

Guide for the determination of thermal endurance properties of electrical insulating materials —

Part 3: Instructions for calculating
thermal endurance characteristics —

Section 3.1 Calculations using mean
values of normally distributed complete
data —

(Implementation of CENELEC
HD 611.3.1 S1:1992)

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National foreword

This Section of BS 5691 has been prepared by Subcommittee GEL/15/2. It implements Harmonization Document HD 611.3.1 S1, which was published by the European Committee for Electrotechnical Standardization (CENELEC). It is identical with IEC 216-3-1:1990 *Guide for the determination of thermal endurance properties of electrical insulating materials. Part 3: Instructions for calculating thermal endurance characteristics. Section 1 — Calculations using mean values of normally distributed complete data*, published by the International Electrotechnical Commission (IEC).

Cross-references

Publication referred to	Corresponding British Standard
	BS 5691 <i>Guide for the determination of thermal endurance properties of electrical insulating materials</i>
HD 611.1 S1:1992 (IEC 216-1:1990)	Part 1:1995 <i>General guidelines for ageing procedures and evaluation of test results</i>
HD 611.2 S1:1992 (IEC 216-2:1990)	Part 2:1995 <i>Choice of test criteria</i>

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the HD title page, pages 2 to 26, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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Guide for the determination of thermal endurance
properties of electrical insulating materials
Part 3: Instructions for calculating thermal endurance
characteristics
Section 1: Calculations using mean values of normally
distributed complete data

(IEC 216-3-1:1990)

Guide pour la détermination des propriétés
d'endurance thermique de matériaux isolants
électriques

Troisième partie: Instructions pour le calcul
des caractéristiques d'endurance thermique
Section un: Calculs basés sur les valeurs
moyennes des résultats complets normalement
distribués

(CEI 216-3-1:1990)

Leitlinie zur Bestimmung der thermischen
Langzeiteigenschaften von
Elektroisolierstoffen

Teil 3: Vorschriften zur Berechnung der
thermischen Langzeitkennwerte
Hauptabschnitt 1: Berechnung mit Hilfe von
Mittelwerten für normalverteilte, vollständige
Daten

(IEC 216-3-1:1990)

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This Harmonization Document exists in three official versions (English, French, German).

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CENELEC

European Committee for Electrotechnical Standardization
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Foreword

The CENELEC questionnaire procedure, performed for finding out whether or not the International Standard IEC 216-3-1:1990 could be accepted without textual changes, has shown that no common modifications were necessary for acceptance as a Harmonization Document.

The reference document was submitted to the CENELEC members for formal vote and was approved by CENELEC as HD 611.3.1 S1 on 16 June 1992.

The following dates were fixed:

- latest date of announcement of the HD at national level (doa) 1992-12-01
- latest date of publication of a harmonized national standard (dop) 1993-06-01
- latest date of withdrawal of conflicting national standards (dow) 1993-06-01

Annexes designated “normative” are part of the body of the standard. In this standard, Annex ZA is normative.

Introduction

IEC Publication 216: Guide for the determination of thermal endurance properties of electrical insulating materials, is composed of several parts:

- *Part 1: General guidelines for ageing procedures and evaluation of test results* (IEC Publication 216-1);
- *Part 2: Choice of test criteria* (IEC Publication 216-2);
- *Part 3: Instructions for calculating thermal endurance characteristics* (IEC Publication 216-3);
- *Part 4: Ageing ovens* (IEC Publication 216-4);
- *Part 5: Guidelines for application of thermal endurance characteristics* (IEC Publication 216-5).

This Part consists of four sections based upon mean values of normally distributed test results. Further sections may be added to take account of other statistical procedures, for example extreme value statistics for those cases where mean value treatments are inadequate. However, there is at present insufficient experience to enable these methods to be used in thermal endurance standards.

The following sections of Part 3 are in preparation. Each section will consist exclusively of calculation instructions. The relevant statistical theory will be found in the appropriate part of IEC Publication 493.

- *Section 2: Calculation procedures for normally distributed results from destructive test procedures* (IEC Publication 216-3-2);
- *Section 3: Calculations for incomplete data: proof test results up to and including the median time to end-point (equal test groups)* (IEC Publication 216-3-3);
- *Section 4: Calculations for relative temperature indices* (IEC Publication 216-3-4).

1 Scope and object

This part of IEC Publication 216 gives instructions for calculation of thermal endurance characteristics from data obtained in accordance with IEC Publications 216-1 and 216-2.

Section 1 gives the main sequence calculation scheme for complete normally distributed data, in accordance with the statistical principles set out in IEC Publication 493-1, to which reference should be made for the mathematical background details. A graphical derivation is also included.

Worked examples, a computer program written in “BASIC” and appropriate statistical tables are given in the appendices.

2 Calculation principles

2.1 Statistical principles

The calculation procedures and instructions given in Clause 3 are based upon the principles and assumptions set out in IEC Publication 493-1. The assumptions made may be expressed in simple form as follows (see IEC Publication 493-1, Sub-clause 3.7.1):

- 1) The relation between the mean of the logarithms of the times taken to reach a given end-point (“mean time to end-point”) and the reciprocal thermodynamic (absolute) ageing temperature is linear.
- 2) The values of the deviations of the logarithms of the times to end-point from this linear relation are normally distributed with a variance which is independent of the ageing temperature.

The best estimates of the coefficients of the linear relationship are obtained by the method of least squares, and the confidence limits associated with an estimate using this linear relationship are obtained by using the methods of generalized regression analysis.

2.2 Data for analysis

2.2.1 The experimental data are obtained as values of temperature (ϑ °C) and time to end-point (t hours). Each value is transformed to an x or y value:

- $$x_i = 1/(\vartheta_i + 273) \text{ value (i) of reciprocal thermodynamic (absolute) temperature}$$
- $$y_{ij} = \log(t_{ij})^a \text{ log of value (j) of time in i'th ageing group (i)}$$
- $$n_i = \text{number of } y \text{ values in group (i)}$$
- $$k = \text{number of groups}$$

^a In principle, calculations may be made using Napierian (base e) or Briggsian (base 10) logarithms, as long as the choice is consistent throughout. For this reason, the symbol $\log(y)$ is used throughout, except in Sub-clause 3.1.4.

In order to enable some intermediate results to be comparable with those of the second edition of IEC Publication 216, the computer program (Appendix D) uses logarithms to base 10.

In most cases the number of test specimens at each test temperature is identical, but even if the endurance test is planned with different numbers n_i of y values in the temperature groups, the analysis can be carried out as described below.

In general, the time to end-point shall be determined for all specimens so that all y_{ij} values are available, otherwise the following analysis is not valid. In exceptional cases where one or a few y values are missing for chance reasons, that is, independently of the time to end-point of the specimen, for instance in the case where a specimen is spoiled during handling, it is permissible to carry out the analysis, but the incident should be mentioned in the test report.

The values of t_{ij} are obtained by direct observation in the case of non-destructive tests or proof tests. In the case of destructive tests they are estimated by the procedures given in IEC Publication 216-3-2.

2.2.2 The data to be used in the common calculation are derived from the primary data as follows.

For each group of y values, the mean, $\bar{y}_i$, and variance s_{1i}^2 are calculated

$$\bar{y}_i = \sum_{j=1}^{n_i} y_{ij} / n_i \quad (1)$$

$$s_{1i}^2 = \left(\sum_{j=1}^{n_i} y_{ij}^2 - n_i \bar{y}_i^2 \right) / (n_i - 1) \quad (2)$$

2.3 Statistical tests

Three tests are included in the calculation procedure.

- Variance equality (Bartlett's χ^2) test.
- Linearity (F) test.
- Dispersion (confidence interval) test.

Tests b) and c) may detect deviations from ideal behaviour which are statistically significant but which are too small to have serious practical consequences. Procedures are included to meet these circumstances.

2.3.1 Bartlett's χ^2 test

Inequalities of variance, other than major inequalities, are not considered to lead to serious errors either of temperature index or confidence interval. The value of χ^2 is calculated, and if this value is greater than that corresponding to a significance level of 0.05, the values of χ^2 and its significance level are reported.

2.3.2 F -test for linearity

The F ratio is the ratio of the variance of the deviations of the ageing group means from the regression line [s_2^2 , see equation (11)] to the variance within the ageing groups [s_1^2 , see equation (10)]. A high value of F may result either from high values of the deviations from the regression line or from low values of the variance of data within the groups.

The F ratio is tested against tabulated values F_0 at a significance level of 0.05.

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 F test has failed in this way, a procedure is included as follows:

- Increase the value of the variance within the ageing groups (s_1^2) so that the F test gives a result which is just acceptable, that is substitute s_1^2 by an adjusted value $(s_1^2)_a = s_1^2 (F/F_0)$, see Sub-clause 3.1.5 b).
- Use this adjusted value to calculate the lower confidence limit of the result, TC_a .
- If the lower confidence interval ($TI - TC_a$) is found acceptable ($TI - TC_a \leq 0.6$ HIC, see Sub-clause 2.3.3) the non-linearity is deemed to be of no practical importance.

2.3.3 Data dispersion test

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

$$TI - TC \leq 0.6 \text{ HIC}$$

In cases where the lower confidence interval exceeds 0.6 HIC by a small margin, still being less than 1.6 HIC, a usable result may yet be obtained (provided $F \leq F_0$) by calculating an adjusted TI_a , that is to say, by subtracting from the calculated TI the amount by which the lower confidence interval exceeds 0.6 HIC,

$$\text{i.e. if } 0.6 \text{ HIC} < TI - TC \leq 1.6 \text{ HIC},$$

$$\text{and at the same time } F \leq F_0$$

report as TI the value

$$TI_a = TI - [(TI - TC) - 0.6 \text{ HIC}] = TC + 0.6 \text{ HIC}$$

instead of the value of TI calculated from the regression equation (see Sub-clause 3.1.7).

If the above conditions are not met, the test result may be reported only in the form $TI_g = \dots$, $HIC_g = \dots$ as in Sub-clause 3.2.3 (see also IEC Publication 216-1, Sub-clause 12.5).

3 Instructions for deriving thermal endurance indices

3.1 Numerical derivation and thermal endurance graph

The calculation procedures described here start from the values of x_i , $\bar{y}_i$, s_{1i}^2 and n_i defined and derived as in Sub-clause 2.2. All summations in Sub-clause 3.1 are with respect to index i over the range 1 to k .

3.1.1 General means

Calculate the values of $\bar{x}$, $\bar{y}$ and N .

$$N = \sum n_i \quad (3)$$

$$\bar{x} = \frac{1}{N} \sum x_i n_i \quad (4)$$

$$\bar{y} = \frac{1}{N} \sum \bar{y}_i n_i \quad (5)$$

3.1.2 Regression equation and thermal endurance graph

Calculate the coefficients of the regression equation

$$y = a + bx \quad (6)$$

using the equations

$$b = \frac{\sum n_i x_i \bar{y}_i - N \bar{x} \bar{y}}{\sum n_i x_i^2 - N \bar{x}^2}$$

$$a = \bar{y} - b \bar{x} \quad (8)$$

When the regression line has been established, it is drawn on the thermal endurance graph, i.e. a graph with $y = \log(t)$ as ordinate, and $x = 1/(\vartheta + 273)$ as abscissa. Usually x is plotted as increasing from the right to the left, and the corresponding values of ϑ in °C are marked on this axis (see Figure 1). Special graph paper is obtainable for this purpose.

Alternatively, a computer program executing this calculation may include a sub-routine to plot the graph on the appropriate non-linear scale.

The individual values $y_{ij} = \log(t_{ij})$, and the mean values $\bar{y}_i$, obtained as in Sub-clause 2.2.2, are plotted on the graph at the corresponding values of

$$x_i = \frac{1}{\vartheta_i + 273} \quad (9)$$

The thermal endurance graph may be completed by drawing the lower 95 % confidence line (see Sub-clause 3.1.6).

3.1.3 Variance calculations

Calculate the weighted mean value of the variance within the ageing groups

$$s_1^2 = \frac{\sum (n_i - 1) s_{1i}^2}{N - k} \quad (10)$$

Calculate the weighted variance of the deviations of the ageing group means from the regression line

$$s_2^2 = \frac{\sum n_i (\bar{y}_i - Y_i)^2}{k - 2} \quad (11)$$

$$\text{where: } Y_i = a + bx_i \quad (12)$$

This may be simplified to

$$s_2^2 = \frac{(\sum n_i \bar{y}_i^2 - N \bar{y}^2) - b (\sum n_i x_i \bar{y}_i - N \bar{x} \bar{y})}{k - 2} \quad (13)$$

Calculate the central second moment of the x values

$$\mu_2(x) = \frac{\sum n_i x_i^2 - N \bar{x}^2}{N} \quad (14)$$

3.1.4 Test for equality of variances

Calculate the value of χ^2 by Bartlett's method

$$\chi^2 = \frac{\ln q}{c} [(N - k) \log_q s_1^2 - \sum (n_i - 1) \log_q s_{1i}^2] \quad (15)$$

$$\text{where: } c = 1 + \frac{\sum \left(\frac{1}{n_i - 1} \right) - \frac{1}{N - k}}{3(k - 1)} \quad (15a)$$

and $\log_q$ designates the logarithm to base q . If Briggsian logarithms (base 10) are used, then $\ln q \approx 2.3$, if Napierian logarithms (base e) are used, then $\ln q = 1$.

Compare the value of χ^2 with the tabulated value for $f = k - 1$ degrees of freedom (Table C.1, Appendix C).

If the value of χ^2 is greater than that tabulated for a significance level of 0.05, report the value of χ^2 and the significance level tabulated for the highest value less than χ^2 . Alternatively, if both χ^2 and its significance level are calculated by a computer program, report these.

3.1.5 Linearity test (*F*-test)

The variance of the deviations from the regression line, s_2^2 , is compared with the pooled variance within the k sets of measurements, s_1^2 , by the *F*-ratio test at a significance level of 0.05.

Calculate the ratio

$$F = s_2^2 / s_1^2 \quad (16)$$

and compare its value with the tabulated value F_0 with $f_n = k - 2$ and $f_d = N - k$ degrees of freedom (Table C.2, Appendix C).

$F_0 = F(0.95, k - 2, N - k)$

a) if $F \leq F_0$, calculate the pooled variance estimate

$$s^2 = \frac{(k - 2) s_2^2 + (N - k) s_1^2}{N - 2} \quad (17a)$$

b) if $F > F_0$, adjust s_1^2 to $(s_1^2)_a = s_1^2 (F/F_0)$ and calculate an adjusted value of s^2

$$s_a^2 = \frac{(k - 2) s_2^2 + (N - k) (s_1^2)_a}{N - 2} \quad (17b)$$

3.1.6 Confidence limits of *X* and *Y* estimates

a) *Y*-estimates

The lower 95 % confidence limit of the estimated value *Y* corresponding to a given value *X* is

$$Y_c = Y - t s_Y \quad (18)$$

where $Y = a + bX$,

$$s_Y^2 = \frac{s^2}{N} \left(1 + \frac{(X - \bar{x})^2}{\mu_2(x)} \right) \quad \text{if } F \leq F_0, \text{ or} \quad (19a)$$

$$s_Y^2 = \frac{s_a^2}{N} \left(1 + \frac{(X - \bar{x})^2}{\mu_2(x)} \right) \quad \text{if } F > F_0 \quad (19b)$$

and t is the tabulated value of Student's t with $N - 2$ degrees of freedom at a confidence level of 95 %, $t(0.95, N - 2)$ (Table C.3, Appendix C).

For the confidence limit curve of the thermal endurance graph (Sub-clause 3.1.2), Y_c is calculated for several (X , Y) pairs of values over the range of interest, and the curve drawn through the points (X , Y_c) plotted on the graph.

b) *X*-estimates

The upper 95 % confidence limit of the value of *X* corresponding to a time to end-point t_f is calculated from

$$X_c = \bar{x} + \frac{(Y - \bar{y})}{b_r} + \frac{t s_r}{b_r} \quad (20)$$

where: $Y = \log(t_f)$ (20a)

$$b_r = b - \frac{t^2 s^2}{N b \mu_2(x)} \quad (20b)$$

$$s_r^2 = \frac{s^2}{N} \left(\frac{b_r}{b} + \frac{(X - \bar{x})^2}{\mu_2(x)} \right) \quad (20c)$$

$$X = \frac{Y - a}{b} \quad (20d)$$

for $F \leq F_0$. If $F > F_0$ the value s_a^2 shall be inserted in equations (20b) and (20c) instead of s^2 .

t is the tabulated value of Student's t with $N - 2$ degrees of freedom at a confidence level of 95 %, $t(0.95, N - 2)$ (Table C.3, Appendix C).

The lower 95 % confidence limit of a temperature estimate may be calculated from the upper confidence limit of the corresponding X estimate, X_c .

$$g_c = \frac{1}{X_c} - 273 \quad (21)$$

3.1.7 Calculation of thermal endurance characteristics

From the regression equation (6) in Sub-clause 3.1.2 calculate the temperature in °C corresponding to a time to end-point of 20 kh. This is the Temperature Index, TI.

Calculate by the same method the temperature corresponding to a time to end-point of 10 kh, TI_{10} . The Halving Interval, HIC, is $TI_{10} - TI$.

Calculate by the method of Sub-clause 3.1.6 b) the lower 95 % confidence limit of TI ($Y = \log [20\ 000]$), TC or TC_a if the adjusted value s_a^2 is used.

Determine the value of $(TI - TC)/HIC$, or $(TI - TC_a)/HIC$.