

INTERNATIONAL STANDARD



Electrical insulating materials – Thermal endurance properties –
Part 6: Determination of thermal endurance indices (TI and ~~RTE~~ RTI) of an
insulating material using the fixed time frame method

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insulating material using the fixed time frame method**

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ELECTROTECHNICAL
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**ELECTRICAL INSULATING MATERIALS –
THERMAL ENDURANCE PROPERTIES –****Part 6: Determination of thermal endurance indices (TI and ~~RTE~~ RTI)
of an insulating material using the fixed time frame method**

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IEC 60216-6 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) clarification of definition of index properties vs. endurance properties;
- b) complete rework of Annex G and the corresponding program.

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

Draft	Report on voting
112/583/FDIS	112/589/RVD

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- withdrawn,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 6: Determination of thermal endurance indices (TI and ~~RTE~~ RTI) of an insulating material using the fixed time frame method

1 Scope

This part of IEC 60216 specifies the experimental and calculation procedures for deriving the thermal endurance characteristics, temperature index (TI) and ~~relative thermal endurance index (RTE)~~ relative temperature index (RTI) of an electrical insulating material (EIM) using the “fixed time frame method (FTFM)”.

In this protocol, the ageing takes place for a small number of fixed times, using the appropriate number of ageing temperatures throughout each time, the properties of the specimens being measured at the end of the relevant time interval. This differs from the procedure of IEC 60216-1, where ageing is conducted at a small number of fixed temperatures, property measurement taking place after ageing times dependent on the progress of ageing.

The diagnostic tests employed in the fixed time frame method are restricted to destructive tests. The method has not yet been applied to non-destructive or proof test procedures.

Both the TI and the ~~RTE~~ RTI determined according to the FTFM protocol are derived from experimental data obtained in accordance with the instructions of IEC 60216-1 and IEC 60216-2 as modified in this part of IEC 60216. The calculation procedures and statistical tests are modified from those of IEC 60216-3 and IEC 60216-5.

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 60212, *Standard conditions for use prior to and during the testing of solid electrical insulating materials*

IEC 60216-1:2004/2013, *Electrical insulating materials – Thermal endurance properties – Part 1: Ageing procedures and evaluation of test results*

IEC 60216-2, *Electrical insulating materials – Thermal endurance properties – Part 2: Determination of thermal endurance properties of electrical insulating materials – Choice of test criteria*

IEC 60216-3:2002/2021, *Electrical insulating materials – Thermal endurance properties – Part 3: Instructions for calculating thermal endurance characteristics*

IEC 60216-4-1, *Electrical insulating materials – Thermal endurance properties – Part 4-1: Ageing ovens – Single-chamber ovens*

IEC 60216-4-2, *Electrical insulating materials – Thermal endurance properties – Part 4-2: Ageing ovens – Precision ovens for use up to 300 °C*

IEC 60216-4-3, *Electrical insulating materials – Thermal endurance properties – Part 4-3: Ageing ovens – Multi-chamber ovens*

IEC 60216-5:2022, *Electrical insulating materials – Thermal endurance properties – Part 5: Determination of ~~relative thermal endurance index (RTE)~~ relative temperature index (RTI) of an insulating material*

IEC 60493-1:1974, *Guide for the statistical analysis of ageing test data – Part 1: Methods based on mean values of normally distributed test results*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

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

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

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

3.1.1

electrical insulating material

EIM

material of low electric conductivity, used to separate conducting parts at different electric potentials or to isolate such parts from the surroundings

3.1.2

~~assessed thermal endurance index~~

~~ATE~~

~~numerical value of the temperature in degrees Celsius, up to which the control material possesses known, satisfactory service performance in the specified application~~

~~NOTE 1—The ATE of a specific material may vary between different applications of the material.~~

~~NOTE 2—ATE is sometimes referred to as “absolute” thermal endurance index.~~

3.1.2

assessed temperature index

ATI

numerical value of the temperature index in degrees Celsius of the reference EIM

Note 1 to entry: The ATI of a specific material may vary between different applications of the material.

3.1.3

ageing temperature

temperature in degrees Celsius at which a group of specimens is thermally aged

3.1.4

end-point temperature

temperature in degrees Celsius at which a specimen is considered to have reached end-point after ageing for a specified time

3.1.5

candidate ~~material~~ EIM

material for which an estimate of the thermal endurance is required to be determined

Note 1 to entry: The determination is made by simultaneous thermal ageing of the material and a ~~control material~~ reference EIM.

3.1.6

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 ~~items~~ in the group

3.1.7

95 % confidence limit

statistical parameter, calculated from test data, which with 95 % confidence constitutes an upper or lower limit for the true value of a quantity estimated by statistical analysis

Note 1 to entry: This implies that there is only 5 % probability that the true value of the quantity estimated is actually larger (or smaller) than the upper (or lower) confidence limit.

Note 2 to entry: In other connections, confidence values other than 95 % may sometimes be used, e.g. in the linearity test for destructive test data.

3.1.8

~~control material~~ reference EIM

material with known ~~assessed~~ thermal endurance ~~index (ATE)~~, preferably derived from service experience, used as a reference for comparative tests with the candidate ~~material~~ EIM

3.1.9

correlation coefficient

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

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

Note 2 to entry: In this standard, the two data sets are the values of the independent variable and the means of the corresponding dependent variable groups.

3.1.10

correlation time ~~(RTE)~~ for RTI

estimated time to end-point of the ~~control material~~ reference EIM at a temperature equal to its ~~ATE~~ ATI in degrees Celsius

Note 1 to entry: In this document, it is expressed by symbol τ_c , see Clause 10.

3.1.11

correlation time for TI

hypothetical time to end-point used to calculate TI

Note 1 to entry: Its usual value is 20 000 h, see Clause D.1.

3.1.12

covariance, <of data sets>

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

3.1.13

degrees of freedom

number of data values minus the number of parameter values

3.1.14

destructive test

diagnostic property test, where the test specimen is irreversibly changed by the property measurement, in a way which precludes a repeated measurement on the same specimen

Note 1 to entry: An example of a destructive test is the measurement of electric strength. An example of a non-destructive test is the measurement of ~~tg~~ dissipation factor $\tan \delta$.

3.1.15

end-point line

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

3.1.16

halving interval

HIC

numerical value of the temperature interval in Kelvin which expresses the halving of the time to end-point taken at a time equal to TI

3.1.17

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

3.1.18

regression coefficients

coefficients of the equation of the best fit line derived by regression analysis

~~3.1.18~~

~~relative thermal endurance index~~

~~RTE~~

~~estimate of the thermal endurance of a candidate material, made by thermal ageing simultaneously with the control material, as described in this standard~~

~~NOTE The value of RTE is the value of the temperature in degrees Celsius at which the estimated time to end-point of the candidate material is the same as the estimated time to end-point of the control material at a temperature equal to its ATE.~~

3.1.19

relative temperature index

RTI

determined by test in relation to the thermal performance of a known reference EIM

3.1.20

significance

probability of a value of a statistical function greater than a specified value

Note 1 to entry: The value is equal to $(1-p)$ where p is the cumulative distribution function value. Significance is conventionally printed in upper case (P).

3.1.21

standard deviation

square root of the variance of a data group or sub-group

3.1.22

standard error of an estimate of the true value of a data group property

value of the standard deviation of the hypothetical sampling population of which the group property may be ~~considered to be~~ a member

Note 1 to entry: For an estimate of the group mean, the standard error is equal to the group standard deviation divided by the square root of the number of data items in the group, and indicates the uncertainty in the estimate of the true value of the mean. This standard is concerned only with means and the difference between two means.

3.1.23**temperature index****TI**

numerical value of the temperature in degrees Celsius ~~derived from the thermal endurance relationship at a time of 20 000 h (or other specified time)~~ determined by test by itself

Note 1 to entry: This rating is based on 20 000 h life, unless otherwise specified, based on one of the end-of-life criteria listed in IEC 60216-2.

3.1.24**temperature group, <of specimens>**

number of specimens being exposed together to thermal ageing at the same temperature in the same oven

Note 1 to entry: Where there is no risk of ambiguity, either temperature groups or test groups may be referred to simply as "groups".

3.1.25**test group, <of specimens>**

number of specimens removed together from a temperature group for destructive testing

Note 1 to entry: Where there is no risk of ambiguity, either temperature groups or test groups may be referred to simply as "groups".

3.1.26**thermal endurance graph**

graph in which the logarithm of the time to reach a specified end-point in a thermal endurance test is plotted against the reciprocal thermodynamic (absolute) test temperature

3.1.27**thermal endurance graph paper**

graph paper having a logarithmic time scale as the ordinate and values proportional to the reciprocal of the thermodynamic (absolute) temperature as the abscissa

Note 1 to entry: The ordinate is usually graduated in powers of ten (from 10 h to 100 000 h is often a convenient range). The abscissa is usually graduated in a non-linear (Celsius) temperature scale oriented with temperature increasing from left to right.

3.1.28**time group, <of specimens>**

all test groups removed for testing at the same time

3.1.29**variance of a data group**

sum of the squares of the deviations of the data from a reference level defined by one or more parameters divided by the number of degrees of freedom

Note 1 to entry: The reference level ~~may~~ can, for example be a mean value (1 parameter) or a line (2 parameters, here intercept on the axis of the independent variable and slope).

3.2 Symbols and abbreviated terms

The following symbols are used in the calculations of Clauses 6, 7, 12 and Annex A, Annex B and Annex C.

Symbol	Description	Clause
a	Regression coefficient: intercept of regression line with x -axis	6.4.4
b	Regression coefficient: slope of regression line relative to y -axis	6.4.4
b_r	Parameter derived from b for calculation of $\hat{Y}_c$	6.5.3
b_p	Regression coefficient for destructive test calculations	6.3.5

Symbol	Description	Clause
c	Parameter in calculation of χ^2	6.5.1
F	F -distributed variance ratio for linearity test	6.3.4, 6.5.2
g, h, i, j	Indexing parameters for regression calculations	6.3, 6.4
HIC	Halving interval	7.1
k	Number of ageing times	6.1.1
N	Total number of x_{ij} values	6.4.3
n_i	Number of x_{ij} values in time group i	6.1.1
P	Significance of the value of a statistical test function	Annex A, Annex B and Annex C
p_e	End-point property value	6.3
p_{gh}	Property value h in temperature group g (time group i implied)	6.3
$\bar{p}_g$	Mean property value in temperature group g (time group i implied)	6.3
q	Base of logarithms in calculation of χ^2	6.5.1
r	Number of temperature groups selected in time group i	6.3.3
r^2	Square of correlation coefficient	6.4.4
s^2	Total (non-regression) variance of x -values	6.5.2
s_{lg}^2	Variance of property values in temperature group g (time group i implied)	6.3.3
s_a^2	Value of s^2 adjusted to allow for acceptable non-linearity	6.5.2
s_r^2	Parameter derived from s^2 for calculation of $\hat{y}_c$	6.5.3
t	Student's t -distributed stochastic variable	6.5.3
TC, TC _a	Lower confidence limit of TI or TI _a (see s_a^2 above)	7.1
$t_{p,N}$	Value of t with probability p and N degrees of freedom	6.5.3
x_{ij}	Value of x , index number j , in time group i	6.3.5
$\bar{x}$	General mean of x -values	6.4.3
$\hat{X}, \hat{X}_c$	Estimate of x , and its confidence limit	6.5.3
y_i	Value of y for time group i	6.1.1
$\bar{y}$	General mean of y -values	6.4.3
$\hat{Y}, \hat{Y}_c$	Estimate of y , and its confidence limit	6.5.3
z_{ij}	Reciprocal kelvin temperature for g_{ij}	6.1.1
$\mu_2(y)$	Central 2 nd moment of y values	6.4.3
v	Total number of property values in time group (i implied)	6.3.3
χ^2	χ^2 distributed variable for variance equality (Bartlett's) test	6.5.1
g_{ij}	Ageing temperature for specimen group j in time group i	6.1.1

Symbol	Description	Clause
θ_0	273,15 K (corresponding to 0 °C)	6.1.1
τ_i	Ageing time for time group i	6.1.1

4 FTFM protocol

4.1 Principles of FTFM protocol

The FTFM (fixed time frame method) protocol is based upon the principle that thermal ageing for determination of thermal endurance characteristics is carried out over a small number of fixed times, with a sufficient range of ageing temperatures at each time to ensure that the property values determined reach the end-point in a satisfactory manner.

In this it differs from the fixed temperature frame procedure of IEC 60216-1, where a small number of ageing temperatures is employed, with ageing being carried out with testing at intervals, until the end-point has been reached.

4.2 Objective of FTFM protocol

~~The objective of~~ The protocol ~~is to~~ shall achieve the following advantages:

The determination of thermal endurance characteristics is completed in a fixed, predetermined time.

This enables much more efficient planning of the determination and will often have substantial commercial advantage. A simple TI determination ~~will~~ can be completed in 5 kh, whereas by the fixed temperature frame procedure, it ~~may~~ can be necessary for ageing to be considerably prolonged past this time to achieve the end-point at the lowest chosen ageing temperature.

Each temperature to end-point (i.e. time-group mean) in the thermal endurance regression is based on the temperatures selected in a time group. The number of temperatures selected may be any number between three and the number of temperature groups in a time group.

Since the largest source of systematic error in the fixed temperature frame procedure is temperature error (actual indication error or temperature distribution error), systematic errors can be considerably reduced. Errors from this source can lead to results which are either inaccurate or invalid through incorrect assessment of linearity.

5 TI determination

5.1 Ageing procedures

Each test procedure shall specify the shape, dimensions and number of the test specimens, the times of exposure, the property to which TI is related, the methods of its determination, the end-point, and the derivation of the thermal endurance characteristics from the experimental data.

The chosen property should, if possible, reflect in a significant fashion a function of the ~~material~~ EIM in practical use. A choice of properties is given in IEC 60216-2.

To provide uniform conditions, the conditioning of specimens after removal from the oven and before measurement ~~may need to~~ should be specified.

5.2 Ageing times and temperatures

In the majority of cases, the required thermal endurance characteristics are for a projected duration of 20 000 h. However, there is often a need for such information related to other, longer or shorter times. In cases of longer times, the times given as requirements or recommendations in the text of this standard (e.g. 5 kh for the minimum value of the longest ageing time) shall be increased in the ratio of the actual specification time to 20 kh.

In cases of shorter specification times, the related times may be decreased in the same ratio if necessary.

Particular care will be needed for very short specification times, since the higher ageing temperatures ~~may~~ can lead into temperature regions which include transition points, e.g. glass transition temperature or partial melting, with consequent non-linearity. Very long specification times ~~may~~ can also lead to non-linearity.

Recommendations for ageing times and temperatures are given in Annex D and illustrated in Figure E.3 to Figure E.5.

5.3 Test specimens

5.3.1 Preparation

The specimens used for the ageing test shall constitute a random sample from the population investigated and shall be treated uniformly.

Since processing conditions may significantly affect the ageing characteristics of some ~~materials~~ EIMs, it shall be ensured that, for example, sampling, cutting sheet from the supply roll, cutting of anisotropic material in a given direction, moulding, curing, preconditioning, are performed in the same manner for all specimens.

The material specifications or the standards for the diagnostic test methods will contain all necessary instructions for the preparation of specimens.

The thickness of specimens is in some cases specified in the list of property measurements for the determination of thermal endurance. See IEC 60216-2. If not, the thickness shall be reported. Some physical properties are sensitive even to minor variations of specimen thickness. In such cases the thickness after each ageing period may need to be determined and reported if required in the relevant specification.

The thickness is also important because the rate of ageing ~~may~~ can vary with thickness. Ageing data of ~~materials~~ EIMs with different thicknesses are not always comparable. Consequently, ~~a material may~~ an EIM can be assigned more than one thermal endurance characteristic derived from the measurement of properties at different thicknesses.

The tolerances of specimen dimensions shall be the same as those normally used for general testing. Where specimen dimensions need smaller tolerances than those normally used, these special tolerances shall be given.

Screening measurements ensure that specimens are of uniform quality and typical of the ~~material~~ EIM to be tested.

5.3.2 Number of specimens

The accuracy of endurance test results depends largely on the number of specimens aged at each temperature.

The total number of specimens (N) is derived as follows:

$$N = a \times b \times c + d$$

where

- a* is the number of specimens in a test group undergoing identical treatment at one temperature and discarded after determination of the property (usually five);
- b* is the number of treatments, i.e. total number of exposure temperatures, at one time;
- c* is the number of ageing time levels;
- d* is the number of specimens in the group used to establish the initial value of the property. Normal practice is to select $d = 2a$ when the diagnostic criterion is a percentage change of the property from its initial level. When the criterion is an absolute property level, *d* is usually given the value of zero, unless reporting of the initial value is required.

It is good practice to prepare additional specimens, or at least to provide a reserve from the original material batch from which such specimens ~~may~~ can subsequently be prepared. In this way any required ageing of additional specimens in case of unforeseen complications will introduce a minimum risk of producing systematic differences between groups of specimens. Such complications ~~may~~ can arise, for example, if the thermal endurance relationship turns out to be non-linear, or if specimens are lost due to thermal runaway of an oven.

5.4 Diagnostic tests

If IEC material specifications are available, property requirements in terms of acceptable lower limits of TI values are usually given. If such material specifications are not available, a selection of properties and methods for the evaluation of thermal endurance is given in IEC 60216-2.

If such a method cannot be found, an international, national or institution standard or a specially devised method should be used in that order of preference. In this case, the diagnostic test shall be stated in the report, including the property, measurement procedure and end-point.

5.5 Selection of end-points

The thermal endurance of ~~materials may need to~~ EIMs can be characterized by different endurance data (derived using different properties and/or end-points), in order to facilitate the adequate selection of the material in respect of its particular application. See IEC 60216-2.

There are two alternative ways in which the end-point ~~may~~ can be defined:

- a) as a percentage increase or decrease in the measured value of the property from the original level. This approach will provide comparisons among ~~materials~~ EIMs but bears a poorer relationship than item b) to the property values required in normal service. For the determination of the initial value, see 5.6;
- b) as a fixed value of the property. This value might be selected with respect to usual service requirements. End-points of proof tests are predominantly given in the form of fixed values of the property.

The end-point should be selected to indicate a degree of deterioration of the ~~insulating material~~ EIM which has reduced its ability to withstand a stress encountered in actual service. The degree of degradation indicated as the end-point of the test should be related to the allowable safe value for the material property which is desired in practice.

5.6 Establishment of initial property value

Select the specimens for the determination of the initial value of the property to constitute a random subset of those prepared for ageing. Before determining the property value these specimens shall be conditioned by exposure to the lowest level of ageing temperature of the test (see 5.2), for two days (48 ± 6) h.

NOTE In some cases (e.g. very thick specimens) times greater than two days ~~may~~ can be ~~necessary~~ useful to establish a stable value.

Unless otherwise stated in the method for determining the diagnostic property (for example, parts of materials specifications dealing with methods of test, or a method listed in IEC 60216-2), the initial value is the arithmetic mean of the test results.

5.7 Ageing conditions

5.7.1 Ageing ovens

Throughout the heat ageing period, ageing ovens shall maintain, in that part of the working space where specimens are placed, a temperature with tolerances as given in the IEC 60216-4 series. Unless otherwise specified, IEC 60216-4-1 shall apply. IEC 60216-4-2 and 60216-4-3 may be specified in special cases.

The circulation of the air within the oven, and the exchange of the air content should be adequate to ensure that the rate of thermal degradation is not influenced by accumulation of decomposition products or oxygen depletion (see 5.7.2).

5.7.2 Environmental conditions

Unless otherwise specified, the ageing shall be carried out in ovens operating in the normal laboratory atmosphere. However, for some materials EIMs very sensitive to the humidity in the ovens, more reliable results are obtained when the absolute humidity in the ageing oven room is maintained at the value equal to the absolute humidity of standard atmosphere B according to IEC 60212. This, or other specified conditions, shall then be reported.

NOTE The effects of special environmental conditions such as extreme humidity, chemical contamination or vibration in many cases may can be more appropriately evaluated by insulation systems tests. Although environmental conditioning, the influence of atmospheres other than air and immersion in liquids, such as oil, may can be important, these are not the concern of this document.

5.7.3 Conditions for property measurement

Unless otherwise specified, the specimens shall be conditioned before measurement, and measured under conditions as stated in the material standard specification.

5.8 Procedure for ageing

Establish a testing scheme, as for example outlined in Annex D.

Prepare a number of specimens following the instructions of 5.3.2. If necessary, determine the initial value of the property as specified in accordance with 5.6. Divide the specimens by random selection into test groups appropriate for the testing scheme. Place the appropriate numbers of groups in each of the ovens at the required temperature.

NOTE Attention should be given to the recommendation in Annex D (NOTE 2) to prepare extra groups of specimens should the thermal endurance characteristics of the material be unsuited to the basic recommendation of Annex D.

As outlined in Annex D (NOTE 2), it is recommended to prepare extra groups of specimens should the thermal endurance characteristics of the EIM be unsuited to the basic recommendation of Annex D.

After each ageing time, select at random one group from each of the appropriate ageing ovens and remove it from the oven. Allow to cool to room temperature unless otherwise specified. If specified, condition for the specified time in the specified atmosphere, and test the specimens by the specified test procedure.

It is recommended to carry out calculations as data become available, particularly for the shortest exposure time.

Evaluate the results as specified in accordance with Clause 6.

6 Calculation procedures

6.1 General principles

6.1.1 Thermal endurance calculation

The general calculation procedures and instructions given in 6.4 are based on the principles set out in IEC 60493-1, modified as follows ~~(see 3.7.1 of IEC 60493-1:1974)~~:

- The relation between the mean of the reciprocals (x) of the thermodynamic (absolute) temperatures at which the specified end-point is reached and the logarithm (y) of the ageing time is linear.
- The values of the deviations of the values of x from the linear relation are normally distributed with a variance which is independent of the ageing time.

The data used in the general calculation procedures are obtained from the experimental data by a preliminary calculation. Calculation data comprise values of z , y , n and k , where

$z_{ij} = 1 / (a_{ij} + a_0)$	= reciprocal of thermodynamic value in K of ageing temperature a_{ij} in °C;
$y_i = \log \tau_i$	= logarithm of value of ageing time in h (τ_i);
n_i	= number of z values in group number i aged for time τ_i ;
k	= number of ageing times or groups of x values.

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

6.1.2 Property value – equivalent temperature transform

(Calculation of hypothetical ageing temperature derived from the value of a property)

When destructive test criteria are employed, each test specimen is destroyed in obtaining a property value; for this reason, time and/or temperature values necessary to reach end-point cannot be directly measured. To enable estimates of the times to end-point to be obtained, the following assumptions are made that in the vicinity of the end-point (for one ageing time):

- the relation between the mean property values and the reciprocals of the thermodynamic temperatures is approximately linear;
- 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 temperature;
- the curves of property versus reciprocal of the ageing (thermodynamic) temperature for the individual test specimens are straight lines parallel to the line representing the relation of a) above.

For application of these assumptions, an ageing curve is drawn of the data obtained at each of the ageing times. The curve for each ageing time is obtained by plotting the mean value of property for each specimen group against the reciprocal of its ageing temperature (thermodynamic). If possible, ageing is conducted at sufficiently high and low ageing temperatures that at least one group mean is above and at least one below the end-point level. An approximately linear region of this curve is drawn (including at least three group means) in the vicinity of the end-point (Figure E.1).

NOTE A non-linear temperature scale graduated in °C is usually employed as the abscissa axis (see Figure E.1).

A statistical test (F -test) is carried out to decide whether deviations from linearity of the selected region are acceptable (see 6.3.3). 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 value of x for that specimen is then the value of the reciprocal of the (thermodynamic) temperature corresponding to the intersection of the line with the end-point line (Figure E.1).

With ~~some~~ the limitations of 6.3.5, 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 6.3.4 and 6.3.5.

6.2 Precision of calculations

Many of the calculation steps involve summing of the differences of numbers or the squares of these differences, where the differences ~~may~~ can be small by comparison with the numbers. In these circumstances, it is necessary that the calculations be made with an internal precision of at least six significant digits, and preferably more, if precision of three digits is to be achieved in the result. In view of the repetitive and tedious nature of the calculations, it is strongly recommended that they be performed using a programmable calculator or ~~micro~~computer, in which case internal precision of ten or more digits is easily available.

6.3 Derivation of temperatures equivalent to property values

6.3.1 General

Within the groups of specimens aged for each time τ_i , carry out the procedures ~~described~~ in accordance with 6.3.2 to 6.3.4.

6.3.2 Preliminary calculations

Calculate the value of y corresponding to each ageing time τ

$$y_i = \log \tau_i \quad (1)$$

Calculate the value of z corresponding to each ageing temperature ϑ

$$z_{ij} = 1/(\vartheta_{ij} + \Theta_0) \quad (2)$$

6.3.3 Regression calculations (property on temperature)

Calculate the mean property value for the data group obtained at each ageing temperature [see Equation (3)] and the corresponding value of z . Plot these values on a graph with the property value p as ordinate and z as abscissa (see Figure E.1).

Fit by visual means a smooth curve through the mean property points.

Select a temperature range within which the curve so fitted is approximately linear (see 6.3.4). Ensure that this temperature range includes at least three mean property values with at least one point on each side of the end-point line $p = p_e$. If this is not the case, and further measurements at higher temperatures cannot be made (for example, because no specimens remain), a small extrapolation is permitted, subject to the conditions of 6.3.4.

The index i is omitted from the expressions in 6.3.3 and 6.3.4 in order to avoid confusing multiple index combinations in print. The calculations of these subclauses shall be carried out separately on the data from each ageing time.

Let the number of selected mean values (and corresponding value groups) be r , the reciprocals of the individual ageing temperatures be z_g and the individual property values be p_{gh} , where

$g = 1 \dots r$ is the order number of the selected group aged at temperature ϑ_g ;

$h = 1 \dots n_g$ is the order number of the property value within group number g ;

n_g is the number of property values in group number g .

NOTE In most cases the numbers n_g of specimens tested at all test temperatures are identical, but this is not a necessary condition, and the calculation can be carried out with different values of n_g for different groups.

Calculate the mean value $\bar{p}_g$ and the variance s_{1g}^2 for each selected property value group.

$$\bar{p}_g = \sum_{h=1}^{n_g} p_{gh} / n_g \quad (3)$$

$$s_{1g}^2 = \left(\sum_{h=1}^{n_g} p_{gh}^2 - n_g \bar{p}_g^2 \right) / (n_g - 1) \quad (4)$$

Make the following calculations:

$$\nu = \sum_{g=1}^r n_g \quad (5)$$

$$\bar{z} = \sum_{g=1}^r z_g n_g / \nu \quad (6)$$

$$\bar{p} = \sum \bar{p}_g n_g / \nu \quad (7)$$

Calculate the coefficients of the regression equation, $p = a_p + b_p z$

$$a_p = \bar{p} - b_p \bar{z} \quad (8)$$

$$b_p = \frac{\left(\sum_{g=1}^r n_g z_g \bar{p}_g - \nu \bar{z} \bar{p} \right)}{\left(\sum_{g=1}^r n_g z_g^2 - \nu \bar{z}^2 \right)} \quad (9)$$

Calculate the pooled variance within the property groups

$$s_1^2 = \sum_{g=1}^r (n_g - 1) s_{1g}^2 / (\nu - r) \quad (10)$$

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

$$s_2^2 = \sum n_g (\bar{p}_g - \hat{p}_g)^2 / (r - 2) \quad (11)$$

where

$$\hat{p}_g = a_p + b_p z_g \quad (12)$$

This may also be expressed as

$$s_2^2 = \left[\left(\sum_{g=1}^r n_g \bar{p}_g^2 - \nu \bar{p}^2 \right) - b_p \left(\sum_{g=1}^r n_g z_g \bar{p}_g - \nu \bar{z} \bar{p} \right) \right] / (r - 2) \quad (13)$$

6.3.4 Linearity test

Make the F -test for non-linearity at significance level 0,05 by calculating

$$F = s_2^2 / s_1^2 \quad (14)$$

If the calculated value of F exceeds the tabulated value F_1 with $f_n = r - 2$ and $f_d = \nu - r$ degrees of freedom (see Table C.3), change the selection in 6.3.3 and repeat the calculations.

If it is not possible to satisfy the F -test on the significance level 0,05 with $r \geq 3$, make the F -test at a significance level 0,005 by comparing the calculated value of F with the tabulated value F_2 with $f_n = r - 2$ and $f_d = \nu - r$ degrees of freedom (see Table C.4).

If the test is satisfied at this level, the calculations may be continued, but the adjustment of TI according to 7.2.2, Equation (48) is not permitted.

If the F -test on significance level 0,005 (i.e. $F \leq F_2$) cannot be satisfied, or the property points plotted in 6.3.3 are all on the same side of the end-point line, an extrapolation may be permitted, subject to the following condition:

If the F -test on significance level 0,05 can be met for a range of values (with $r \geq 3$) where all mean values $\bar{p}_g$ are on the same side of the end-point value p_e , an extrapolation may be made provided that the absolute value of the difference between the end-point value p_e and the mean value $\bar{p}_g$ closest to the end-point (usually $\bar{p}_r$) is less than one quarter of the absolute value of the difference $(\bar{p}_1 - \bar{p}_r)$.

NOTE—In Figure E.1, if p_e were 5 000, the calculation would be as follows:

$\bar{p}_1$ is the value of the mean of the leftmost data group in the selection box, $\bar{p}_r$ of the rightmost data group. The condition is then $|\bar{p}_r - p_e| \leq |\bar{p}_1 - \bar{p}_r| / 4$. The enclosing vertical lines imply the absolute value of the content.

In this case calculations can be continued, but again it is not permitted to carry out the adjustment of TI according to 7.2.2, Equation (48).

6.3.5 Estimation of end-point temperatures equivalent to property values

For each of the h values of property in each of the g selected groups, calculate the equivalent reciprocal end-point temperature:

$$x_{ij} = z_g - \frac{(p_{gh} - p_e)}{b_p} \quad (15)$$

and
$$n_i = \nu \quad (16)$$

where

$j = 1 \dots n_i$ is the order number of the x -value in the group of estimated x -values at ageing time τ_i and z_g is the reciprocal of the ageing temperature;

the n_i values of x_{ij} are reciprocal end-point temperature values to be used in the calculations of 6.4.

6.4 Regression analysis (temperature on time)

6.4.1 General

NOTE—Where the determination is part of the determination of ~~RTE~~ RTI (see Clause 3) the results from some equations will be required as input data for both ~~control~~ reference and candidate materials EIMs. ~~If the calculations are made by computer program, a subroutine to save them to a data file will be useful.~~

Results from Equations (19), (20), (21), (23), (25), (26), (33) or (34) and (46) will be required. In addition, the value of the logarithm of the longest ageing time will be required to complete the input data.

6.4.2 Group means and variances

Calculate the mean and variance of the group of x -values, x_{ij} , obtained at each ageing time τ_i :

$$\bar{x}_i = \sum_{j=1}^{n_i} x_{ij} / n_i \quad (17)$$

$$s_{1i}^2 = \left(\sum_{j=1}^{n_i} x_{ij}^2 - n_i \bar{x}_i^2 \right) / (n_i - 1) \quad (18)$$

6.4.3 General means and variances

Calculate the total number of x_{ij} values, N , the weighted mean value of x , $(\bar{x})$, and the weighted mean value of y , $(\bar{y})$:

$$N = \sum_{i=1}^k n_i \quad (19)$$

$$\bar{x} = \sum n_i \bar{x}_i / N \quad (20)$$

$$\bar{y} = \sum n_i y_i / N \quad (21)$$

Calculate the pooled variance within the data groups:

$$s_1^2 = \sum_{i=1}^k (n_i - 1) s_{1i}^2 / (N - k) \quad (22)$$

Calculate the second central moment of the y values:

$$\mu_2(y) = \frac{\left(\sum_{i=1}^k n_i y_i^2 - N \bar{y}^2 \right)}{N} \quad (23)$$

6.4.4 Regression

In the expression for the regression line:

$$x = a + by \quad (24)$$

Calculate the slope:

$$b = \frac{\left(\sum_{i=1}^k n_i \bar{x}_i y_i - N \bar{x} \bar{y} \right)}{\left(\sum_{i=1}^k n_i y_i^2 - N \bar{y}^2 \right)} \quad (25)$$

the intercept on the y -axis

$$a = \bar{x} - b \bar{y} \quad (26)$$

and the square of the correlation coefficient:

$$r^2 = \frac{\left(\sum_{i=1}^k n_i \bar{x}_i y_i - N \bar{x} \bar{y} \right)^2}{\left(\sum_{i=1}^k n_i \bar{x}_i^2 - N \bar{x}^2 \right) \left(\sum_{i=1}^k n_i y_i^2 - N \bar{y}^2 \right)} \quad (27)$$

Calculate the variance of the deviations of the x -means from the regression line:

$$s_2^2 = \sum_{i=1}^k \frac{n_i (\bar{x}_i - \hat{X}_i)^2}{(k-2)} \quad , \quad \hat{X}_i = a + b y_i \quad (28)$$

or

$$s_2^2 = \frac{(1-r^2)}{(k-2)} \left(\sum_{i=1}^k n_i \bar{x}_i^2 - N \bar{x}^2 \right) \quad (29)$$

6.5 Statistical tests

6.5.1 Variance equality test

Calculate the value of Bartlett's χ^2 function:

$$\chi^2 = \frac{\ln q}{c} \left[(N-k) \log_q s_1^2 - \sum_{i=1}^k (n_i - 1) \log_q s_i^2 \right] \quad (30)$$

where

$$c = 1 + \frac{\left(\sum_{i=1}^k \frac{1}{(n_i - 1)} - \frac{1}{(N - k)} \right)}{3(k - 1)} \quad (31)$$

q is the base of the logarithms used in this Equation (30). It ~~need~~ does not have to be the same as that used in the calculations elsewhere in this clause.

If q = 10, ln q = 2,303; if q = e, ln q = 1.

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

If the value of χ^2 is greater than the value 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.

6.5.2 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 groups of measurements s_1^2 by the F -test at a significance level of 0,05.

Calculate the ratio

$$F = s_2^2 / s_1^2 \quad (32)$$

and compare its value with the tabulated value $F_0 = F(0,95, k-2, N-k)$ with $f_n = k-2$ and $f_d = N-k$ degrees of freedom (Table C.3).

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

$$s^2 = \frac{(N-k)s_1^2 + (k-2)s_2^2}{(N-2)} \quad (33)$$

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

$$s_a^2 = \frac{(N-k)(s_1^2)_a + (k-2)s_2^2}{(N-2)} \quad (34)$$

6.5.3 Estimates of x and y and their confidence limits

Obtain the tabulated value of Student's t with $N-2$ degrees of freedom at a confidence level of 0,95, $t_{0,95, N-2}$ (Table C.2).

a) X -estimates

Calculate the Y -value corresponding to the time, τ , at which the estimate is required:

Calculate the estimated value of X corresponding to the given Y , and its upper 95 % confidence limit $\hat{X}_c$:

$$\hat{X}_c = \hat{X} + t s_x \quad ; \quad \hat{X} = a - bY \quad ; \quad t = t_{0,95, N-2} \quad (35)$$

$$s_x^2 = \frac{s^2}{N} \left[1 + \frac{(Y - \bar{y})^2}{\mu_2(y)} \right] \quad (36)$$

where $Y = \log \tau$ (37)

Calculate the temperatures corresponding to the values of $\hat{X}$ and $\hat{X}_c$:

$$\vartheta = \frac{1}{X} - \theta_0 \quad (38)$$

For the confidence limit curve of the thermal endurance graph (see 6.6), $\hat{X}_c$ is calculated for several values of Y over the range of interest, and a smooth curve drawn through the points $(\hat{X}_c, Y)$ plotted on the graph.

If $F > F_0$ the value of s^2 shall be replaced by s_a^2 (Equation 34).

b) Y -estimates

Calculate the value of $\hat{Y}$ and its lower 95 % confidence limit, corresponding to an end-point temperature ϑ_f

$$\hat{Y}_c = \bar{y} + \frac{(X - \bar{x})}{b_r} - \frac{t s_r}{b_r} \quad , \quad t = t_{0,95, N-2} \quad (39)$$

$$X = 1/(\vartheta_f + \theta_0) \quad : \quad \hat{Y} = (X - a)/b \quad (40)$$

$$b_r = b - \frac{t^2 s^2}{N b \mu_2(y)} \quad (41)$$

$$s_r^2 = \frac{s^2}{N} \left(\frac{b_r}{b} + \frac{(\hat{Y} - \bar{y})^2}{\mu_2(y)} \right) \quad (42)$$

The time estimate and its lower 95 % confidence limit shall be calculated from the corresponding Y estimate and its lower confidence limit:

$$\tau = q^{\hat{Y}} \quad , \quad \tau_c = q^{\hat{Y}_c} \quad (43)$$

where q is the base of the logarithms used in the calculations (see Note in 6.1.1).

6.6 Thermal endurance graph

When the regression line has been established, it is drawn on the thermal endurance graph, i.e. a graph with $y = \log(\tau)$ as ordinate and $x = 1/(\vartheta + \theta_0)$ as abscissa. Usually, x is plotted as increasing from right to left and the corresponding values of ϑ in degrees Celsius (°C) are marked on this axis (see Figure E.2). Special graph paper is obtainable for this purpose.

Alternatively, a computer program executing this calculation ~~may~~ **should** include a subroutine to plot the graph on the appropriate non-linear scale.

The individual values x_{ij} and the mean values $\bar{x}_i$ obtained as in 6.4.2 are plotted on the graph at the corresponding values of y_i :

$$y_i = \log \tau_i \quad (44)$$

The thermal endurance graph may be completed by drawing the lower 95 % confidence curve (see 6.5.3).

7 Calculation and requirements for results

7.1 Calculation of thermal endurance characteristics

Using the regression equation

$$y = (x - a) / b \quad (45)$$

(the coefficients a and b being calculated according to 6.4.4), calculate the temperature in degrees Celsius (°C) corresponding to a time to end-point of 20 kh, TI_{20} . The numerical value of this temperature is the temperature index, TI.

Calculate by the same method the numerical value of the temperature corresponding to a time to end-point of 10 kh, TI_{10} . The halving interval HIC is:

$$HIC = TI_{10} - TI_{20} \quad (46)$$

Calculate by the method of 6.5.3 a), with $Y = \log 20\,000$, the lower 95 % confidence limit of TI: TC or TC_a if the adjusted value s_a^2 is used.

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

Plot the thermal endurance graph (see 6.6).

7.2 Reporting of results

7.2.1 Summary of statistical tests and reporting

In Annex B, if the condition in the column headed "Test" is not met, the action is as indicated in the final column. If the condition is met, the action is as indicated at the next step. The same sequence is indicated in the decision flow chart for thermal endurance calculations, (see Annex A).

7.2.2 Report format

If the value of $(TI - TC)/HIC$ is $\leq 0,6$, the test result shall be reported in the format

$$TI \text{ (HIC): } xxx \text{ (xx,x)} \quad (47)$$

in accordance with 6.8 of IEC 60216-1:2013.

If $0,6 < (TI - TC)/HIC \leq 1,6$ and at the same time, $F \leq F_0$ (see 6.3.2), the value

$$TI_a = TC + 0,6 \text{ HIC} \quad (48)$$

together with HIC shall be reported as TI (HIC): xxx (xx,x).

In all other cases the result shall be reported in the format

$$TI_g = \dots, \quad HIC_g = \dots \quad (49)$$

If a time different from 20 000 h has been used for deriving the TI, the relevant time expressed in kh shall be stated, followed by "kh". The format of the TI is then:

$$TI \text{ xx kh (HIC): } xxx \text{ (xx,x)} \quad (50)$$

and correspondingly for TI_a and TI_g .

8 Report

The test report shall include:

- a description of the tested ~~material~~ EIM including dimensions and any conditioning of the specimens;
- the property investigated, the chosen end-point, and, if it was required to be determined, the initial value of the property;
- the test method used for determination of the property (for example by reference to an IEC publication);
- any relevant information on the test procedure, for example ageing environment;
- the individual test times, the ageing temperatures and individual property values, with the graphs of variation of property with ageing temperature;
- the thermal endurance graph;
- the temperature index and halving interval reported in the format defined in 7.2.2;
- the value of χ^2 and P if required by 6.5.1.

9 RTE RTI determination

9.1 ~~Objectives of RTE determination~~

The objectives of the determination are in alignment with IEC 60216-5 as follows:

- To exploit an assumed relationship between thermal endurance (with an appropriate test criterion for ageing) and service performance, and to use this to predict a value for initial assessment of service temperature of a ~~material~~ EIM for which there is relatively little service experience (by comparison with a known ~~control material~~ reference EIM – see Clauses 11 and 12).

NOTE In the majority of cases, this will involve extrapolation to a longer time or lower temperature than is present in the experimental data. This extrapolation should be kept to a minimum by appropriate choice of ageing temperatures and times (see Clause D.2 and Figure E.5), since the uncertainty in the result increases rapidly as the extrapolation is increased. However, even when there is no extrapolation, there is still a non-zero uncertainty, on account of the variances of the experimental data and other experimental errors.

- To improve the precision of a thermal endurance determination by reduction of systematic errors in the ageing process. If after ageing, the results for the ~~control material~~ reference EIM are found to be significantly different from earlier experience, this ~~may~~ can indicate changes in material or equipment. This may be investigated and possibly corrected. In any case, the simultaneous ageing of ~~control~~ reference and candidate will at least partially compensate for systematic changes. Statistical procedures for use in assessing the significance of changes are outlined in Annex F.

10 Additional symbols

These symbols are additional to those of 3.2 and ~~are relevant only to Clauses 11 to 13~~ used only in Clauses 12 to 13.

Symbol	Description	Subclause
A	Subscript indicating ~~control material~~ reference EIM	
~~ATE~~ ATI	Known thermal endurance characteristic of ~~control material~~ reference EIM	12.3
B	Subscript indicating candidate ~~material~~ EIM	
HIC _{B(c)}	Halving interval of candidate ~~material~~ EIM at correlation time	13.1

N_D	Total number of values in combined data of candidate and ~~control materials~~ reference EIMs	12.4
~~RTE~~ RTI	Estimated thermal endurance characteristic of candidate ~~material~~ EIM (temperature index at correlation time)	12.3
s_D^2	Variance of combined data of candidate and reference EIMs	12.4
s_D	Standard error of ~~RTE~~ RTI (square root of s_D^2)	12.4
x_A	Reciprocal thermodynamic temperature of ~~ATE~~ ATI	12.3
x_B	Reciprocal thermodynamic temperature of ~~RTE~~ RTI	12.3
$X_{c(B)}$	Confidence limit of x_B	12.4
Y_c	Logarithm of correlation time	12.3
τ_c	Correlation time (time corresponding to ~~ATE~~ ATI of ~~control material~~ reference EIM)	12.3
τ_k	Longest ageing time	12.5
ϑ_{RTI}	Value of ~~RTE~~ RTI in degrees Celsius	12.3
$\vartheta_{c(B)}$	Confidence limit of ~~RTE~~ RTI (upper or lower)	12.4
ϑ_c	Lower confidence limit of ~~RTE~~ RTI	12.4
Δ_R	Lower confidence interval of ~~RTE~~ RTI	12.4

11 Experimental procedures

11.1 Selection of ~~control material~~ reference EIM

The primary requirement for the ~~control material~~ reference EIM is that the value of ~~ATE~~ ATI for the application under consideration is known. The ~~ATE~~ ATI, if determined by a thermal endurance procedure, shall be supported by actual service experience. The basis of the ~~ATE~~ ATI shall be reported.

The expected ageing mechanisms and rates of both ~~materials~~ EIMs shall be similar and relevant to the application.

11.2 Selection of diagnostic test for extent of ageing

The diagnostic test shall be one considered relevant to the application for which the ~~RTE~~ RTI is required. The same test and end-point shall be applied to both ~~control~~ reference and candidate ~~material~~ EIM.

11.3 Ageing procedures

The number and type of test specimens and the ageing times and temperatures for both ~~materials~~ EIMs shall be ~~as specified~~ in accordance with Clause 5. If employing the recommendations of Annex D, the lowest ageing temperature should be the lower of the expected TI values for the two ~~materials~~ EIMs.

At each ageing temperature, the oven load shall comprise appropriate numbers of specimens of both ~~materials~~ EIMs. The specimens shall be distributed in the oven so that there is likely to be no systematic difference between the conditions applied to the specimens of the two ~~materials~~ EIMs.

12 Calculation procedures

12.1 General principles

The basis of the calculations is to calculate the thermal endurance characteristics of both ~~materials~~ EIMs (see 6.1.1 and 9 a)).

From the thermal endurance data obtained for the ~~control material~~ reference EIM, the time is calculated at which the temperature index is equal to its known temperature characteristic (this is the time referred to as the "correlation time"). From the thermal endurance data obtained for the candidate ~~material~~ EIM, the temperature index is calculated at the correlation time. This value is the desired ~~RTE~~ RTI.

The confidence intervals associated with this result are calculated by standard statistical procedures.

12.2 Input data

For both ~~materials~~ EIMs, ~~control~~ reference and candidate, the following intermediate data values are required from the calculations of TI (see 6.4).

Table 1 – Intermediate data values

Intermediate value	Symbol	Equation
Slope of regression line relative to y-axis	b	(25)
Intercept of regression line on x-axis	a	(26)
Weighted mean of y-values	$\bar{y}$	(21)
Central 2nd moment of y-values	$\mu_2(y)$	(23)
Weighted mean of data x-values	$\bar{x}$	(20)
Pooled total variance of data x-values	s^2	(33) or (34)
Number of x-values	N	(19)
Halving interval	HIC	(46)
Longest ageing time	τ_k	

12.3 ~~RTE~~ RTI

Calculate the reciprocal thermodynamic temperature of ~~ATE~~ ATI:

$$x_A = \frac{1}{(ATI + \theta_0)} \quad (51)$$

Calculate the correlation time τ_c and Y_c , its logarithm:

$$Y_c = \frac{(x_A - a_A)}{b_A} \quad \tau_c = q^{Y_c} \quad (52)$$

where q is the base of logarithms used in the calculations (see Note in 6.1.1).

Calculate the estimate of x at the correlation time for the candidate ~~material~~ EIM:

$$x_B = a_B + Y_c b_B \quad (53)$$

The value of ~~RTE~~ RTI is:

$$g_{RTI} = \frac{1}{x_B} - \Theta_0 \quad (54)$$

12.4 Confidence limits

Calculate the estimate of x at the correlation time for the ~~control material~~ reference EIM:

$$x_A = a_A + Y_c b_A \quad (55)$$

NOTE Numerically, x_A is equal to X_A . However, the latter is a scalar (i.e. non-variable) quantity while the former is random and normally distributed. The variance of the estimate of ~~RTE~~ RTI is determined by the variance of the difference of x_A and x_B .

Calculate the variance of x_A :

$$s_A^2 = \left[s^2 \left(1 + \frac{(Y_c - \bar{y})^2}{\mu_{2(y)}} \right) \right]_A \quad (56)$$

Similarly, calculate the variance of x_B :

$$s_B^2 = \left[s^2 \left(1 + \frac{(Y_c - \bar{y})^2}{\mu_{2(y)}} \right) \right]_B \quad (57)$$

Calculate the value of the variance ratio, F :

$$F = \frac{s_B^2}{s_A^2} \text{ if } s_B^2 > s_A^2, \text{ otherwise } F = \frac{s_A^2}{s_B^2} \quad (58)$$

If the value of F is less than the value in Table C.3 for $f_n = N_A - 2$ and $f_d = N_B - 2$ degrees of freedom, then the variances are not considered significantly different. In this case, merge the variances, using Equations (58) and (59), otherwise using Equations (60) and (61).

Statistically equal variances:

$$s_D^2 = \frac{s_A^2 (N_A - 2) + s_B^2 (N_B - 2)}{(N_A + N_B - 4)} \left(\frac{1}{N_A} + \frac{1}{N_B} \right) \quad (59)$$

$$N_D = (N_A + N_B - 4) \quad (60)$$

Statistically unequal variances:

$$s_D^2 = \frac{s_A^2}{N_A} + \frac{s_B^2}{N_B} \quad (61)$$

$$N_D = \frac{(s_D^2)^2}{\frac{\left(\frac{s_A^2}{N_A}\right)^2}{N_A - 2} + \frac{\left(\frac{s_B^2}{N_B}\right)^2}{N_B - 2}} \quad (62)$$

If, in the second case, N_D is not integral, round its value to the nearest integer.

Calculate the confidence limits of X_B :

$$X_{c(B)} = X_B \pm t_{(N_D)} s_D \quad (63)$$

where $t_{(N_D)}$ is the value of t in Table C.2 for N_D degrees of freedom.

The confidence limits of ~~RTE~~ RTI are:

$$g_{c(B)} = \frac{1}{X_B \pm t_{(N_D)} s_D} - \theta_0 \quad (64)$$

Normally, the lower confidence limit of ~~RTE~~ RTI, g_{lc} is required, corresponding to the upper confidence limit of X_B .

The lower confidence interval Δ_R shall be calculated by Equation (64):

$$\Delta_R = g_{RTI} - g_{lc} \quad (65)$$

12.5 Extrapolation

Calculate the extrapolation as the ratio $\frac{\tau_c}{\tau_k}$.

13 Results and report

13.1 Results of statistical and numerical tests

The following criteria apply.

- Linearity of thermal endurance relationship (see 6.3.2 and 6.3.3 of IEC 60216-3:2021). Both ~~control~~ reference and candidate EIM data shall satisfy the requirements ~~of IEC 60216-3~~.
- Extrapolation to the correlation time (see 12.5). The extrapolation, expressed as the ratio of correlation time to greatest ageing time, shall be less than 4.
- Lower confidence interval of ~~RTE~~ RTI (see 12.4). The value of Δ_R shall be less than the halving interval ($HIC_{B(c)}$) of the candidate ~~material~~ EIM at a time equal to the correlation time (see 7.1 of IEC 60216-3:2021).

$$HIC_{B(c)} = b_B \left[\frac{1}{(\ln(\tau_c / 2) - a_B)} - \frac{1}{(\ln \tau_c - a_B)} \right] \quad (66)$$

13.2 Result

The result shall be determined from the calculations of 12.4 and 12.5 and expressed as follows:

- If all three test criteria (see 13.1) are satisfied, the result shall be the value of ~~RTE~~ RTI. The result shall be reported in the format "~~RTE~~ RTI according to IEC 60216-6 = xxx"
- If one of the test criteria is not satisfied, the result shall be the lower 95 % confidence limit of ~~RTE~~ RTI. The result shall be reported in the format "~~RTE according to IEC 60216-6 = xxx~~" "RTI lower 95 % confidence limit = xxx"
- If two or more of the criteria are not satisfied, a result in accordance with the requirements of IEC 60216-6 cannot be reported. The result may be reported in the format "~~RTE~~ RTI = xxx. (Result not validated by the statistical analysis)"

13.3 Report

The report shall comprise the following:

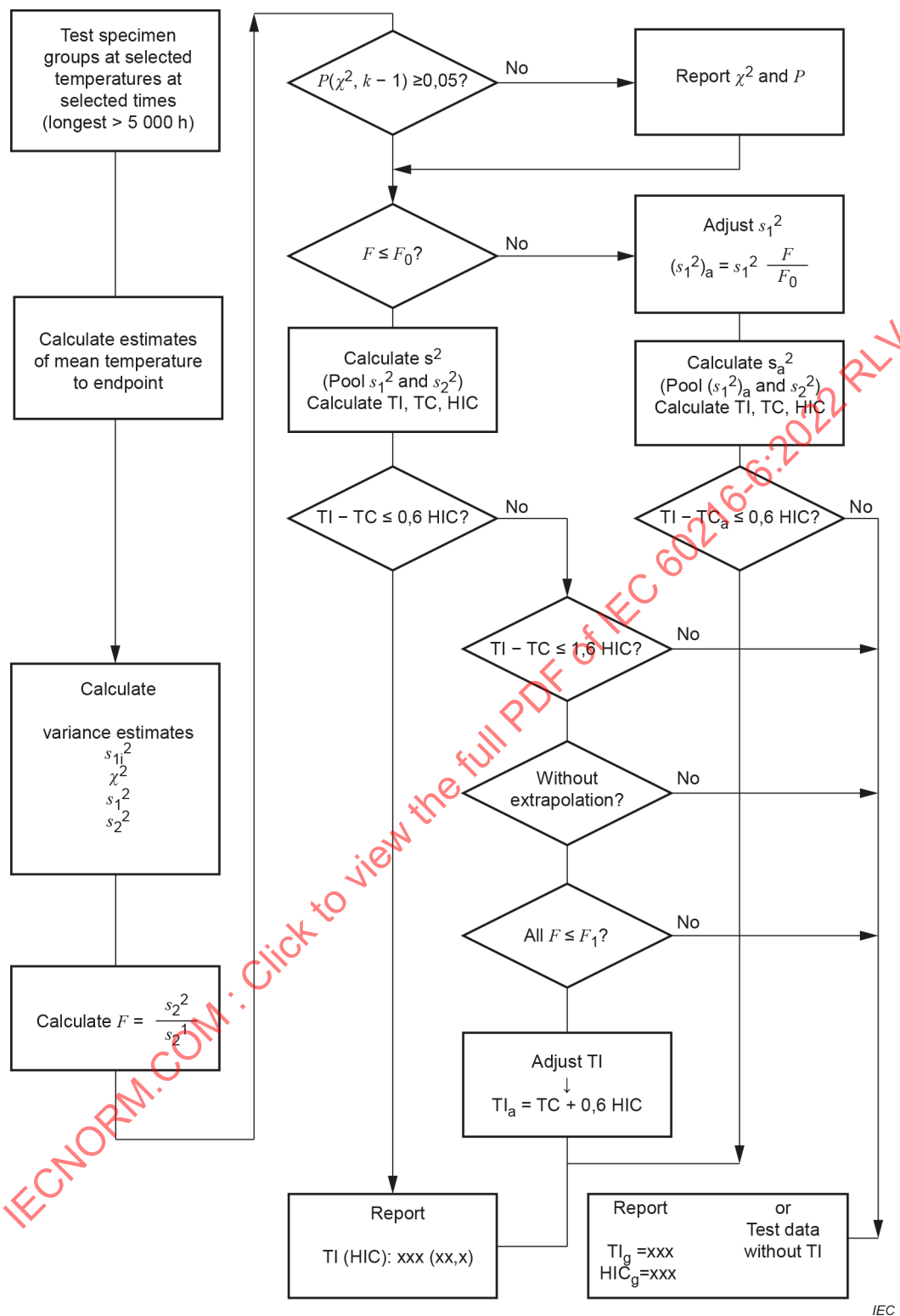
- the result;
- the identification of the ~~control material~~ reference EIM, its ~~ATE~~ ATI and the basis of the ~~ATE~~ ATI;
- the diagnostic test employed and the end-point;
- the thermal endurance reports according to IEC 60216-1 for the ~~control~~ reference and candidate ~~materials~~ EIMs;
- for a result in category 13.2 c) above, the details of the failure of statistical validation.

Annex A (normative)

Decision flow chart

If the time to end-point used to calculate the thermal endurance indices is other than 20 000 h (see 3.1.11), the value of 5 000 h in Annex A and Annex B shall be replaced by one quarter of the time used.

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Figure A.1 – Decision flow chart

Annex B (normative)

Decision table

Table B.1 – Decision table

Step	Test (?) or action	Reference	Action if NO in test
1	Test specimen groups at selected temperatures for selected times (longest > 5 000 h)	5.2	
2	Calculate estimates of mean temperature to endpoint	6.4.2	
3	Calculate estimates of variances s_{1i}^2 Calculate χ^2 Calculate s_1^2 Calculate s_2^2	6.3, 6.4.2 Equation 18 6.5.1 6.4.3 6.4.4	
4	Calculate F	6.5.2	
5	? $P(\chi^2, k-1) \geq 0,05$	6.5.1	Report χ^2 and P : Go to step 6
6	? $F \leq F_0$	6.5.2	Go to step 14
7	Calculate s^2 : (Pool s_1^2 and s_2^2) Calculate TI, TC, HIC	6.5.2 a)	
8	? $TI - TC \leq 0,6 \text{ HIC}$	7.2.2	Go to step 10
9	Report TI (HIC): ... (..)	7.2.2	
10	? $TI - TC \leq 1,6 \text{ HIC}$	7.2.2	Go to step 18
11	? Were data processed without extrapolation	6.3.4	Go to step 18
12	? Were all values of $F \leq F_1$	6.3.3	Go to step 18
13	Report $TI_a = TC + 0,6 \text{ HIC}$ as TI (HIC): ... (..)	7.2.2	
14	Adjust s_1^2 : $(s_1^2)_a = s_1^2 \frac{F}{F_0}$	6.5.2	
15	Calculate s^2 : (Pool $(s_1^2)_a$ and s_2^2) Calculate TI, TC_a , HIC	6.5.2	
16	? $TI - TC_a \leq 0,6 \text{ HIC}$	7.2.2	Go to step 18
17	Report TI (HIC): ... (..)	7.2.2	
18	Report $TI_g = \dots$, $HIC_g = \dots$, or test data without TI	7.2.2	

If the time to end-point used to calculate the thermal endurance indices is other than 20 000 h (see 3.1.11), the value of 5 000 h in Annex A and Annex B shall be replaced by one quarter of the time used.

Annex C (informative)

Statistical tables

Table C.1 presents the values of χ^2 for significance levels (P) of 0,05, 0,01 and 0,005.

Table C.1 – χ^2 -function

Degrees of freedom	$P = 0,05$	$P = 0,01$	$P = 0,005$
1	3,8	6,6	7,9
2	6,0	9,2	10,6
3	7,8	11,3	12,8
4	9,5	13,3	14,9
5	11,1	15,1	16,7
6	12,6	16,8	18,5

Table C.2 gives the values of Student's t for significance levels (P) of 0,05 and 0,005.

The columns of the table represent the number (ν) of degrees of freedom and the rows the significance level (P).

Table C.2 – t -function

	10	11	12	13	14	15	16	17	18
$P = 0,05$	1,812	1,796	1,782	1,771	1,761	1,753	1,746	1,740	1,734
$P = 0,005$	3,169	3,106	3,055	3,012	2,977	2,947	2,921	2,898	2,878

	19	20	25	30	40	50	100	500
$P = 0,05$	1,729	1,725	1,708	1,697	1,684	1,676	1,660	1,648
$P = 0,005$	2,861	2,845	2,787	2,750	2,704	2,678	2,626	2,586

Table C.3 gives the values of F for significance level 0,05.

The columns of Table C.3 and Table C.4 represent the number of degrees of freedom of the numerator (f_n) and the rows the number of degrees of freedom of the denominator (f_d).

Table C.3 – *F*-function, $P = 0,05$

	1	2	3	4	5	6	7	8	9
10	4,965	4,103	3,708	3,478	3,326	3,217	3,135	3,072	3,020
11	4,844	3,982	3,587	3,357	3,204	3,095	3,012	2,948	2,896
12	4,747	3,885	3,490	3,259	3,106	2,996	2,913	2,849	2,796
13	4,667	3,806	3,411	3,179	3,025	2,915	2,832	2,767	2,714
14	4,600	3,739	3,344	3,112	2,958	2,848	2,764	2,699	2,646
15	4,543	3,682	3,287	3,056	2,901	2,790	2,707	2,641	2,588
16	4,494	3,634	3,239	3,007	2,852	2,741	2,657	2,591	2,538
17	4,451	3,592	3,197	2,965	2,810	2,699	2,614	2,548	2,494
18	4,414	3,555	3,160	2,928	2,773	2,661	2,577	2,510	2,456
19	4,381	3,522	3,127	2,895	2,740	2,628	2,544	2,477	2,423
20	4,351	3,493	3,098	2,866	2,711	2,599	2,514	2,447	2,393
25	4,242	3,385	2,991	2,759	2,603	2,490	2,405	2,337	2,282
30	4,171	3,316	2,922	2,690	2,534	2,421	2,334	2,266	2,211
40	4,085	3,232	2,839	2,606	2,449	2,336	2,249	2,180	2,124
50	4,034	3,183	2,790	2,557	2,400	2,286	2,199	2,130	2,073
100	3,936	3,087	2,696	2,463	2,305	2,191	2,103	2,032	1,975
500	3,86	3,014	2,623	2,39	2,232	2,117	2,028	1,957	1,899

	10	11	12	13	14	15	16	17	18
10	2,978	2,943	2,913	2,887	2,865	2,845	2,828	2,812	2,798
11	2,854	2,818	2,788	2,761	2,739	2,719	2,701	2,685	2,671
12	2,753	2,717	2,687	2,660	2,637	2,617	2,599	2,583	2,568
13	2,671	2,635	2,604	2,577	2,554	2,533	2,515	2,499	2,484
14	2,602	2,565	2,534	2,507	2,484	2,463	2,445	2,428	2,413
15	2,544	2,507	2,475	2,448	2,424	2,403	2,385	2,368	2,353
16	2,494	2,456	2,425	2,397	2,373	2,352	2,333	2,317	2,302
17	2,450	2,413	2,381	2,353	2,329	2,308	2,289	2,272	2,257
18	2,412	2,374	2,342	2,314	2,290	2,269	2,250	2,233	2,217
19	2,378	2,340	2,308	2,280	2,256	2,234	2,215	2,198	2,182
20	2,348	2,310	2,278	2,250	2,225	2,203	2,184	2,167	2,151
25	2,236	2,198	2,165	2,136	2,111	2,089	2,069	2,051	2,035
30	2,165	2,126	2,092	2,063	2,037	2,015	1,995	1,976	1,960
40	2,077	2,038	2,003	1,974	1,948	1,924	1,904	1,885	1,868
50	2,026	1,986	1,952	1,921	1,895	1,871	1,850	1,831	1,814
100	1,927	1,886	1,850	1,819	1,792	1,768	1,746	1,726	1,708
500	1,850	1,808	1,772	1,740	1,712	1,686	1,664	1,643	1,625

	19	20	25	30	40	50	100	500
10	2,785	2,774	2,730	2,700	2,661	2,637	2,588	2,548
11	2,658	2,646	2,601	2,570	2,531	2,507	2,457	2,415
12	2,555	2,544	2,498	2,466	2,426	2,401	2,350	2,307
13	2,471	2,459	2,412	2,380	2,339	2,314	2,261	2,218
14	2,400	2,388	2,341	2,308	2,266	2,241	2,187	2,142

15	2,340	2,328	2,280	2,247	2,204	2,178	2,123	2,078
16	2,288	2,276	2,227	2,194	2,151	2,124	2,068	2,022
17	2,243	2,230	2,181	2,148	2,104	2,077	2,020	1,973
18	2,203	2,191	2,141	2,107	2,063	2,035	1,978	1,929
19	2,168	2,155	2,106	2,071	2,026	1,999	1,940	1,891
20	2,137	2,124	2,074	2,039	1,994	1,966	1,907	1,856
25	2,021	2,007	1,955	1,919	1,872	1,842	1,779	1,725
30	1,945	1,932	1,878	1,841	1,792	1,761	1,695	1,637
40	1,853	1,839	1,783	1,744	1,693	1,66	1,589	1,526
50	1,798	1,784	1,727	1,687	1,634	1,599	1,525	1,457
100	1,691	1,676	1,616	1,573	1,515	1,477	1,392	1,308
500	1,607	1,592	1,528	1,482	1,419	1,376	1,275	1,159

Table C.4 gives the values of F for significance level 0,005.

The columns of Table C.3 and Table C.4 represent the number of degrees of freedom of the numerator (f_n) and the rows the number of degrees of freedom of the denominator (f_d).

Table C.4 – F -function, $P = 0,005$

	1	2	3	4	5	6	7	8	9
10	12,826	9,427	8,081	7,343	6,872	6,545	6,302	6,116	5,968
11	12,226	8,912	7,600	6,881	6,422	6,102	5,865	5,682	5,537
12	11,754	8,510	7,226	6,521	6,071	5,757	5,525	5,345	5,202
13	11,374	8,186	6,926	6,233	5,791	5,482	5,253	5,076	4,935
14	11,060	7,922	6,680	5,998	5,562	5,257	5,031	4,857	4,717
15	10,798	7,701	6,476	5,803	5,372	5,071	4,847	4,674	4,536
16	10,575	7,514	6,303	5,638	5,212	4,913	4,692	4,521	4,384
17	10,384	7,354	6,156	5,497	5,075	4,779	4,559	4,389	4,254
18	10,218	7,215	6,028	5,375	4,956	4,663	4,445	4,276	4,141
19	10,073	7,093	5,916	5,268	4,853	4,561	4,345	4,177	4,043
20	9,944	6,986	5,818	5,174	4,762	4,472	4,257	4,090	3,956
25	9,475	6,598	5,462	4,835	4,433	4,150	3,939	3,776	3,645
30	9,180	6,355	5,239	4,623	4,228	3,949	3,742	3,580	3,450
40	8,828	6,066	4,976	4,374	3,986	3,713	3,509	3,350	3,222
50	8,626	5,902	4,826	4,232	3,849	3,579	3,376	3,219	3,092
100	8,241	5,589	4,542	3,963	3,589	3,325	3,127	2,972	2,847
500	7,950	5,355	4,330	3,763	3,396	3,137	2,941	2,789	2,665

	10	11	12	13	14	15	16	17	18
10	5,847	5,746	5,661	5,589	5,526	5,471	5,422	5,379	5,340
11	5,418	5,320	5,236	5,165	5,103	5,049	5,001	4,959	4,921
12	5,085	4,988	4,906	4,836	4,775	4,721	4,674	4,632	4,595
13	4,820	4,724	4,643	4,573	4,513	4,460	4,413	4,372	4,334
14	4,603	4,508	4,428	4,359	4,299	4,247	4,200	4,159	4,122
15	4,424	4,329	4,250	4,181	4,122	4,070	4,024	3,983	3,946
16	4,272	4,179	4,099	4,031	3,972	3,920	3,875	3,834	3,797
17	4,142	4,050	3,971	3,903	3,844	3,793	3,747	3,707	3,670
18	4,030	3,938	3,860	3,793	3,734	3,683	3,637	3,597	3,560
19	3,933	3,841	3,763	3,696	3,638	3,587	3,541	3,501	3,465

20	3,847	3,756	3,678	3,611	3,553	3,502	3,457	3,416	3,380
25	3,537	3,447	3,370	3,304	3,247	3,196	3,151	3,111	3,075
30	3,344	3,255	3,179	3,113	3,056	3,006	2,961	2,921	2,885
40	3,117	3,028	2,953	2,888	2,831	2,781	2,737	2,697	2,661
50	2,988	2,900	2,825	2,760	2,703	2,653	2,609	2,569	2,533
100	2,744	2,657	2,583	2,518	2,461	2,411	2,367	2,326	2,290
500	2,562	2,476	2,402	2,337	2,281	2,230	2,185	2,145	2,108

	19	20	25	30	40	50	100	500
10	5,305	5,274	5,153	5,071	4,966	4,902	4,772	4,666
11	4,886	4,855	4,736	4,654	4,551	4,488	4,359	4,252
12	4,561	4,530	4,412	4,331	4,228	4,165	4,037	3,931
13	4,301	4,270	4,153	4,073	3,970	3,908	3,780	3,674
14	4,089	4,059	3,942	3,862	3,760	3,698	3,569	3,463
15	3,913	3,883	3,766	3,687	3,585	3,523	3,394	3,287
16	3,764	3,734	3,618	3,539	3,437	3,375	3,246	3,139
17	3,637	3,607	3,492	3,412	3,311	3,248	3,119	3,012
18	3,527	3,498	3,382	3,303	3,201	3,139	3,009	2,901
19	3,432	3,402	3,287	3,208	3,106	3,043	2,913	2,804
20	3,347	3,318	3,203	3,123	3,022	2,959	2,828	2,719
25	3,043	3,013	2,898	2,819	2,716	2,652	2,519	2,406
30	2,853	2,823	2,708	2,628	2,524	2,459	2,323	2,207
40	2,628	2,598	2,482	2,401	2,296	2,230	2,088	1,965
50	2,500	2,470	2,353	2,272	2,164	2,097	1,951	1,821
100	2,257	2,227	2,108	2,024	1,912	1,840	1,681	1,529
500	2,075	2,044	1,922	1,835	1,717	1,640	1,460	1,260

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Annex D (informative)

Suggested ageing times and temperatures

D.1 TI determination

D.1.1 Correlation time (TI) = 20 000 h

When the time for TI calculation is the conventional 20 000 h (see 7.1) the following four ageing times and ten ageing oven temperatures are suggested.

The temperatures cover a range of 90 K in intervals of 10 K, the lowest temperature being equal to the expected value of TI, rounded to the nearest multiple of 10. In the following table, each * represents one group of specimens to be loaded into the oven concerned.

Table D.1 – Ageing temperatures and times

Temperature	TI	TI+10	TI+20	TI+30	TI+40	TI+50	TI+60	TI+70	TI+80	TI+90
Ageing time										
5 040 h	*	*	*	*	*	*	*			
2 016 h		*	*	*	*	*	*	*		
1 008 h			*	*	*	*	*	*	*	
552 h				*	*	*	*	*	*	*

NOTE 1 The above four ageing times are suggested as convenient multiples of 24 h (1 day) or 168 h (1 week), close to the values of ≥ 500 h, $\approx 1\ 000$ h, $\approx 2\ 000$ h and $\geq 5\ 000$ h, covering a range of 1 to 10 in four approximately equal logarithmic steps.

NOTE 2 These ageing times and temperatures are expected to give acceptable extents of ageing, such that satisfactory selection of data for the regression analyses (see 6.1.2 and 6.3.2) can be made if the expected value of TI is within ± 10 K of the actual value and the value of HIC is between 8 K and 13 K. If the values are outside these ranges, it ~~may~~ can be necessary to employ an additional higher temperature. In order to allow this, it is recommended to prepare specimens additional to those indicated by the above figures.

For illustration of this, see Figure E.3 and Figure E.4 which show the ageing times and temperatures in relation to the actual thermal endurance graph for hypothetical cases. In the data of Figure E.3, at all ageing times, approximately equal numbers of temperature groups lie above and below the "temperature for end-point", i.e. the intersection with the regression line. This is not true for the data of Figure E.4, where an extrapolation would be required at times of 552 h and 1 008 h.

D.1.2 Other correlation times for TI calculation (see 12.3)

Where the correlation time (time for TI calculation) is greater than 20 000 h, it is advisable to increase the number of times to 5 and of temperatures to 11, making the longest ageing time equal to approximately one quarter of the correlation time, and the lowest temperature equal to the value of TI (see 12.3). The number of ovens providing samples for each ageing time remains at seven (see Figure E.5).

D.2 RTE RTI determination

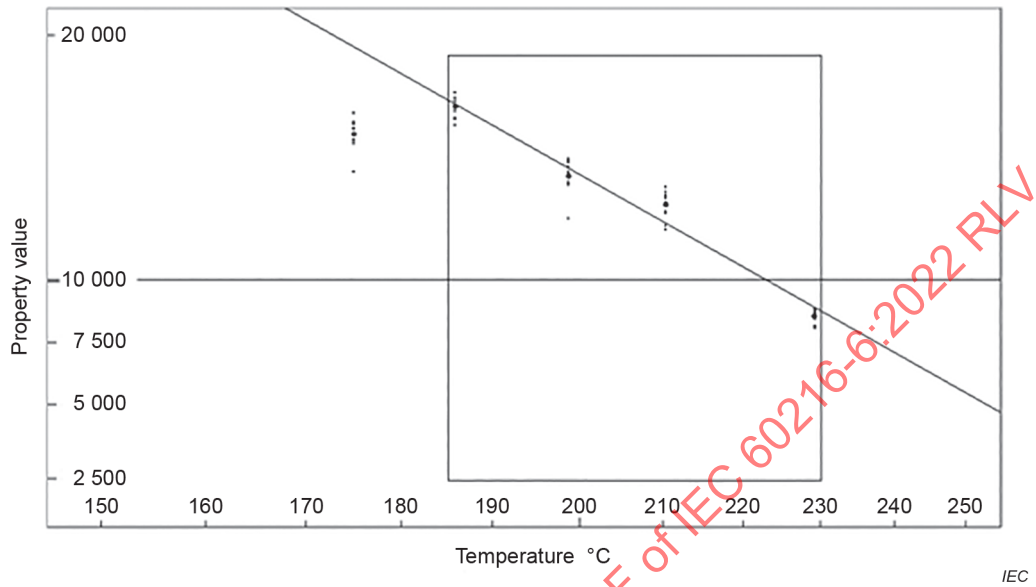
The start point for the above table should be the lower of the expected TI values for the ~~control~~ reference and candidate ~~materials~~ EIMs, rounded to the nearest 10 K. The remaining temperatures should be chosen as in D.1.2 above.

NOTE—It may reasonably be expected that these ageing times and temperatures will be acceptable if both actual TI values are within ± 10 K of the chosen value and both HIC values are within the range (8 to 13) K.

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Annex E (informative)

Figures



The data are for ageing time 2 016 h of the data group represented below (Figure E.2). The data selected for regression are in the inner rectangular outline box.

Figure E.1 – Property-temperature graph with regression line

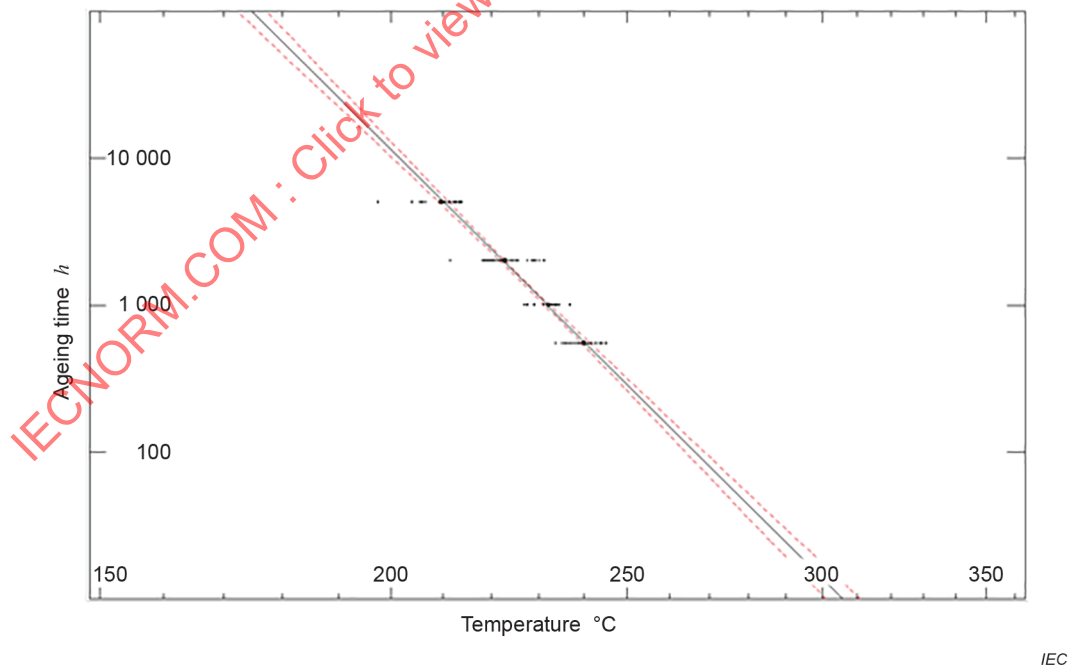
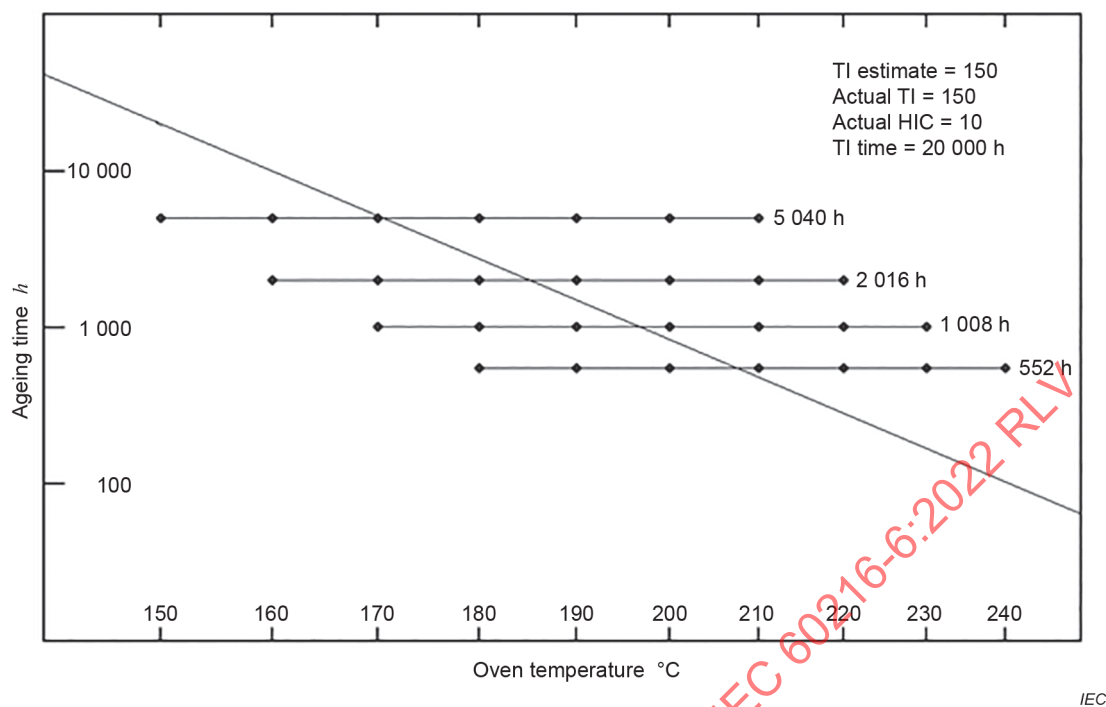
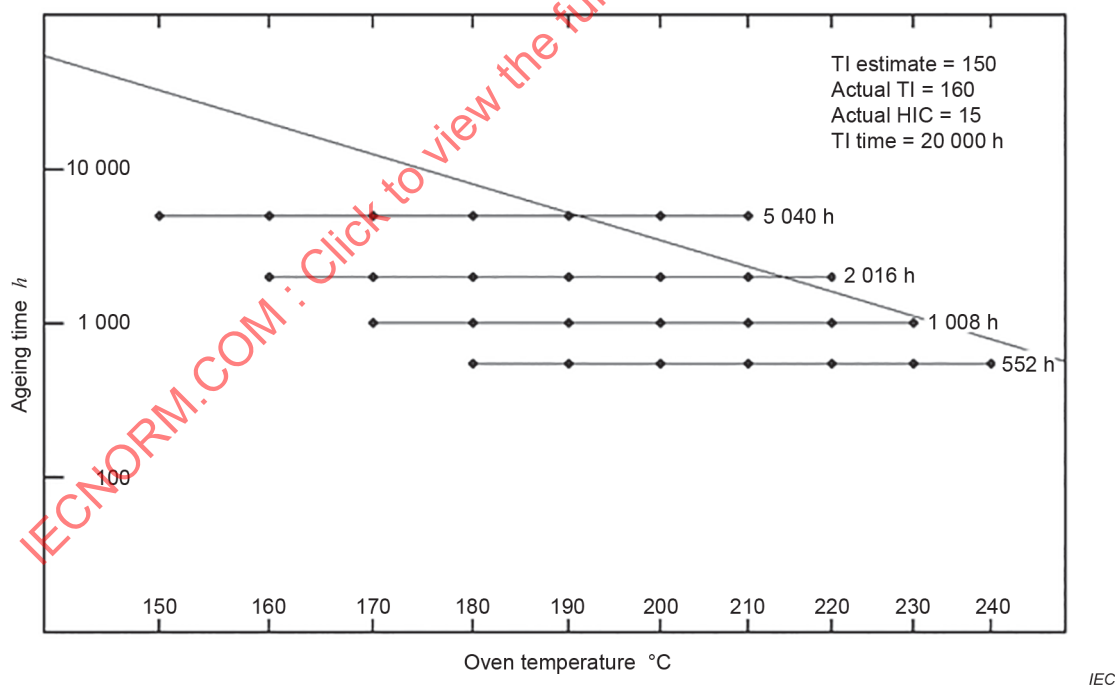


Figure E.2 – Thermal endurance graph



(Accurate expectation value for TI and average HIC)

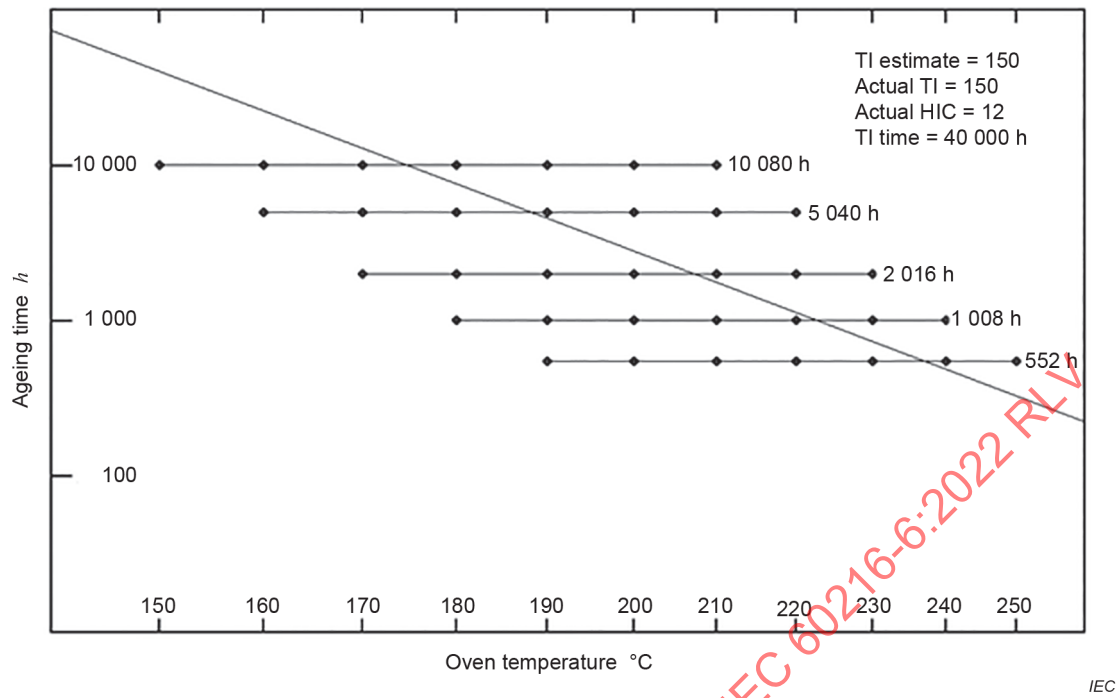
Figure E.3 – Ageing times and temperatures in relation to thermal endurance graph



(Low expectation of TI and large value of HIC)

Higher ageing temperatures needed

Figure E.4 – Ageing times and temperatures in relation to thermal endurance graph



Extra, longer ageing time for correlation time = 40 kh

The additional ageing time of 10 kh was chosen for illustration as one quarter of 40 kh.

Figure E.5 – Ageing times and temperatures in relation to thermal endurance graph

Annex F (normative)

Statistical significance of the difference between two regression estimates

Where multiple determinations of a ~~thermal endurance~~ temperature index are made (e.g. the determination may be made several times on a ~~control material~~ reference EIM), the admissibility of the differences between two results may be assessed using the equations of 12.4.

NOTE In the following discussion, the suffixes A and B refer to the two sets of data on the one ~~material~~ EIM: the first data set (A) is treated as ~~ATE~~ATI-data, the second set (B) as candidate ~~material~~ EIM data. Data set A ~~may~~ can be a pooled value from several other values.

- Calculate the value of x corresponding to the TI value for the first data set (the ~~ATE~~(equation ATI) (Equation 50), the correlation time (Equation 51) and the variance of x_A [Equation (55)].
- At this correlation time, calculate the corresponding values of x_B [Equation (52)] and its variance [Equation (56)].
- Calculate the number of degrees of freedom of the difference ($x_B - x_A$) [Equations (58 to 61)].
- Calculate the value of t for this difference and compare its value with that in Table C.2 of Annex C, at significance level 0,05.

$$t_{(N_D)} = \frac{(x_B - x_A)}{s_D}$$

A value greater than that tabulated (Table C.2) implies a significant difference between the results. This may imply a change in the ~~control material~~ reference EIM or in the conditions of ageing. This should be investigated, and if necessary, corrected.

Annex G (informative)

Computer programs ~~for IEC 60216-6~~

~~G.1 Introduction~~

~~The programs on the accompanying CD-ROM for calculations in Part 6 of IEC 60216 are for use in conjunction with the disk operating system MSDOS⁴⁾ or equivalent.~~

~~CD-ROM content~~

~~Annex-G.doc~~

~~Entry-6.bas, Entry-6.exe~~

~~216-6.bas, 216-6.exe~~

~~Rte-6.bas, Rte-6.exe~~

~~Control.ftd, Control.ftr, Control.ftc~~

~~Candidat.ftc~~

~~The text based program files (*.bas) may be edited if necessary using either a text editor or the “Quick Basic” programs QB45 or QBX and saved as ASCII files with the filename ending in “.bas”. They may then be executed using QB45 or QBX or compiled for stand-alone execution. The resultant executable files will have the ending “.exe” and the same file stem as the “.bas” files.~~

~~These executable files are suitable for direct execution in DOS, and may be executed in Windows 95 or later (98, etc.) by creating an icon for the file and double-clicking that icon. The “short-cut” options should be set so that the program is run in a normal window.~~

~~To create the icon, in Windows Explorer, right-click the file name and select “Create Shortcut”, or drag the program into the desktop.~~

~~G.2 216-6.bas (or .exe)~~

~~The program requires data to be entered in the form of an ASCII text file obtained using the associated program Entry-6.bas described below. As default it assumes the file ending for the data file “.ftd” if no file ending is entered. However, other file endings may be entered.~~

~~The file structure is similar to that of destructive test data in IEC 60216-3, modified so that the most significant test variable is time rather than temperature, the roles of time and temperature being interchanged.~~

~~Data analysis and statistical tests in accordance with IEC 60216-6 are carried out and the results reported in the appropriate format. The report is recorded in a text file with the ending “.ftr”, which may be edited in a word processor program.~~

⁴⁾ ~~MSDOS, Quick Basic, Windows 95, Windows 98 and Windows Explorer are the trade names of products supplied by Microsoft, Inc.. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the products named. Equivalent products may be used if they can be shown to lead to the same results.~~

Result parameters as required for calculation of RTE are automatically entered into a file having the same name as the experimental data file and with the ending “.ftc”.

G.3 Entry-6.bas (or .exe)

Data obtained using the procedures of IEC 60216-6 are entered following the screen instructions to generate a data file having by default the ending “.ftd”. Other file endings may be entered if required.

The data in the enclosed file “Control.ftd” may be printed and used to gain familiarity with the data entry program.

G.4 RTE-6.bas (or .exe)

Data files obtained using 216-6.exe or 216-6.bas are required for both the control and candidate materials. Statistical tests are carried out, and the results reported, in accordance with the standard. The report may be saved in a file with the same name as that of the candidate material and the extension “.fte”.

G.5 Data files

Two data files are provided for entry to RTE-6. These are named Control.ftc and Candidat.ftc. The ATE originally provided for Control.ftd was 170. Control.ftc is derived from Control.ftd.

G.5.1 Content of file Control.ftd

The data on which Control.ftd is based are as follows (S = included in calculations to produce the reports etc supplied on this disc):

Time Temperature Property values

552

199		18810	18080	18710	18090	18430	17990	19200	17860	17940	18700
210	S	18480	18700	18370	18750	18010	17260	18950	18680	16450	18260
219	S	14290	15130	15930	15000	14520	14840	14430	16540	15840	15380
229	S	12010	13200	13460	12550	12910	12670	14040	14080	12770	12060
241	S	10590	9820	10230	9680	9220	9720	10100	9880	10340	10070
250		5710	5180	5100	6050	5650	5270	5440	5180	4930	5260

1008

211		14570	14910	14560	14560						
221	S	11890	11030	11970	10930	11840					
228	S	10730	11300	10750	10500	10880					
240	S	8580	9020	8880	9130	9060					

2016

175		15740	15630	14470	16020	16210	16870	16500	16250	16410	15790
186	S	17470	16950	16670	17480	17190	17340	17240	17670	16610	16370
199	S	14660	14440	14850	12550	13940	14010	14460	14900	14070	15010
210	S	11850	11260	10520	11790	11630	10660	11180	12060	11920	12240
229	S	8210	8560	8470	8810	8900	8720	8700	8740	8690	8130

5040

150		15740	15750	15330	15120	15310	15300	15590	14450	14850	14830
160		15690	15340	14900	15400	14860	16020	15360	15910	15640	16100
175		15040	15340	15230	15380	15370	15420	15990	14980	15060	15760

~~— 185 — S 14590 13940 13850 12360 14610 14930 15170 15140 15100 14940~~
~~— 200 — S 11710 12000 12280 11040 11750~~
~~— 210 — S 10130 10460 10340 9060 10050~~

~~Endpoint 10080~~

~~The actual file content is as shown below (next page). The data in the columns are in the file as one continuous column, one number per line.~~

~~The functions of the numbers are indicated in the comments associated with a selection of the numbers.~~

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~~4 (Number of exposure times)~~	~~15130~~	~~10340~~	~~11840~~
~~6 (Max number of temperatures at any time)~~	~~15930~~	~~10070~~	~~228~~
~~10 (Max number of specimens in any temperature group)~~	~~15000~~	~~250~~	~~5~~
~~552 (Ageing time #1)~~	~~14520~~	~~10~~	~~10730~~
~~6 (Number of temperature groups)~~	~~14840~~	~~5710~~	~~11300~~
~~199 (Ageing temperature #1,1)~~	~~14430~~	~~5180~~	~~10750~~
~~10 (Number of specimens)~~	~~16540~~	~~5100~~	~~10500~~
~~18810 (Property value #1,1,1)~~	~~15840~~	~~6050~~	~~10880~~
~~18080 (Property value #1,1,2)~~	~~15380~~	~~5650~~	~~240~~
~~18710~~	~~220~~	~~5270~~	~~5~~
~~18090~~	~~10~~	~~5440~~	~~8580~~
~~18430~~	~~12010~~	~~5180~~	~~9020~~
~~17990~~	~~13200~~	~~4930~~	~~8880~~
~~19200~~	~~13460~~	~~5260~~	~~9130~~
~~17860~~	~~12550~~	~~1008~~	~~9060~~
~~17940~~	~~12910~~	~~(Time #2)~~	~~2016~~
~~18700~~	~~12670~~	~~4~~	~~5~~
~~210 (Temperature #1,2)~~	~~14040~~	~~211~~	~~175~~
~~10~~	~~14080~~	~~(Temperature #2,1)~~	~~10~~
~~18480~~	~~12770~~		~~15740~~
~~18700~~	~~12060~~	~~4~~	~~15630~~
~~18370~~	~~241~~	~~14570~~	~~14470~~
~~18750~~	~~10~~	~~(Property value #2,1,1)~~	~~16020~~
~~18010~~	~~10590~~	~~14910~~	~~16210~~
~~17260~~	~~9820~~	~~14560~~	~~16870~~
~~18950~~	~~10230~~	~~14560~~	~~16500~~
~~18680~~	~~9680~~	~~221~~	~~16250~~
~~16450~~		~~5~~	
~~18260~~	~~9220~~	~~11890~~	~~16410~~
~~219~~	~~9720~~	~~11030~~	~~15790~~
~~10~~	~~10100~~	~~11970~~	~~186~~
~~14290~~	~~9880~~	~~10930~~	~~10~~

-17470	-11920	-15340	-14940
-16950	-12240	-14900	-200
-16670	-229	-15400	-5
-17480	-10	-14860	-11710
-17190	-8210	-16020	-12000
-17340	-8560	-15360	-12280
-17240	-8470	-15910	-11040
-17670	-8810	-16640	-11750
-16610	-8900	-16100	-210
-16370	-8720	-175	-5
-199	-8700	-10	-10130
-10	-8740	-15040	-10460
-14660	-8690	-15340	-10340
-14440	-8130	-15230	-9060
-14850	-5040	-15380	-10050
-12550	-6	-15370	-10080
-13940	-150	-15420	
-14010	-10	-15990	
-14460	-15740	-14980	
-14900	-15750	-15060	
-14070	-15330	-15760	
-15010	-15120	-185	
-210	-15310	-10	
-10	-15300	-14590	
-11850		-13940	
-11260	-15590	-13850	
-10520	-14450	-12360	
-11790	-14850	-14610	
-11630	-14830	-14930	
-10660	-160	-15170	
-11180	-10	-15140	
-12060	-15690	-15100	

G.5.2 Report file

The report file generated for the above data is control.ftr; its content is:

filename: d:\temp\control.ftr

The result is TI (HIC): 190.6 (– 8.8)

Lower 95% confidence limit of TI 188.5

Chi-Squared (DF) 8.3164 (– 3)

F (nn, nd) 6.095 (2, 111)

Longest mean time to endpoint 5040

Compensated non-linearity

Non-linearity + destructive test non-linearity

Selected ageing temperatures

Time 552 210 219 229 241

Time 1008 221 228 240

Time 2016 186 199 210 229

Time 5040 185 200 210

Linearity tests

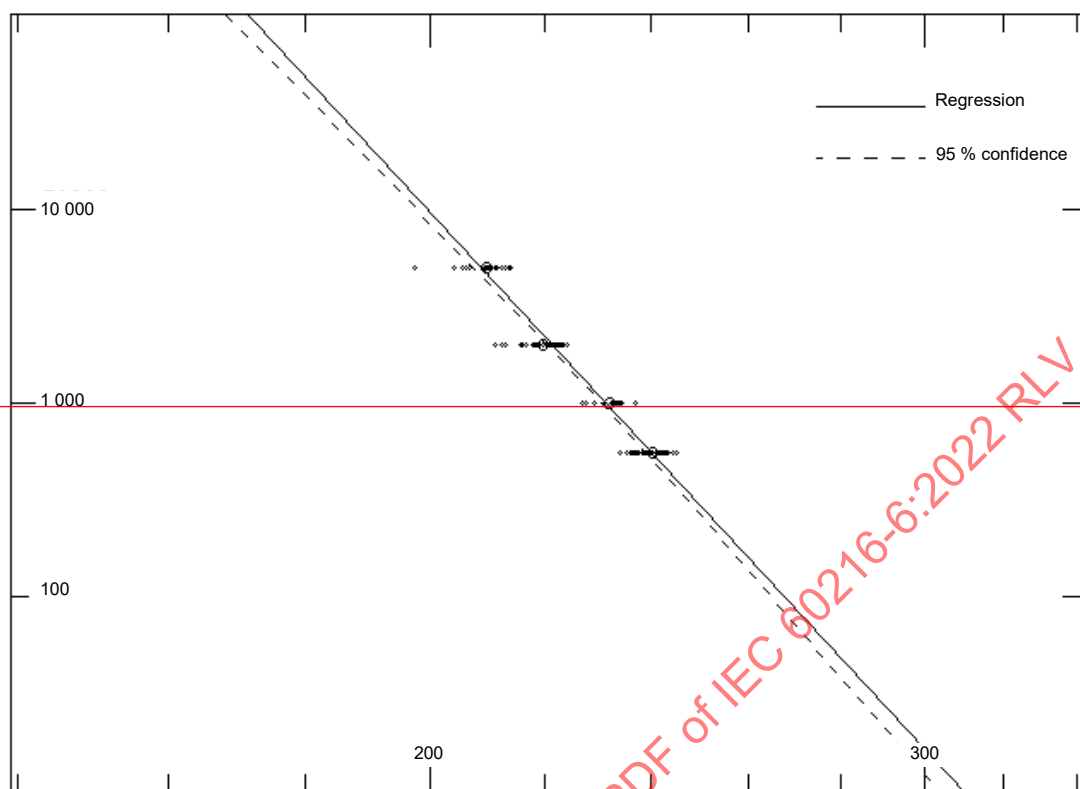
Time 552 F = 1.852 F(0.95, 2, 36) = 3.162 F(0.995, 2, 36) = 6.044

Time 1008 F = 1.962 F(0.95, 1, 12) = 4.743 F(0.995, 1, 12) = 11.715

Time 2016 F = 5.294 F(0.95, 2, 36) = 3.162 F(0.995, 2, 36) = 6.044

Time 5040 F = 0.003 F(0.95, 1, 17) = 4.487 F(0.995, 1, 17) = 10.365

G.5.3 Thermal endurance graph



IEC 998/06

Figure G.1 – Thermal endurance graph

The thermal endurance graph is presented in a graphics format which may be copied into the Windows clipboard (see Figure G.1). The graph may then be imported into another Windows program (e.g. a word processor) in the usual way. Graphs for materials having different ageing properties are produced with compatible temperature scales, each being in effect a “window” of fixed width in an infinitely long reciprocal temperature scale.

G.6 Content of file Control.ftc

This file contains the information required for the RTE calculations (a similar file is required for the candidate material). The actual values contained are:

-7.2272680519088
 -0.646666369249988
 -2.00152633394296D-03
 -3.38025166055829D-10
 -115
 -5.78159898962069D-05
 -1.58367467727663D-03
 -5040

These values are as specified in 12.2 of this standard. They are calculated and saved in the file as double precision floating point numbers.

G.7 Copying graphs to word processor reports

~~If it is required to include the graphs in a report, the word processor program should be started before the 216-6 program, which should be set up to run in a DOS window. Although the graphs are displayed full screen, the change from and back to a DOS (text) window is automatic.~~

~~When the graph is displayed, it is copied to the Windows clipboard by pressing Print Screen or ALT + Print Screen key (ALT + Print Screen copies the active window: Print Screen copies the active screen). The word processor may then be brought to the screen by pressing ALT + Esc or ALT + Tab, if necessary, repeatedly. The transfer is then completed by means of the menu function Edit / Paste Special / Device Independent Bitmap. Do not use the Control + V shortcut, as this will insert the graph in an inconvenient format (changing this is a very tedious process). The graph may be edited for size and position in the usual way. Unwanted material can generally be removed with the crop function of the drawing toolbar.~~

~~Return to the 216-6 program is then carried out from either the 216-6 label on the Windows taskbar or by (repeatedly) pressing ALT + Tab or ALT + Esc.~~

~~The report file *.ftr may be imported directly into a word processor report and edited or formatted in the usual way.~~

G.1 General

G.1.1 Overview

The program supplementing this document as well as IEC 60216-3:2021 and IEC 60216-5:2022, is written in the programming language Java² and makes use of the JavaFX technology for graphical user interfaces. It is for use in conjunction with a Java Runtime Environment (JRE) from Oracle[®] in version 1.8.101 or later. The JRE is available for download at <https://www.java.com/download> for several operating systems³ running on either 32-bit or 64-bit computers.

The package itself is available for download from <https://www.iec.ch/tc112/supportingdocuments>. The downloaded files are stored in the standard unencrypted zip-format. Such file archives can be extracted with any zip tool, see e.g. <https://download.cnet.com/s/zip-tools/>.

NOTE 1 All Hyperlinks can be subjected to change, which is not under control of the authors of this document.

The package consists of the following parts:

- Compiled Java code and 3rd party program libraries:
 - IEC60216fx.jar (main program)
 - IEC60216fx.exe (optional program launcher for Windows)
 - lib/commons-math3-3.6.1 (statistical functions)
 - lib/poi-3.17.jar (Import and Export in OOXML format (*.xlsx))
- Example data files
 - Cenex3.dta – see IEC 60216-3:2021; Table D.1
 - Test2.dta – see IEC 60216-3:2021; Table D.2

² Java[®] and Oracle[®] are registered trademarks of Oracle and/or its affiliates. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the products named. Equivalent products may be used if they can be shown to lead to the same results.

³ Microsoft Windows[®], Linux[®] and Apple macOS[®] are examples of suitable products available. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of these products.

- N3.dst and N3_selected.xlsx – see IEC 60216-3:2021; Table D.3
 - Control.dta – see IEC 60216-5
 - Candidate.dta – see IEC 60216-5
 - Control6.ftd and Control6_selected.xlsx – see Annex G.2
 - The usage of the deprecated intermediate file formats such as *.int and *.ftc is not supported in the graphical user interface. However, the application programming interface (API) implements methods to read and write these file formats.
- Java source code
- Package: datamodel – class AgingData and subclasses to comprise raw data
 - Package: mathematics – calculate results
 - Package: fxm_gui – the JavaFX graphical user interface
 - Package: ressources – example files as listed above
- Javadoc
- A number of automatically generated linked html pages for offline usage with a web browser. They describe the classes, constructors and methods of the packages 'datamodel' and 'mathematics' for use by Java programmers. New or modified user interfaces can be developed which use the tested class AgingData to store and evaluate aging data.
- JUnit tests
- The testing refers to packages 'datamodel' and 'mathematics'. The output of all JUnit tests is compiled in one document named Testing_2017-10-12.pdf.

The IEC60216fx.jar is suitable for direct execution by the JRE. In a terminal window change to the directory or folder, where this file is stored and type <JRE8 root path>\jre\bin\java.exe -jar "IEC60216fx.jar". Thereby, <JRE8 root path> stands for the directory or folder, where the JRE is stored.

NOTE 2 In Windows the directory separator is a "\", while in Linux and macOS it is a "/".

Three different ways of making the execution of the program more convenient, are described in G.1.2. The first is the recommended method, because it implies the least system requirements.

G.1.2 Convenience program execution

G.1.2.1 First (and default) method

It is important to know, that Java programs do not need installation/setup in a conventional way. Instead, the JAR files residing in one folder and the JRE residing in another folder just need to be linked together:

- download and decompress the file dist_v100.zip in a folder with write access (e.g. Documents\IEC60216fx\dist)
- download and decompress the JRE in any other folder with write access (e.g. Documents\JRE)
- create a new shortcut on the Desktop
 - a) Command: <JRE8 root path>\jre\bin\java.exe -jar "IEC60216fx.jar"
 - b) Folder Path: <Application root path>\dist

In MS-Windows (screenshot: Windows 7, english language version) the shortcut properties look like:

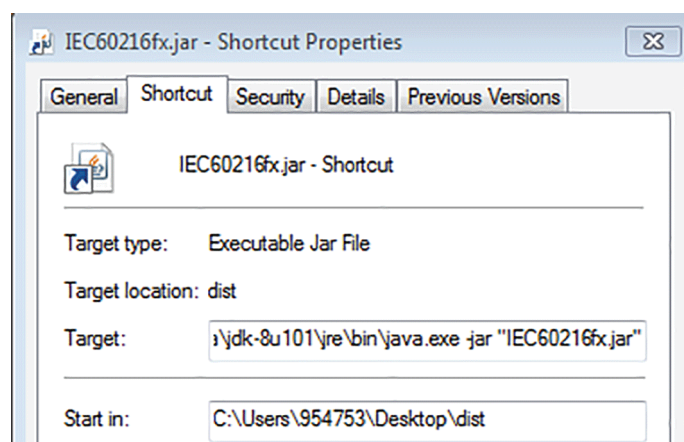


Figure G.1 – Shortcut property dialog for program launch

A double-click on the short-cut launches the application. Likewise, such a shortcut can be created in other operating systems and used for convenience program execution.

G.1.2.2 Second method

The IEC60216fx.exe is provided with the IEC60216fx.jar file in the same zip archive. It is a convenience launcher for MS-Windows, that runs the program directly with a double-click. It requires one of the following:

- a) The JRE version 1.8.101 or later is properly installed (i.e. registered) on the computer.
Or
- b) Administrator privileges are granted: in that case, the launcher will first download and install the appropriate JRE and then run the program. For the second and further launches, Administrator privileges are no longer required, unless the JRE was uninstalled meanwhile.

NOTE If the JRE is installed correctly, a double-click on the IEC60216fx.jar file will also launch the application.

G.1.2.3 Third method

Similarly, a double-click on the file IEC60216fx.html provided with the IEC60216fx.jar in the same zip archive, attempts to launch the program in the default web browser of the system. However, this functionality is blocked in many browsers by default. It needs to be enabled manually in the browser properties and can create a system vulnerability.

NOTE The file IEC60216fx.jnlp is a text file in XML format to configure this functionality.

G.2 Data files

The data file formats are described in IEC 60216-3:2021, Annex E, Clause E.2. Two example files are provided specifically for this document. These are named Control6.ftc and Candidat6.ftc. The ATI originally provided for Control6.ftd was 170. Control6.ftc is derived from Control6.ftd.

G.2.1 Content of file Control6.ftd

The data on which Control6.ftd is based are as follows (S = selection included in calculations to produce the reports etc supplied on this disc):

Time Temperature Property values

552

199		18 810 18 080 18 710 18 090 18 430 17 990 19 200 17 860 17 940 18 700
210	S	18 480 18 700 18 370 18 750 18 010 17 260 18 950 18 680 16 450 18 260
219	S	14 290 15 130 15 930 15 000 14 520 14 840 14 430 16 540 15 840 15 380
229	S	12 010 13 200 13 460 12 550 12 910 12 670 14 040 14 080 12 770 12 060
241	S	10 590 9 820 10 230 9 680 9 220 9 720 10 100 9 880 10 340 10 070
250		5 710 5 180 5 100 6 050 5 650 5 270 5 440 5 180 4 930 5 260

1 008

211		14 570 14 910 14 560 14 560
221	S	11 890 11 030 11 970 10 930 11 840
228	S	10 730 11 300 10 750 10 500 10 880
240	S	8 580 9 020 8 880 9 130 9 060

2 016

175		15 740 15 630 14 470 16 020 16 210 16 870 16 500 16 250 16 410 15 790
186	S	17 470 16 950 16 670 17 480 17 190 17 340 17 240 17 670 16 610 16 370
199	S	14 660 14 440 14 850 12 550 13 940 14 010 14 460 14 900 14 070 15 010
210	S	11 850 11 260 10 520 11 790 11 630 10 660 11 180 12 060 11 920 12 240
229	S	8 210 8 560 8 470 8 810 8 900 8 720 8 700 8 740 8 690 8 130

5 040

150		15 740 15 750 15 330 15 120 15 310 15 300 15 590 14 450 14 850 14 830
160		15 690 15 340 14 900 15 400 14 860 16 020 15 360 15 910 15 640 16 100
175		15 040 15 340 15 230 15 380 15 370 15 420 15 990 14 980 15 060 15 760
185	S	14 590 13 940 13 850 12 360 14 610 14 930 15 170 15 140 15 100 14 940
200	S	11 710 12 000 12 280 11 040 11 750
210	S	10 130 10 460 10 340 9 060 10 050

Endpoint 10 080

The actual file content is as shown below (next page). The data in the columns are in the file as one continuous column, one number per line.

The functions of the numbers are indicated in the comments in brackets associated with a selection of the numbers.

4 (Number of exposure times)		16250	15310
6 (Max number of temperatures at any time)	9220		15300
10 (Max number of specimens in any temperature group)	9720	16410	
	10100	15790	15590
552 (Ageing time #1)	9880	186	14450
6 (Number of temperature groups)	10340	10	14850
199 (Ageing temperature #1,1)	10070	17470	14830
10 (Number of specimens)	250	16950	160
18810 (Property value #1,1,1)	10	16670	10
18080 (Property value #1,1,2)	5710	17480	15690
18710	5180	17190	15340
18090	5100	17340	14900
18430	6050	17240	15400
17990	5650	17670	14860
19200	5270	16610	16020
17860	5440	16370	15360
17940	5180	199	15910
18700	4930	10	15640
210 (Temperature #1,2)	5260	14660	16100
10	1008 (Time #2)	14440	175
18480	4	14850	10
18700	211 (Temperature #2,1)	12550	15040
18370	4	13940	15340
18750	14570 (Property value #2,1,1)	14010	15230
18010	14910	14460	15380
17260	14560	14900	15370
18950	14560	14070	15420
18680	14560	15010	15990
16450	221	210	14980
18260	5	10	15060
219	11890	11850	15760
10	11030	11260	185
14290	11970	10520	10
15130	10930	11790	14590
15930	11840	11630	13940
15000	228	10660	13850
14520	5	11180	12360
14840	10730	12060	14610
14430	11300	11920	14930
16540	10750	12240	15170

15840	10500	229	15140
15380	10880	10	15100
229	240	8210	14940
10	5	8560	200
12010	8580	8470	5
13200	9020	8810	11710
13460	8880	8900	12000
12550	9130	8720	12280
12910	9060	8700	11040
12670	2016	8740	11750
14040	5	8690	210
14080	175	8130	5
12770	10	5040	10130
12060	15740	6	10460
241	15630	150	10340
10	14470	10	9060
10590	16020	15740	10050
9820	16210	15750	10080
10230	16870	15330	
9680	16500	15120	

G.2.2 Report

The content of the report generated for the above data is:

The result is TI (HIC): 191 (8,8)

TC (lower 95 % confidence limit of TI): 188,5 °C

Longest mean time to endpoint: 5 040 h

Value χ^2 (k-1): 8,3164 (3)

Test χ^2 (P, k-1): 7,8147 (0,05, 3) -> inequality of variances, P: 0,040

F(k-2, N-k): 6.095 (2, 111) -> non-significant departure from linearity

Selected ageing temperatures and estimated mean end-point [°C]

Time 552 h: 210 219 229 241 -> 240

Time 1008 h: 221 228 240 -> 232

Time 2016 h: 186 199 210 229 -> 220

Time 5040 h: 185 200 210 -> 210

End-point criteria: 10080

Linearity tests

Time 552 h, $F=1,852$: $F1(2, 36)=3,259$ -> satisfying

Time 1008 h, $F=1,962$: $F1(1, 12)=4,747$ -> satisfying

Time 2016 h, $F=5,294$: $F1(2, 36)=3,259$: $F2(2, 36)=6,161$ -> satisfying, T1a excluded

Time 5040 h, $F=0,003$: $F1(1, 17)=4,451$ -> satisfying

NOTE The computer program depicts floating numbers with a point as decimal sign.

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G.2.3 Thermal endurance graph

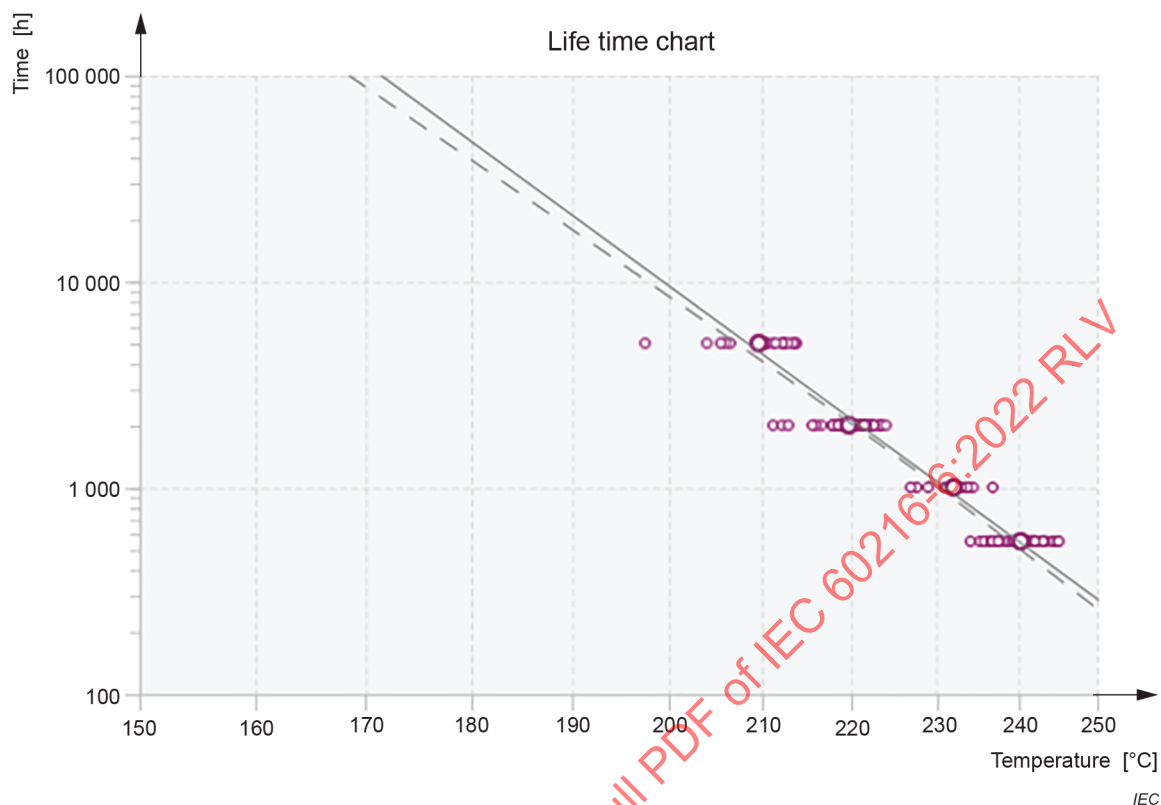


Figure G.2 – Thermal endurance graph

The thermal endurance graph is presented in a graphics format which can be copied into the Windows clipboard (see Figure G.2). The graph can then be imported into another Windows program (e.g. a word processor) in the usual way. Graphs for EIMs having different ageing properties are produced with compatible temperature scales, each being in effect a “window” of fixed width in an infinitely long reciprocal temperature scale.

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INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Electrical insulating materials – Thermal endurance properties –
Part 6: Determination of thermal endurance indices (TI and RTI) of an insulating
material using the fixed time frame method**

**Matériaux isolants électriques – Propriétés d'endurance thermique –
Partie 6: Détermination des indices d'endurance thermique (IT et ITR) d'un
matériau isolant en utilisant la méthode de trame de durées fixes**

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**ELECTRICAL INSULATING MATERIALS –
THERMAL ENDURANCE PROPERTIES –****Part 6: Determination of thermal endurance indices (TI and RTI)
of an insulating material using the fixed time frame method****FOREWORD**

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IEC 60216-6 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) clarification of definition of index properties vs. endurance properties;
- b) complete rework of Annex G and the corresponding program.

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

Draft	Report on voting
112/583/FDIS	112/589/RVD

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
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ELECTRICAL INSULATING MATERIALS – THERMAL ENDURANCE PROPERTIES –

Part 6: Determination of thermal endurance indices (TI and RTI) of an insulating material using the fixed time frame method

1 Scope

This part of IEC 60216 specifies the experimental and calculation procedures for deriving the thermal endurance characteristics, temperature index (TI) and relative temperature index (RTI) of an electrical insulating material (EIM) using the “fixed time frame method (FTFM)”.

In this protocol, the ageing takes place for a small number of fixed times, using the appropriate number of ageing temperatures throughout each time, the properties of the specimens being measured at the end of the relevant time interval. This differs from the procedure of IEC 60216-1, where ageing is conducted at a small number of fixed temperatures, property measurement taking place after ageing times dependent on the progress of ageing.

The diagnostic tests employed in the fixed time frame method are restricted to destructive tests. The method has not yet been applied to non-destructive or proof test procedures.

Both the TI and the RTI determined according to the FTFM protocol are derived from experimental data obtained in accordance with the instructions of IEC 60216-1 and IEC 60216-2 as modified in this part of IEC 60216. The calculation procedures and statistical tests are modified from those of IEC 60216-3 and IEC 60216-5.

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 60212, *Standard conditions for use prior to and during the testing of solid electrical insulating materials*

IEC 60216-1:2013, *Electrical insulating materials – Thermal endurance properties – Part 1: Ageing procedures and evaluation of test results*

IEC 60216-2, *Electrical insulating materials – Thermal endurance properties – Part 2: Determination of thermal endurance properties of electrical insulating materials – Choice of test criteria*

IEC 60216-3:2021, *Electrical insulating materials – Thermal endurance properties – Part 3: Instructions for calculating thermal endurance characteristics*

IEC 60216-4-1, *Electrical insulating materials – Thermal endurance properties – Part 4-1: Ageing ovens – Single-chamber ovens*

IEC 60216-4-2, *Electrical insulating materials – Thermal endurance properties – Part 4-2: Ageing ovens – Precision ovens for use up to 300 °C*

IEC 60216-4-3, *Electrical insulating materials – Thermal endurance properties – Part 4-3: Ageing ovens – Multi-chamber ovens*

IEC 60216-5:2022, *Electrical insulating materials – Thermal endurance properties – Part 5: Determination of relative temperature index (RTI) of an insulating material*

IEC 60493-1, *Guide for the statistical analysis of ageing test data – Part 1: Methods based on mean values of normally distributed test results*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

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

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

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

3.1.1

electrical insulating material

EIM

material of low electric conductivity, used to separate conducting parts at different electric potentials or to isolate such parts from the surroundings

3.1.2

assessed temperature index

ATI

numerical value of the temperature index in degrees Celsius of the reference EIM

Note 1 to entry: The ATI of a specific material may vary between different applications of the material.

3.1.3

ageing temperature

temperature in degrees Celsius at which a group of specimens is thermally aged

3.1.4

end-point temperature

temperature in degrees Celsius at which a specimen is considered to have reached end-point after ageing for a specified time

3.1.5

candidate EIM

material for which an estimate of the thermal endurance is required to be determined

Note 1 to entry: The determination is made by simultaneous thermal ageing of the material and a reference EIM.

3.1.6

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 items in the group

3.1.7

95 % confidence limit

statistical parameter, calculated from test data, which with 95 % confidence constitutes an upper or lower limit for the true value of a quantity estimated by statistical analysis

Note 1 to entry: This implies that there is only 5 % probability that the true value of the quantity estimated is actually larger (or smaller) than the upper (or lower) confidence limit.

Note 2 to entry: In other connections, confidence values other than 95 % may sometimes be used, e.g. in the linearity test for destructive test data.

3.1.8

reference EIM

material with known thermal endurance, preferably derived from service experience, used as a reference for comparative tests with the candidate EIM

3.1.9

correlation coefficient

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

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

Note 2 to entry: In this standard, the two data sets are the values of the independent variable and the means of the corresponding dependent variable groups.

3.1.10

correlation time for RTI

estimated time to end-point of the reference EIM at a temperature equal to its ATI in degrees Celsius

Note 1 to entry: In this document, it is expressed by symbol τ_c , see Clause 10.

3.1.11

correlation time for TI

hypothetical time to end-point used to calculate TI

Note 1 to entry: Its usual value is 20 000 h, see Clause D.1.

3.1.12

covariance, <of data sets>

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

3.1.13

degrees of freedom

number of data values minus the number of parameter values

3.1.14

destructive test

diagnostic property test, where the test specimen is irreversibly changed by the property measurement, in a way which precludes a repeated measurement on the same specimen

Note 1 to entry: An example of a destructive test is the measurement of electric strength. An example of a non-destructive test is the measurement of dissipation factor $\tan \delta$.

3.1.15

end-point line

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

3.1.16

halving interval

HIC

numerical value of the temperature interval in Kelvin which expresses the halving of the time to end-point taken at a time equal to TI

3.1.17

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

3.1.18

regression coefficients

coefficients of the equation of the best fit line derived by regression analysis

3.1.19

relative temperature index

RTI

determined by test in relation to the thermal performance of a known reference EIM

3.1.20

significance

probability of a value of a statistical function greater than a specified value

Note 1 to entry: The value is equal to $(1-p)$ where p is the cumulative distribution function value. Significance is conventionally printed in upper case (P).

3.1.21

standard deviation

square root of the variance of a data group or sub-group

3.1.22

standard error of an estimate of the true value of a data group property

value of the standard deviation of the hypothetical sampling population of which the group property may be a member

Note 1 to entry: For an estimate of the group mean, the standard error is equal to the group standard deviation divided by the square root of the number of data items in the group, and indicates the uncertainty in the estimate of the true value of the mean. This standard is concerned only with means and the difference between two means.

3.1.23

temperature index

TI

numerical value of the temperature in degrees Celsius determined by test by itself

Note 1 to entry: This rating is based on 20 000 h life, unless otherwise specified, based on one of the end-of-life criteria listed in IEC 60216-2.

3.1.24

temperature group, <of specimens>

number of specimens being exposed together to thermal ageing at the same temperature in the same oven

Note 1 to entry: Where there is no risk of ambiguity, either temperature groups or test groups may be referred to simply as "groups".

3.1.25

test group, <of specimens>

number of specimens removed together from a temperature group for destructive testing

Note 1 to entry: Where there is no risk of ambiguity, either temperature groups or test groups may be referred to simply as "groups".

3.1.26

thermal endurance graph

graph in which the logarithm of the time to reach a specified end-point in a thermal endurance test is plotted against the reciprocal thermodynamic (absolute) test temperature

3.1.27**thermal endurance graph paper**

graph paper having a logarithmic time scale as the ordinate and values proportional to the reciprocal of the thermodynamic (absolute) temperature as the abscissa

Note 1 to entry: The ordinate is usually graduated in powers of ten (from 10 h to 100 000 h is often a convenient range). The abscissa is usually graduated in a non-linear (Celsius) temperature scale oriented with temperature increasing from left to right.

3.1.28**time group, <of specimens>**

all test groups removed for testing at the same time

3.1.29**variance of a data group**

sum of the squares of the deviations of the data from a reference level defined by one or more parameters divided by the number of degrees of freedom

Note 1 to entry: The reference level can, for example be a mean value (1 parameter) or a line (2 parameters, here intercept on the axis of the independent variable and slope).

3.2 Symbols and abbreviated terms

The following symbols are used in the calculations of Clauses 6, 7, 12 and Annex A, Annex B and Annex C.

Symbol	Description	Clause
a	Regression coefficient: intercept of regression line with x -axis	6.4.4
b	Regression coefficient: slope of regression line relative to y -axis	6.4.4
b_r	Parameter derived from b for calculation of $\hat{Y}_c$	6.5.3
b_p	Regression coefficient for destructive test calculations	6.3.5
c	Parameter in calculation of χ^2	6.5.1
F	F -distributed variance ratio for linearity test	6.3.4, 6.5.2
g, h, i, j	Indexing parameters for regression calculations	6.3, 6.4
HIC	Halving interval	7.1
k	Number of ageing times	6.1.1
N	Total number of x_{ij} values	6.4.3
n_i	Number of x_{ij} values in time group i	6.1.1
P	Significance of the value of a statistical test function	Annex A, Annex B and Annex C
p_e	End-point property value	6.3
p_{gh}	Property value h in temperature group g (time group i implied)	6.3
$\bar{p}_g$	Mean property value in temperature group g (time group i implied)	6.3
q	Base of logarithms in calculation of χ^2	6.5.1
r	Number of temperature groups selected in time group i	6.3.3
r^2	Square of correlation coefficient	6.4.4

Symbol	Description	Clause
s^2	Total (non-regression) variance of x -values	6.5.2
s_{lg}^2	Variance of property values in temperature group g (time group i implied)	6.3.3
s_a^2	Value of s^2 adjusted to allow for acceptable non-linearity	6.5.2
s_r^2	Parameter derived from s^2 for calculation of $\hat{y}_c$	6.5.3
t	Student's t -distributed stochastic variable	6.5.3
TC, TC _a	Lower confidence limit of TI or TI _a (see s_a^2 above)	7.1
$t_{p,N}$	Value of t with probability p and N degrees of freedom	6.5.3
x_{ij}	Value of x , index number j , in time group i	6.3.5
$\bar{x}$	General mean of x -values	6.4.3
$\hat{x}$, $\hat{x}_c$	Estimate of x , and its confidence limit	6.5.3
y_i	Value of y for time group i	6.1.1
$\bar{y}$	General mean of y -values	6.4.3
$\hat{y}$, $\hat{y}_c$	Estimate of y , and its confidence limit	6.5.3
z_{ij}	Reciprocal kelvin temperature for θ_{ij}	6.1.1
$\mu_2(y)$	Central 2 nd moment of y values	6.4.3
ν	Total number of property values in time group (i implied)	6.3.3
χ^2	χ^2 distributed variable for variance equality (Bartlett's) test	6.5.1
θ_{ij}	Ageing temperature for specimen group j in time group i	6.1.1
θ_0	273,15 K (corresponding to 0 °C)	6.1.1
τ_i	Ageing time for time group i	6.1.1

4 FTFM protocol

4.1 Principles of FTFM protocol

The FTFM (fixed time frame method) protocol is based upon the principle that thermal ageing for determination of thermal endurance characteristics is carried out over a small number of fixed times, with a sufficient range of ageing temperatures at each time to ensure that the property values determined reach the end-point in a satisfactory manner.

In this it differs from the fixed temperature frame procedure of IEC 60216-1, where a small number of ageing temperatures is employed, with ageing being carried out with testing at intervals, until the end-point has been reached.

4.2 Objective of FTFM protocol

The protocol shall achieve the following advantages:

The determination of thermal endurance characteristics is completed in a fixed, predetermined time.

This enables much more efficient planning of the determination and will often have substantial commercial advantage. A simple TI determination can be completed in 5 kh, whereas by the fixed temperature frame procedure, it can be necessary for ageing to be considerably prolonged past this time to achieve the end-point at the lowest chosen ageing temperature.

Each temperature to end-point (i.e. time-group mean) in the thermal endurance regression is based on the temperatures selected in a time group. The number of temperatures selected may be any number between three and the number of temperature groups in a time group.

Since the largest source of systematic error in the fixed temperature frame procedure is temperature error (actual indication error or temperature distribution error), systematic errors can be considerably reduced. Errors from this source can lead to results which are either inaccurate or invalid through incorrect assessment of linearity.

5 TI determination

5.1 Ageing procedures

Each test procedure shall specify the shape, dimensions and number of the test specimens, the times of exposure, the property to which TI is related, the methods of its determination, the end-point, and the derivation of the thermal endurance characteristics from the experimental data.

The chosen property should, if possible, reflect in a significant fashion a function of the EIM in practical use. A choice of properties is given in IEC 60216-2.

To provide uniform conditions, the conditioning of specimens after removal from the oven and before measurement should be specified.

5.2 Ageing times and temperatures

In the majority of cases, the required thermal endurance characteristics are for a projected duration of 20 000 h. However, there is often a need for such information related to other, longer or shorter times. In cases of longer times, the times given as requirements or recommendations in the text of this standard (e.g. 5 kh for the minimum value of the longest ageing time) shall be increased in the ratio of the actual specification time to 20 kh.

In cases of shorter specification times, the related times may be decreased in the same ratio if necessary.

Particular care will be needed for very short specification times, since the higher ageing temperatures can lead into temperature regions which include transition points, e.g. glass transition temperature or partial melting, with consequent non-linearity. Very long specification times can also lead to non-linearity.

Recommendations for ageing times and temperatures are given in Annex D and illustrated in Figure E.3 to Figure E.5.

5.3 Test specimens

5.3.1 Preparation

The specimens used for the ageing test shall constitute a random sample from the population investigated and shall be treated uniformly.

Since processing conditions may significantly affect the ageing characteristics of some EIMs, it shall be ensured that, for example, sampling, cutting sheet from the supply roll, cutting of anisotropic material in a given direction, moulding, curing, preconditioning, are performed in the same manner for all specimens.

The material specifications or the standards for the diagnostic test methods will contain all necessary instructions for the preparation of specimens.

The thickness of specimens is in some cases specified in the list of property measurements for the determination of thermal endurance. See IEC 60216-2. If not, the thickness shall be reported. Some physical properties are sensitive even to minor variations of specimen thickness. In such cases the thickness after each ageing period may need to be determined and reported if required in the relevant specification.

The thickness is also important because the rate of ageing can vary with thickness. Ageing data of EIMs with different thicknesses are not always comparable. Consequently, an EIM can be assigned more than one thermal endurance characteristic derived from the measurement of properties at different thicknesses.

The tolerances of specimen dimensions shall be the same as those normally used for general testing. Where specimen dimensions need smaller tolerances than those normally used, these special tolerances shall be given.

Screening measurements ensure that specimens are of uniform quality and typical of the EIM to be tested.

5.3.2 Number of specimens

The accuracy of endurance test results depends largely on the number of specimens aged at each temperature.

The total number of specimens (N) is derived as follows:

$$N = a \times b \times c + d$$

where

- a is the number of specimens in a test group undergoing identical treatment at one temperature and discarded after determination of the property (usually five);
- b is the number of treatments, i.e. total number of exposure temperatures, at one time;
- c is the number of ageing time levels;
- d is the number of specimens in the group used to establish the initial value of the property. Normal practice is to select $d = 2a$ when the diagnostic criterion is a percentage change of the property from its initial level. When the criterion is an absolute property level, d is usually given the value of zero, unless reporting of the initial value is required.

It is good practice to prepare additional specimens, or at least to provide a reserve from the original material batch from which such specimens can subsequently be prepared. In this way any required ageing of additional specimens in case of unforeseen complications will introduce a minimum risk of producing systematic differences between groups of specimens. Such complications can arise, for example, if the thermal endurance relationship turns out to be non-linear, or if specimens are lost due to thermal runaway of an oven.

5.4 Diagnostic tests

If IEC material specifications are available, property requirements in terms of acceptable lower limits of TI values are usually given. If such material specifications are not available, a selection of properties and methods for the evaluation of thermal endurance is given in IEC 60216-2.

If such a method cannot be found, an international, national or institution standard or a specially devised method should be used in that order of preference. In this case, the diagnostic test shall be stated in the report, including the property, measurement procedure and end-point.

5.5 Selection of end-points

The thermal endurance of EIMs can be characterized by different endurance data (derived using different properties and/or end-points), in order to facilitate the adequate selection of the material in respect of its particular application. See IEC 60216-2.

There are two alternative ways in which the end-point can be defined:

- a) as a percentage increase or decrease in the measured value of the property from the original level. This approach will provide comparisons among EIMs but bears a poorer relationship than item b) to the property values required in normal service. For the determination of the initial value, see 5.6;
- b) as a fixed value of the property. This value might be selected with respect to usual service requirements. End-points of proof tests are predominantly given in the form of fixed values of the property.

The end-point should be selected to indicate a degree of deterioration of the EIM which has reduced its ability to withstand a stress encountered in actual service. The degree of degradation indicated as the end-point of the test should be related to the allowable safe value for the material property which is desired in practice.

5.6 Establishment of initial property value

Select the specimens for the determination of the initial value of the property to constitute a random subset of those prepared for ageing. Before determining the property value these specimens shall be conditioned by exposure to the lowest level of ageing temperature of the test (see 5.2), for two days (48 ± 6) h.

NOTE In some cases (e.g. very thick specimens) times greater than two days can be useful to establish a stable value.

Unless otherwise stated in the method for determining the diagnostic property (for example, parts of materials specifications dealing with methods of test, or a method listed in IEC 60216-2), the initial value is the arithmetic mean of the test results.

5.7 Ageing conditions

5.7.1 Ageing ovens

Throughout the heat ageing period, ageing ovens shall maintain, in that part of the working space where specimens are placed, a temperature with tolerances as given in the IEC 60216-4 series. Unless otherwise specified, IEC 60216-4-1 shall apply. IEC 60216-4-2 and 60216-4-3 may be specified in special cases.

The circulation of the air within the oven, and the exchange of the air content should be adequate to ensure that the rate of thermal degradation is not influenced by accumulation of decomposition products or oxygen depletion (see 5.7.2).

5.7.2 Environmental conditions

Unless otherwise specified, the ageing shall be carried out in ovens operating in the normal laboratory atmosphere. However, for some EIMs very sensitive to the humidity in the ovens, more reliable results are obtained when the absolute humidity in the ageing oven room is maintained at the value equal to the absolute humidity of standard atmosphere B according to IEC 60212. This, or other specified conditions, shall then be reported.

NOTE The effects of special environmental conditions such as extreme humidity, chemical contamination or vibration in many cases can be more appropriately evaluated by insulation systems tests. Although environmental conditioning, the influence of atmospheres other than air and immersion in liquids, such as oil, can be important, these are not the concern of this document.

5.7.3 Conditions for property measurement

Unless otherwise specified, the specimens shall be conditioned before measurement, and measured under conditions as stated in the material standard specification.

5.8 Procedure for ageing

Establish a testing scheme, as for example outlined in Annex D.

Prepare a number of specimens following the instructions of 5.3.2. If necessary, determine the initial value of the property in accordance with 5.6. Divide the specimens by random selection into test groups appropriate for the testing scheme. Place the appropriate numbers of groups in each of the ovens at the required temperature.

As outlined in Annex D (NOTE 2), it is recommended to prepare extra groups of specimens should the thermal endurance characteristics of the EIM be unsuited to the basic recommendation of Annex D.

After each ageing time, select at random one group from each of the appropriate ageing ovens and remove it from the oven. Allow to cool to room temperature unless otherwise specified. If specified, condition for the specified time in the specified atmosphere, and test the specimens by the specified test procedure.

It is recommended to carry out calculations as data become available, particularly for the shortest exposure time.

Evaluate the results in accordance with Clause 6.

6 Calculation procedures

6.1 General principles

6.1.1 Thermal endurance calculation

The general calculation procedures and instructions given in 6.4 are based on the principles set out in IEC 60493-1, modified as follows:

- The relation between the mean of the reciprocals (x) of the thermodynamic (absolute) temperatures at which the specified end-point is reached and the logarithm (y) of the ageing time is linear.
- The values of the deviations of the values of x from the linear relation are normally distributed with a variance which is independent of the ageing time.

The data used in the general calculation procedures are obtained from the experimental data by a preliminary calculation. Calculation data comprise values of z , y , n and k , where

$z_{ij} = 1 / (g_{ij} + \theta_0)$	= reciprocal of thermodynamic value in K of ageing temperature g_{ij} in °C;
$y_i = \log \tau_i$	= logarithm of value of ageing time in h (τ_i);
n_i	= number of z values in group number i aged for time τ_i ;
k	= number of ageing times or groups of x 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.

6.1.2 Property value – equivalent temperature transform

(Calculation of hypothetical ageing temperature derived from the value of a property)

When destructive test criteria are employed, each test specimen is destroyed in obtaining a property value: for this reason, time and/or temperature values necessary to reach end-point cannot be directly measured. To enable estimates of the times to end-point to be obtained, the following assumptions are made that in the vicinity of the end-point (for one ageing time):

- a) the relation between the mean property values and the reciprocals of the thermodynamic temperatures 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 temperature;
- c) the curves of property versus reciprocal of the ageing (thermodynamic) temperature for the individual test specimens are straight lines parallel to the line representing the relation of a) above.

For application of these assumptions, an ageing curve is drawn of the data obtained at each of the ageing times. The curve for each ageing time is obtained by plotting the mean value of property for each specimen group against the reciprocal of its ageing temperature (thermodynamic). If possible, ageing is conducted at sufficiently high and low ageing temperatures that at least one group mean is above and at least one below the end-point level. An approximately linear region of this curve is drawn (including at least three group means) in the vicinity of the end-point (Figure E.1).

NOTE A non-linear temperature scale graduated in °C is usually employed as the abscissa axis (see Figure E.1).

A statistical test (F -test) is carried out to decide whether deviations from linearity of the selected region are acceptable (see 6.3.3). 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 value of x for that specimen is then the value of the reciprocal of the (thermodynamic) temperature corresponding to the intersection of the line with the end-point line (Figure E.1).

With the limitations of 6.3.5, 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 6.3.4 and 6.3.5.

6.2 Precision of calculations

Many of the calculation steps involve summing of the differences of numbers or the squares of these differences, where the differences can be small by comparison with the numbers. In these circumstances, it is necessary that the calculations be made with an internal precision of at least six significant digits, and preferably more, if precision of three digits is to be achieved in the result. In view of the repetitive and tedious nature of the calculations, it is strongly recommended that they be performed using a programmable calculator or computer, in which case internal precision of ten or more digits is easily available.

6.3 Derivation of temperatures equivalent to property values

6.3.1 General

Within the groups of specimens aged for each time τ_i , carry out the procedures in accordance with 6.3.2 to 6.3.4.

6.3.2 Preliminary calculations

Calculate the value of y corresponding to each ageing time τ

$$y_i = \log \tau_i \quad (1)$$

Calculate the value of z corresponding to each ageing temperature g

$$z_{ij} = 1/(g_{ij} + \theta_0) \quad (2)$$

6.3.3 Regression calculations (property on temperature)

Calculate the mean property value for the data group obtained at each ageing temperature [see Equation (3)] and the corresponding value of z . Plot these values on a graph with the property value p as ordinate and z as abscissa (see Figure E.1).

Fit by visual means a smooth curve through the mean property points.

Select a temperature range within which the curve so fitted is approximately linear (see 6.3.4). Ensure that this temperature range includes at least three mean property values with at least one point on each side of the end-point line $p = p_e$. If this is not the case, and further measurements at higher temperatures cannot be made (for example, because no specimens remain), a small extrapolation is permitted, subject to the conditions of 6.3.4.

The index i is omitted from the expressions in 6.3.3 and 6.3.4 in order to avoid confusing multiple index combinations in print. The calculations of these subclauses shall be carried out separately on the data from each ageing time.

Let the number of selected mean values (and corresponding value groups) be r , the reciprocals of the individual ageing temperatures be z_g and the individual property values be p_{gh} , where

$g = 1 \dots r$ is the order number of the selected group aged at temperature g_g ;

$h = 1 \dots n_g$ is the order number of the property value within group number g ;

n_g is the number of property values in group number g .

NOTE In most cases the numbers n_g of specimens tested at all test temperatures are identical, but this is not a necessary condition, and the calculation can be carried out with different values of n_g for different groups.

Calculate the mean value $\bar{p}_g$ and the variance s_{1g}^2 for each selected property value group.

$$\bar{p}_g = \sum_{h=1}^{n_g} p_{gh} / n_g \quad (3)$$

$$s_{1g}^2 = \left(\sum_{h=1}^{n_g} p_{gh}^2 - n_g \bar{p}_g^2 \right) / (n_g - 1) \quad (4)$$

Make the following calculations:

$$v = \sum_{g=1}^r n_g \quad (5)$$

$$\bar{z} = \sum_{g=1}^r z_g n_g / v \quad (6)$$

$$\bar{p} = \sum \bar{p}_g n_g / v \quad (7)$$

Calculate the coefficients of the regression equation, $p = a_p + b_p z$

$$a_p = \bar{p} - b_p \bar{z} \quad (8)$$

$$b_p = \frac{\left(\sum_{g=1}^r n_g z_g \bar{p}_g - v \bar{z} \bar{p} \right)}{\left(\sum_{g=1}^r n_g z_g^2 - v \bar{z}^2 \right)} \quad (9)$$

Calculate the pooled variance within the property groups

$$s_1^2 = \sum_{g=1}^r (n_g - 1) s_{1g}^2 / (v - r) \quad (10)$$

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

$$s_2^2 = \sum n_g (\bar{p}_g - \hat{p}_g)^2 / (r - 2) \quad (11)$$

where
$$\hat{P}_g = a_p + b_p z_g \quad (12)$$

This can also be expressed as

$$s_2^2 = \left[\left(\sum_{g=1}^r n_g \bar{p}_g^2 - \nu \bar{p}^2 \right) - b_p \left(\sum_{g=1}^r n_g z_g \bar{p}_g - \nu \bar{z} \bar{p} \right) \right] / (r-2) \quad (13)$$

6.3.4 Linearity test

Make the F -test for non-linearity at significance level 0,05 by calculating

$$F = s_2^2 / s_1^2 \quad (14)$$

If the calculated value of F exceeds the tabulated value F_1 with $f_n = r - 2$ and $f_d = \nu - r$ degrees of freedom (see Table C.3), change the selection in 6.3.3 and repeat the calculations.

If it is not possible to satisfy the F -test on the significance level 0,05 with $r \geq 3$, make the F -test at a significance level 0,005 by comparing the calculated value of F with the tabulated value F_2 with $f_n = r - 2$ and $f_d = \nu - r$ degrees of freedom (see Table C.4).

If the test is satisfied at this level, the calculations may be continued, but the adjustment of TI according to 7.2.2, Equation (48) is not permitted.

If the F -test on significance level 0,005 (i.e. $F \leq F_2$) cannot be satisfied, or the property points plotted in 6.3.3 are all on the same side of the end-point line, an extrapolation may be permitted, subject to the following condition:

If the F -test on significance level 0,05 can be met for a range of values (with $r \geq 3$) where all mean values $\bar{p}_g$ are on the same side of the end-point value p_e , an extrapolation may be made provided that the absolute value of the difference between the end-point value p_e and the mean value $\bar{p}_g$ closest to the end-point (usually $\bar{p}_r$) is less than one quarter of the absolute value of the difference $(\bar{p}_1 - \bar{p}_r)$.

In Figure E.1, if p_e were 5 000, the calculation would be as follows:

$\bar{p}_1$ is the value of the mean of the leftmost data group in the selection box, $\bar{p}_r$ of the rightmost data group. The condition is then $|\bar{p}_r - p_e| \leq |\bar{p}_1 - \bar{p}_r| / 4$. The enclosing vertical lines imply the absolute value of the content.

In this case calculations can be continued, but again it is not permitted to carry out the adjustment of TI according to 7.2.2, Equation (48).

6.3.5 Estimation of end-point temperatures equivalent to property values

For each of the h values of property in each of the g selected groups, calculate the equivalent reciprocal end-point temperature:

$$x_{ij} = z_g - \frac{(p_{gh} - p_e)}{b_p} \quad (15)$$

and
$$n_i = \nu \quad (16)$$

where

$j = 1 \dots n_i$ is the order number of the x -value in the group of estimated x -values at ageing time τ_i and z_g is the reciprocal of the ageing temperature;

the n_i values of x_{ij} are reciprocal end-point temperature values to be used in the calculations of 6.4.

6.4 Regression analysis (temperature on time)

6.4.1 General

Where the determination is part of the determination of RTI (see Clause 3) the results from some equations will be required as input data for both reference and candidate EIMs.

Results from Equations (19), (20), (21), (23), (25), (26), (33) or (34) and (46) will be required. In addition, the value of the logarithm of the longest ageing time will be required to complete the input data.

6.4.2 Group means and variances

Calculate the mean and variance of the group of x -values, x_{ij} , obtained at each ageing time τ_i :

$$\bar{x}_i = \sum_{j=1}^{n_i} x_{ij} / n_i \quad (17)$$

$$s_{li}^2 = \left(\sum_{j=1}^{n_i} x_{ij}^2 - n_i \bar{x}_i^2 \right) / (n_i - 1) \quad (18)$$

6.4.3 General means and variances

Calculate the total number of x_{ij} values, N , the weighted mean value of x , $(\bar{x})$, and the weighted mean value of y , $(\bar{y})$:

$$N = \sum_{i=1}^k n_i \quad (19)$$

$$\bar{x} = \sum n_i \bar{x}_i / N \quad (20)$$

$$\bar{y} = \sum n_i y_i / N \quad (21)$$

Calculate the pooled variance within the data groups:

$$s_1^2 = \sum_{i=1}^k (n_i - 1) s_{1i}^2 / (N - k) \quad (22)$$

Calculate the second central moment of the y values:

$$\mu_2(y) = \frac{\left(\sum_{i=1}^k n_i y_i^2 - N \bar{y}^2 \right)}{N} \quad (23)$$

6.4.4 Regression

In the expression for the regression line:

$$x = a + by \quad (24)$$

Calculate the slope:

$$b = \frac{\left(\sum_{i=1}^k n_i \bar{x}_i y_i - N \bar{x} \bar{y} \right)}{\left(\sum_{i=1}^k n_i y_i^2 - N \bar{y}^2 \right)} \quad (25)$$

the intercept on the y -axis

$$a = \bar{x} - b \bar{y} \quad (26)$$

and the square of the correlation coefficient:

$$r^2 = \frac{\left(\sum_{i=1}^k n_i \bar{x}_i y_i - N \bar{x} \bar{y} \right)^2}{\left(\sum_{i=1}^k n_i \bar{x}_i^2 - N \bar{x}^2 \right) \left(\sum_{i=1}^k n_i y_i^2 - N \bar{y}^2 \right)} \quad (27)$$

Calculate the variance of the deviations of the x -means from the regression line:

$$s_2^2 = \sum_{i=1}^k \frac{n_i (\bar{x}_i - \hat{X}_i)^2}{(k-2)}, \quad \hat{X}_i = a + b y_i \quad (28)$$

or

$$s_2^2 = \frac{(1-r^2)}{(k-2)} \left(\sum_{i=1}^k n_i \bar{x}_i^2 - N \bar{x}^2 \right) \quad (29)$$

6.5 Statistical tests

6.5.1 Variance equality test

Calculate the value of Bartlett's χ^2 function:

$$\chi^2 = \frac{\ln q}{c} \left[(N-k) \log_q s_1^2 - \sum_{i=1}^k (n_i - 1) \log_q s_{1i}^2 \right] \quad (30)$$

where

$$c = 1 + \frac{\left(\sum_{i=1}^k \frac{1}{(n_i - 1)} - \frac{1}{(N - k)} \right)}{3(k-1)} \quad (31)$$

q is the base of the logarithms used in this Equation (30). It does not have to be the same as that used in the calculations elsewhere in this clause.

If $q = 10$, $\ln q = 2,303$; if $q = e$, $\ln q = 1$.

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

If the value of χ^2 is greater than the value 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.

6.5.2 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 groups of measurements s_1^2 by the F -test at a significance level of 0,05.

Calculate the ratio
$$F = s_2^2 / s_1^2 \quad (32)$$

and compare its value with the tabulated value $F_0 = F(0,95, k-2, N-k)$ with $f_n = k-2$ and $f_d = N-k$ degrees of freedom (Table C.3).

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

$$s^2 = \frac{(N-k)s_1^2 + (k-2)s_2^2}{(N-2)} \quad (33)$$

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

$$s_a^2 = \frac{(N-k)(s_1^2)_a + (k-2)s_2^2}{(N-2)} \quad (34)$$

6.5.3 Estimates of x and y and their confidence limits

Obtain the tabulated value of Student's t with $N-2$ degrees of freedom at a confidence level of 0,95, $t_{0,95, N-2}$ (Table C.2).

a) X -estimates

Calculate the Y -value corresponding to the time, τ , at which the estimate is required:

Calculate the estimated value of X corresponding to the given Y , and its upper 95 % confidence limit $\hat{X}_c$:

$$\hat{X}_c = \hat{X} + t s_x \quad ; \quad \hat{X} = a - bY \quad ; \quad t = t_{0,95, N-2} \quad (35)$$

$$s_x^2 = \frac{s^2}{N} \left[1 + \frac{(Y - \bar{y})^2}{\mu_2(y)} \right] \quad (36)$$

where $Y = \log \tau$ (37)

Calculate the temperatures corresponding to the values of $\hat{X}$ and $\hat{X}_c$:

$$\vartheta = \frac{1}{X} - \theta_0 \quad (38)$$

For the confidence limit curve of the thermal endurance graph (see 6.6), $\hat{X}_c$ is calculated for several values of Y over the range of interest, and a smooth curve drawn through the points $(\hat{X}_c, Y)$ plotted on the graph.

If $F > F_0$ the value of s^2 shall be replaced by s_a^2 (Equation 34).

b) Y -estimates

Calculate the value of $\hat{Y}$ and its lower 95 % confidence limit, corresponding to an end-point temperature ϑ_f

$$\hat{Y}_c = \bar{y} + \frac{(X - \bar{x})}{b_r} - \frac{t s_r}{b_r}, \quad t = t_{0,95, N-2}, \quad (39)$$

$$X = 1/(\vartheta_f + \theta_0) : \hat{Y} = (X - a)/b \quad (40)$$

$$b_r = b - \frac{t^2 s^2}{N b \mu_2(y)} \quad (41)$$

$$s_r^2 = \frac{s^2}{N} \left(\frac{b_r}{b} + \frac{(\hat{Y} - \bar{y})^2}{\mu_2(y)} \right) \quad (42)$$

The time estimate and its lower 95 % confidence limit shall be calculated from the corresponding Y estimate and its lower confidence limit:

$$\tau = q^{\hat{Y}}, \quad \tau_c = q^{\hat{Y}_c} \quad (43)$$

where q is the base of the logarithms used in the calculations (see Note in 6.1.1).

6.6 Thermal endurance graph

When the regression line has been established, it is drawn on the thermal endurance graph, i.e. a graph with $y = \log(\tau)$ as ordinate and $x = 1/(\vartheta + \theta_0)$ as abscissa. Usually, x is plotted as increasing from right to left and the corresponding values of ϑ in degrees Celsius (°C) are marked on this axis (see Figure E.2). Special graph paper is obtainable for this purpose.

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

The individual values x_{ij} and the mean values $\bar{x}_i$ obtained as in 6.4.2 are plotted on the graph at the corresponding values of y_i :

$$y_i = \log \tau_i \quad (44)$$

The thermal endurance graph may be completed by drawing the lower 95 % confidence curve (see 6.5.3).

7 Calculation and requirements for results

7.1 Calculation of thermal endurance characteristics

Using the regression equation

$$y = (x - a) / b \quad (45)$$

(the coefficients a and b being calculated according to 6.4.4), calculate the temperature in degrees Celsius (°C) corresponding to a time to end-point of 20 kh, TI_{20} . The numerical value of this temperature is the temperature index, TI.

Calculate by the same method the numerical value of the temperature corresponding to a time to end-point of 10 kh, TI_{10} . The halving interval HIC is:

$$HIC = TI_{10} - TI_{20} \quad (46)$$

Calculate by the method of 6.5.3 a), with $Y = \log 20\,000$, the lower 95 % confidence limit of TI: TC or TC_a if the adjusted value s_a^2 is used.

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

Plot the thermal endurance graph (see 6.6).

7.2 Reporting of results

7.2.1 Summary of statistical tests and reporting

In Annex B, if the condition in the column headed "Test" is not met, the action is as indicated in the final column. If the condition is met, the action is as indicated at the next step. The same sequence is indicated in the decision flow chart for thermal endurance calculations, (see Annex A).

7.2.2 Report format

If the value of $(TI - TC)/HIC$ is $\leq 0,6$, the test result shall be reported in the format

$$TI (HIC): xxx (xx,x) \quad (47)$$

in accordance with 6.8 of IEC 60216-1:2013.

If $0,6 < (TI - TC)/HIC \leq 1,6$ and at the same time, $F \leq F_0$ (see 6.3.2), the value

$$TI_a = TC + 0,6 HIC \quad (48)$$

together with HIC shall be reported as TI (HIC): xxx (xx,x).

In all other cases the result shall be reported in the format

$$TI_g = \dots, \quad HIC_g = \dots \quad (49)$$

If a time different from 20 000 h has been used for deriving the TI, the relevant time expressed in kh shall be stated, followed by "kh". The format of the TI is then:

$$TI \text{ xx kh (HIC): } xxx (xx,x) \quad (50)$$

and correspondingly for TI_a and TI_g .

8 Report

The test report shall include:

- a description of the tested EIM including dimensions and any conditioning of the specimens;
- the property investigated, the chosen end-point, and, if it was required to be determined, the initial value of the property;
- the test method used for determination of the property (for example by reference to an IEC publication);
- any relevant information on the test procedure, for example ageing environment;
- the individual test times, the ageing temperatures and individual property values, with the graphs of variation of property with ageing temperature;

- f) the thermal endurance graph;
- g) the temperature index and halving interval reported in the format defined in 7.2.2;
- h) the value of χ^2 and P if required by 6.5.1.

9 RTI determination

The objectives of the determination are in alignment with IEC 60216-5 as follows:

- a) To exploit an assumed relationship between thermal endurance (with an appropriate test criterion for ageing) and service performance, and to use this to predict a value for initial assessment of service temperature of a EIM for which there is relatively little service experience (by comparison with a known reference EIM – see Clauses 11 and 12).

In the majority of cases, this will involve extrapolation to a longer time or lower temperature than is present in the experimental data. This extrapolation should be kept to a minimum by appropriate choice of ageing temperatures and times (see Clause D.2 and Figure E.5), since the uncertainty in the result increases rapidly as the extrapolation is increased. However, even when there is no extrapolation, there is still a non-zero uncertainty, on account of the variances of the experimental data and other experimental errors.

- b) To improve the precision of a thermal endurance determination by reduction of systematic errors in the ageing process. If after ageing, the results for the reference EIM are found to be significantly different from earlier experience, this can indicate changes in material or equipment. This may be investigated and possibly corrected. In any case, the simultaneous ageing of reference and candidate will at least partially compensate for systematic changes. Statistical procedures for use in assessing the significance of changes are outlined in Annex F.

10 Additional symbols

These symbols are additional to those of 3.2 and used only in Clauses 12 to 13.

Symbol	Description	Subclause
A	Subscript indicating reference EIM	
ATI	Known thermal endurance characteristic of reference EIM	12.3
B	Subscript indicating candidate EIM	
$HIC_{B(c)}$	Halving interval of candidate EIM at correlation time	13.1
N_D	Total number of values in combined data of candidate and reference EIMs	12.4
RTI	Estimated thermal endurance characteristic of candidate EIM (temperature index at correlation time)	12.3
s_D^2	Variance of combined data of candidate and reference EIMs	12.4
s_D	Standard error of RTI (square root of s_D^2)	12.4
x_A	Reciprocal thermodynamic temperature of ATI	12.3
x_B	Reciprocal thermodynamic temperature of RTI	12.3
$X_{c(B)}$	Confidence limit of x_B	12.4
Y_C	Logarithm of correlation time	12.3
τ_C	Correlation time (time corresponding to ATI of reference EIM)	12.3
τ_k	Longest ageing time	12.5
ϑ_{RTI}	Value of RTI in degrees Celsius	12.3

$g_{c(B)}$	Confidence limit of RTI (upper or lower)	12.4
g_c	Lower confidence limit of RTI	12.4
Δ_R	Lower confidence interval of RTI	12.4

11 Experimental procedures

11.1 Selection of reference EIM

The primary requirement for the reference EIM is that the value of ATI for the application under consideration is known. The ATI, if determined by a thermal endurance procedure, shall be supported by actual service experience. The basis of the ATI shall be reported.

The expected ageing mechanisms and rates of both EIMs shall be similar and relevant to the application.

11.2 Selection of diagnostic test for extent of ageing

The diagnostic test shall be one considered relevant to the application for which the RTI is required. The same test and end-point shall be applied to both reference and candidate EIM.

11.3 Ageing procedures

The number and type of test specimens and the ageing times and temperatures for both EIMs shall be in accordance with Clause 5. If employing the recommendations of Annex D, the lowest ageing temperature should be the lower of the expected TI values for the two EIMs.

At each ageing temperature, the oven load shall comprise appropriate numbers of specimens of both EIMs. The specimens shall be distributed in the oven so that there is likely to be no systematic difference between the conditions applied to the specimens of the two EIMs.

12 Calculation procedures

12.1 General principles

The basis of the calculations is to calculate the thermal endurance characteristics of both EIMs (see 6.1.1 and 9 a)).

From the thermal endurance data obtained for the reference EIM, the time is calculated at which the temperature index is equal to its known temperature characteristic (this is the time referred to as the "correlation time"). From the thermal endurance data obtained for the candidate EIM, the temperature index is calculated at the correlation time. This value is the desired RTI.

The confidence intervals associated with this result are calculated by standard statistical procedures.

12.2 Input data

For both EIMs, reference and candidate, the following intermediate data values are required from the calculations of TI (see 6.4).

Table 1 – Intermediate data values

Intermediate value	Symbol	Equation
Slope of regression line relative to y-axis	b	(25)
Intercept of regression line on x-axis	a	(26)
Weighted mean of y-values	$\bar{y}$	(21)
Central 2nd moment of y-values	$\mu_2(y)$	(23)
Weighted mean of data x-values	$\bar{x}$	(20)
Pooled total variance of data x-values	s^2	(33) or (34)
Number of x-values	N	(19)
Halving interval	HIC	(46)
Longest ageing time	τ_k	

12.3 RTI

Calculate the reciprocal thermodynamic temperature of ATI:

$$x_A = \frac{1}{(ATI + \Theta_0)} \quad (51)$$

Calculate the correlation time τ_c and Y_c , its logarithm:

$$Y_c = \frac{(x_A - a_A)}{b_A} \quad \tau_c = q^{Y_c} \quad (52)$$

where q is the base of logarithms used in the calculations (see Note in 6.1.1).

Calculate the estimate of x at the correlation time for the candidate EIM:

$$x_B = a_B + Y_c b_B \quad (53)$$

The value of RTI is:

$$g_{RTI} = \frac{1}{x_B} - \Theta_0 \quad (54)$$

12.4 Confidence limits

Calculate the estimate of x at the correlation time for the reference EIM:

$$x_A = a_A + Y_c b_A \quad (55)$$

NOTE Numerically, x_A is equal to X_A . However, the latter is a scalar (i.e. non-variable) quantity while the former is random and normally distributed. The variance of the estimate of RTI is determined by the variance of the difference of x_A and x_B .

Calculate the variance of x_A :

$$s_A^2 = \left[s^2 \left(1 + \frac{(Y_c - \bar{y})^2}{\mu_{2(y)}} \right) \right]_A \quad (56)$$

Similarly, calculate the variance of x_B :

$$s_B^2 = \left[s^2 \left(1 + \frac{(Y_c - \bar{y})^2}{\mu_{2(y)}} \right) \right]_B \quad (57)$$

Calculate the value of the variance ratio, F :

$$F = \frac{s_B^2}{s_A^2} \text{ if } s_B^2 > s_A^2, \text{ otherwise } F = \frac{s_A^2}{s_B^2} \quad (58)$$

If the value of F is less than the value in Table C.3 for $f_n = N_A - 2$ and $f_d = N_B - 2$ degrees of freedom, then the variances are not considered significantly different. In this case, merge the variances, using Equations (58) and (59), otherwise using Equations (60) and (61).

Statistically equal variances:

$$s_D^2 = \frac{s_A^2 (N_A - 2) + s_B^2 (N_B - 2)}{(N_A + N_B - 4)} \left(\frac{1}{N_A} + \frac{1}{N_B} \right) \quad (59)$$

$$N_D = (N_A + N_B - 4) \quad (60)$$

Statistically unequal variances:

$$s_D^2 = \frac{s_A^2}{N_A} + \frac{s_B^2}{N_B} \quad (61)$$

$$N_D = \frac{\left(s_D^2\right)^2}{\frac{\left(\frac{s_A^2}{N_A}\right)^2}{N_A - 2} + \frac{\left(\frac{s_B^2}{N_B}\right)^2}{N_B - 2}} \quad (62)$$

If, in the second case, N_D is not integral, round its value to the nearest integer.

Calculate the confidence limits of X_B :

$$X_{c(B)} = X_B \pm t_{(N_D)} s_D \quad (63)$$

where $t_{(N_D)}$ is the value of t in Table C.2 for N_D degrees of freedom.

The confidence limits of RTI are:

$$g_{c(B)} = \frac{1}{X_B \pm t_{(N_D)} s_D} - \theta_0 \quad (64)$$

Normally, the lower confidence limit of RTI, g_{lc} is required, corresponding to the upper confidence limit of X_B .

The lower confidence interval Δ_R shall be calculated by Equation (64):

$$\Delta_R = g_{RTI} - g_{lc} \quad (65)$$

12.5 Extrapolation

Calculate the extrapolation as the ratio τ_c / τ_k .

13 Results and report

13.1 Results of statistical and numerical tests

The following criteria apply.

- Linearity of thermal endurance relationship (see 6.3.2 and 6.3.3 of IEC 60216-3:2021). Both reference and candidate EIM data shall satisfy the requirements.
- Extrapolation to the correlation time (see 12.5). The extrapolation, expressed as the ratio of correlation time to greatest ageing time, shall be less than 4.
- Lower confidence interval of RTI (see 12.4). The value of Δ_R shall be less than the halving interval ($HIC_{B(c)}$) of the candidate EIM at a time equal to the correlation time (see 7.1 of IEC 60216-3:2021).

$$HIC_{B(c)} = b_B \left[\frac{1}{(\ln(\tau_c / 2) - a_B)} - \frac{1}{(\ln \tau_c - a_B)} \right] \quad (66)$$

13.2 Result

The result shall be determined from the calculations of 12.4 and 12.5 and expressed as follows:

- If all three test criteria (see 13.1) are satisfied, the result shall be the value of RTI. The result shall be reported in the format "RTI according to IEC 60216-6 = xxx"
- If one of the test criteria is not satisfied, the result shall be the lower 95 % confidence limit of RTI. The result shall be reported in the format "RTI lower 95 % confidence limit = xxx"
- If two or more of the criteria are not satisfied, a result in accordance with the requirements of IEC 60216-6 cannot be reported. The result may be reported in the format "RTI = xxx. (Result not validated by the statistical analysis)"

13.3 Report

The report shall comprise the following:

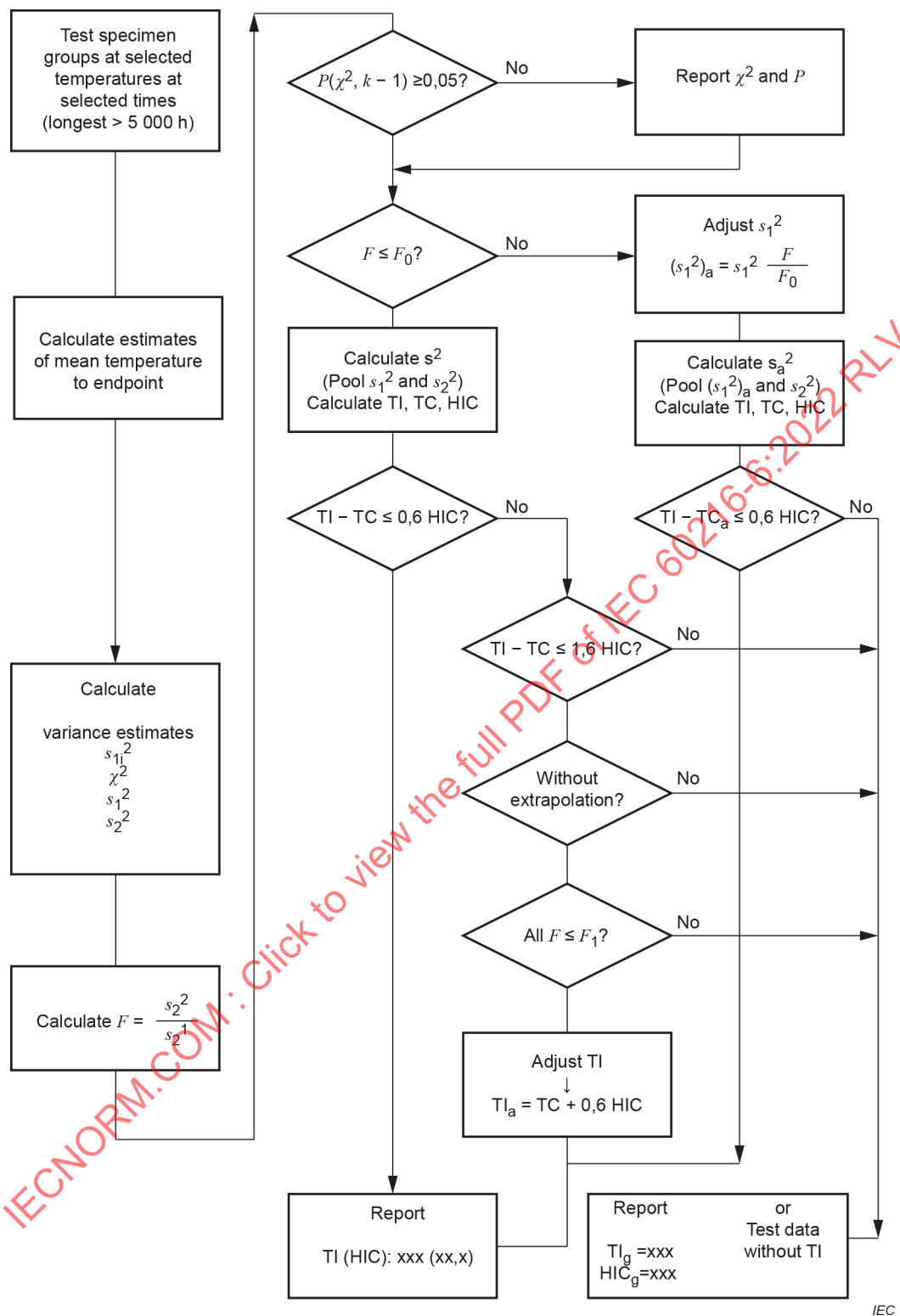
- the result;
- the identification of the reference EIM, its ATI and the basis of the ATI;
- the diagnostic test employed and the end-point;
- the thermal endurance reports according to IEC 60216-1 for the reference and candidate EIMs;
- for a result in category 13.2 c) above, the details of the failure of statistical validation.

Annex A (normative)

Decision flow chart

If the time to end-point used to calculate the thermal endurance indices is other than 20 000 h (see 3.1.11), the value of 5 000 h in Annex A and Annex B shall be replaced by one quarter of the time used.

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Figure A.1 – Decision flow chart

Annex B (normative)

Decision table

Table B.1 – Decision table

Step	Test (?) or action	Reference	Action if NO in test
1	Test specimen groups at selected temperatures for selected times (longest > 5 000 h)	5.2	
2	Calculate estimates of mean temperature to endpoint	6.4.2	
3	Calculate estimates of variances s_{1i}^2 Calculate χ^2 Calculate s_1^2 Calculate s_2^2	6.3, 6.4.2 Equation 18 6.5.1 6.4.3 6.4.4	
4	Calculate F	6.5.2	
5	? $P(\chi^2, k-1) \geq 0,05$	6.5.1	Report χ^2 and P : Go to step 6
6	? $F \leq F_0$	6.5.2	Go to step 14
7	Calculate s^2 : (Pool s_1^2 and s_2^2) Calculate TI, TC, HIC	6.5.2 a)	
8	? $TI - TC \leq 0,6 \text{ HIC}$	7.2.2	Go to step 10
9	Report TI (HIC): ... (..)	7.2.2	
10	? $TI - TC \leq 1,6 \text{ HIC}$	7.2.2	Go to step 18
11	? Were data processed without extrapolation	6.3.4	Go to step 18
12	? Were all values of $F \leq F_1$	6.3.3	Go to step 18
13	Report $TI_a = TC + 0,6 \text{ HIC}$ as TI (HIC): ... (..)	7.2.2	
14	Adjust s_1^2 : $(s_1^2)_a = s_1^2 \frac{F}{F_0}$	6.5.2	
15	Calculate s^2 : (Pool $(s_1^2)_a$ and s_2^2) Calculate TI, TC_a , HIC	6.5.2	
16	? $TI - TC_a \leq 0,6 \text{ HIC}$	7.2.2	Go to step 18
17	Report TI (HIC): ... (..)	7.2.2	
18	Report $TI_g = \dots$, $HIC_g = \dots$, or test data without TI	7.2.2	

If the time to end-point used to calculate the thermal endurance indices is other than 20 000 h (see 3.1.11), the value of 5 000 h in Annex A and Annex B shall be replaced by one quarter of the time used.

Annex C (informative)

Statistical tables

Table C.1 presents the values of χ^2 for significance levels (P) of 0,05, 0,01 and 0,005.

Table C.1 – χ^2 -function

Degrees of freedom	$P = 0,05$	$P = 0,01$	$P = 0,005$
1	3,8	6,6	7,9
2	6,0	9,2	10,6
3	7,8	11,3	12,8
4	9,5	13,3	14,9
5	11,1	15,1	16,7
6	12,6	16,8	18,5

Table C.2 gives the values of Student's t for significance levels (P) of 0,05 and 0,005.

The columns of the table represent the number (ν) of degrees of freedom and the rows the significance level (P).

Table C.2 – t -function

	10	11	12	13	14	15	16	17	18
$P = 0,05$	1,812	1,796	1,782	1,771	1,761	1,753	1,746	1,740	1,734
$P = 0,005$	3,169	3,106	3,055	3,012	2,977	2,947	2,921	2,898	2,878

	19	20	25	30	40	50	100	500
$P = 0,05$	1,729	1,725	1,708	1,697	1,684	1,676	1,660	1,648
$P = 0,005$	2,861	2,845	2,787	2,750	2,704	2,678	2,626	2,586

Table C.3 gives the values of F for significance level 0,05.

The columns of Table C.3 and Table C.4 represent the number of degrees of freedom of the numerator (f_n) and the rows the number of degrees of freedom of the denominator (f_d).

Table C.3 – *F*-function, $P = 0,05$

	1	2	3	4	5	6	7	8	9
10	4,965	4,103	3,708	3,478	3,326	3,217	3,135	3,072	3,020
11	4,844	3,982	3,587	3,357	3,204	3,095	3,012	2,948	2,896
12	4,747	3,885	3,490	3,259	3,106	2,996	2,913	2,849	2,796
13	4,667	3,806	3,411	3,179	3,025	2,915	2,832	2,767	2,714
14	4,600	3,739	3,344	3,112	2,958	2,848	2,764	2,699	2,646
15	4,543	3,682	3,287	3,056	2,901	2,790	2,707	2,641	2,588
16	4,494	3,634	3,239	3,007	2,852	2,741	2,657	2,591	2,538
17	4,451	3,592	3,197	2,965	2,810	2,699	2,614	2,548	2,494
18	4,414	3,555	3,160	2,928	2,773	2,661	2,577	2,510	2,456
19	4,381	3,522	3,127	2,895	2,740	2,628	2,544	2,477	2,423
20	4,351	3,493	3,098	2,866	2,711	2,599	2,514	2,447	2,393
25	4,242	3,385	2,991	2,759	2,603	2,490	2,405	2,337	2,282
30	4,171	3,316	2,922	2,690	2,534	2,421	2,334	2,266	2,211
40	4,085	3,232	2,839	2,606	2,449	2,336	2,249	2,180	2,124
50	4,034	3,183	2,790	2,557	2,400	2,286	2,199	2,130	2,073
100	3,936	3,087	2,696	2,463	2,305	2,191	2,103	2,032	1,975
500	3,86	3,014	2,623	2,39	2,232	2,117	2,028	1,957	1,899

	10	11	12	13	14	15	16	17	18
10	2,978	2,943	2,913	2,887	2,865	2,845	2,828	2,812	2,798
11	2,854	2,818	2,788	2,761	2,739	2,719	2,701	2,685	2,671
12	2,753	2,717	2,687	2,660	2,637	2,617	2,599	2,583	2,568
13	2,671	2,635	2,604	2,577	2,554	2,533	2,515	2,499	2,484
14	2,602	2,565	2,534	2,507	2,484	2,463	2,445	2,428	2,413
15	2,544	2,507	2,475	2,448	2,424	2,403	2,385	2,368	2,353
16	2,494	2,456	2,425	2,397	2,373	2,352	2,333	2,317	2,302
17	2,450	2,413	2,381	2,353	2,329	2,308	2,289	2,272	2,257
18	2,412	2,374	2,342	2,314	2,290	2,269	2,250	2,233	2,217
19	2,378	2,340	2,308	2,280	2,256	2,234	2,215	2,198	2,182
20	2,348	2,310	2,278	2,250	2,225	2,203	2,184	2,167	2,151
25	2,236	2,198	2,165	2,136	2,111	2,089	2,069	2,051	2,035
30	2,165	2,126	2,092	2,063	2,037	2,015	1,995	1,976	1,960
40	2,077	2,038	2,003	1,974	1,948	1,924	1,904	1,885	1,868
50	2,026	1,986	1,952	1,921	1,895	1,871	1,850	1,831	1,814
100	1,927	1,886	1,850	1,819	1,792	1,768	1,746	1,726	1,708
500	1,850	1,808	1,772	1,740	1,712	1,686	1,664	1,643	1,625

	19	20	25	30	40	50	100	500
10	2,785	2,774	2,730	2,700	2,661	2,637	2,588	2,548
11	2,658	2,646	2,601	2,570	2,531	2,507	2,457	2,415
12	2,555	2,544	2,498	2,466	2,426	2,401	2,350	2,307
13	2,471	2,459	2,412	2,380	2,339	2,314	2,261	2,218
14	2,400	2,388	2,341	2,308	2,266	2,241	2,187	2,142

15	2,340	2,328	2,280	2,247	2,204	2,178	2,123	2,078
16	2,288	2,276	2,227	2,194	2,151	2,124	2,068	2,022
17	2,243	2,230	2,181	2,148	2,104	2,077	2,020	1,973
18	2,203	2,191	2,141	2,107	2,063	2,035	1,978	1,929
19	2,168	2,155	2,106	2,071	2,026	1,999	1,940	1,891
20	2,137	2,124	2,074	2,039	1,994	1,966	1,907	1,856
25	2,021	2,007	1,955	1,919	1,872	1,842	1,779	1,725
30	1,945	1,932	1,878	1,841	1,792	1,761	1,695	1,637
40	1,853	1,839	1,783	1,744	1,693	1,66	1,589	1,526
50	1,798	1,784	1,727	1,687	1,634	1,599	1,525	1,457
100	1,691	1,676	1,616	1,573	1,515	1,477	1,392	1,308
500	1,607	1,592	1,528	1,482	1,419	1,376	1,275	1,159

Table C.4 gives the values of F for significance level 0,005.

The columns of Table C.3 and Table C.4 represent the number of degrees of freedom of the numerator (f_n) and the rows the number of degrees of freedom of the denominator (f_d).

Table C.4 – F -function, $P = 0,005$

	1	2	3	4	5	6	7	8	9
10	12,826	9,427	8,081	7,343	6,872	6,545	6,302	6,116	5,968
11	12,226	8,912	7,600	6,881	6,422	6,102	5,865	5,682	5,537
12	11,754	8,510	7,226	6,521	6,071	5,757	5,525	5,345	5,202
13	11,374	8,186	6,926	6,233	5,791	5,482	5,253	5,076	4,935
14	11,060	7,922	6,680	5,998	5,562	5,257	5,031	4,857	4,717
15	10,798	7,701	6,476	5,803	5,372	5,071	4,847	4,674	4,536
16	10,575	7,514	6,303	5,638	5,212	4,913	4,692	4,521	4,384
17	10,384	7,354	6,156	5,497	5,075	4,779	4,559	4,389	4,254
18	10,218	7,215	6,028	5,375	4,956	4,663	4,445	4,276	4,141
19	10,073	7,093	5,916	5,268	4,853	4,561	4,345	4,177	4,043
20	9,944	6,986	5,818	5,174	4,762	4,472	4,257	4,090	3,956
25	9,475	6,598	5,462	4,835	4,433	4,150	3,939	3,776	3,645
30	9,180	6,355	5,239	4,623	4,228	3,949	3,742	3,580	3,450
40	8,828	6,066	4,976	4,374	3,986	3,713	3,509	3,350	3,222
50	8,626	5,902	4,826	4,232	3,849	3,579	3,376	3,219	3,092
100	8,241	5,589	4,542	3,963	3,589	3,325	3,127	2,972	2,847
500	7,950	5,355	4,330	3,763	3,396	3,137	2,941	2,789	2,665

	10	11	12	13	14	15	16	17	18
10	5,847	5,746	5,661	5,589	5,526	5,471	5,422	5,379	5,340
11	5,418	5,320	5,236	5,165	5,103	5,049	5,001	4,959	4,921
12	5,085	4,988	4,906	4,836	4,775	4,721	4,674	4,632	4,595
13	4,820	4,724	4,643	4,573	4,513	4,460	4,413	4,372	4,334
14	4,603	4,508	4,428	4,359	4,299	4,247	4,200	4,159	4,122
15	4,424	4,329	4,250	4,181	4,122	4,070	4,024	3,983	3,946
16	4,272	4,179	4,099	4,031	3,972	3,920	3,875	3,834	3,797
17	4,142	4,050	3,971	3,903	3,844	3,793	3,747	3,707	3,670
18	4,030	3,938	3,860	3,793	3,734	3,683	3,637	3,597	3,560
19	3,933	3,841	3,763	3,696	3,638	3,587	3,541	3,501	3,465

20	3,847	3,756	3,678	3,611	3,553	3,502	3,457	3,416	3,380
25	3,537	3,447	3,370	3,304	3,247	3,196	3,151	3,111	3,075
30	3,344	3,255	3,179	3,113	3,056	3,006	2,961	2,921	2,885
40	3,117	3,028	2,953	2,888	2,831	2,781	2,737	2,697	2,661
50	2,988	2,900	2,825	2,760	2,703	2,653	2,609	2,569	2,533
100	2,744	2,657	2,583	2,518	2,461	2,411	2,367	2,326	2,290
500	2,562	2,476	2,402	2,337	2,281	2,230	2,185	2,145	2,108

	19	20	25	30	40	50	100	500
10	5,305	5,274	5,153	5,071	4,966	4,902	4,772	4,666
11	4,886	4,855	4,736	4,654	4,551	4,488	4,359	4,252
12	4,561	4,530	4,412	4,331	4,228	4,165	4,037	3,931
13	4,301	4,270	4,153	4,073	3,970	3,908	3,780	3,674
14	4,089	4,059	3,942	3,862	3,760	3,698	3,569	3,463
15	3,913	3,883	3,766	3,687	3,585	3,523	3,394	3,287
16	3,764	3,734	3,618	3,539	3,437	3,375	3,246	3,139
17	3,637	3,607	3,492	3,412	3,311	3,248	3,119	3,012
18	3,527	3,498	3,382	3,303	3,201	3,139	3,009	2,901
19	3,432	3,402	3,287	3,208	3,106	3,043	2,913	2,804
20	3,347	3,318	3,203	3,123	3,022	2,959	2,828	2,719
25	3,043	3,013	2,898	2,819	2,716	2,652	2,519	2,406
30	2,853	2,823	2,708	2,628	2,524	2,459	2,323	2,207
40	2,628	2,598	2,482	2,401	2,296	2,230	2,088	1,965
50	2,500	2,470	2,353	2,272	2,164	2,097	1,951	1,821
100	2,257	2,227	2,108	2,024	1,912	1,840	1,681	1,529
500	2,075	2,044	1,922	1,835	1,717	1,640	1,460	1,260

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Annex D (informative)

Suggested ageing times and temperatures

D.1 TI determination

D.1.1 Correlation time (TI) = 20 000 h

When the time for TI calculation is the conventional 20 000 h (see 7.1) the following four ageing times and ten ageing oven temperatures are suggested.

The temperatures cover a range of 90 K in intervals of 10 K, the lowest temperature being equal to the expected value of TI, rounded to the nearest multiple of 10. In the following table, each * represents one group of specimens to be loaded into the oven concerned.

Table D.1 – Ageing temperatures and times

Temperature	TI	TI+10	TI+20	TI+30	TI+40	TI+50	TI+60	TI+70	TI+80	TI+90
Ageing time										
5 040 h	*	*	*	*	*	*	*			
2 016 h		*	*	*	*	*	*	*		
1 008 h			*	*	*	*	*	*	*	
552 h				*	*	*	*	*	*	*

NOTE The above four ageing times are suggested as convenient multiples of 24 h (1 day) or 168 h (1 week), close to the values of ≥ 500 h, $\approx 1\,000$ h, $\approx 2\,000$ h and $\geq 5\,000$ h, covering a range of 1 to 10 in four approximately equal logarithmic steps.

These ageing times and temperatures are expected to give acceptable extents of ageing, such that satisfactory selection of data for the regression analyses (see 6.1.2 and 6.3.2) can be made if the expected value of TI is within ± 10 K of the actual value and the value of HIC is between 8 K and 13 K. If the values are outside these ranges, it can be necessary to employ an additional higher temperature. In order to allow this, it is recommended to prepare specimens additional to those indicated by the above figures.

For illustration of this, see Figure E.3 and Figure E.4 which show the ageing times and temperatures in relation to the actual thermal endurance graph for hypothetical cases. In the data of Figure E.3, at all ageing times, approximately equal numbers of temperature groups lie above and below the "temperature for end-point", i.e. the intersection with the regression line. This is not true for the data of Figure E.4, where an extrapolation would be required at times of 552 h and 1 008 h.

D.1.2 Other correlation times for TI calculation (see 12.3)

Where the correlation time (time for TI calculation) is greater than 20 000 h, it is advisable to increase the number of times to 5 and of temperatures to 11, making the longest ageing time equal to approximately one quarter of the correlation time, and the lowest temperature equal to the value of TI (see 12.3). The number of ovens providing samples for each ageing time remains at seven (see Figure E.5).

D.2 RTI determination

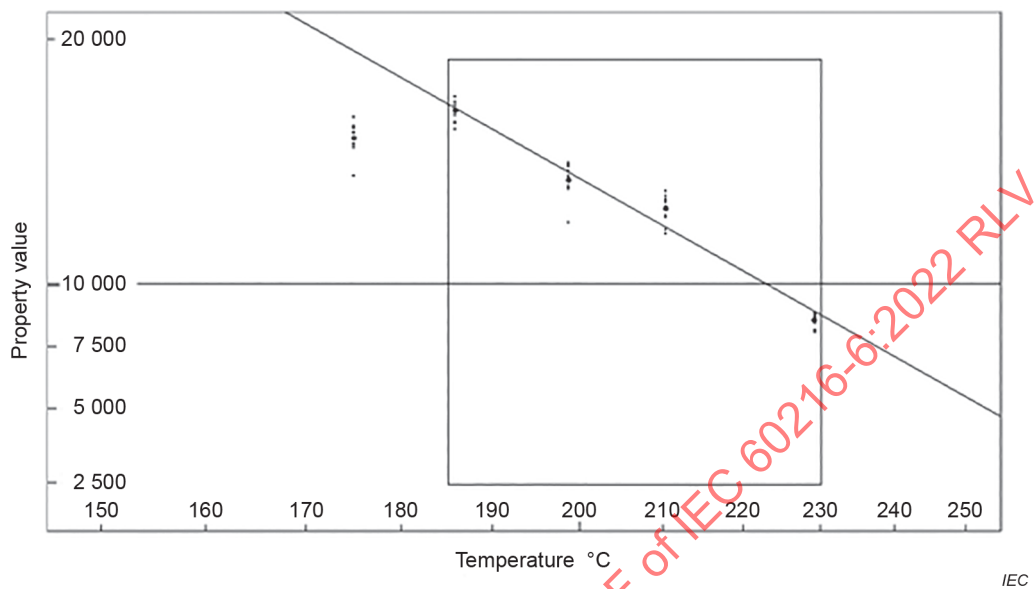
The start point for the above table should be the lower of the expected TI values for the reference and candidate EIMs, rounded to the nearest 10 K. The remaining temperatures should be chosen as in D.1.2 above.

It may reasonably be expected that these ageing times and temperatures will be acceptable if both actual TI values are within ± 10 K of the chosen value and both HIC values are within the range (8 to 13) K.

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Annex E (informative)

Figures



The data are for ageing time 2 016 h of the data group represented below (Figure E.2). The data selected for regression are in the inner rectangular outline box.

Figure E.1 – Property-temperature graph with regression line

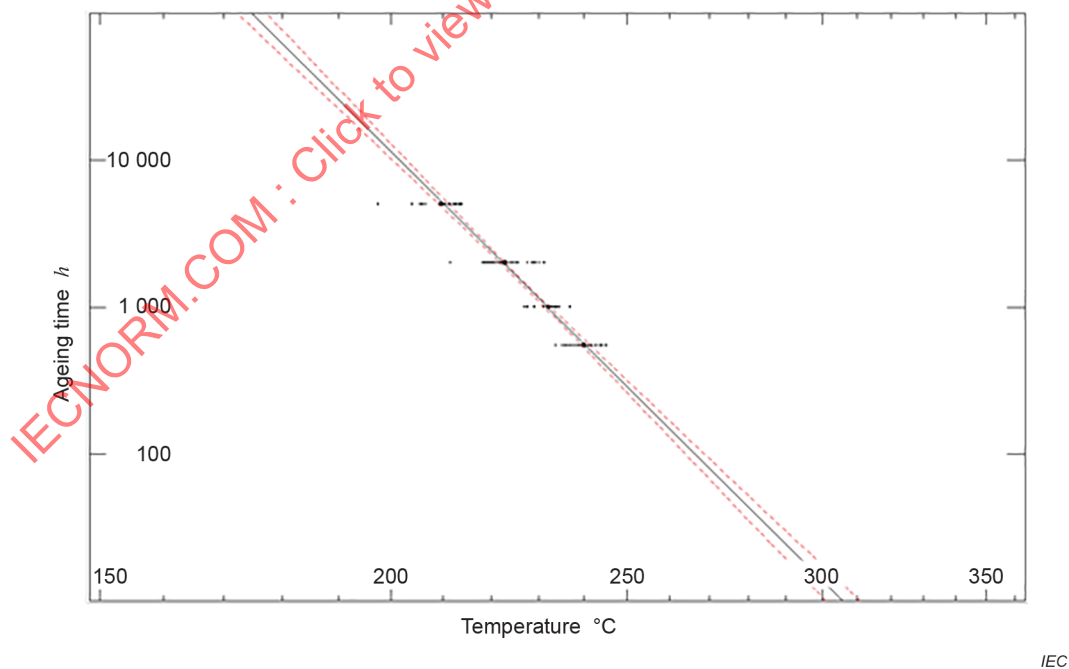
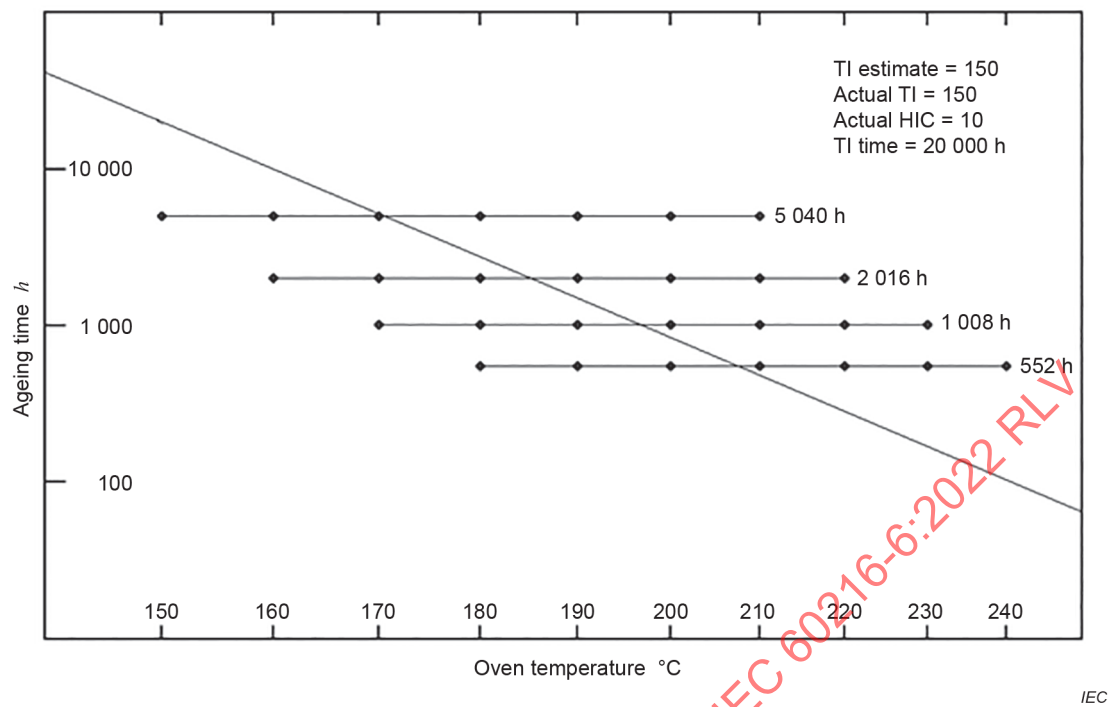
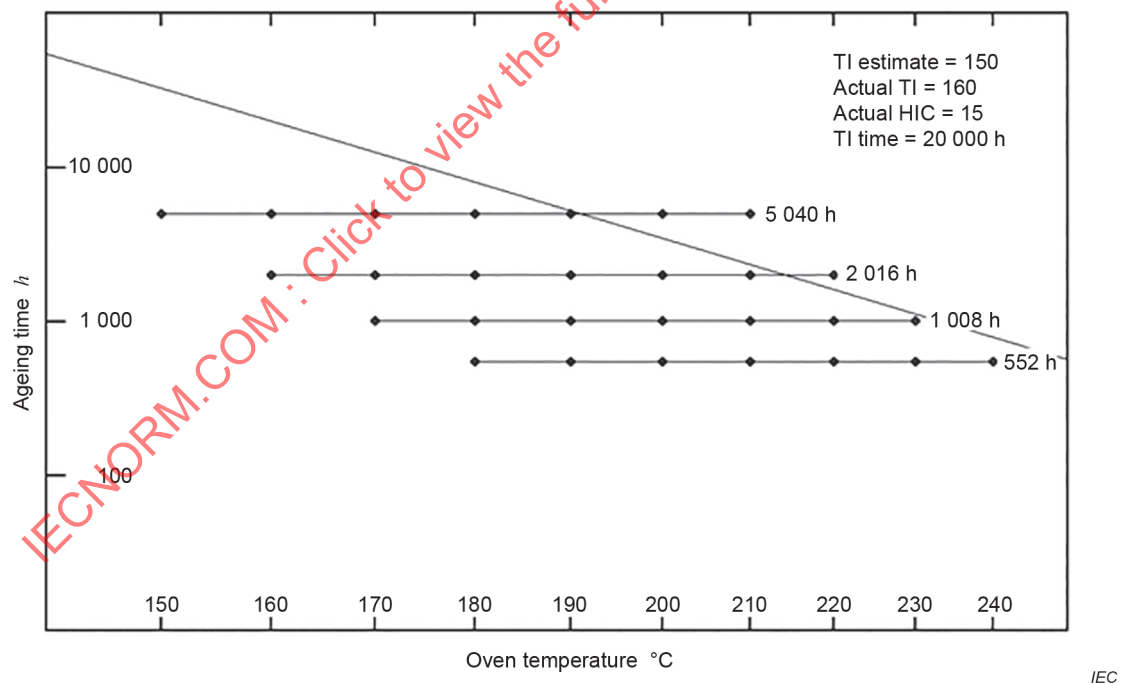


Figure E.2 – Thermal endurance graph



(Accurate expectation value for TI and average HIC)

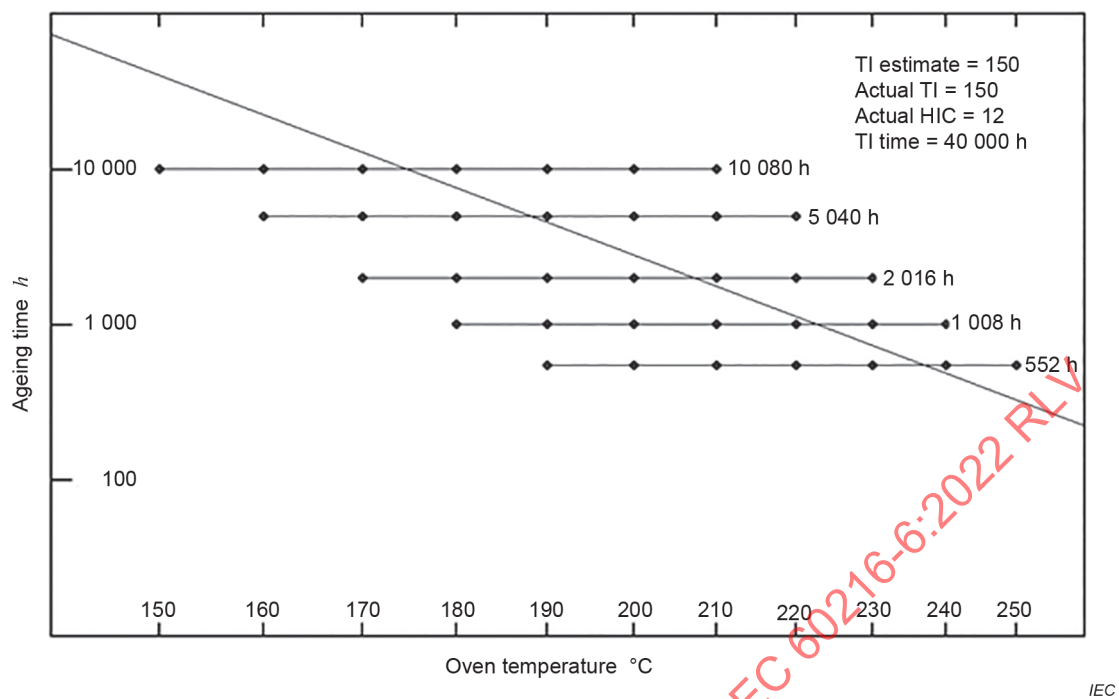
Figure E.3 – Ageing times and temperatures in relation to thermal endurance graph



(Low expectation of TI and large value of HIC)

Higher ageing temperatures needed

Figure E.4 – Ageing times and temperatures in relation to thermal endurance graph



Extra, longer ageing time for correlation time = 40 kh

The additional ageing time of 10 kh was chosen for illustration as one quarter of 40 kh.

Figure E.5 – Ageing times and temperatures in relation to thermal endurance graph

Annex F (normative)

Statistical significance of the difference between two regression estimates

Where multiple determinations of a temperature index are made (e.g. the determination may be made several times on a reference EIM), the admissibility of the differences between two results may be assessed using the equations of 12.4.

NOTE In the following discussion, the suffixes A and B refer to the two sets of data on the one EIM: the first data set (A) is treated as ATI-data, the second set (B) as candidate EIM data. Data set A can be a pooled value from several other values.

- Calculate the value of x corresponding to the TI value for the first data set (the ATI) (Equation 50), the correlation time (Equation 51) and the variance of x_A [Equation (55)].
- At this correlation time, calculate the corresponding values of x_B [Equation (52)] and its variance [Equation (56)].
- Calculate the number of degrees of freedom of the difference ($x_B - x_A$) [Equations (58 to 61)].
- Calculate the value of t for this difference and compare its value with that in Table C.2 of Annex C, at significance level 0,05.

$$t_{(N_D)} = \frac{(x_B - x_A)}{s_D}$$

A value greater than that tabulated (Table C.2) implies a significant difference between the results. This may imply a change in the reference EIM or in the conditions of ageing. This should be investigated, and if necessary, corrected.

Annex G (informative)

Computer program

G.1 General

G.1.1 Overview

The program supplementing this document as well as IEC 60216-3:2021 and IEC 60216-5:2022, is written in the programming language Java^{®1} and makes use of the JavaFX technology for graphical user interfaces. It is for use in conjunction with a Java Runtime Environment (JRE) from Oracle[®] in version 1.8.101 or later. The JRE is available for download at <https://www.java.com/download> for several operating systems² running on either 32-bit or 64-bit computers.

The package itself is available for download from <https://www.iec.ch/tc112/supportingdocuments>. The downloaded files are stored in the standard unencrypted zip-format. Such file archives can be extracted with any zip tool, see e.g. <https://download.cnet.com/s/zip-tools/>.

NOTE 1 All Hyperlinks can be subjected to change, which is not under control of the authors of this document.

The package consists of the following parts:

- Compiled Java code and 3rd party program libraries:
 - IEC60216fx.jar (main program)
 - IEC60216fx.exe (optional program launcher for Windows)
 - lib/commons-math3-3.6.1 (statistical functions)
 - lib/poi-3.17.jar (Import and Export in OOXML format (*.xlsx))
- Example data files
 - Cenex3.dta – see IEC 60216-3:2021; Table D.1
 - Test2.dta – see IEC 60216-3:2021; Table D.2
 - N3.dst and N3_selected.xlsx – see IEC 60216-3:2021; Table D.3
 - Control.dta – see IEC 60216-5
 - Candidate.dta – see IEC 60216-5
 - Control6.ftd and Control6_selected.xlsx – see Annex G.2
 - The usage of the deprecated intermediate file formats such as *.int and *.ftc is not supported in the graphical user interface. However, the application programming interface (API) implements methods to read and write these file formats.

¹ Java[®] and Oracle[®] are registered trademarks of Oracle and/or its affiliates. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the products named. Equivalent products may be used if they can be shown to lead to the same results.

² Microsoft Windows[®], Linux[®] and Apple macOS[®] are examples of suitable products available. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of these products.

- Java source code
 - Package: datamodel – class AgingData and subclasses to comprise raw data
 - Package: mathematics – calculate results
 - Package: fxml_gui – the JavaFX graphical user interface
 - Package: ressources – example files as listed above
- Javadoc
 - A number of automatically generated linked html pages for offline usage with a web browser. They describe the classes, constructors and methods of the packages 'datamodel' and 'mathematics' for use by Java programmers. New or modified user interfaces can be developed which use the tested class AgingData to store and evaluate aging data.
- JUnit tests
 - The testing refers to packages 'datamodel' and 'mathematics'. The output of all JUnit tests is compiled in one document named Testing_2017-10-12.pdf.

The IEC60216fx.jar is suitable for direct execution by the JRE. In a terminal window change to the directory or folder, where this file is stored and type <JRE8 root path>\jre\bin\java.exe -jar "IEC60216fx.jar". Thereby, <JRE8 root path> stands for the directory or folder, where the JRE is stored.

NOTE 2 In Windows the directory separator is a "\", while in Linux and macOS it is a "/".

Three different ways of making the execution of the program more convenient, are described in G.1.2. The first is the recommended method, because it implies the least system requirements.

G.1.2 Convenience program execution

G.1.2.1 First (and default) method

It is important to know, that Java programs do not need installation/setup in a conventional way. Instead, the JAR files residing in one folder and the JRE residing in another folder just need to be linked together:

- download and decompress the file dist_v100.zip in a folder with write access (e.g. Documents\IEC60216fx\dist)
- download and decompress the JRE in any other folder with write access (e.g. Documents\JRE)
- create a new shortcut on the Desktop
 - a) Command: <JRE8 root path>\jre\bin\java.exe -jar "IEC60216fx.jar"
 - b) Folder Path: <Application root path>\dist

In MS-Windows (screenshot: Windows 7, english language version) the shortcut properties look like:

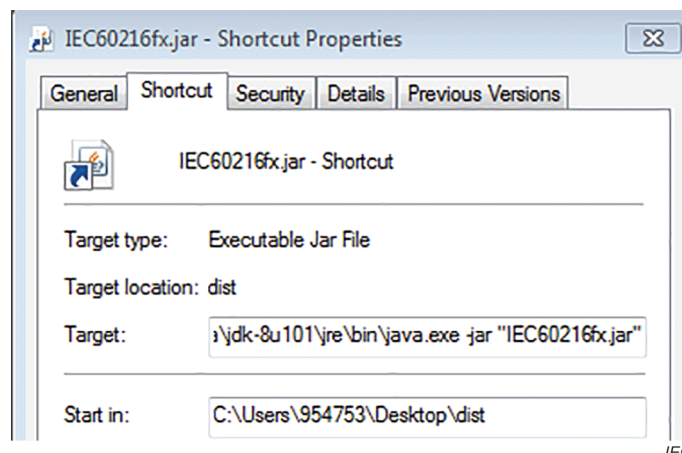


Figure G.1 – Shortcut property dialog for program launch

A double-click on the short-cut launches the application. Likewise, such a shortcut can be created in other operating systems and used for convenience program execution.

G.1.2.2 Second method

The IEC60216fx.exe is provided with the IEC60216fx.jar file in the same zip archive. It is a convenience launcher for MS-Windows, that runs the program directly with a double-click. It requires one of the following:

- a) The JRE version 1.8.101 or later is properly installed (i.e. registered) on the computer.
Or
- b) Administrator privileges are granted: in that case, the launcher will first download and install the appropriate JRE and then run the program. For the second and further launches, Administrator privileges are no longer required, unless the JRE was uninstalled meanwhile.

NOTE If the JRE is installed correctly, a double-click on the IEC60216fx.jar file will also launch the application.

G.1.2.3 Third method

Similarly, a double-click on the file IEC60216fx.html provided with the IEC60216fx.jar in the same zip archive, attempts to launch the program in the default web browser of the system. However, this functionality is blocked in many browsers by default. It needs to be enabled manually in the browser properties and can create a system vulnerability.

NOTE The file IEC60216fx.jnlp is a text file in XML format to configure this functionality.

G.2 Data files

The data file formats are described in IEC 60216-3:2021, Annex E, Clause E.2. Two example files are provided specifically for this document. These are named Control6.ftc and Candidat6.ftc. The ATI originally provided for Control6.ftd was 170. Control6.ftc is derived from Control6.ftd.

G.2.1 Content of file Control6.ftd

The data on which Control6.ftd is based are as follows (S = selection included in calculations to produce the reports etc supplied on this disc):

Time Temperature Property values

552

199		18 810	18 080	18 710	18 090	18 430	17 990	19 200	17 860	17 940	18 700
210	S	18 480	18 700	18 370	18 750	18 010	17 260	18 950	18 680	16 450	18 260
219	S	14 290	15 130	15 930	15 000	14 520	14 840	14 430	16 540	15 840	15 380
229	S	12 010	13 200	13 460	12 550	12 910	12 670	14 040	14 080	12 770	12 060
241	S	10 590	9 820	10 230	9 680	9 220	9 720	10 100	9 880	10 340	10 070
250		5 710	5 180	5 100	6 050	5 650	5 270	5 440	5 180	4 930	5 260

1 008

211		14 570	14 910	14 560	14 560	
221	S	11 890	11 030	11 970	10 930	11 840
228	S	10 730	11 300	10 750	10 500	10 880
240	S	8 580	9 020	8 880	9 130	9 060

2 016

175		15 740	15 630	14 470	16 020	16 210	16 870	16 500	16 250	16 410	15 790
186	S	17 470	16 950	16 670	17 480	17 190	17 340	17 240	17 670	16 610	16 370
199	S	14 660	14 440	14 850	12 550	13 940	14 010	14 460	14 900	14 070	15 010
210	S	11 850	11 260	10 520	11 790	11 630	10 660	11 180	12 060	11 920	12 240
229	S	8 210	8 560	8 470	8 810	8 900	8 720	8 700	8 740	8 690	8 130

5 040

150		15 740	15 750	15 330	15 120	15 310	15 300	15 590	14 450	14 850	14 830
160		15 690	15 340	14 900	15 400	14 860	16 020	15 360	15 910	15 640	16 100
175		15 040	15 340	15 230	15 380	15 370	15 420	15 990	14 980	15 060	15 760
185	S	14 590	13 940	13 850	12 360	14 610	14 930	15 170	15 140	15 100	14 940
200	S	11 710	12 000	12 280	11 040	11 750					
210	S	10 130	10 460	10 340	9 060	10 050					

Endpoint 10 080

The actual file content is as shown below (next page). The data in the columns are in the file as one continuous column, one number per line.

The functions of the numbers are indicated in the comments in brackets associated with a selection of the numbers.

4 (Number of exposure times)		16250	15310
6 (Max number of temperatures at any time)	9220		15300
10 (Max number of specimens in any temperature group)	9720	16410	
	10100	15790	15590
552 (Ageing time #1)	9880	186	14450
6 (Number of temperature groups)	10340	10	14850
199 (Ageing temperature #1,1)	10070	17470	14830
10 (Number of specimens)	250	16950	160
18810 (Property value #1,1,1)	10	16670	10
18080 (Property value #1,1,2)	5710	17480	15690
18710	5180	17190	15340
18090	5100	17340	14900
18430	6050	17240	15400
17990	5650	17670	14860
19200	5270	16610	16020
17860	5440	16370	15360
17940	5180	199	15910
18700	4930	10	15640
210 (Temperature #1,2)	5260	14660	16100
10	1008 (Time #2)	14440	175
18480	4	14850	10
18700	211 (Temperature #2,1)	12550	15040
18370	4	13940	15340
18750	14570 (Property value #2,1,1)	14010	15230
18010		14460	15380
17260	14910	14900	15370
18950	14560	14070	15420
18680	14560	15010	15990
16450	221	210	14980
18260	5	10	15060
219	11890	11850	15760
10	11030	11260	185
14290	11970	10520	10
15130	10930	11790	14590
15930	11840	11630	13940
15000	228	10660	13850
14520	5	11180	12360
14840	10730	12060	14610
14430	11300	11920	14930
16540	10750	12240	15170
15840	10500		

15380	10880	229	15140
229	240	10	15100
10	5	8210	14940
12010	8580	8560	200
13200	9020	8470	5
13460	8880	8810	11710
12550	9130	8900	12000
12910	9060	8720	12280
12670	2016	8700	11040
14040	5	8740	11750
14080	175	8690	210
12770	10	8130	5
12060	15740	5040	10130
241	15630	6	10460
10	14470	150	10340
10590	16020	10	9060
9820	16210	15740	10050
10230	16870	15750	10080
9680	16500	15330	
		15120	

G.2.2 Report

The content of the report generated for the above data is:

The result is TI (HIC): 191 (8,8)

TC (lower 95 % confidence limit of TI): 188,5 °C

Longest mean time to endpoint: 5 040 h

Value χ^2 (k-1): 8,3164 (3)

Test χ^2 (P, k-1): 7,8147 (0,05, 3) -> inequality of variances, P: 0,040

F(k-2, N-k): 6.095 (2, 111) -> non-significant departure from linearity

Selected ageing temperatures and estimated mean end-point [°C]

Time 552 h: 210 219 229 241 -> 240

Time 1008 h: 221 228 240 -> 232

Time 2016 h: 186 199 210 229 -> 220

Time 5040 h: 185 200 210 -> 210

End-point criteria: 10080

Linearity tests

Time 552 h, $F=1,852$: $F1(2, 36)=3,259$ -> satisfying

Time 1008 h, $F=1,962$: $F1(1, 12)=4,747$ -> satisfying

Time 2016 h, $F=5,294$: $F1(2, 36)=3,259$; $F2(2, 36)=6,161$ -> satisfying, T1a excluded

Time 5040 h, $F=0,003$: $F1(1, 17)=4,451$ -> satisfying

NOTE The computer program depicts floating numbers with a point as decimal sign.

G.2.3 Thermal endurance graph

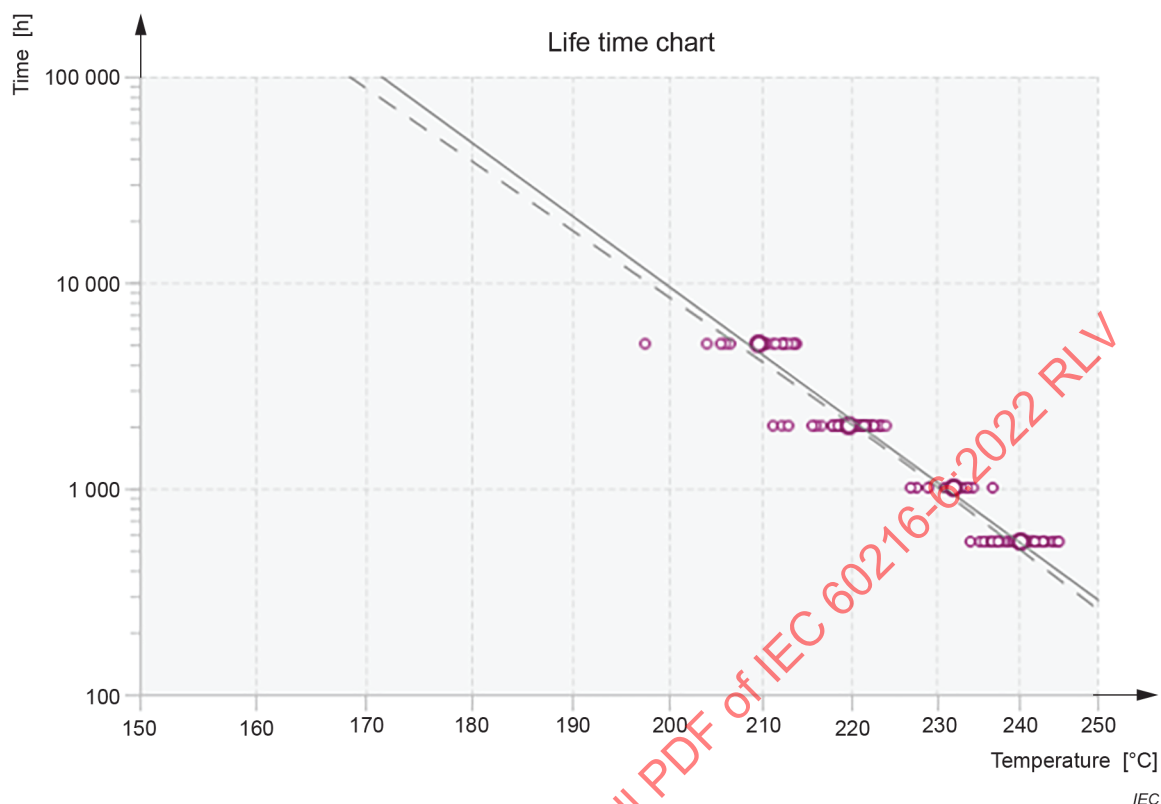


Figure G.2 – Thermal endurance graph

The thermal endurance graph is presented in a graphics format which can be copied into the Windows clipboard (see Figure G.2). The graph can then be imported into another Windows program (e.g. a word processor) in the usual way. Graphs for EIMs having different ageing properties are produced with compatible temperature scales, each being in effect a “window” of fixed width in an infinitely long reciprocal temperature scale.

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

**MATÉRIAUX ISOLANTS ÉLECTRIQUES –
PROPRIÉTÉS D'ENDURANCE THERMIQUE –****Partie 6: Détermination des indices d'endurance thermique (IT et ITR)
d'un matériau isolant en utilisant la méthode de trame de durées fixes**

AVANT-PROPOS

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L'IEC 60216-6 a été établie par le comité d'études 112 de l'IEC: Évaluation et qualification des systèmes et matériaux d'isolement électrique. Il s'agit d'une Norme internationale.

Cette troisième édition annule et remplace la deuxième édition parue en 2006. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

- a) clarification de la définition des propriétés d'indice par rapport aux propriétés d'endurance;
- b) remaniement complet de l'Annexe G et du programme correspondant.

Le texte de cette Norme internationale est issu des documents suivants:

Projet	Rapport de vote
112/583/FDIS	112/589/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

La langue employée pour l'élaboration de cette Norme internationale est l'anglais.

Le présent document a été rédigé selon les Directives ISO/IEC, Partie 2, il a été développé selon les Directives ISO/IEC, Partie 1 et les Directives ISO/IEC, Supplément IEC, disponibles sous www.iec.ch/members_experts/refdocs. Les principaux types de documents développés par l'IEC sont décrits plus en détail sous www.iec.ch/standardsdev/publications.

Une liste de toutes les parties de la série IEC 60216, publiées sous le titre général *Matériaux isolants électriques – Propriétés d'endurance thermique*, se trouve sur le site web de l'IEC.

Le comité a décidé que le contenu de ce document ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous webstore.iec.ch dans les données relatives au document recherché. À cette date, le document sera

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MATÉRIAUX ISOLANTS ÉLECTRIQUES – PROPRIÉTÉS D'ENDURANCE THERMIQUE –

Partie 6: Détermination des indices d'endurance thermique (IT et ITR) d'un matériau isolant en utilisant la méthode de trame de durées fixes

1 Domaine d'application

La présente partie de l'IEC 60216 spécifie les procédures expérimentales et de calcul à utiliser pour déduire les caractéristiques d'endurance thermique, l'indice de température (IT) et l'indice de température relatif (ITR) d'un matériau isolant électrique (MIE) à l'aide de la "méthode de trame de durées fixes" (FTFM - fixed time frame method).

Avec ce protocole, le vieillissement se produit après un petit nombre de durées déterminées, en utilisant le nombre approprié de températures de vieillissement tout au long de chaque durée pertinente, et les propriétés des éprouvettes sont mesurées à la fin de chaque intervalle de temps. Ce protocole diffère de la procédure de l'IEC 60216-1, dans laquelle le vieillissement est effectué à un petit nombre de températures déterminées, et le mesurage des propriétés des éprouvettes est effectué après des temps de vieillissement variables en fonction de la progression du vieillissement.

Les essais de diagnostic utilisés dans la méthode de trame de durées fixes sont limités aux essais destructifs. La méthode n'a pas encore été appliquée aux essais non destructifs ni aux procédures d'essais d'épreuve.

Les deux indices d'endurance thermique IT et ITR déterminés selon le protocole FTFM, sont déduits des données expérimentales obtenues conformément aux instructions de l'IEC 60216-1 et de l'IEC 60216-2, et conformément aux modifications de la présente partie de l'IEC 60216. Les procédures de calcul et les essais statistiques sont modifiés par rapport à ceux de l'IEC 60216-3 et de l'IEC 60216-5.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60212, *Conditions normales à observer avant et pendant les essais de matériaux isolants électriques solides*

IEC 60216-1:2013, *Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 1: Méthodes de vieillissement et évaluation des résultats d'essai*

IEC 60216-2, *Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 2: Détermination des propriétés d'endurance thermique de matériaux isolants électriques – Choix de critères d'essai*

IEC 60216-3:2021, *Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 3: Instructions pour le calcul des caractéristiques d'endurance thermique*

IEC 60216-4-1, *Electrical insulating materials – Thermal endurance properties – Part 4-1: Ageing ovens – Single-chamber ovens* (disponible en anglais seulement)

IEC 60216-4-2, *Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 4-2: Étuves de vieillissement – Étuves de précision pour des utilisations pouvant atteindre 300 °C*

IEC 60216-4-3, *Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 4-3: Étuves de vieillissement – Étuves à chambres multiples*

IEC 60216-5:2022, *Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 5: Détermination de l'indice de température relatif (ITR) d'un matériau isolant*

IEC 60493-1, *Guide pour l'analyse statistique de données d'essai de vieillissement – Partie 1: Méthodes basées sur les valeurs moyennes de résultats d'essais normalement distribués*

3 Termes, définitions, symboles et abréviations

3.1 Termes et définitions

Pour les besoins du présent document, les termes et définitions suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse <https://www.electropedia.org/>
- ISO Online browsing platform: disponible à l'adresse <https://www.iso.org/obp>

3.1.1

matériau isolant électrique

MIE

matériau de conductivité électrique faible, utilisé pour séparer des pièces conductrices portées à des potentiels électriques différents ou pour isoler ces pièces de l'environnement

3.1.2

indice de température évaluée

ATI

valeur numérique de l'indice de température en degrés Celsius du MIE de référence

Note 1 à l'article: L'ATI d'un matériau spécifique peut varier selon les différentes utilisations de ce matériau.

Note 2 à l'article: L'abréviation "ATI" est dérivée du terme anglais développé correspondant "assessed temperature index".

3.1.3

température de vieillissement

température, exprimée en degrés Celsius, à laquelle un groupe d'éprouvettes est vieilli thermiquement

3.1.4

température de point limite

température, exprimée en degrés Celsius, à laquelle une éprouvette est considérée comme ayant atteint son point limite après avoir vieilli pendant une durée spécifiée

3.1.5

MIE candidat

matériau pour lequel une estimation de l'endurance thermique doit être réalisée

Note 1 à l'article: L'estimation est réalisée par vieillissement thermique simultané du matériau et d'un MIE de référence.

3.1.6**moment centré d'ordre 2 d'un groupe de données**

somme des carrés des différences entre les valeurs des données et la valeur de la moyenne du groupe divisée par le nombre de données dans le groupe

3.1.7**limite de confiance à 95 %**

paramètre statistique, calculé à partir des données d'essai, constituant avec un taux de confiance de 95 %, une limite supérieure ou inférieure de la valeur vraie d'une grandeur estimée par analyse statistique

Note 1 à l'article: Cela implique qu'il n'y a que 5 % de probabilité que la valeur vraie de la grandeur estimée soit effectivement supérieure (ou inférieure) à la limite supérieure (ou inférieure) de confiance.

Note 2 à l'article: Dans d'autres contextes, des valeurs de confiance autres que 95 % peuvent parfois être utilisées, par exemple dans l'essai de linéarité pour des données d'essai destructif.

3.1.8**MIE de référence**

matériau à l'endurance thermique connue, de préférence déduite de l'expérience en service, utilisé comme référence pour des essais comparatifs avec le MIE candidat

3.1.9**coefficient de corrélation**

nombre exprimant l'intégrité de la relation entre les membres de deux ensembles de données, égal à la covariance divisée par la racine carrée du produit des variances des ensembles

Note 1 à l'article: Le carré de la valeur de ce coefficient est compris entre 0 (pas de corrélation) et 1 (corrélation parfaite).

Note 2 à l'article: Dans la présente norme, les deux ensembles de données sont les valeurs de la variable indépendante et les moyennes des groupes de la variable dépendante correspondants.

3.1.10**temps de corrélation pour l'ITR**

durée estimée jusqu'au point limite du MIE de référence obtenue pour une température en degrés Celsius égale à son ATI

Note 1 à l'article: Il est exprimé dans le présent document par le symbole τ_c (voir l'Article 10).

Note 2 à l'article: L'abréviation "ATI" est dérivée du terme anglais développé correspondant "assessed temperature index".

3.1.11**temps de corrélation pour l'IT**

durée hypothétique jusqu'au point limite utilisée pour calculer l'indice de température (IT)

Note 1 à l'article: 20 000 h est la valeur usuelle du temps de corrélation, voir l'Article D.1.

3.1.12**covariance, <d'ensembles de données>**

pour deux ensembles de données avec un nombre égal d'éléments où chaque élément dans un ensemble correspondant à un élément dans l'autre, somme des produits des écarts des membres correspondants par rapport à leur moyenne d'ensemble, divisée par le nombre de degrés de liberté

3.1.13**degrés de liberté**

nombre de valeurs de données diminué du nombre de paramètres

3.1.14

essai destructif

essai d'une propriété pour réaliser un diagnostic, au cours duquel l'éprouvette est modifiée de manière irréversible par le mesurage de la propriété, de telle manière que cela interdise un mesurage répété sur la même éprouvette

Note 1 à l'article: Le mesurage de la rigidité diélectrique est un exemple d'essai destructif. Le mesurage du facteur de dissipation $\tan \delta$ est un exemple d'essai non destructif.

3.1.15

ligne de point limite

droite parallèle à l'axe des températures coupant l'axe des propriétés au point limite

3.1.16

intervalle de division par deux

IDC

valeur numérique de l'intervalle de température en kelvin, qui exprime la division par deux du temps pour atteindre le point limite, pris au temps de l'indice IT

3.1.17

analyse de régression

processus de déduction de la droite du meilleur ajustement exprimant la relation liant les membres correspondants de deux groupes de données, en réduisant le plus possible la somme des carrés des écarts des membres de l'un des groupes par rapport à la droite

3.1.18

coefficients de régression

coefficients de l'équation de la droite du meilleur ajustement déduite par l'analyse de régression

3.1.19

indice de température relatif

ITR

indice déterminé par essai par rapport aux performances thermiques d'un MIE de référence connu

3.1.20

signification statistique

probabilité d'une valeur d'une fonction statistique supérieure à une valeur spécifiée

Note 1 à l'article: La valeur est égale à $(1-p)$ où p est la valeur de la fonction de distribution cumulative. La signification statistique est conventionnellement imprimée en majuscule (P).

3.1.21

écart-type

racine carrée de la variance d'un groupe ou d'un sous-groupe de données

3.1.22

erreur type d'une estimation de la valeur vraie d'une propriété d'un groupe de données

valeur de l'écart-type de la population échantillon retenue par hypothèse pour laquelle la propriété du groupe peut être membre de ce groupe

Note 1 à l'article: Pour une estimation de la moyenne du groupe, l'erreur type est égale à l'écart-type du groupe divisé par la racine carrée du nombre de données dans le groupe, et elle indique l'incertitude dans l'estimation de la valeur vraie de la moyenne. La présente norme concerne uniquement les moyennes et la différence entre deux moyennes.

3.1.23**indice de température****IT**

valeur numérique de la température, en degrés Celsius, déterminée par l'essai lui-même

Note 1 à l'article: Cette caractéristique assignée repose sur une durée de vie de 20 000 h, sauf spécification contraire, fondée sur l'un des critères de fin de vie énumérés dans l'IEC 60216-2.

3.1.24**groupe de températures, <des éprouvettes>**

nombre d'éprouvettes exposées en même temps au vieillissement thermique à la même température dans la même étuve

Note 1 à l'article: En l'absence de tout risque d'ambiguïté, les groupes de températures ou les groupes d'essai peuvent être appelés simplement "groupes".

3.1.25**groupe d'essai, <des éprouvettes>**

nombre d'éprouvettes retirées en même temps d'un groupe de températures pour être soumises à l'essai destructif

Note 1 à l'article: En l'absence de tout risque d'ambiguïté, les groupes de températures ou les groupes d'essai peuvent être appelés simplement "groupes".

3.1.26**graphique d'endurance thermique**

graphique dans lequel le logarithme du temps pour atteindre un point limite spécifié, lors d'un essai d'endurance thermique, est tracé en fonction de l'inverse de la température thermodynamique (absolue) d'essai

3.1.27**papier pour graphique d'endurance thermique**

papier graphique comportant une échelle de temps logarithmique en ordonnée et des valeurs inversement proportionnelles à la température thermodynamique (absolue) d'essai en abscisse

Note 1 à l'article: L'ordonnée est généralement graduée en puissances de dix (10 h à 100 000 h constitue souvent une échelle pratique). L'abscisse est généralement graduée en échelle de température (Celsius) non linéaire, la température augmentant de la gauche vers la droite.

3.1.28**groupe de durée, <des éprouvettes>**

tous les groupes d'essai retirés pour être soumis à l'essai au même moment

3.1.29**variance d'un groupe de données**

somme des carrés des écarts des données par rapport à un niveau de référence défini par un ou plusieurs paramètres, divisée par le nombre de degrés de liberté

Note 1 à l'article: Le niveau de référence peut être, par exemple, une valeur moyenne (1 paramètre) ou une droite (2 paramètres, dans le cas présent l'intersection avec l'axe de la variable indépendante et la pente).

3.2 Symboles et abréviations

Les symboles suivants sont utilisés dans les calculs des Articles 6, 7 et 12, ainsi que de l'Annexe A, l'Annexe B et l'Annexe C.

Symbole	Description	Article/ Paragraphe
a	Coefficient de régression: intersection de la droite de régression avec l'axe des x	6.4.4
b	Coefficient de régression: pente de la droite de régression par rapport à l'axe des y	6.4.4
b_r	Paramètre déduit de b pour calculer $\hat{Y}_c$	6.5.3
b_p	Coefficient de régression pour les calculs d'essai destructif	6.3.5
c	Paramètre de calcul de χ^2	6.5.1
F	Rapport de variance distribuée F pour essai de linéarité	6.3.4, 6.5.2
g, h, i, j	Paramètres d'indexation pour les calculs de régression	6.3, 6.4
IDC	Intervalle de division par deux	7.1
k	Nombre de temps de vieillissement	6.1.1
N	Nombre total de valeurs de x_{ij}	6.4.3
n_i	Nombre de valeurs de x_{ij} d'un groupe de durée i	6.1.1
P	Signification statistique de la valeur d'une fonction d'essai statistique	Annexe A, Annexe B et Annexe C
p_e	Valeur de propriété de point limite	6.3
p_{gh}	Valeur de propriété h dans un groupe de températures g (groupe de durée i retenu par hypothèse)	6.3
$\bar{p}_g$	Valeur moyenne de propriété dans un groupe de températures g (groupe de durée i retenu par hypothèse)	6.3
q	Base de logarithmes dans le calcul de χ^2	6.5.1
r	Nombre de groupes de températures choisis dans le groupe de durée i	6.3.3
r^2	Carré du coefficient de corrélation	6.4.4
s^2	Variance (non-régression) totale des valeurs de x	6.5.2
s_{lg}^2	Variance de valeurs de propriété dans un groupe de températures g (groupe de durée i retenu par hypothèse)	6.3.3
s_a^2	Valeur de s^2 ajustée pour permettre une non-linéarité acceptable	6.5.2
s_r^2	Paramètre déduit de s^2 pour calculer $\hat{Y}_c$	6.5.3
t	Variable stochastique distribuée t selon la loi de Student	6.5.3
TC, TC _a	Limite inférieure de confiance de IT ou IT _a (voir s_a^2 ci-dessus)	7.1
$t_{p,N}$	Valeur de t à la probabilité p et à N degrés de liberté	6.5.3
x_{ij}	Valeur de x , numéro d'indice j , dans le groupe de durée i	6.3.5
$\bar{x}$	Moyenne générale des valeurs de x	6.4.3

Symbole	Description	Article/ Paragraphe
$\hat{X}, \hat{X}_c$	Estimation de x et de sa limite de confiance	6.5.3
y_i	Valeur de y pour un groupe de durée i	6.1.1
$\bar{y}$	Moyenne générale des valeurs de y	6.4.3
$\hat{Y}, \hat{Y}_c$	Estimation de y et de sa limite de confiance	6.5.3
z_{ij}	Température kelvin inverse pour ϑ_{ij}	6.1.1
$\mu_2(y)$	Moment centré d'ordre 2 des valeurs de y	6.4.3
ν	Nombre total des valeurs de propriété dans un groupe de durée (i retenu par hypothèse)	6.3.3
χ^2	Variable distribuée χ^2 pour essai (de Bartlett) d'égalité de variance	6.5.1
ϑ_{ij}	Température de vieillissement pour un groupe d'éprouvettes j dans un groupe de durée i	6.1.1
ϑ_0	273,15 K (correspond à 0 °C)	6.1.1
τ_i	Temps de vieillissement pour un groupe de durée i	6.1.1

4 Protocole FTFM

4.1 Principes du protocole FTFM

Le protocole FTFM (méthode de trame de durées fixes) repose sur le principe selon lequel le vieillissement thermique pour déterminer des caractéristiques d'endurance thermique est effectué sur un faible nombre de durées fixes, avec une plage de températures de vieillissement suffisante pour chaque durée afin d'assurer que les valeurs de propriétés déterminées atteignent le point limite d'une manière satisfaisante.

En cela, il diffère de la procédure de trame à température fixe de l'IEC 60216-1 dans laquelle un petit nombre de températures de vieillissement est utilisé et dans laquelle le vieillissement est effectué par essais à intervalles jusqu'à ce que le point limite soit atteint.

4.2 Objectif du protocole FTFM

Le protocole doit permettre d'obtenir les avantages suivants:

La détermination des caractéristiques d'endurance thermique est réalisée dans le cadre d'une durée prédéterminée fixe.

Cela permet de planifier bien plus efficacement la détermination, ce qui s'avère souvent être une source d'avantages commerciaux substantiels. La détermination simple de l'IT peut être réalisée en 5 kh, alors qu'avec la procédure de trame à température fixe, il peut être nécessaire de prolonger considérablement le vieillissement au-delà de cette durée avant d'atteindre le point limite à la température de vieillissement choisie la plus basse.

Chaque température jusqu'au point limite (c'est-à-dire la température moyenne d'un groupe de durée) dans la régression d'endurance thermique est fondée sur des températures choisies dans un groupe de durée. Le nombre de températures choisies peut être compris entre trois et le nombre de groupes de températures dans un groupe de durée.

Comme la plus grande source d'erreur systématique dans la procédure de trame à température fixe est l'erreur de température (erreur d'indication réelle ou erreur de distribution de température), les erreurs systématiques peuvent être considérablement réduites. Les erreurs qui en sont issues peuvent conduire à des résultats inexacts ou non valides par suite d'une évaluation incorrecte de la linéarité.

5 Détermination de l'IT

5.1 Procédures de vieillissement

Chaque procédure d'essai doit spécifier la forme, les dimensions et le nombre d'éprouvettes, les durées d'exposition, la propriété à laquelle l'IT est lié, les méthodes de sa détermination, le point limite, et la déduction des caractéristiques d'endurance thermique à partir des données expérimentales.

Il convient que la propriété choisie reflète si possible de manière significative une fonction du MIE dans la pratique. Un choix de propriétés est donné dans l'IEC 60216-2.

Pour fournir des conditions d'essai uniformes, il convient de spécifier le conditionnement des éprouvettes après leur retrait de l'étuve et avant le mesurage.

5.2 Températures et temps de vieillissement

Dans la majorité des cas, les caractéristiques d'endurance thermique exigées correspondent à une durée prévue de 20 000 h. Cependant, ces informations sont souvent nécessaires pour d'autres durées plus longues ou plus courtes. Dans le cas de durées plus longues, les durées données sous la forme d'exigences ou de recommandations dans le texte de la présente norme (par exemple, 5 kh pour la valeur minimale du temps de vieillissement le plus long) doivent être augmentées dans la même proportion par rapport à la durée de spécification réelle jusqu'à 20 kh.

Dans le cas de durées de spécification plus courtes, les durées concernées peuvent être diminuées dans les mêmes proportions, si cela est nécessaire.

Un soin particulier est nécessaire pour les durées de spécification très courtes, car les températures de vieillissement les plus élevées peuvent conduire à des zones de température qui incluent des points de transition, par exemple, la température de transition vitreuse ou la fusion partielle, ayant pour conséquence une non-linéarité. Des durées de spécification très longues peuvent aussi conduire à une non-linéarité.

Des recommandations pour les températures et temps de vieillissement sont données à l'Annexe D et représentées de la Figure E.3 à la Figure E.5.

5.3 Éprouvettes

5.3.1 Préparation

Les éprouvettes utilisées pour l'essai de vieillissement doivent constituer un échantillon aléatoire, extrait de la population étudiée, et doivent être traitées de manière uniforme.

Comme les conditions de traitement peuvent affecter de manière significative les caractéristiques de vieillissement de certains MIE, il faut assurer que, par exemple, l'échantillonnage, le découpage d'une feuille dans un rouleau support, le découpage d'un matériau anisotrope dans une direction donnée, le moulage, le durcissement et le préconditionnement sont réalisés de manière identique pour toutes les éprouvettes.

Les spécifications du matériau ou les normes pour les méthodes d'essai de diagnostic contiennent toutes les instructions nécessaires à la préparation des éprouvettes.

L'épaisseur des éprouvettes fait partie, dans certains cas spécifiés de la liste des mesurages de propriétés prévus pour déterminer l'endurance thermique. Voir l'IEC 60216-2. Si ce n'est pas le cas, l'épaisseur doit être consignée. Certaines propriétés physiques sont sensibles à des variations même mineures de l'épaisseur de l'éprouvette. Dans ces cas, il peut être nécessaire de déterminer et de consigner l'épaisseur après chaque période de vieillissement, si cela est exigé dans la spécification concernée.

L'épaisseur est aussi importante parce qu'elle peut faire varier le taux de vieillissement. Les données de vieillissement des MIE de différentes épaisseurs ne sont pas toujours comparables. Par conséquent, il est possible d'assigner à un MIE plus d'une caractéristique d'endurance thermique déduite à partir du mesurage des propriétés pour différentes épaisseurs.

Les tolérances de dimensions d'éprouvette doivent être identiques aux tolérances normalement utilisées pour les essais généraux. S'il est nécessaire que les dimensions d'éprouvette aient des tolérances inférieures à celles normalement utilisées, ces tolérances spéciales doivent être indiquées.

Les mesurages de sélection assurent que les éprouvettes sont de qualité uniforme et caractéristiques du MIE à soumettre à l'essai.

5.3.2 Nombre d'éprouvettes

L'exactitude des résultats d'essai d'endurance dépend en grande partie du nombre d'éprouvettes vieilles pour chaque température.

Le nombre total d'éprouvettes (N) est déduit de la façon suivante:

$$N = a \times b \times c + d$$

où

- a est le nombre d'éprouvettes dans un groupe d'essai soumis à un traitement identique, pour une température donnée, et éliminé après la détermination de la propriété (généralement cinq);
- b est le nombre de traitements, c'est-à-dire le nombre total de températures d'exposition, pour une durée donnée;
- c est le nombre de niveaux de temps de vieillissement;
- d est le nombre d'éprouvettes du groupe utilisé pour établir la valeur initiale de la propriété. Il est d'usage de choisir $d = 2a$ si le critère de diagnostic est une variation exprimée en pour-cent de la propriété en fonction de son niveau initial. Si le critère est un niveau absolu de propriété, d est généralement la valeur zéro, sauf s'il est exigé de consigner la valeur initiale.

Il est de bon usage de préparer des éprouvettes supplémentaires, ou au moins de fournir une réserve du lot de matériau d'origine à partir duquel de telles éprouvettes peuvent être préparées par la suite. De cette manière, tout vieillissement à partir d'éprouvettes supplémentaires exigé en cas de complications imprévues introduit un risque minimal de production de différences systématiques entre les groupes d'éprouvettes. Ces complications peuvent survenir, par exemple, si la relation d'endurance thermique devient non linéaire ou si les éprouvettes sont perdues en raison d'un emballement thermique dans une étuve.

5.4 Essais de diagnostic

Si des spécifications de matériau IEC sont disponibles, les exigences relatives à la propriété en matière de limites inférieures d'acceptation des valeurs d'IT sont généralement mentionnées. Si ces spécifications de matériau ne sont pas disponibles, un choix de propriétés et de méthode d'évaluation d'endurance thermique est donné dans l'IEC 60216-2.

Si une telle méthode ne peut pas être identifiée, il convient d'utiliser une norme internationale, nationale ou institutionnelle, voire une méthode spécialement conçue, dans cet ordre de préférence. Dans ce cas, l'essai de diagnostic doit être noté dans le rapport, y compris la propriété, la procédure de mesure et le point limite.

5.5 Choix des points limites

L'endurance thermique des MIE peut être caractérisée par des données d'endurance différentes (déduites de l'utilisation de propriétés et/ou de points limites différents), afin de faciliter le choix approprié du matériau en fonction de son utilisation particulière. Voir l'IEC 60216-2.

Le point limite peut être défini de deux manières différentes:

- a) sous forme de pourcentage d'augmentation ou de diminution de la valeur mesurée de la propriété par rapport au niveau d'origine. Cette approche permet des comparaisons entre MIE, mais constitue une relation moins riche que celle proposée en b) pour ce qui concerne les valeurs de la propriété exigées en service normal. Pour la détermination de la valeur initiale, voir 5.6;
- b) sous forme d'une valeur fixe de la propriété. Cette valeur peut être choisie en fonction des exigences correspondant à une utilisation normale. Les points limites correspondant aux essais d'épreuve sont majoritairement donnés sous forme de valeurs fixes de la propriété.

Il convient de choisir le point limite pour indiquer le degré de détérioration du MIE dont l'aptitude à supporter une contrainte rencontrée en service réel a diminué. Il convient que le degré de détérioration indiqué sous forme de point limite pour l'essai corresponde à une valeur admissible du matériau pour laquelle la sécurité souhaitée dans la pratique est assurée.

5.6 Détermination de la valeur de propriété initiale

Choisir les éprouvettes pour déterminer la valeur initiale de la propriété afin de constituer un sous-ensemble aléatoire d'éprouvettes préparées pour le vieillissement. Avant de déterminer la valeur de propriété, ces éprouvettes doivent être conditionnées, pendant deux jours (48 ± 6) h, par exposition au niveau le plus bas de température de vieillissement prévu pour l'essai (voir 5.2).

NOTE Dans certains cas (par exemple, pour des éprouvettes très épaisses), des durées supérieures à deux jours peuvent être utiles pour déterminer une valeur stable.

Sauf spécification contraire indiquée dans la méthode de détermination de la propriété de diagnostic (par exemple, parties relatives aux spécifications de matériaux qui traitent des méthodes d'essai ou méthode indiquée dans l'IEC 60216-2), la valeur initiale est la moyenne arithmétique des résultats d'essai.

5.7 Conditions de vieillissement

5.7.1 Étuves de vieillissement

Pendant toute la période de vieillissement thermique, les étuves de vieillissement doivent maintenir, pour la partie qui concerne l'espace de travail où sont placées les éprouvettes, une température donnée avec les tolérances indiquées dans la série IEC 60216-4. Sauf spécification contraire, l'IEC 60216-4-1 doit s'appliquer. L'IEC 60216-4-2 et l'IEC 60216-4-3 peuvent s'appliquer dans des cas particuliers.

Il convient que la circulation de l'air dans l'étuve et l'échange d'air soient adéquats pour d'assurer que le taux de dégradation thermique n'est pas influencé par l'accumulation des produits de décomposition ou par la raréfaction de l'oxygène (voir 5.7.2).

5.7.2 Conditions d'environnement

Sauf spécification contraire, le vieillissement doit être réalisé dans des étuves qui fonctionnent dans l'atmosphère normale de laboratoire. Cependant, pour certains MIE très sensibles à l'humidité dans les étuves, des résultats plus fiables sont obtenus si l'humidité absolue de la chambre de l'étuve de vieillissement est maintenue à une valeur égale à l'humidité absolue de l'atmosphère normalisée B conformément à l'IEC 60212. Ces conditions, ou d'autres conditions particulières, doivent alors être consignés.

NOTE Les effets des conditions particulières d'environnement comme l'extrême humidité, la contamination chimique ou les vibrations peuvent, dans de nombreux cas, être évalués de manière plus appropriée par des essais de systèmes d'isolation. Bien que les conditions d'environnement, l'influence d'atmosphères autres que l'air et l'immersion dans des liquides comme l'huile puissent être importantes, elles ne font pas l'objet du présent document.

5.7.3 Conditions de mesure de propriété

Sauf spécification contraire, les éprouvettes doivent être conditionnées avant le mesurage, et mesurées dans les conditions indiquées dans la spécification normalisée des matériaux.

5.8 Procédure de vieillissement

Établir un plan d'essai, par exemple celui qui est indiqué à l'Annexe D.

Préparer un nombre donné d'éprouvettes en suivant les instructions du 5.3.2. Si cela est nécessaire, déterminer la valeur initiale de la propriété conformément au 5.6. Répartir les éprouvettes aléatoirement en groupes d'essai appropriés au plan d'essai. Placer les nombres appropriés de groupes dans chacune des étuves à la température exigée.

Comme cela est indiqué à l'Annexe D (NOTE 2), il est recommandé de préparer des groupes d'éprouvettes supplémentaires si les caractéristiques d'endurance thermique du MIE ne correspondent pas aux recommandations de base de l'Annexe D.

Après chaque temps de vieillissement, choisir un groupe de manière aléatoire à partir de chacune des étuves de vieillissement appropriées et le retirer de l'étuve. Permettre le refroidissement jusqu'à température ambiante sauf spécification contraire. Lorsque spécifié, conditionner ce groupe d'éprouvettes pendant la durée spécifiée dans l'atmosphère définie et soumettre les éprouvettes à l'essai à l'aide de la procédure d'essai spécifiée.

Il est recommandé d'effectuer les calculs à mesure que les données sont disponibles, en particulier pour la durée d'exposition la plus courte.

Évaluer les résultats conformément à l'Article 6.

6 Procédures de calcul

6.1 Principes généraux

6.1.1 Calcul de l'endurance thermique

Les procédures et instructions générales de calcul données en 6.4 reposent sur les principes établis dans l'IEC 60493-1, modifiés comme suit:

- la relation entre la moyenne des inverses (x) des températures thermodynamiques (absolues) pour lesquelles le point limite spécifié est atteint et le logarithme (y) du temps de vieillissement est linéaire;
- les valeurs des écarts des valeurs de x à partir de la relation linéaire sont normalement distribuées avec une variance indépendante du temps de vieillissement.

Les données utilisées dans les procédures générales de calcul sont obtenues à partir des données expérimentales par un calcul préliminaire. Les données de calcul comprennent les valeurs de z , y , n et k , où

$z_{ij} = 1 / (g_{ij} + \theta_0)$ = inverse de la valeur thermodynamique en K de la température de vieillissement g_{ij} en °C;

$y_i = \log \tau_i$ = logarithme de la valeur du temps de vieillissement en h (τ_i);

n_i = nombre de valeurs z dans le nombre de groupes i vieillis pendant une durée τ_i ;

k = nombre de temps de vieillissement ou de groupes de valeurs x .

NOTE Tout nombre peut servir de base pour les logarithmes, à condition d'observer une cohérence dans les calculs. L'utilisation de logarithmes naturels (base e) est utile, puisque la plupart des langages de programmation et des calculateurs scientifiques ont cette possibilité.

6.1.2 Valeur de propriété – transformée de température équivalente (Calcul de température de vieillissement hypothétique déduit à partir de la valeur d'une propriété)

Lorsque des critères d'essai destructif sont utilisés, chaque éprouvette est détruite en obtenant une valeur de propriété: pour cette raison, les valeurs de durée et/ou de température nécessaires pour atteindre le point limite ne peuvent pas être mesurées directement. Pour permettre l'obtention des estimations de durées jusqu'au point limite, les hypothèses suivantes sont formulées: à proximité du point limite (pour un temps de vieillissement donné):

- la relation entre les valeurs moyennes de la propriété et les inverses des températures thermodynamiques est approximativement linéaire;
- les valeurs des écarts entre les valeurs de la propriété et cette relation linéaire sont normalement distribuées avec une variance indépendante de la température;
- les courbes de propriété en fonction de l'inverse de la température (thermodynamique) de vieillissement pour les éprouvettes individuelles sont des lignes droites parallèles à la droite qui représente la relation a) ci-dessus.

Pour l'application de ces hypothèses, une courbe de vieillissement est tracée pour les données obtenues à chacun des temps de vieillissement. La courbe pour chacun des temps de vieillissement est obtenue en traçant la valeur moyenne de propriété pour chaque groupe d'éprouvettes par rapport à l'inverse de leur température (thermodynamique) de vieillissement. Si cela est possible, le vieillissement est conduit à des températures de vieillissement suffisamment hautes et basses pour qu'au moins une des moyennes de groupe soit au-dessus du niveau de point limite et qu'au moins une des moyennes de groupe soit au-dessous du niveau de point limite. Une zone approximativement linéaire de cette courbe est tracée (incluant au moins trois moyennes de groupe) à proximité du point limite (Figure E.1).

NOTE Une échelle de température non linéaire graduée en °C est généralement utilisée comme axe des abscisses (voir la Figure E.1).

Un essai statistique (essai F) est effectué pour déterminer si les écarts de linéarité de la zone choisie sont acceptables (voir 6.3.3). S'ils le sont, les points qui représentent les propriétés de chacune des éprouvettes sont alors tracés sur le même graphique. Une droite parallèle à la droite de vieillissement est tracée pour chaque point des données d'éprouvette: l'estimation de la valeur de x pour cette éprouvette est alors la valeur inverse de la température (thermodynamique) qui correspond à l'intersection de cette droite avec la ligne de point limite (Figure E.1).

Avec les limitations spécifiées en 6.3.5, une extrapolation du graphique de la valeur moyenne linéaire jusqu'au point limite est admise.

Les opérations ci-dessus sont réalisées numériquement dans les calculs décrits en 6.3.4 et 6.3.5.

6.2 Précision des calculs

De nombreuses étapes de calcul impliquent la sommation des différences de nombres ou des carrés de ces différences, alors que les différences peuvent être faibles par rapport aux nombres. Dans ces cas, il est nécessaire de réaliser les calculs avec une précision interne d'au moins six chiffres significatifs, et plus de préférence, si une précision de trois chiffres doit être atteinte dans le résultat. Compte tenu de la nature répétitive et fastidieuse des calculs, il est fortement recommandé de les effectuer à l'aide d'un calculateur programmable ou d'un ordinateur, auquel cas il est facile d'obtenir une précision interne de dix chiffres ou plus.

6.3 Dédution des températures équivalentes aux valeurs de propriété

6.3.1 Généralités

Dans les groupes d'éprouvettes vieilles, mettre en œuvre pour chaque durée τ_i les procédures conformément aux dispositions spécifiées du 6.3.2 au 6.3.4.

6.3.2 Calculs préliminaires

Calculer la valeur de y qui correspond à chaque temps de vieillissement τ

$$y_i = \log \tau_i \quad (1)$$

Calculer la valeur de z qui correspond à chaque température de vieillissement ϑ

$$z_{ij} = 1 / (\vartheta_{ij} + \vartheta_0) \quad (2)$$

6.3.3 Calculs de régression (propriété sur la température)

Calculer la valeur moyenne de la propriété pour le groupe de données obtenu à chaque température de vieillissement [voir l'Équation (3)] et la valeur correspondante de z . Tracer ces valeurs sur un graphique avec la valeur de propriété p en ordonnée et z en abscisse (voir la Figure E.1).

Tracer de façon visible une courbe régulière qui relie les points moyens de la propriété.

Choisir une plage de températures dans laquelle la courbe ainsi tracée est approximativement linéaire (voir 6.3.4). Assurer que cette plage de températures comprend au moins trois valeurs moyennes de la propriété avec au moins un point de chaque côté de la ligne de point limite $p = p_e$. Si ce n'est pas le cas, et que d'autres mesurages à des températures plus élevées ne peuvent être effectués (par exemple, parce qu'il ne reste aucune éprouvette), une petite extrapolation est admise sous réserve de respecter les conditions du 6.3.4.

L'indice i est omis des expressions du 6.3.3 et du 6.3.4 afin d'éviter la confusion des différents indices à l'impression. Les calculs spécifiés dans ces paragraphes doivent être effectués séparément avec les données de chaque temps de vieillissement.

Soit r le nombre de valeurs moyennes choisies (et les groupes de valeurs correspondants), z_g l'inverse de chaque température de vieillissement et p_{gh} , les valeurs de propriété individuelles, où

$g = 1 \dots r$ est le nombre séquentiel du groupe choisi vieilli à la température ϑ_g ;

$h = 1 \dots n_g$ est le nombre séquentiel de la valeur de propriété dans le nombre de groupes g ;

n_g est le nombre de valeurs de propriété dans le nombre de groupes g .

NOTE Dans la plupart des cas, le nombre n_g d'éprouvettes soumises à l'essai pour chaque température d'essai est identique, mais ne constitue pas une condition nécessaire, et le calcul peut être effectué avec différentes valeurs de n_g pour différents groupes.

Calculer la valeur moyenne $\bar{p}_g$ et la variance s_{1g}^2 pour chaque groupe choisi de valeurs de propriété.

$$\bar{p}_g = \sum_{h=1}^{n_g} p_{gh} / n_g \quad (3)$$

$$s_{1g}^2 = \left(\sum_{h=1}^{n_g} p_{gh}^2 - n_g \bar{p}_g^2 \right) / (n_g - 1) \quad (4)$$

Faire les calculs suivants:

$$v = \sum_{g=1}^r n_g \quad (5)$$

$$\bar{z} = \sum_{g=1}^r z_g n_g / v \quad (6)$$

$$\bar{p} = \sum \bar{p}_g n_g / v \quad (7)$$

Calculer les coefficients de l'équation de régression, $p = a_p + b_p z$

$$a_p = \bar{p} - b_p \bar{z} \quad (8)$$

$$b_p = \frac{\left(\sum_{g=1}^r n_g z_g \bar{p}_g - \nu \bar{z} \bar{p} \right)}{\left(\sum_{g=1}^r n_g z_g^2 - \nu \bar{z}^2 \right)} \quad (9)$$

Calculer la variance combinée dans les groupes de propriétés

$$s_1^2 = \sum_{g=1}^r (n_g - 1) s_{1g}^2 / (\nu - r) \quad (10)$$

Calculer la variance pondérée des écarts des moyennes de groupes de propriétés par rapport à la droite de régression

$$s_2^2 = \sum n_g (\bar{p}_g - \hat{p}_g)^2 / (r - 2) \quad (11)$$

où

$$\hat{p}_g = a_p + b_p z_g \quad (12)$$

Ce qui peut aussi s'exprimer comme

$$s_2^2 = \left[\left(\sum_{g=1}^r n_g \bar{p}_g^2 - \nu \bar{p}^2 \right) - b_p \left(\sum_{g=1}^r n_g z_g \bar{p}_g - \nu \bar{z} \bar{p} \right) \right] / (r - 2) \quad (13)$$

6.3.4 Essai de linéarité

Réaliser l'essai F pour une non-linéarité au niveau de signification statistique de 0,05 en calculant

$$F = s_2^2 / s_1^2 \quad (14)$$

Si la valeur calculée de F dépasse la valeur F_1 du tableau avec des degrés de liberté $f_n = r - 2$ et $f_d = \nu - r$ (voir le Tableau C.3), modifier le choix du 6.3.3 et répéter les calculs.

S'il n'est pas possible de satisfaire à l'essai F au niveau de signification statistique de 0,05 avec $r \geq 3$, effectuer l'essai F à un niveau de signification statistique de 0,005, en comparant la valeur calculée de F à la valeur F_2 du tableau avec des degrés de liberté $f_n = r - 2$ et $f_d = \nu - r$ (voir le Tableau C.4).

Si l'essai est satisfaisant à ce niveau, les calculs peuvent être poursuivis, mais l'ajustement de l'IT selon l'Équation (48) du 7.2.2 n'est pas admis.

Si l'essai F au niveau de signification statistique de 0,005 (c'est-à-dire $F \leq F_2$) ne peut pas être satisfait, ou si les points de propriété tracés en 6.3.3 sont tous du même côté de la ligne de point limite, une extrapolation peut être admise sous réserve de respecter la condition suivante:

Si l'essai F au niveau de signification statistique de 0,05 peut être satisfait pour une plage de valeurs (avec $r \geq 3$) où toutes les valeurs moyennes $\bar{p}_g$ sont du même côté de la valeur de point limite p_e , une extrapolation peut être effectuée à condition que la valeur absolue de la différence entre la valeur de point limite p_e et la valeur moyenne $\bar{p}_g$ la plus proche du point limite (généralement $\bar{p}_r$) soit inférieure au quart de la valeur absolue de la différence $(\bar{p}_1 - \bar{p}_r) \cdot$

À la Figure E.1, si p_e était de 5 000, le calcul serait le suivant:

$\bar{p}_1$ est la valeur de la moyenne du groupe de données le plus à gauche dans la case de sélection, $\bar{p}_r$ celle du groupe de données le plus à droite. La condition est alors $|\bar{p}_r - p_e| \leq |\bar{p}_1 - \bar{p}_r| / 4$. Les traits verticaux de délimitation impliquent que la valeur considérée est en valeur absolue.

Dans ce cas, les calculs peuvent être poursuivis, mais l'ajustement de l'IT selon l'Équation (48) du 7.2.2 n'est à nouveau pas admis.

6.3.5 Estimation des températures de point limite équivalentes aux valeurs de propriété

Pour chacune des valeurs de propriété h dans chacun des groupes choisis g , calculer la température inverse de point limite équivalente:

$$x_{ij} = z_g - \frac{(p_{gh} - p_e)}{b_p} \quad (15)$$

et
$$n_i = \nu \quad (16)$$

où

$j = 1 \dots n_i$ est le nombre séquentiel de la valeur x dans le groupe des valeurs d'estimation de x pendant le temps de vieillissement τ_i et z_g est l'inverse de la température de vieillissement;

Les valeurs n_i de x_{ij} sont les valeurs de température inverse de point limite à utiliser dans les calculs du 6.4.

6.4 Analyse de régression (température en fonction du temps)

6.4.1 Généralités

Lorsque la détermination fait partie de la détermination de l'ITR (voir l'Article 3), les résultats de certaines équations sont exigés en données d'entrée à la fois pour le MIE de référence et le MIE candidat.