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INTERNATIONAL STANDARD

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colour inside

Electrical insulating materials – Thermal endurance properties – Part 3: Instructions for calculating thermal endurance characteristics

Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 3: Instructions pour le calcul des caractéristiques d'endurance thermique

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ELECTRICAL INSULATING MATERIALS –
THERMAL ENDURANCE PROPERTIES –

Part 3: Instructions for calculating thermal endurance characteristics

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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IEC 60216-3 has been prepared by IEC technical committee 112: Evaluation and qualification of electrical insulating materials and systems. It is an International Standard.

This third edition cancels and replaces the second edition published in 2006. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) a new computer program has been included;
b) Annex E " has been completely reworked.

The text of this International Standard is based on the following documents:

Draft	Report on voting
112/475/CDV	112/495/RVC

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 60216 series, published under the general title *Electrical insulating materials – Thermal endurance properties*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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ELECTRICAL INSULATING MATERIALS – THERMAL ENDURANCE PROPERTIES –

Part 3: Instructions for calculating thermal endurance characteristics

1 Scope

This part of IEC 60216 specifies the calculation procedures used for deriving thermal endurance characteristics from experimental data obtained in accordance with the instructions of IEC 60216-1 and IEC 60216-2 [1][1], using fixed ageing temperatures and variable ageing times.

The experimental data can be obtained using non-destructive, destructive or proof tests. Data obtained from non-destructive or proof tests can be incomplete, in that it is possible that measurement of times taken to reach the end-point will have been terminated at some point after the median time but before all specimens have reached end-point.

The procedures are illustrated by worked examples, and suitable computer programs are recommended to facilitate the calculations.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60216-1:2013, *Electrical insulating materials – Thermal endurance properties – Part 1: Ageing procedures and evaluation of test results*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1.1
ordered data
group of data arranged in sequence so that in the appropriate direction through the sequence each member is greater than, or equal to, its predecessor

Note 1 to entry: In this document, ascending order implies that the data is ordered in this way, the first being the smallest.

1 Numbers in square brackets refer to the bibliography.

Note 2 to entry: It has been established that the term "group" is used in the theoretical statistics literature to represent a subset of the whole data set. The group comprises those data having the same value of one of the parameters of the set (e.g. ageing temperature). A group may itself comprise a number of sub-groups characterized by another parameter (e.g. time in the case of destructive tests).

3.1.2
order-statistic
assigned numerical position in the sequence of individual values in a group of ordered data

3.1.3
incomplete data
ordered data, where the values above and/or below defined points are not known

3.1.4
censored data
incomplete data, where the number of unknown values is known

Note 1 to entry: If the censoring is begun above/below a specified numerical value, the censoring is Type I. If above/below a specified order-statistic it is Type II. This document is concerned only with Type II.

3.1.5
degrees of freedom
number of data values minus the number of parameter values

3.1.6
variance of a data group
sum of the squares of the deviations of the data from a reference level

Note 1 to entry: The reference level may be defined by one or more parameters, for example a mean value (one parameter) or a line (two parameters, slope and intercept), divided by the number of degrees of freedom.

3.1.7
central second moment of a data group
sum of the squares of the differences between the data values and the value of the group mean, divided by the number of data in the group

3.1.8
covariance of data groups
for two groups of data with equal numbers of elements where each element in one group corresponds to one in the other, the sum of the products of the deviations of the corresponding members from their group means, divided by the number of degrees of freedom

3.1.9
regression analysis
process of deducing the best-fit line expressing the relation of corresponding members of two data groups by minimizing the sum of squares of deviations of members of one of the groups from the line

Note 1 to entry: The parameters are referred to as the regression coefficients.

3.1.10
correlation coefficient
number expressing the completeness of the relation between members of two data groups, equal to the covariance divided by the square root of the product of the variances of the groups

Note 1 to entry: The value of its square is between 0 (no correlation) and 1 (complete correlation).

3.1.11
end-point line
line parallel to the time axis intercepting the property axis at the end-point value

Note 1 to entry: For guidance on the choice of end-point value, refer to IEC 60216-2.

3.2 Symbols and abbreviated terms

		Subclause
a	Regression coefficient (y-intercept)	4.3, 6.2
a_p	Regression coefficient for destructive test calculations	6.1
b	Regression coefficient (slope)	4.3, 6.2
b_p	Regression coefficient for destructive test calculations	6.1
b_r	Intermediate constant (calculation of $\hat{X}_c$)	6.3
c	Intermediate constant (calculation of χ^2)	6.3
f	Number of degrees of freedom	Table C.2 to Table C.5
F	Fisher distributed stochastic variable	4.2, 6.1, 6.3
F_0	Tabulated value of F (linearity of thermal endurance graph)	4.4, 6.3
F_1	Tabulated value of F (linearity of property graph – significance 0,05)	6.1
F_2	Tabulated value of F (linearity of property graph – significance 0,005)	6.1
g	Order number of ageing time for destructive tests	6.1
h	Order number of property value for destructive tests	6.1
HIC	Halving interval at temperature equal to TI	4.3, Clause 7
HIC_g	Halving interval corresponding to TI_g	7.3
i	Order number of exposure temperature	4.1, 6.2
j	Order number of time to end-point	4.1, 6.2
k	Number of ageing temperatures	4.1, 6.2
m_i	Number of specimens aged at temperature ϑ_i	4.1, 6.1
N	Total number of times to end-point	6.2
n_g	Number of property values in group aged for time τ_g	6.1
n_i	Number of values of y at temperature ϑ_i	4.1, 6.1
$\overline{P}$	Mean value of property values in selected groups	6.1
p	Value of diagnostic property	6.1
P	Significance level of χ^2 distribution	4.4, 6.3.1
p_e	Value of diagnostic property at end-point for destructive tests	6.1
$\overline{p}_g$	Mean of property values in group aged for time τ_g	6.1
p_{gh}	Individual property value	6.1
q	Base of logarithms	6.3
r	Number of ageing times selected for inclusion in calculation (destructive tests)	6.1
r^2	Square of correlation coefficient	6.2.3
s^2	Weighted mean of s_1^2 and s_2^2	6.3

		Subclause
s_1^2	Weighted mean of s_{1i}^2, pooled variance within selected groups	4.3, 6.1 to 6.3
$\left(s_1^2\right)_a$	Adjusted value of s_1^2	4.4, 6.3
s_{1g}^2	Variance of property values in group aged for time τ_g	6.1
s_{1i}^2	Variance of y_{ij} values at temperature ϑ_i	4.3, 6.2
s_2^2	Variance about regression line	6.1 to 6.3
s_a^2	Adjusted value of s^2	6.3
s_r^2	Intermediate constant	6.3
s_Y^2	Variance of Y	6.3
t	Student distributed stochastic variable	6.3
t_c	Adjusted value of t (incomplete data)	6.3
TC	Lower 95 % confidence limit of TI	4.4, 7
$\mathrm{TC_a}$	Adjusted value of TC	7.1
TI	Temperature index	4.3, Clause 7
$\mathrm{TI_{10}}$	Temperature index at 10 kh	7.1
$\mathrm{TI_a}$	Adjusted value of TI	7.3
TI_g	Temperature index obtained by graphical means or without defined confidence limits	7.3
x	Independent variable: reciprocal of thermodynamic temperature	
$\overline{x}$	Weighted mean value of x	6.2
X	Specified value of x for estimation of y	6.3
$\hat{X}$	Estimated value of x at specified value of y	6.3
$\hat{X}_c$	Upper 95 % confidence limit of $\hat{X}$	6.3
x_i	Reciprocal of thermodynamic temperature corresponding to ϑ_i	4.1, 6.1
$\overline{y}$	Weighted mean value of y	6.2
y	Dependent variable: logarithm of time to end-point	
$\hat{Y}$	Estimated value of y at specified value of x	6.3
Y	Specified value of y for estimation of x	6.3
$\hat{Y}_c$	Lower 95 % confidence limit of $\hat{Y}$	6.3
$\overline{y}_i$	Mean values of y_{ij} at temperature ϑ_i	4.3, 6.2
y_{ij}	Value of y corresponding to τ_{ij}	4.1, 6.1
$\overline{z}$	Mean value of z_g	6.1
z_g	Logarithm of ageing time for destructive tests – group g	6.1
α	Censored data coefficient for variance	4.3, 6.2
β	Censored data coefficient for variance	4.3, 6.2
ε	Censored data coefficient for variance of mean	4.3, 6.2

		Subclause
Θ_0	Temperature 0 °C on the thermodynamic scale (273,15 K)	4.1, 6.1
$\hat{\vartheta}$	Estimate of temperature for temperature index	6.3.3
$\hat{\vartheta}_c$	Confidence limit of $\hat{\vartheta}$	6.3.3
ϑ_i	Ageing temperature for group i	4.1, 6.1
μ	Censored data coefficient for mean	4.3, 6.2
$\mu_2(x)$	Central second moment of x values	6.2, 6.3
v	Total number of property values selected at one ageing temperature	6.1
τ_f	Time selected for estimate of temperature	6.3
τ_g	Time of ageing for selected group g	6.1
τ_{ij}	Times to end-point	6.4
χ^2	χ^2-distributed stochastic variable	6.3

4 Principles of calculations

4.1 General principles

The general calculation procedures and instructions given in Clause 6 are based on the principles set out in IEC 60493-1 [2]. These may be simplified as follows:

a) the relation between the mean of the logarithms of the times taken to reach the specified end-point (times to end-point) and the reciprocal of the thermodynamic (absolute) temperature is linear;

b) the values of the deviations of the logarithms of the times to end-point from the linear relation are normally distributed with a variance which is independent of the ageing temperature.

The data used in the general calculation procedures are obtained from the experimental data by a preliminary calculation. The details of this calculation are dependent on the character of the diagnostic test: non-destructive, proof or destructive (see 4.2). In all cases the data comprise values of x, y, m, n and k

where

$x_i = 1/(\vartheta_i + \Theta_0)$	is the reciprocal of thermodynamic value of ageing temperature ϑ_i in °C;
$y_{ij} = \log \tau_{ij}$	is the logarithm of the value of time (j) to end-point at temperature ϑ_i;
n_i	is the number of y values in group number i aged at temperature ϑ_i;
m_i	is the number of samples in group number i aged at temperature ϑ_i (different from n_i for censored data);
k	is the number of ageing temperatures or groups of y values.

NOTE Any number can be used as the base for logarithms, provided consistency is observed throughout calculations. The use of natural logarithms (base e) is beneficial, since most computer programming languages and scientific calculators have this facility.

4.2 Preliminary calculations

4.2.1 General

In all cases, the reciprocals of the thermodynamic values of the ageing temperatures are calculated as the values of x_i.

The values of y_{ij} are calculated as the values of the logarithms of the individual times to end-point τ_{ij} obtained as described below.

In many cases of non-destructive and proof tests, it is advisable for economic reasons, (for example, when the scatter of the data is high) to stop ageing before all specimens have reached the end-point, at least for some temperature groups. In such cases, the procedure for calculation on censored data (see 6.2.1.3) shall be carried out on the (x, y) data available.

Groups of complete and incomplete data or groups censored at a different point for each ageing temperature may be used together in one calculation in 6.2.1.3.

4.2.2 Non-destructive tests

Non-destructive tests (for example, loss of mass on ageing) give directly the value of the diagnostic property of each specimen each time it is measured, at the end of an ageing period. The time to end-point τ_{ij} is therefore available, either directly or by linear interpolation between consecutive measurements.

4.2.3 Proof tests

The time to end-point τ_{ij} for an individual specimen is taken as the mid-point of the ageing period immediately prior to reaching the end-point.

4.2.4 Destructive tests

When destructive test criteria are employed, each test specimen is destroyed in obtaining a property value and its time to end-point cannot therefore be measured directly.

To enable estimates of the times to end-point to be obtained, the assumptions are made that in the vicinity of the end-point:

a) the relation between the mean property values and the logarithm of the ageing time is approximately linear;
b) the values of the deviations of the individual property values from this linear relation are normally distributed with a variance which is independent of the ageing time;
c) the curves of property versus logarithm of time for the individual test specimens are straight lines parallel to the line representing the relation of a) above.

For the application of these assumptions, an ageing curve is drawn for the data obtained at each of the ageing times. The curve is obtained by plotting the mean value of property for each specimen group against the logarithm of its ageing time. If possible, ageing is continued at each temperature until at least one group mean is beyond the end-point level. An approximately linear region of this curve is drawn in the vicinity of the end-point line (see Figure D.2).

A statistical test (F-test) is carried out to decide whether deviations from linearity of the selected region are acceptable (see 6.1.4, step 4). If acceptable, then, on the same graph, points representing the properties of the individual specimens are drawn. A line parallel to the ageing line is drawn through each individual specimen data point. The estimate of the logarithm of the time to end-point for that specimen (y_{ij}) is then the value of the logarithm of time corresponding to the intersection of the line with the end-point line (Figure D.2).

With some limitations, an extrapolation of the linear mean value graph to the end-point level is permitted.

The above operations are executed numerically in the calculations detailed in 6.1.4.

4.3 Variance calculations

Commencing with the values of x and y obtained in 4.2, the following calculations are made:

For each group of y_{ij} values, the mean $\overline{y}_i$ and variance s_{1i}^2 are calculated, and from the latter the pooled variance within the groups, s_1^2, is derived, weighting the groups according to size.

For incomplete data, the calculations have been developed from those originated by Saw [3] and given in 6.2.1.3. For the coefficients required (μ for mean, α, β for variance and ε for deriving the variance of mean from the group variance) see Annex C, Table C.1. For multiple groups, the variances are pooled, weighting according to the group size. The mean value of the group values of ε is obtained without weighting, and multiplied by the pooled variance.

NOTE The weighting according to the group size is implicit in the definition of ε, which here is equal to that originally proposed by Saw, multiplied by the group size. This makes for simpler representation in equations.

From the means $\overline{y}_i$ and the values of x_i, the coefficients a and b (the coefficients of the best fit linear representation of the relationship between x and y) are calculated by linear regression analysis.

From the regression coefficients, the values of TI and HIC are calculated. The variance of the deviations from the regression line is calculated from the regression coefficients and the group means.

4.4 Statistical tests

The following statistical tests are made:

a) Fisher test for linearity (Fisher test, F-test) on destructive test data prior to the calculation of estimated times to end-point (see 4.2.4);

b) variance equality (Bartlett's χ^2-test) to establish whether the variances within the groups of y values differ significantly;

c) F-test to establish whether the ratio of the deviations from the regression line to the pooled variance within the data groups is greater than the reference value F_0, i.e. to test the validity of the Arrhenius hypothesis as applied to the test data.

In the case of data of very small dispersion, it is possible for a non-linearity to be detected as statistically significant which is of little practical importance.

In order that a result may be obtained even where the requirements of the F-test are not met, a procedure is included as follows:

1) increase the value of the pooled variance within the groups $\left(s_1^2\right)$ by the factor F/F_0 so that the F-test gives a result which is just acceptable (see 6.3.2);

2) use this adjusted value $\left(s_1^2\right)_a$ to calculate the lower confidence limit TC_a of the result;

3) if the lower confidence interval ($TI - TC_a$) is found acceptable, the non-linearity is deemed to be of no practical importance (see 6.3.2);

4) from the components of the data dispersion, $\left(s_1^2\right)$ and $\left(s_2^2\right)$ the confidence interval of an estimate is calculated using the regression equation.

When the temperature index (TI), its lower confidence limit (TC) and the halving interval (HIC) have been calculated, (see 7.1), the result is considered acceptable if

$$TI - TC \leq 0{,}6\ HIC \qquad (1)$$

When the lower confidence interval (TI – TC) exceeds 0,6 HIC by a small margin, a usable result may still be obtained, provided $F \leq F_0$, by substituting (TC + 0,6 HIC) for the value of TI (see Clause 7).

4.5 Results

The temperature index (TI), its halving interval (HIC) and its lower 95 % confidence limit (TC) are calculated from the regression equation, making allowance as described above for minor deviations from the specified results of the statistical tests.

The mode of reporting of the temperature index and halving interval is determined by the results of the statistical tests (see 7.2).

It is necessary to emphasize the need to present the thermal endurance graph as part of the report, since a single numerical result, TI (HIC), cannot present an overall qualitative view of the test data, and appraisal of the data cannot be complete without this.

5 Requirements and recommendations for valid calculations

5.1 Requirements for experimental data

5.1.1 General

The data submitted to the procedures of this document shall conform to the requirements of IEC 60216-1.

5.1.2 Non-destructive tests

For most diagnostic properties in this category, groups of five specimens will be adequate. However, if the data dispersion (confidence interval, see 6.3.3) is found to be too great, more satisfactory results are likely to be obtained by using a greater number of specimens. This is particularly true if it is necessary to terminate ageing before all specimens have reached end-point.

5.1.3 Proof tests

Not more than one specimen in any group shall reach end-point during the first ageing period: if more than one group contains such a specimen, the experimental procedure should be carefully examined (see 6.1.3) and the occurrence included in the test report.

The number of specimens in each group shall be at least five, and for practical reasons the maximum number treatable is restricted to 31 (Table C.1). The recommended number for most purposes is 21.

5.1.4 Destructive tests

At each temperature, ageing should be continued until the property value mean of at least one group is above and at least one below the end-point level. In some circumstances, and with appropriate limitations, a small extrapolation of the property value mean past the end-point level may be permitted (see 6.1.4, step 4). This shall not be permitted for more than one temperature group.