plot the VE graph and obtain a reliable prediction of the long-time behaviour of the material under test. In any case, no fewer than three test voltages are required. Other diagnostic measurements are also useful.

When the material or system under test shows a linear trend of the VE graph on log-log plot, tests with progressive stress and low rate of voltage rise are useful to check the value of the VEC.

When the graph shows a tendency towards a threshold stress, a test at a stress about 5 % below the expected threshold stress, interrupted after a few thousand hours and followed by short-time electric strength measurements, may be a useful tool to check for the existence of a threshold. No decrease of electric strength should be found if the voltage applied is actually below the threshold.

6 Evaluation of voltage endurance

6.1 Significance of the VEC

By considering the normal VE line, it is clear that the larger the VEC, the longer the time to dielectric breakdown for the same value of the ordinate (E/E_o), all other parameters being equal. In other words, when a stress equal to the same percentage of E_o is applied to two materials having different VECs, the time to dielectric breakdown is longer for the one having the larger VEC. Therefore, the VEC is an important parameter for voltage endurance evaluation of insulating materials.

Since the VE line may be curved and thus the VEC is not constant, it is important to specify the stress range within which the VEC has been determined. If the constancy of the VEC has not been proved and an average has been obtained, this should be reported. In the case of a curved line, the differential coefficient, n_d, has been described in 4.6. The range of stress at which n_d has been determined constitutes additional information which should be provided.

It can be noted that n_d gives direct information on the actual slope of the line. Therefore, a specification such as: "n_d decreasing from 15 to 8 for stresses decreasing from 100 % to 50 % of E_o", is a useful way to describe the VE line in that range of stresses.

6.2 Significance of the electrical threshold stress

If the material or system under consideration presents an electrical threshold stress of technical interest (that is to say, not so low that its practical importance is negligible), this threshold stress becomes a useful factor to be determined in the VE test.

6.3 Dispersion of data and precision requirements

When the stress applied to an insulating material or system is higher than the threshold stress, the dielectric breakdown risk should be calculated by statistical treatment of test data, as described in IEC 62539. In order to obtain statistically valid results it is necessary that:

a) the test specimens are taken by a random procedure from a large batch (coming from the same manufacturing process);

b) specimens of uniform thickness and consistency are tested

c) identical test cells or test objects are used for every specimen and that the ambient conditions do not change significantly during each test or from one test to another.

In many cases, the VE line for very low dielectric breakdown probabilities has a greater interest than the mean or the median VE line. Statistical treatment of the test data is then carried out to calculate times to dielectric breakdown at low probabilities, generally using the Weibull distribution, besides checking the linearity of the graph.

The difference between the mean or median time to dielectric breakdown and the time to dielectric breakdown with a given low dielectric breakdown probability is a function of the dispersion of times to dielectric breakdown inherent in the material under test. By increasing the number of specimens or of punctures for each specimen, more precise estimates of this dispersion and thus low dielectric breakdown probability times can be obtained with reasonable confidence.

To have an immediate view of test accuracy, the confidence bounds for each experimentally determined point on the VE graph should be reported.

An *F*-test may be effective to check that the data satisfy tolerance regarding departure from linearity. The data should span several decades in time. The higher the value of the VEC, the larger the number of decades required to define it with precision.

6.4 Presentation of the results

In order to have a complete evaluation of a material's voltage endurance, the VE line (preferably the lines corresponding to different percentiles) should be shown, including the confidence intervals. This graph is difficult and expensive to obtain and can rarely be plotted in a reliable way over long time spans. Nevertheless, the VE graph should always accompany the test report, which should include all the data necessary to understand the graph and its reliability. The following items should be indicated in the report:

- unique identification of the material;
- thickness and shape of specimens;
- preparation technique;
- conditioning of specimens (if any);
- shape and dimensions of electrodes;
- test method and apparatus used;
- rate of voltage rise for any progressive stress test;
- frequency of the test voltage;
- air temperature near the test cell;
- number of specimens tested at each test voltage;
- scatter or confidence bounds of each point reported in the graph;
- any other information of interest.

If the results are given in terms of VEC, the requirement of linearity of the graph should be satisfied. If the graph does not satisfy such requirements, values of n_d may be supplied, together with the corresponding stress ranges.

The type of statistical analysis used should also be specified and, if possible, graphs on probability paper should be shown. Special conditions to be satisfied for any particular kind of VE test will be indicated by special documents.

Annex A
(informative)

The Weibull distribution

A.1 Weibull distribution times to dielectric breakdown

The two-parameter Weibull distribution of the times to dielectric breakdown is usually written as:

$$P(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{A.1}$$

where

$P(t)$ is the dielectric breakdown probability at time t;

β is the shape parameter;

α is the time corresponding to P = 1 - 1/e = 0,632.

By taking logarithms twice one obtains:

$$\ln \ln (1/(1-P)) = \beta \ln (t/\alpha) \tag{A.2}$$

which, in coordinates ln ln (1/(1-P)) versus ln (t), represents a straight line of slope β.

The Weibull paper is a special plotting paper having the scales according to such a coordinate system.

A.2 Weibull distribution dielectric breakdown stresses

The *Weibull distribution of the dielectric breakdown stresses* can be written as:

$$P(E) = 1 - \exp(-mE^{\gamma}) \tag{A.3}$$

where

γ is the shape parameter

m is proportional to the dimensional ratio, R (see 5.4)

On Weibull paper, a straight line of slope γ is obtained.

If two elements of different dimensions are stressed by two stresses, E_1 and E_2, so that their dielectric breakdown probability is the same, P, then;

$$1 - P = \exp(-m_1 E_1^{\gamma}) = \exp(-m_2 E_2^{\gamma}) = \exp(-Rm_1 E_2^{\gamma}) \tag{A.4}$$

From Equation (A.4), relationship (10) of 5.4 is easily derived.