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REDLINE VERSION

INTERNATIONAL STANDARD

Test procedure for the determination of the temperature index of enamelled and tape wrapped winding wires

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

TEST PROCEDURE FOR THE DETERMINATION OF THE TEMPERATURE INDEX OF ENAMELLED AND TAPE WRAPPED WINDING WIRES

FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

International Standard IEC 60172 has been prepared by IEC Technical Committee 55: Winding wires.

This fifth edition cancels and replaces the fourth edition published in 2015. This edition constitutes a technical revision.

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

– revision of 3.1, definition of thermal index;
– revision of 3.3, time to failure;
– revisions to 5.1.1 for clarity and to reduce the range wire size range to which the test applies;
– revisions to 5.1.2 for tape wrapped round and enamelled or tape wrapped rectangular wire for clarity;
– revision to Clause 9 to add the correlation coefficient, r to the report.

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

FDIS	Report on voting
55/1876/FDIS	55/1893/RVD

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

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

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://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- withdrawn,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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TEST PROCEDURE FOR THE DETERMINATION OF THE TEMPERATURE INDEX OF ENAMELLED AND TAPE WRAPPED WINDING WIRES

1 Scope

This International Standard specifies, in accordance with the provisions of IEC 60216-1, a method for evaluating the temperature index of enamelled wire, varnished or unvarnished with an impregnating agent, and of tape wrapped round and rectangular wire, in air at atmospheric pressure by periodically monitoring changes in response to AC proof voltage tests. This procedure does not apply to fibre-insulated wire or wire covered with tapes containing inorganic fibres.

NOTE The data obtained according to this test procedure provide the designer and development engineer with information for the selection of winding wire for further evaluation of insulation systems and equipment tests.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

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

3.1
temperature index
TI
~~numerical value of the Celsius temperature expressed in degrees Celsius characterizing the thermal capability of an insulating material or an insulation system~~

number which permits comparison of the temperature/time characteristics of an electrical insulating material, or a simple combination of materials, based on the temperature in degrees Celsius which is obtained by extrapolating the Arrhenius plot of life versus temperature to a lifetime of 20 000 h

~~Note 1 to entry: In case of insulating materials, the temperature index is derived from the thermal endurance relationship at a given time, normally 20 000 hours. It may be used as basis for determination of the material's temperature class.~~

Note ~~2~~ 1 to entry: In case of insulation systems, the temperature index may be derived from known service experience or from a known comparative functional evaluation of an evaluated and established reference insulation system as basis.

[SOURCE: IEC 60050-212:2010, 212-12-11 modified by merging Note 1 into the definition, and to specify a lifetime of 20 000 h.]

3.2
specimen failure time
number of hours at the exposure temperature that have elapsed at the time a specimen fails the proof test

3.3
time to failure
~~*L*~~
number of hours to failure calculated from the specimen mean value or logarithmic mean value failure times for a set of specimens at one exposure temperature, in accordance with 8.2

4 Summary of procedure

A set of specimens in accordance with Clause 5 is subjected to a testing cycle. This cycle consists of a ~~heat-storing~~ heat-exposure period at a temperature given in Clause 6, followed by a proof voltage test at room temperature in accordance with Clause 7.

This cycle is repeated until a sufficient number of specimens has failed. The time to failure is calculated in accordance with Clause 8. The test is carried out at three or more temperatures. A regression line is calculated in accordance with 8.4 and the time to failure values plotted on thermal endurance graph paper as a function of the exposure temperature.

The temperature in degrees Celsius, corresponding to the point of intersection of the regression line with the ordinate of 20 000 h endurance represents the temperature index of the winding wire under test.

5 Test specimens

5.1 Preparation

5.1.1 ~~Enamelled round wire with a nominal conductor diameter of 0,224 mm up to and including 2,65 mm~~ Enamelled non-tape wrapped round wire

~~The grade of insulation used for determining the thermal index shall be grade 2 or grade 2B for self-bonding winding wires.~~

~~Wire sizes 0,315 mm and 0,28 mm are permitted for use when the specification size range is limited to 0,50 mm and finer.~~

~~NOTE For round enamelled winding wires, in order to avoid undue fragility of the test specimen, experience has shown that nominal conductor diameters of 0,800 mm up to and including 2,65 mm are generally found convenient to handle and test.~~

This procedure applies to enamelled round wires that are not tape wrapped. The thermal index can be determined by evaluating enamelled non-tape wrapped round wire with a nominal conductor diameter of 0,224 mm up to and including 2,65 mm.

NOTE For round enamelled winding wires, experience has shown that nominal conductor diameters of 0,800 mm up to and including 1,60 mm are generally found convenient to handle and test.

Wires with a nominal conductor diameter between 0,280 mm and 0,500 mm are permitted for use when the specification range of diameters is limited to 0,500 mm and finer.

The grade of insulation used for determining the thermal index shall be grade 2 or grade 2B for self-bonding winding wires.

Specimens shall be prepared as follows:

a) A wire specimen approximately 400 mm in length shall be twisted together over a distance of 125 mm with a device as shown in Figure 1. The force (weight) applied to the wire pair while being twisted and the number of twists are specified in Table 1.

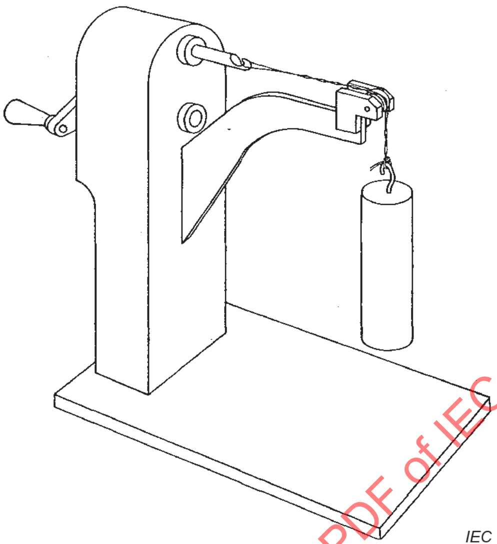


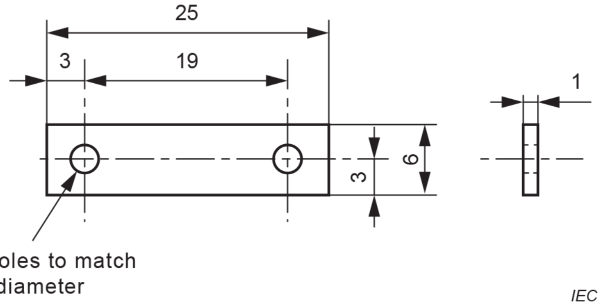
Figure 1 – Device used to form enamelled round wire test specimen

Table 1 – Force and number of twists for specimens

Nominal diameter mm		Force applied to wire pairs N	Number of twists per 125 mm
Over	**Up to and including**		
0,224	0,25	0,85	33
0,25	0,35	1,7	23
0,35	0,50	3,4	16
0,50	0,75	7,0	12
0,75	1,05	13,5	8
1,05	1,50	27,0	6
1,50	2,15	54,0	4
2,15	~~3,50~~ 2,65	108,0	3

b) Spacers may be prepared as shown in Figure 2. Such thermally stable insulating materials as ceramic or silicone glass fibre laminate may be used. The spacers are marked with a suitable identifying letter or number.

Dimensions in millimetres

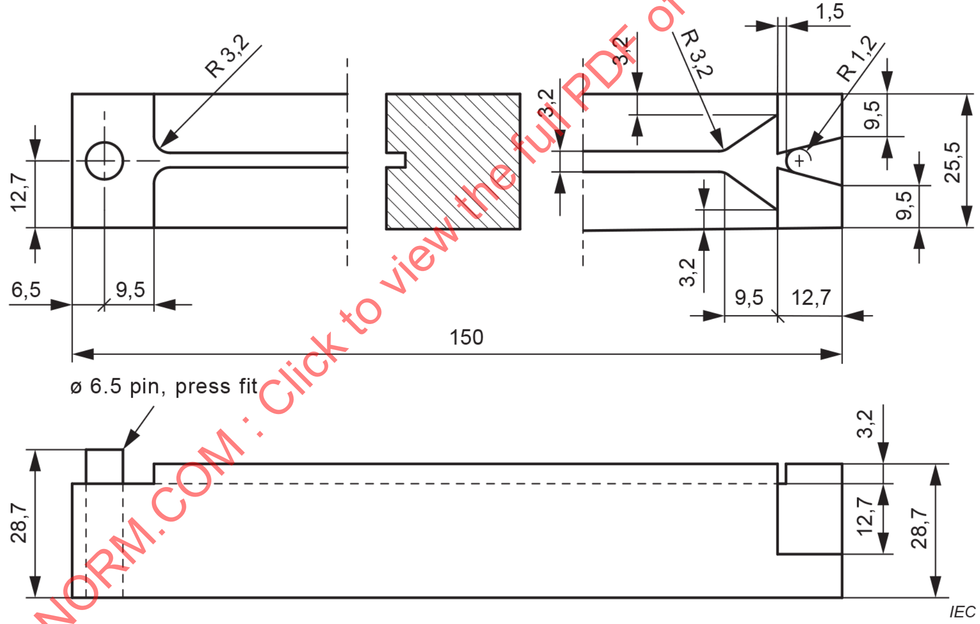


Material: Silicone glass laminate

Figure 2 – Spacer

c) The test specimens may be shaped in a jig, an engineering drawing of which is shown in Figure 3. A specimen is placed in the jig and a spacer, placed on the parallel leads of the twisted pair, is brought up to the face of the jig as shown in Figure 4. The leads are then bent parallel to hold the spacer in position. The forming jig provides more uniform test specimens. If a specimen holder is used, the spacers are unnecessary.

Dimensions in millimetres



R = Radius of bend

Figure 3 – Twist forming jig

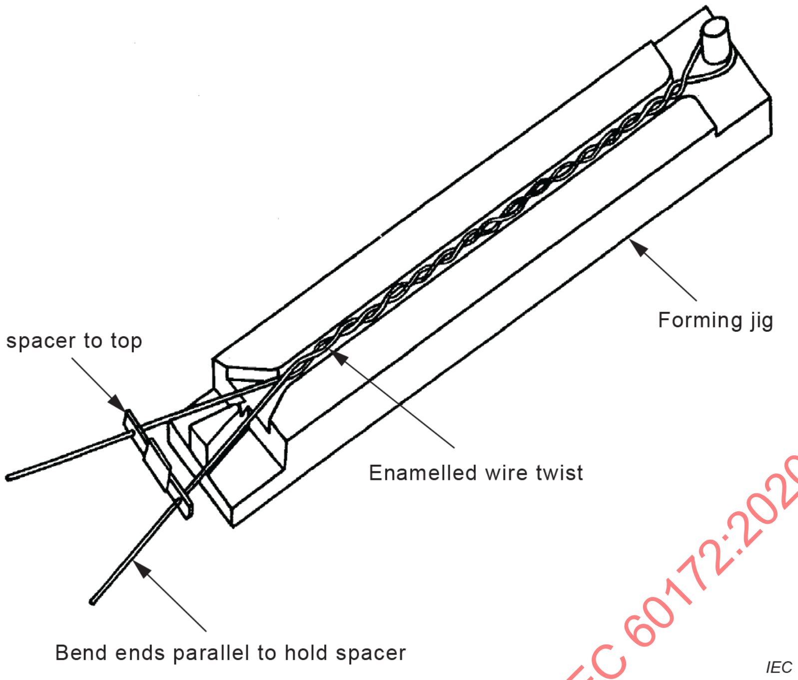


Figure 4 – Test specimen set up in forming jig

d) The loop at the end of the twisted section shall be cut at two places (not one) to provide the maximum spacing between the cut ends as shown in Figure 5. Any bending of the wires, at this end or the other untwisted end, to ensure adequate separation between the wires shall avoid sharp bends or damage to the insulation.

Figure 5 – Test specimen formed with loop cut

~~e)~~ In order to ensure homogeneity of the ~~batch~~ set of test specimens, it is recommended that test specimens be subjected to, and withstand without breakdown, a test voltage three times the value given in Table 2 for 1 s prior to starting thermal exposure cycling.

Table 2 – Proof voltage for round enamelled wire

Increase in diameter due to the insulation (mm)		Voltage (rms)
Over	**Up to and including**	
–	0,015	300
0,015	0,024	300
0,024	0,035	400
0,035	0,050	500
0,050	0,070	700
0,070	0,090	1 000
0,090	0,130	1 200

5.1.2 Tape wrapped round wire and enamelled or tape wrapped rectangular wire

~~NOTE This procedure applies to any convenient dimension of round or rectangular wire. However, selecting wires having dimensions that minimize the bending force needed to shape the test specimen will make the procedure easier to perform. Wire with high stiffness will yield specimens with poor wire-to-wire contact areas.~~

This procedure applies to any convenient dimension of tape wrapped round or tape wrapped or enamelled rectangular wire.

It is recommended to select a wire having dimensions that minimize the bending force necessary to shape the test specimen, since wire with high stiffness will yield specimens with poor wire-to-wire contact areas.

Specimens shall be prepared as follows:

a) Two straight specimens of wire each of 250 mm length shall be cut from the supply spool.
b) 10 mm to 15 mm of the insulation shall be removed from one end of each piece of wire to provide for electrical connection.
c) Each specimen shall be formed in a jig, as shown in Figure 6. This produces a straight centre section of about 150 mm with bent ends, which provide the necessary flare at both ends of the final specimen.

Dimensions in millimetres

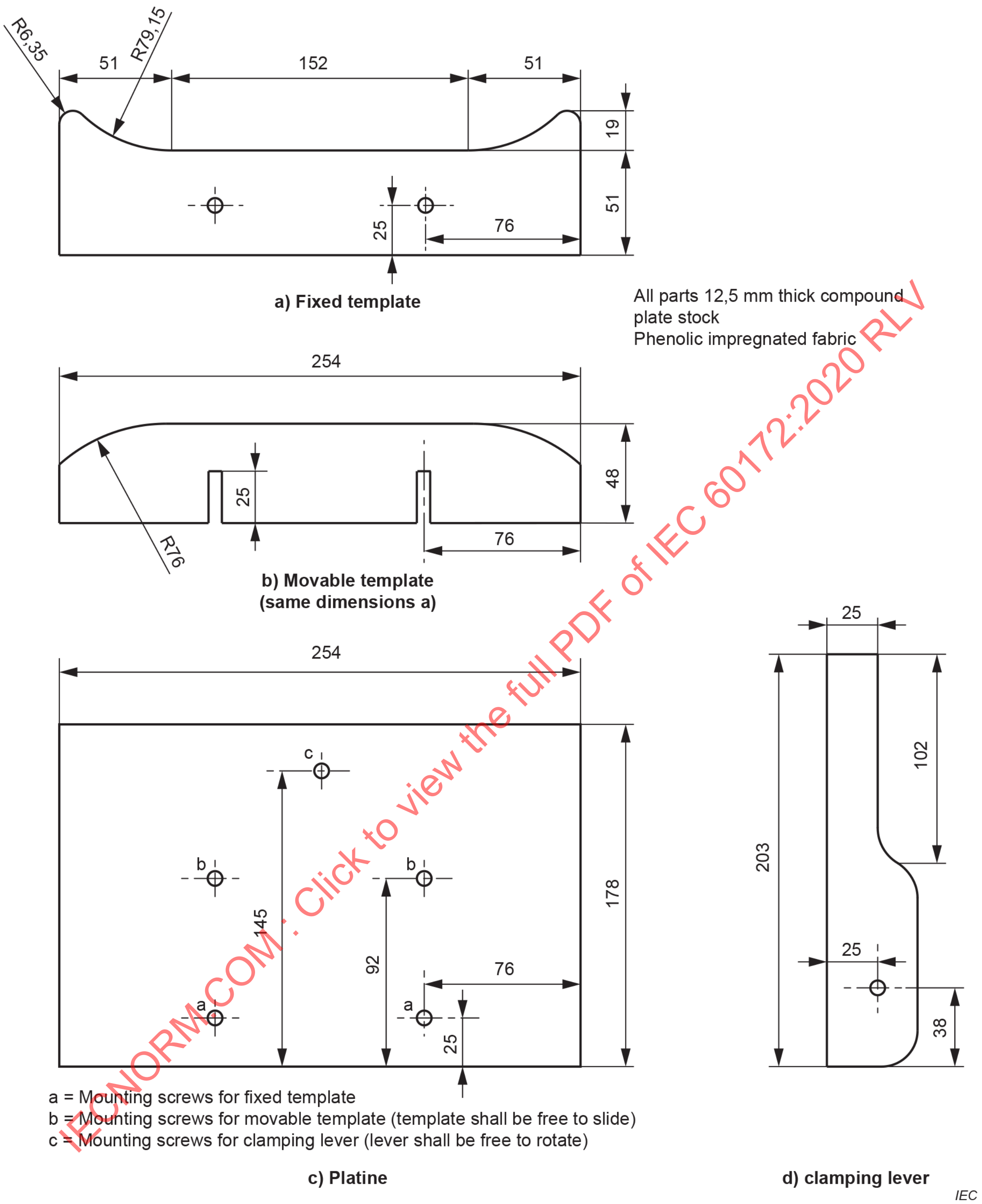


Figure 6 – Jig for bending large magnet wire, dielectric test specimen

d) The two formed specimens shall be placed together back-to-back and tightly wrapped with glass yarn over the straight centre section of the specimen, as shown in Figure 7.

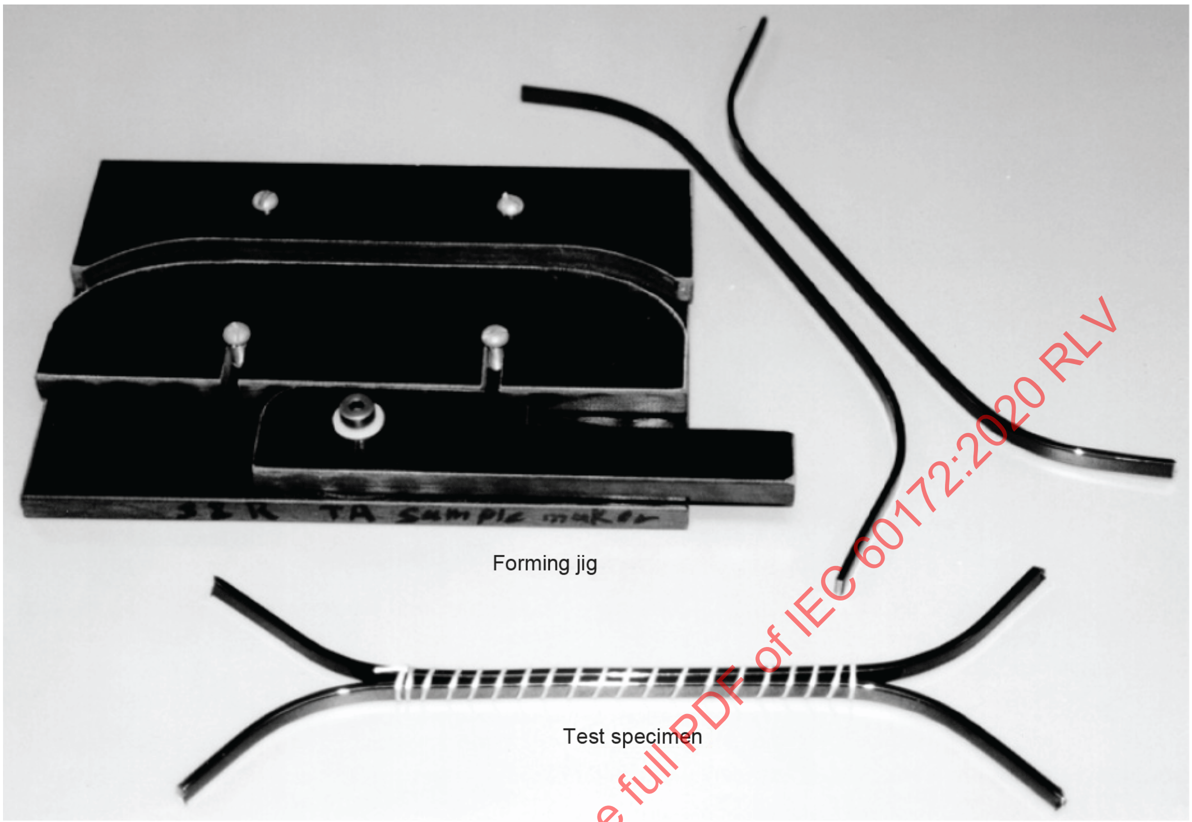


Figure 7 – Forming jig and test specimen

Care shall be taken that the centre section shows a close contact between the two pieces.

After tying, further bending of the ends shall be avoided. Pre-annealing of the specimen prior to testing or impregnating will remove stress and craze marks and therefore may be desirable with certain material.

e) Prior to ~~testing~~ starting the thermal exposure cycles, the specimen shall be proof-tested at 1 000 V AC.

5.2 Varnish impregnation

~~Experience has shown that~~ Insulated wire according to IEC 60317 and impregnating agents according to IEC 60455-3-5 or IEC 60464-3-2 can affect one another during the thermal ageing process.

NOTE 1 Testing varnished specimens will allow for evaluation of the compatibility of the wire insulation with an impregnating agent. Thus, the temperature indices of different combinations can be compared.

Interaction between wire insulation and such agent may increase or decrease the relative thermal life of this combination compared with the life of the wire tested without impregnation. Therefore, with impregnated specimens, this test procedure may give an indication of the thermal endurance of a combination of wire insulation and impregnating agent.

If such impregnation is required, the following procedure shall be applied:

With the specimen in the vertical position, it shall be immersed in the impregnating agent for (60 ± 10) s ~~(see note)~~. It shall be removed slowly and uniformly at a rate of about 1 mm/s. It shall be drained horizontally for 10 min to 15 min and cured horizontally according to the manufacturer's recommendation or to an agreed schedule. If more than one treatment is to be given, immerse, drain and cure the specimen vertically reversing the specimen for each subsequent treatment.

NOTE 2 Some impregnating agents, such as high viscosity or thixotropic products require alternative processing methods.

5.3 Notes on number of test specimens

The accuracy of the test results depends largely upon the number of test specimens aged at each temperature. A greater number of test specimens is required to achieve an acceptable degree of accuracy if there is a wide spread in results among the specimens exposed at each temperature.

Experience has shown that twenty specimens without impregnation and ten specimens with impregnation give results with an acceptable tolerance. A minimum of ten specimens shall be used.

5.4 Specimen holder

5.4.1 For specimens according to 5.1.1

Since individual handling of the twisted specimens may result in premature failures, it is recommended that the specimens be placed in a suitable holder, as shown in Figure 8. The holder should be designed in a manner that will protect the twisted specimens from external mechanical damage and warping. The holder will be so constructed as to allow the ends of the twist to protrude from the holder to make electrical connections for ~~the~~ proof testing ~~as shown in Figure 9~~. The holder shall be designed for at least ten specimens to decrease handling time.

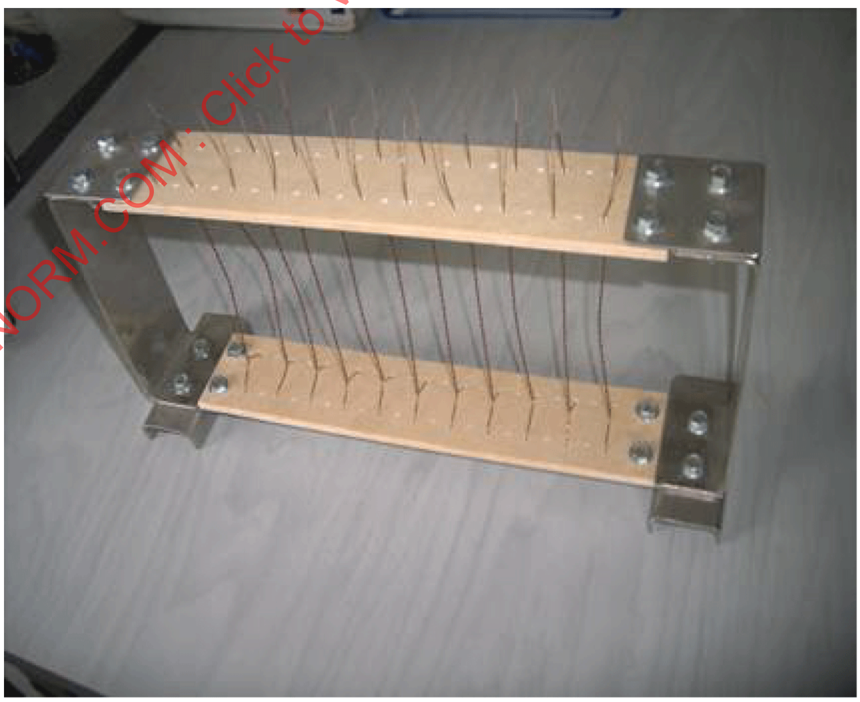


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Figure 8 – Specimen holder

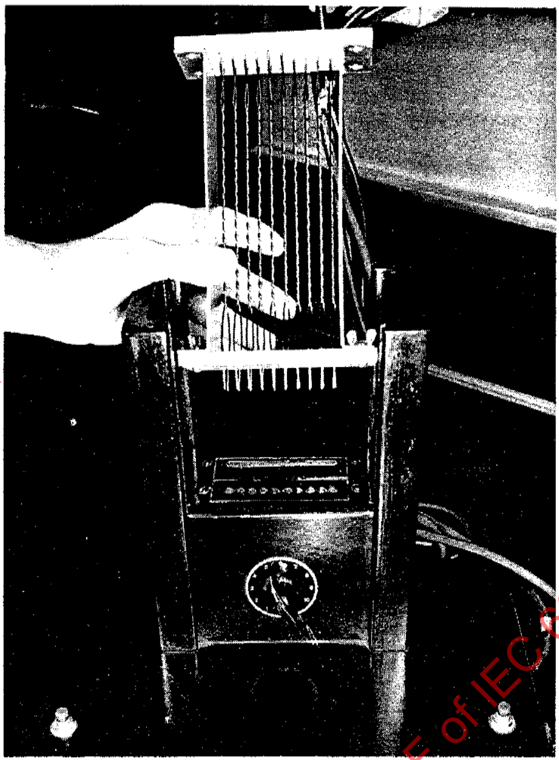

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Figure 9 – Specimen holder and electrical connection fixture

5.4.2 For specimens according to 5.1.2

The specimen shall be hung in the oven. No special holder is required.

6 Temperature exposure

Recommended temperatures to which the test specimens are subjected are given in this Clause 6.

Test specimens shall be subjected to the temperatures given in this Clause 6.

In Table 3, the recommended The test temperature and time of exposure in each cycle are given in Table 3. A test cycle is defined as one exposure to a high temperature followed by one proof-voltage test at room temperature (20 – 30 °C). The test specimens shall be placed directly into and removed from the ageing ovens without controlling the heating or cooling rate.

The ovens should shall be heated to the proper temperatures before the specimens are subjected to the exposure temperature.

The specimens should shall be aged in a forced air circulation oven which is capable of maintaining the temperature of the specimens under test within 2 °C of the selected exposure temperature.

The exposure times are selected to subject the test specimens to approximately 10 cycles at each temperature before the time to failure is reached.

Table 3 – Recommended exposure times in days per cycle

Exposure or ageing temperature (°C)	Estimated temperature index						
	105-109	**120-130**	**150-159**	**180-189**	**200-209**	**220-239**	**240-249**
320	–	–	–	–	–	–	1
310	–	–	–	–	–	–	2
300	–	–	–	–	–	1	4
290	–	–	–	–	–	2	7
280	–	–	–	–	1	4	14
270	–	–	–	–	2	7	28
260	–	–	–	1	4	14	49
250	–	–	–	2	7	28	–
240	–	–	–	4	14	49	–
230	–	–	–	7	28	–	–
220	–	–	1	14	49	–	–
210	–	1	2	28	–	–	–
200	–	2	4	49	–	–	–
190	1	4	7	–	–	–	–
180	2	7	14	–	–	–	–
170	4	14	28	–	–	–	–
160	7	28	49	–	–	–	–
150	14	49	–	–	–	–	–
140	28	–	–	–	–	–	–
130	49	–	–	–	–	–	–
120	–	–	–	–	–	–	–

~~NOTE The recommendations in Table 3 differ from those in IEC 60216-3 but have been found to be more suitable for enamelled wires.~~

Thermal endurance values obtained from test specimens subjected to an average of less than eight or more than twenty cycles at the exposed temperature may not be reliable and should not be used to predict the temperature rating of the enamelled wire. Therefore, a shorter or longer cycle time than those given in Table 3 may be chosen for certain exposure temperatures, to ensure that the average number of cycles to failure falls within this range.

After the specimens have been subjected to a particular cycle, the time may be appropriately increased or decreased to control the number of cycles required to reach the time to failure.

Test specimens ~~should~~ shall be exposed to a minimum of three and preferably four exposure temperatures. The lowest temperature, recommended at 20 °C above the desired thermal class, ~~should~~ shall be one which results in a time frame to failure of more than 5 000 h. The highest exposure temperature shall have a value of at least 100 h to be considered a valid data point. Exposure temperatures should not be more than 20 °C apart. The accuracy of the temperature index predicted from the results will improve as the exposure temperature approaches the temperature to which the insulation is exposed in service.

7 Test voltage and its application

The voltage to be applied shall be an AC voltage and shall have a nominal frequency of 50 Hz or 60 Hz of an approximately sine-wave form, the peak factor being within the limits of √2 ± 5 % (1,34 to 1,48). The test transformer shall have a rated power of at least 500 VA and shall provide a current of essentially undistorted waveform under test conditions.

To detect failure, the overcurrent indication device shall operate when a current of 5 mA or more flows through the high-voltage circuit. The test voltage source shall have a capacity to supply the detection current (5 mA or more) with a maximum voltage drop of 10 %.

The test specimens are removed from the ovens and cooled to room temperature. Each specimen shall be subjected to a proof voltage according to the ~~increase in diameter due to insulation~~ average thickness of the enamel as specified in Table 3 for specimens according to 5.1.1 and in Table 4 for specimens according to 5.1.2. In the case of self-bonding wires, the self-bonding layer is included in the increase in diameter due to the insulation.

Table 4 – Proof voltage for tape-wrapped round and for enamelled or tape-wrapped rectangular wire

Increase in dimension due to the insulation (mm)		Voltage (rms)
Over	**Up to and including**	
0,035	0,050	300
0,050	0,065	375
0,065	0,080	450
0,080	0,090	550
0,090	0,100	650
0,100	0,115	700
0,115	0,130	750
0,130	0,140	800
0,140	0,150	850

The proof voltage shall be applied to the test specimens for approximately 1 s.

NOTE A relatively short time of application of the test voltage ~~is desirable to minimize~~ minimizes the effects of corona and dielectric fatigue.

Care shall be taken in all cases to avoid mechanical damage to the test specimens. The specimens that fail the proof test ~~shall~~ can be discarded and the remaining specimens returned to the oven for another temperature exposure.

8 Calculations

8.1 Specimen failure time

The failure time of an individual specimen at one exposure temperature is determined by calculating the mid-point between the total hours of exposure temperature at which the specimen failed the proof voltage and the total hours of exposure of the previous cycles. This assumes that the specimen would probably have failed the proof voltage at some point in the middle of the last temperature exposure cycle. Thus, the specimen failure time is the sum of the total hours at the time to failure, minus half the hours of the last exposure cycle.

8.2 Time to failure

The time to failure of a set of specimens at one exposure temperature shall be calculated by using either the median value or the logarithmic mean value. For many materials, the median value is statistically valid. In most cases, use of the median will significantly reduce testing time, since the test ceases once the median value has been obtained.

When using the median value, the time to failure is calculated as follows:

Where there are a total number of n specimens in a set of specimens, the time to failure of the set equals:

a) the specimen failure time of specimen number $(n + 1)/2$; if n is odd ~~(see 8.1)~~;

b) the ~~logarithmic~~ mean value of the specimen failure times of specimen~~s~~ number $n/2$ and $(n + 2)/2$; if n is even ~~(see 8.1)~~.

For instance, if n is 12, the time to failure of the set would be the mean value of the specimen failure times of the sixth and the seventh specimen. For convenience, it is suggested that when the median value is used for calculating the time to failure of the set, the total number of specimens of a set be odd, thus simplifying calculation.

When using the logarithmic mean value, the time to failure is calculated by dividing the sum of the logarithms of the specimen failure times of the set ~~(see 8.1)~~ by the total number n of specimens in the set. The antilogarithm of this mean value is the time to failure of the set.

8.3 Linearity of data

To avoid misleading extrapolations (see 8.4), the correlation coefficient ~~should~~ shall be calculated as shown in Annex B, to provide a measure of linearity.

If the correlation coefficient r is equal to or greater than 0,95, the data are said to be linear and the data points will be reasonably close to a straight line. In the event that the correlation coefficient is less than 0,95, the data are said to be non-linear and an additional test ~~should~~ shall be performed at a temperature below the lowest previous temperature.

The new temperature point may be 10 °C below the previous lowest temperature point. When re-calculating the temperature Index and correlation coefficient, one temperature point may be deleted, starting with the highest temperature, for each new temperature point obtained.

The data will be linear if the thermal deterioration of the enamelled wire or the varnished enamelled wire appears as one chemical reaction. Non-linearity may indicate that:

a) two or more reactions which have different activation energies (slopes) are predominant at different temperatures within the testing range; or

b) errors have been introduced through the sampling technique and/or the testing procedure.

Non-linear data ~~should~~ shall not be used for extrapolation.

8.4 Calculating and plotting thermal endurance and temperature index

Thermal endurance is graphically presented by plotting the time to failure (see 8.2) versus its respective exposure temperature on graph paper having a logarithmic time scale as the ordinate and the reciprocal of absolute temperature as the abscissa. The exposure temperatures at 2 000 h and 20 000 h are estimated based on the first order regression calculation presented in Annex A. A regression line is drawn through these two points on the graph, which represents the thermal endurance of the enamelled winding wire (see Figure 9).

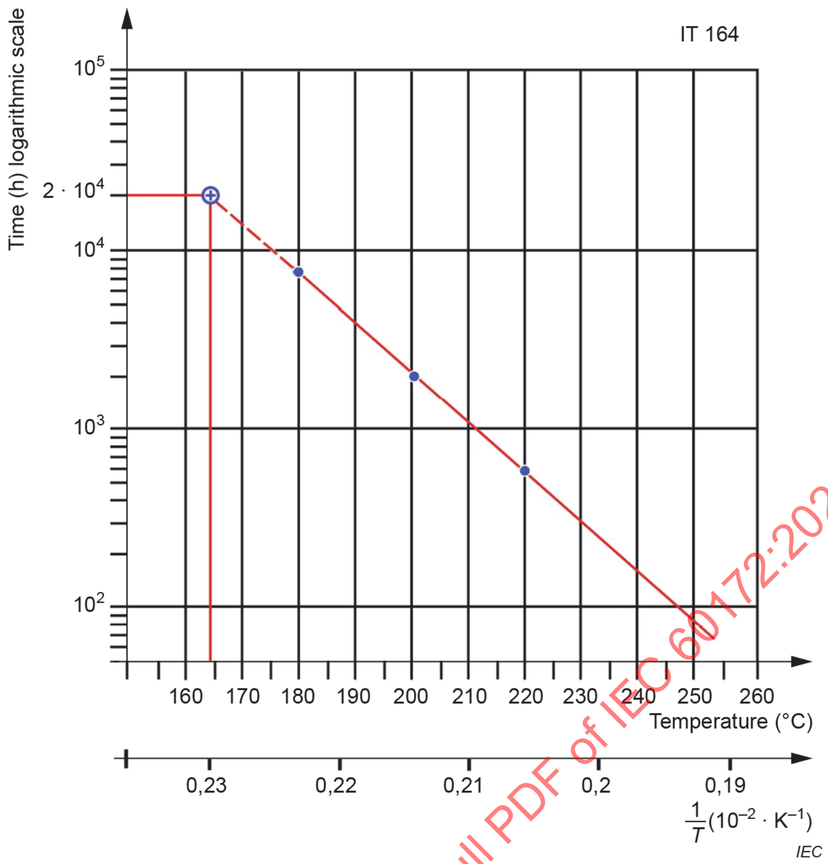

Figure 9 – Thermal endurance graph – Temperature index

The temperature index of the enamelled wire is the number corresponding to the temperature in degrees Celsius at which the regression line intersects the 20 000 h line. It is listed without reference to degrees Celsius.

If further statistical analysis of the data is necessary, reference may be made to IEC 60216-3.

9 Report

The report of the results shall contain the following information as a minimum:

a) identification or description of the wire enamel, grade and the type of conductor (e.g. copper, aluminium, etc.);

b) identification or description of the impregnating varnish and varnishing process;

c) time to failure of each set of specimens at each exposure temperature;

d) a graph of the first order regression line through the time to failure values;

e) the temperature index (TI);

f) the correlation coefficient, r.

Annex A
(normative)

Method for calculation of the regression line

Annex A presents a method for quickly plotting the regression line for thermal endurance data. This method may be used for any number of measurements at various test temperatures. If information concerning the confidence limits is required, a more detailed analysis shall be made in accordance with IEC 60216-3.

It has been established that many insulations deteriorate in such a manner that the following formula applies:

$$L = Ae^{B/T} \quad (A.1)$$

where:

L	=	insulation endurance in hours;
T	=	absolute temperature in kelvins;
A, B	=	constants for each insulation, and
e	=	base of natural logarithms.

Formula (A.1) may be expressed as a linear function by taking logarithms:

$$\log_{10} L = \log_{10} A + (\log_{10} e) \cdot \frac{B}{T} \quad (A.2)$$

Let:

Y	=	$\log_{10} L$;
a	=	$\log_{10} A$;
X	=	$1/T$;
b	=	$(\log_{10} e)\ B$.

Then:

$$Y = a + bX \quad (A.3)$$

Thus, data from testing at higher temperatures may be plotted on $\log_{10}$ L versus 1/ T graph paper and a straight line extrapolated to lower temperatures. However, since the nature of logarithmic plots does not allow accurate extrapolation by the method of drawing the best apparent straight line through the data points, a more rigorous method shall be used for greater accuracy and uniformity. By using the method of least squares, the constants a and b may be derived in terms of the experimental data obtained. These equations are as follows:

$$a = \frac{\sum Y - b \sum X}{N} \quad (A.4)$$

$$b = \frac{N\sum XY - \sum X \sum Y}{N\sum X^2 - (\sum X)^2} \qquad \text{(A.5)}$$

where:

X	=	$1/T$ = reciprocal of the test temperature in kelvins (θ °C + 273 °C);
N	=	number of test temperatures used;
Y	=	$\log_{10} L$ = logarithm of time to failure;
Σ	=	summation of N values.

Knowing the constant a, and the slope b of the regression line, the temperature at any required life value may be calculated as follows:

$$Y = a + bX$$

$$T = \frac{1}{X} = \frac{b}{Y - a} \qquad \text{(A.6)}$$

Temperature at 20 000 h in °C = $\dfrac{b}{4{,}3010 - a} - 273$ (A.7)

(temperature index)

Temperature at 2 000 h in °C = $\dfrac{b}{3{,}3010 - a} - 273$ (A.8)

To simplify the handling of the test data used in Formulae (A.4) to (A.8), it is suggested that the steps for a sample calculation be followed as outlined below (see Table A.1 and Table A.2):

a) In column 1, list the temperatures in °C, as illustrated in Table A.2, at which a set of specimens was tested;

b) In columns 2 and 3, list the reciprocals (X = $1/T$) and the reciprocals squared (X^2 = $1/T^2$) of the above test temperatures converted to kelvins (see also Table A.1);

c) In the column 4, list the time to failure L, in hours, of each set of specimens, and in the column 5, list the $\log_{10}$ of the values in the fourth column (Y = $\log_{10} L$);

d) In column 6, list the products of X and Y;

e) Provide summation for columns 2, 3, 5 and 6 and enter the summation (indicated by Σ) at the bottom of the respective column;

f) Indicate the number N of times to failure on the worksheet;

g) Using the values obtained in steps e) and f), compute b (Formula (A.5)) and a (Formula (A.4)) in that order. The constant a will always be negative;

h) Using constants a and b, calculate the temperature in degrees °C at 20 000 h (Formula (A.7)) and at 2 000 h (Formula (A.8));

i) Plot the above two temperature points from step h) on a $\log_{10}$L versus $1/T$ ~~graph paper~~ graphing system and draw the regression line through them as shown in Figure A.1. It is recommended that this graph supplement the minimum test report information required in Clause 9;

j) Plot the times to failure L at their respective temperatures on the same graph.

Table A.1 – Commonly used test temperatures in degrees Celsius and the corresponding kelvins with its reciprocal and reciprocal squared values

θ (°C)	**T** (K)	**X = 1/T** (K^{-1})	**$X^2 = 1/T^2$** (K^{-2})
105	378	$2,646 \times 10^{-3}$	$6,999 \times 10^{-6}$
120	393	$2,545 \times 10^{-3}$	$6,475 \times 10^{-6}$
125	398	$2,513 \times 10^{-3}$	$6,313 \times 10^{-6}$
130	403	$2,481 \times 10^{-3}$	$6,157 \times 10^{-6}$
140	413	$2,421 \times 10^{-3}$	$5,863 \times 10^{-6}$
150	423	$2,364 \times 10^{-3}$	$5,589 \times 10^{-6}$
155	428	$2,336 \times 10^{-3}$	$5,459 \times 10^{-6}$
165	438	$2,283 \times 10^{-3}$	$5,212 \times 10^{-6}$
175	448	$2,232 \times 10^{-3}$	$4,982 \times 10^{-6}$
180	453	$2,208 \times 10^{-3}$	$4,873 \times 10^{-6}$
185	458	$2,183 \times 10^{-3}$	$4,767 \times 10^{-6}$
190	463	$2,160 \times 10^{-3}$	$4,665 \times 10^{-6}$
200	473	$2,114 \times 10^{-3}$	$4,470 \times 10^{-6}$
210	483	$2,070 \times 10^{-3}$	$4,287 \times 10^{-6}$
220	493	$2,028 \times 10^{-3}$	$4,114 \times 10^{-6}$
225	498	$2,008 \times 10^{-3}$	$4,032 \times 10^{-6}$
230	503	$1,988 \times 10^{-3}$	$3,952 \times 10^{-6}$
240	513	$1,949 \times 10^{-3}$	$3,800 \times 10^{-6}$
250	523	$1,912 \times 10^{-3}$	$3,656 \times 10^{-6}$
260	533	$1,876 \times 10^{-3}$	$3,520 \times 10^{-6}$
270	543	$1,842 \times 10^{-3}$	$3,392 \times 10^{-6}$
280	553	$1,808 \times 10^{-3}$	$3,270 \times 10^{-6}$
300	573	$1,745 \times 10^{-3}$	$3,048 \times 10^{-6}$
320	593	$1,686 \times 10^{-3}$	$2,844 \times 10^{-6}$

NOTE Calculations for X^2 are based on non-rounded values.

Table A.2 – Sample calculation

Column 1 Temperature (°C)	Column 2 $X = 1/T$	Column 3 $X^2 = 1/T^2$	Column 4 L (h)	Column 5 $Y = \log_{10}L$	Column 6 $XY = (\log_{10}L)/T$
170	$2{,}257\,73 \times 10^{-3}$	$5{,}095\,57 \times 10^{-6}$	5 600	3,748 19	$8{,}460\,92 \times 10^{-3}$
185	$2{,}183\,41 \times 10^{-3}$	$4{,}767\,26 \times 10^{-6}$	2 600	3,414 97	$7{,}456\,27 \times 10^{-3}$
200	$2{,}114\,16 \times 10^{-3}$	$4{,}469\,69 \times 10^{-6}$	1 500	3,176 09	$6{,}714\,78 \times 10^{-3}$
215	$2{,}049\,18 \times 10^{-3}$	$4{,}199\,14 \times 10^{-6}$	640	2,806 18	$5{,}750\,37 \times 10^{-3}$
Σ	$8{,}604\,09 \times 10^{-3}$	$18{,}531\,66 \times 10^{-6}$		13,145 43	$28{,}382\,34 \times 10^{-3}$

N = 4

$$b = \frac{N\sum XY - \sum X \sum Y}{N\sum X^2 - (\sum X)^2} = \frac{4 x 28{,}38234 x 10^{-3} - 8{,}60409 x 10^{-3} x 13{,}14543}{4 x 18{,}53166 x 10^{-6} - 8{,}60409 x 10^{-3} x 8{,}60409 x 10^{-3}} = 4413$$

$$a = \frac{\sum Y - b\sum X}{N} = \frac{13{,}14543 - 4413 x 8{,}60409 x 10^{-3}}{4} = -6{,}20610$$

Temperature at 20 000 h in degrees °C = $\frac{b}{Y-a} - 273$

$$\frac{4413}{4{,}3010 + 6{,}20610} - 273 = 147 \ {}^\circ\mathrm{C}$$

Temperature at 2 000 h in degrees Celsius = $\frac{b}{Y-a} - 273$

$$\frac{4413}{3{,}3010 + 6{,}20610} - 273 = 191 \ {}^\circ\mathrm{C}$$

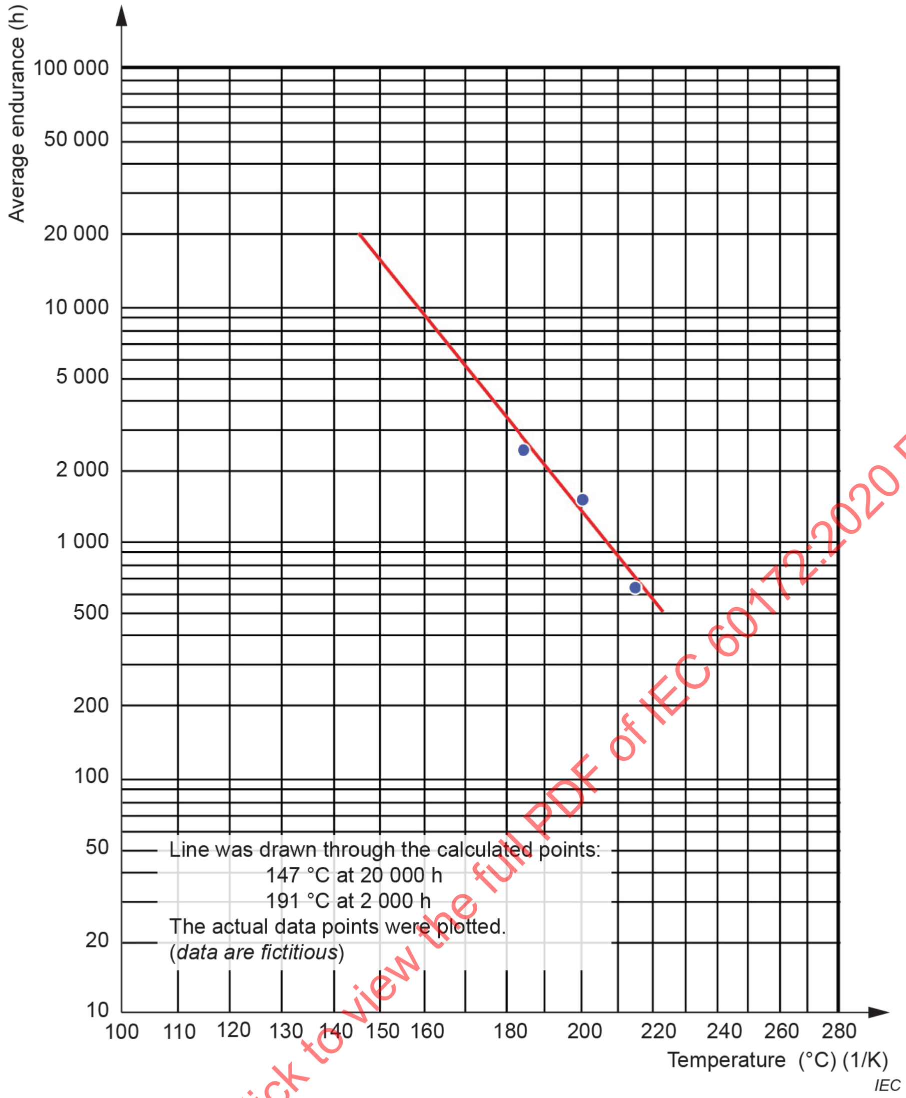

Figure A.1 – Plot of regression line based on sample calculation (Table A.2)

Annex B
(normative)

Correlation coefficient

The correlation coefficient r is a measure of the amount of relationship between variables.

When r = 1,0, a perfect association between the variable exists, and when r = 0, a completely random relation exists.

$$r = \sqrt{\frac{aY + bXY - N(Avg\,Y)^2}{Y^2 - N(Avg\,Y)^2}} \quad \text{(B.1)}$$

where:

a	=	Y intercept of the regression line;
b	=	Slope of the regression line;
X	=	$1/T$ = reciprocal of the test temperature in kelvins (8 °C + 273 °C);
N	=	number of test temperatures used;
X, Y	=	the variables.

Using the example data in Table A.2 in Annex A, the correlation coefficient is calculated according to the following formula:

$$\sqrt{\frac{a\Sigma Y + b\Sigma XY - N(\text{Avg}\,Y)^2}{\Sigma Y^2 - N(\text{Avg}\,Y)^2}} = 0{,}996 \quad \text{(B.2)}$$

If the correlation coefficient r is equal to or greater than 0,95, the data is said to be linear and the data points will be reasonably close to a straight line.

In the event that the correlation coefficient is less than 0,95, the data is said to be nonlinear and additional tests at other test temperatures are required. It is recommended that the new temperature point be 10 °C below the previous lowest temperature point.

When recalculating the temperature index and correlation coefficient, it is permissible for one temperature point to be deleted, starting with the highest temperature, provided that there are still three valid data points.

The data will be linear if the thermal deterioration of the film insulated wire or the varnished film insulated wire appears as one chemical reaction. Nonlinearity possibly indicates the following:

a) Two or more reactions that have different activation energies (slopes) are predominant at different temperatures within the testing range; or

b) Errors have been introduced through the sampling technique or the testing procedure, or both.

It shall be noted that nonlinear results provide useful engineering data when plotted on the thermal endurance graph even when the data cannot be extrapolated appropriately to give a temperature index (TI).

Bibliography

IEC 60317 (all parts), *Specifications for particular types of winding wires*

IEC 60455-3-5, *Resin based reactive compounds used for electrical insulation – Part 3: Specifications for individual materials – Sheet 5: Unsaturated polyester based impregnating resins*

IEC 60464-3-2, *Varnishes used for electrical insulation – Part 3: Specifications for individual materials – Sheet 2: Hot curing impregnating varnishes*

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IEC 60172

Edition 5.0 2020-11

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Test procedure for the determination of the temperature index of enamelled and tape wrapped winding wires

Méthode d'essai pour la détermination de l'indice de température des fils de bobinage émaillés et enveloppés de ruban

IEC 60172:2020-11(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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TEST PROCEDURE FOR THE DETERMINATION OF THE TEMPERATURE INDEX OF ENAMELLED AND TAPE WRAPPED WINDING WIRES

FOREWORD

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

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International Standard IEC 60172 has been prepared by IEC Technical Committee 55: Winding wires.

This fifth edition cancels and replaces the fourth edition published in 2015. This edition constitutes a technical revision.

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

– revision of 3.1, definition of thermal index;

– revision of 3.3, time to failure;

– revisions to 5.1.1 for clarity and to reduce the range wire size range to which the test applies;

– revisions to 5.1.2 for tape wrapped round and enamelled or tape wrapped rectangular wire for clarity;

– revision to Clause 9 to add the correlation coefficient, r to the report.

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

FDIS	Report on voting
55/1876/FDIS	55/1893/RVD

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

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

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://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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TEST PROCEDURE FOR THE DETERMINATION OF THE TEMPERATURE INDEX OF ENAMELLED AND TAPE WRAPPED WINDING WIRES

1 Scope

This International Standard specifies, in accordance with the provisions of IEC 60216-1, a method for evaluating the temperature index of enamelled wire, varnished or unvarnished with an impregnating agent, and of tape wrapped round and rectangular wire, in air at atmospheric pressure by periodically monitoring changes in response to AC proof voltage tests. This procedure does not apply to fibre-insulated wire or wire covered with tapes containing inorganic fibres.

NOTE The data obtained according to this test procedure provide the designer and development engineer with information for the selection of winding wire for further evaluation of insulation systems and equipment tests.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

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

3.1
temperature index
TI
number which permits comparison of the temperature/time characteristics of an electrical insulating material, or a simple combination of materials, based on the temperature in degrees Celsius which is obtained by extrapolating the Arrhenius plot of life versus temperature to a lifetime of 20 000 h

Note 1 to entry: In case of insulation systems, the temperature index may be derived from known service experience or from a known comparative functional evaluation of an evaluated and established reference insulation system as basis.

[SOURCE: IEC 60050-212:2010, 212-12-11] modified by merging Note 1 into the definition, and to specify a lifetime of 20 000 h.]

3.2
specimen failure time
number of hours at the exposure temperature that have elapsed at the time a specimen fails the proof test

3.3
time to failure
number of hours to failure calculated from the specimen mean value or logarithmic mean value failure times for a set of specimens at one exposure temperature, in accordance with 8.2

4 Summary of procedure

A set of specimens in accordance with Clause 5 is subjected to a testing cycle. This cycle consists of a heat-exposure period at a temperature given in Clause 6, followed by a proof voltage test at room temperature in accordance with Clause 7.

This cycle is repeated until a sufficient number of specimens has failed. The time to failure is calculated in accordance with Clause 8. The test is carried out at three or more temperatures. A regression line is calculated in accordance with 8.4 and the time to failure values plotted on thermal endurance graph paper as a function of the exposure temperature.

The temperature in degrees Celsius, corresponding to the point of intersection of the regression line with the ordinate of 20 000 h endurance represents the temperature index of the winding wire under test.

5 Test specimens

5.1 Preparation

5.1.1 Enamelled non-tape wrapped round wire

This procedure applies to enamelled round wires that are not tape wrapped. The thermal index can be determined by evaluating enamelled non-tape wrapped round wire with a nominal conductor diameter of 0,224 mm up to and including 2,65 mm.

NOTE For round enamelled winding wires, experience has shown that nominal conductor diameters of 0,800 mm up to and including 1,60 mm are generally found convenient to handle and test.

Wires with a nominal conductor diameter between 0,280 mm and 0,500 mm are permitted for use when the specification range of diameters is limited to 0,500 mm and finer.

The grade of insulation used for determining the thermal index shall be grade 2 or grade 2B for self-bonding winding wires.

Specimens shall be prepared as follows:

a) A wire specimen approximately 400 mm in length shall be twisted together over a distance of 125 mm with a device as shown in Figure 1. The force (weight) applied to the wire pair while being twisted and the number of twists are specified in Table 1.

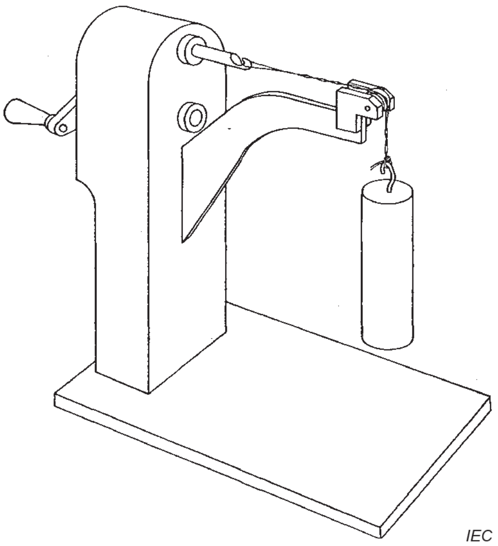


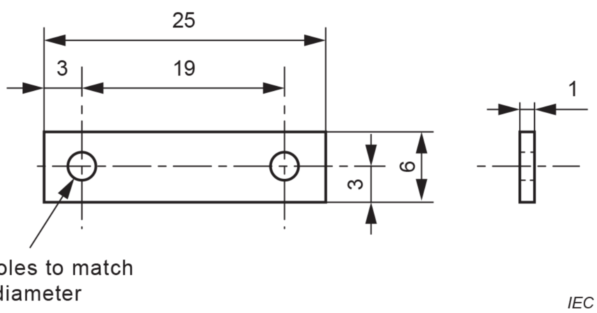
Figure 1 – Device used to form enamelled round wire test specimen

Table 1 – Force and number of twists for specimens

Nominal diameter mm		**Force applied to wire pairs** N	**Number of twists per** **125 mm**
Over	**Up to and including**		
0,224	0,25	0,85	33
0,25	0,35	1,7	23
0,35	0,50	3,4	16
0,50	0,75	7,0	12
0,75	1,05	13,5	8
1,05	1,50	27,0	6
1,50	2,15	54,0	4
2,15	2,65	108,0	3

b) Spacers may be prepared as shown in Figure 2. Such thermally stable insulating materials as ceramic or silicone glass fibre laminate may be used. The spacers are marked with a suitable identifying letter or number.

Dimensions in millimetres

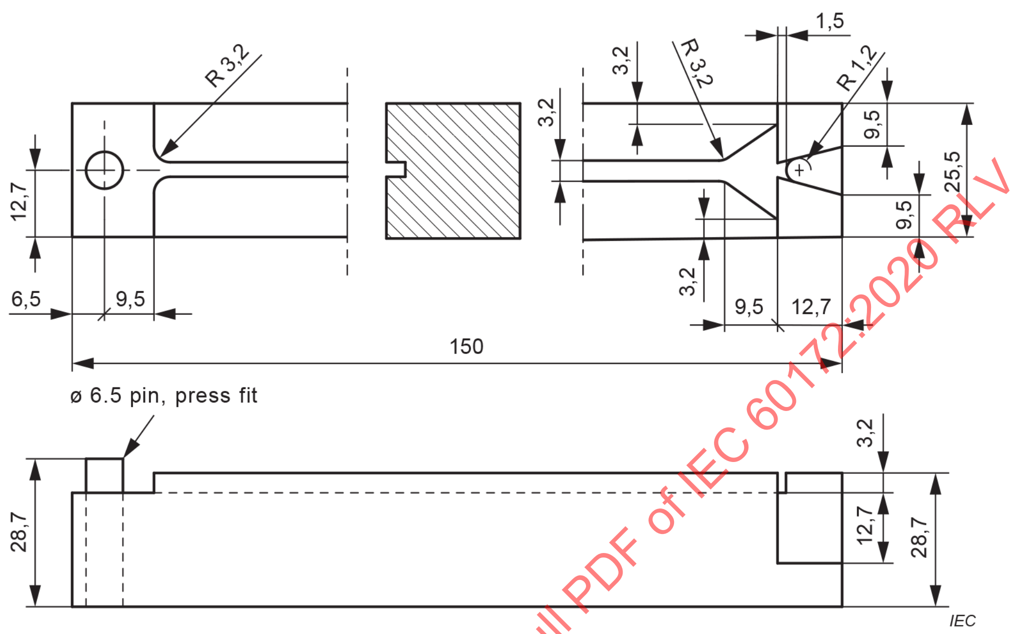


Material: Silicone glass laminate

Figure 2 – Spacer

c) The test specimens may be shaped in a jig, an engineering drawing of which is shown in Figure 3. A specimen is placed in the jig and a spacer, placed on the parallel leads of the twisted pair, is brought up to the face of the jig as shown in Figure 4. The leads are then bent parallel to hold the spacer in position. The forming jig provides more uniform test specimens. If a specimen holder is used, the spacers are unnecessary.

Dimensions in millimetres



R = Radius of bend

Figure 3 – Twist forming jig

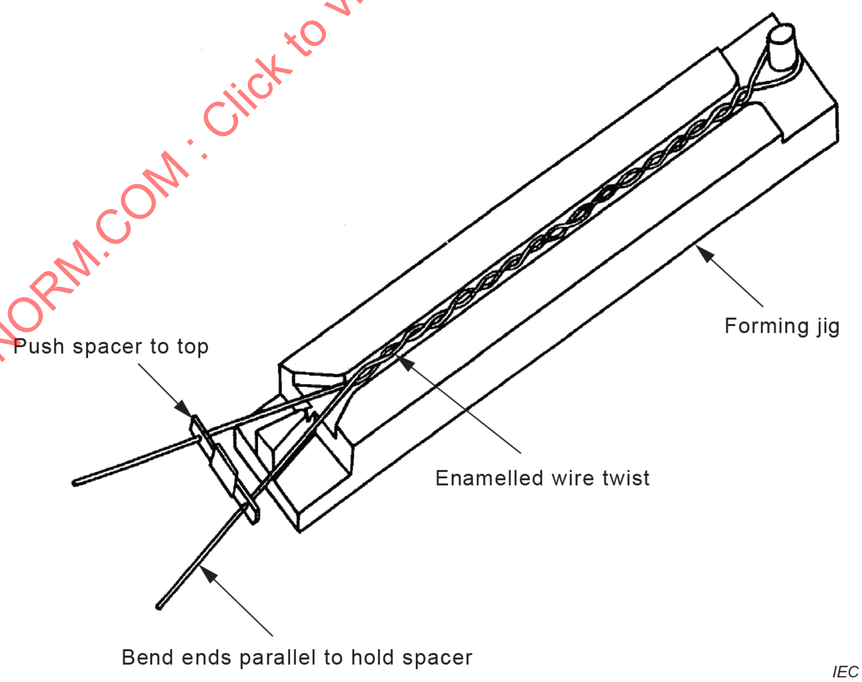


Figure 4 – Test specimen set up in forming jig

d) The loop at the end of the twisted section shall be cut at two places (not one) to provide the maximum spacing between the cut ends as shown in Figure 5. Any bending of the wires, at this end or the other untwisted end, to ensure adequate separation between the wires shall avoid sharp bends or damage to the insulation.

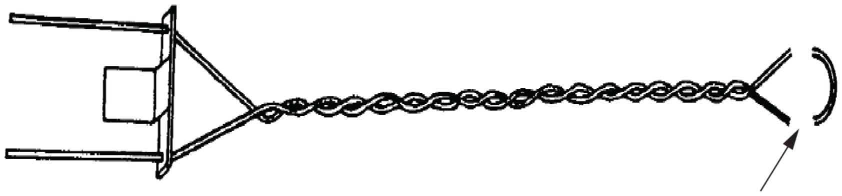


Figure 5 – Test specimen formed with loop cut

In order to ensure homogeneity of the set of test specimens, it is recommended that test specimens be subjected to, and withstand without breakdown, a test voltage three times the value given in Table 2 for 1 s prior to starting thermal exposure cycling.

Table 2 – Proof voltage for round enamelled wire

Increase in diameter due to the insulation (mm)		**Voltage** (rms)
Over	**Up to and including**	
–	0,015	300
0,015	0,024	300
0,024	0,035	400
0,035	0,050	500
0,050	0,070	700
0,070	0,090	1 000
0,090	0,130	1 200

5.1.2 Tape wrapped round wire and enamelled or tape wrapped rectangular wire

This procedure applies to any convenient dimension of tape wrapped round or tape wrapped or enamelled rectangular wire.

It is recommended to select a wire having dimensions that minimize the bending force necessary to shape the test specimen, since wire with high stiffness will yield specimens with poor wire-to-wire contact areas.

Specimens shall be prepared as follows:

a) Two straight specimens of wire each of 250 mm length shall be cut from the supply spool.

b) 10 mm to 15 mm of the insulation shall be removed from one end of each piece of wire to provide for electrical connection.

c) Each specimen shall be formed in a jig, as shown in Figure 6. This produces a straight centre section of about 150 mm with bent ends, which provide the necessary flare at both ends of the final specimen.

Dimensions in millimetres

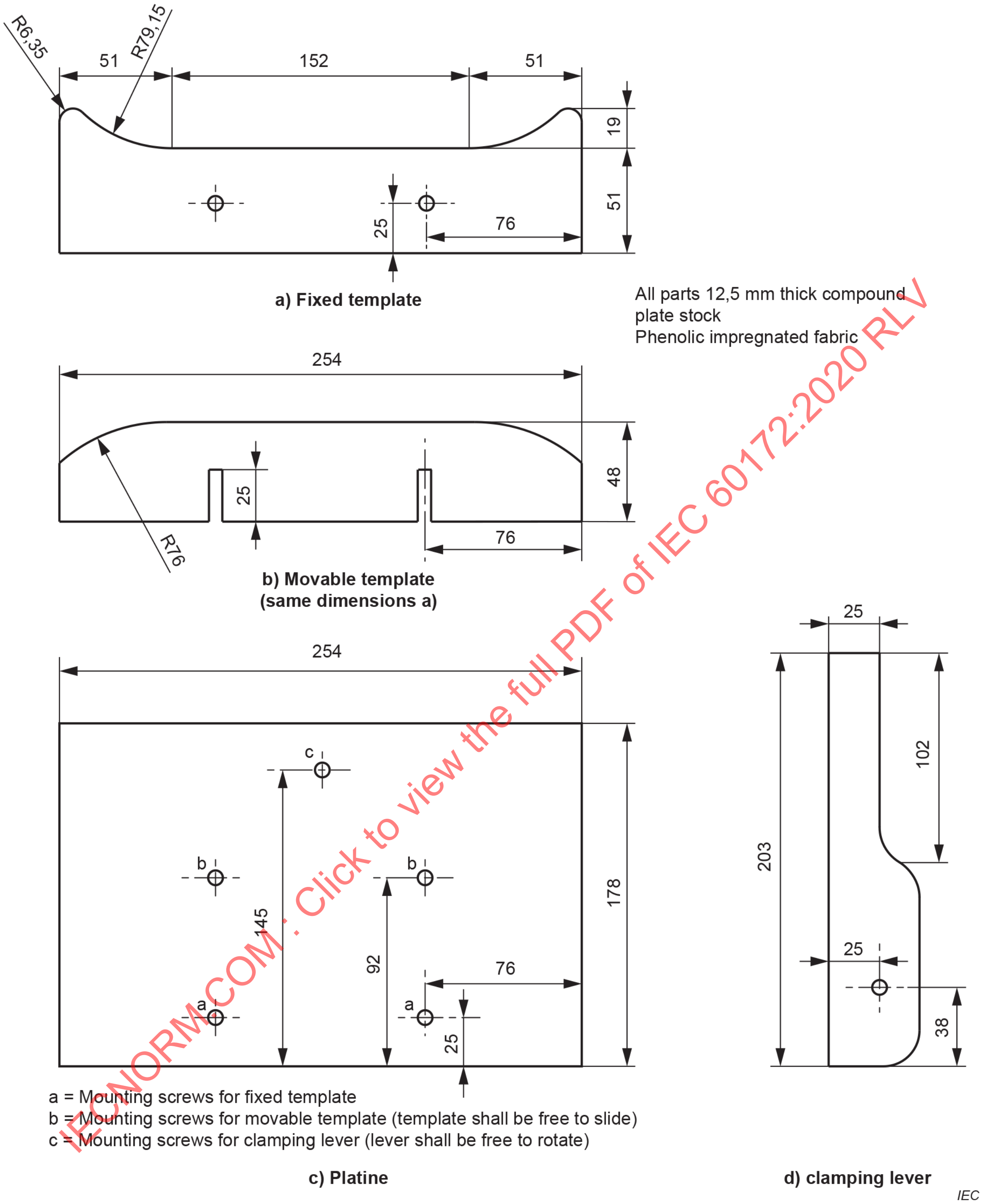


Figure 6 – Jig for bending large magnet wire, dielectric test specimen

d) The two formed specimens shall be placed together back-to-back and tightly wrapped with glass yarn over the straight centre section of the specimen, as shown in Figure 7.

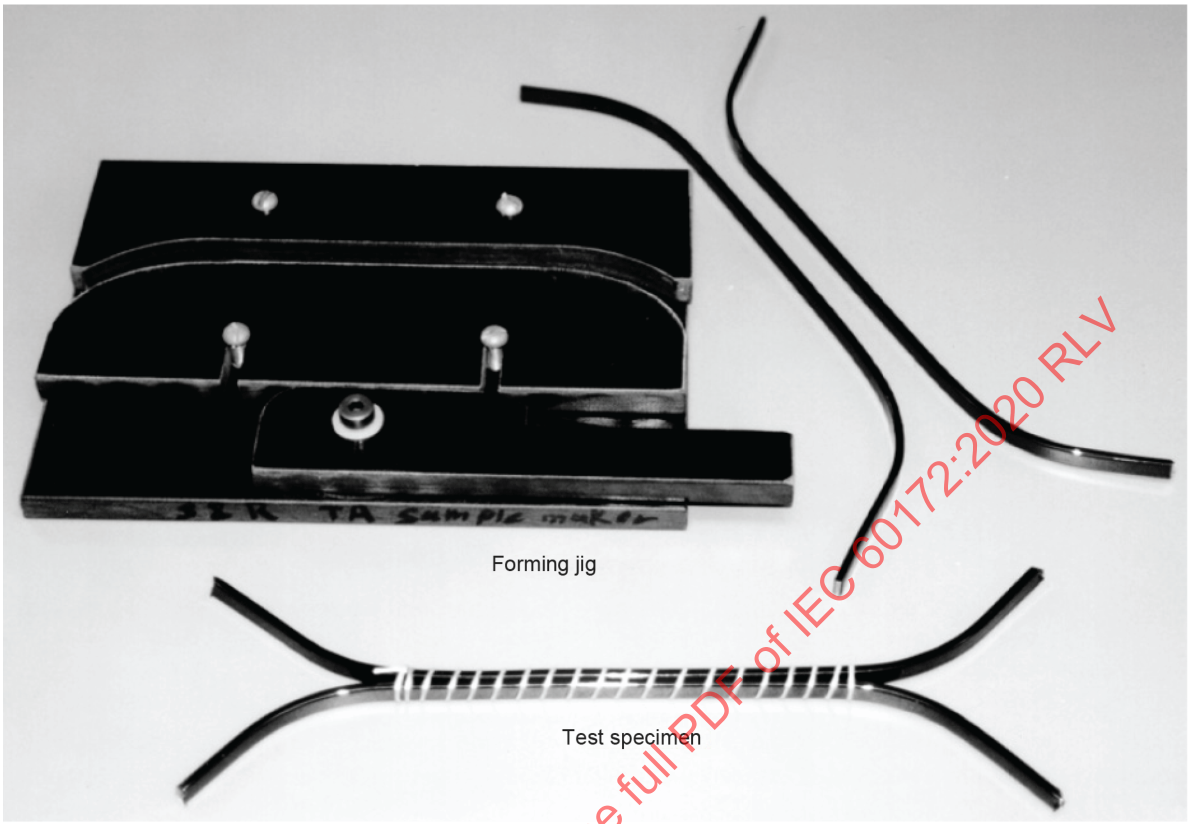


Figure 7 – Forming jig and test specimen

Care shall be taken that the centre section shows a close contact between the two pieces.

After tying, further bending of the ends shall be avoided. Pre-annealing of the specimen prior to testing or impregnating will remove stress and craze marks and therefore may be desirable with certain material.

e) Prior to starting the thermal exposure cycles, the specimen shall be proof-tested at 1 000 V AC.

5.2 Varnish impregnation

Insulated wire according to IEC 60317 and impregnating agents according to IEC 60455-3-5 or IEC 60464-3-2 can affect one another during the thermal ageing process.

NOTE 1 Testing varnished specimens will allow for evaluation of the compatibility of the wire insulation with an impregnating agent. Thus, the temperature indices of different combinations can be compared.

Interaction between wire insulation and such agent may increase or decrease the relative thermal life of this combination compared with the life of the wire tested without impregnation. Therefore, with impregnated specimens, this test procedure may give an indication of the thermal endurance of a combination of wire insulation and impregnating agent.

If such impregnation is required, the following procedure shall be applied:

With the specimen in the vertical position, it shall be immersed in the impregnating agent for (60 ± 10) s. It shall be removed slowly and uniformly at a rate of about 1 mm/s. It shall be drained horizontally for 10 min to 15 min and cured horizontally according to the manufacturer's recommendation or to an agreed schedule. If more than one treatment is to be given, immerse, drain and cure the specimen vertically reversing the specimen for each subsequent treatment.

NOTE 2 Some impregnating agents, such as high viscosity or thixotropic products require alternative processing methods.

5.3 Notes on number of test specimens

The accuracy of the test results depends largely upon the number of test specimens aged at each temperature. A greater number of test specimens is required to achieve an acceptable degree of accuracy if there is a wide spread in results among the specimens exposed at each temperature.

Experience has shown that twenty specimens without impregnation and ten specimens with impregnation give results with an acceptable tolerance. A minimum of ten specimens shall be used.

5.4 Specimen holder

5.4.1 For specimens according to 5.1.1

Since individual handling of the twisted specimens may result in premature failures, it is recommended that the specimens be placed in a suitable holder, as shown in Figure 8. The holder should be designed in a manner that will protect the twisted specimens from external mechanical damage and warping. The holder will be so constructed as to allow the ends of the twist to protrude from the holder to make electrical connections for proof testing. The holder shall be designed for at least ten specimens to decrease handling time.

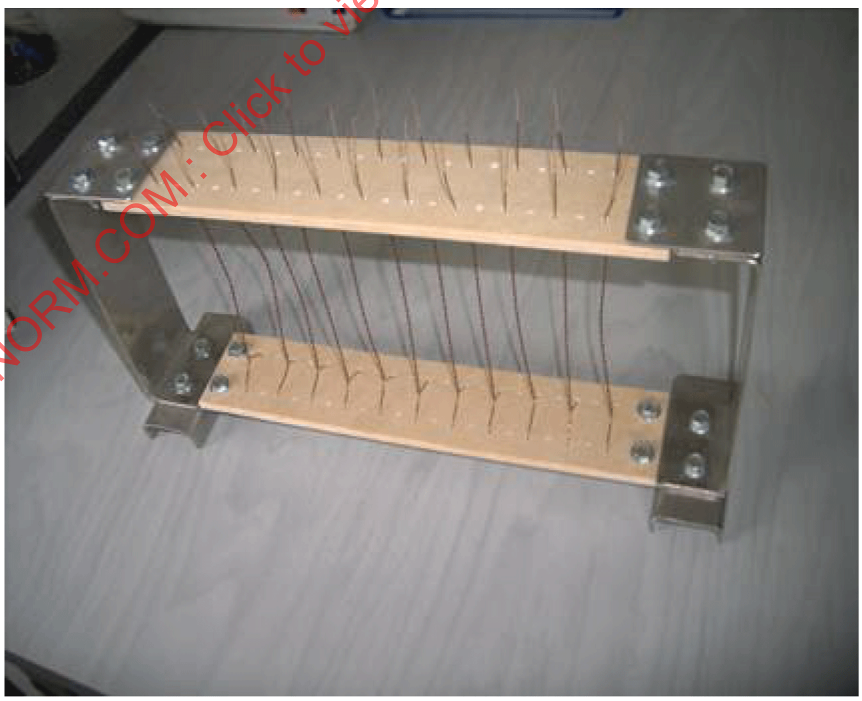


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Figure 8 – Specimen holder

5.4.2 For specimens according to 5.1.2

The specimen shall be hung in the oven. No special holder is required.

6 Temperature exposure

Test specimens shall be subjected to the temperatures given in this Clause 6.

The test temperature and time of exposure in each cycle are given in Table 3. A test cycle is defined as one exposure to a high temperature followed by one proof-voltage test at room temperature (20 – 30 °C). The test specimens shall be placed directly into and removed from the ageing ovens without controlling the heating or cooling rate.

The ovens shall be heated to the proper temperatures before the specimens are subjected to the exposure temperature.

The specimens shall be aged in a forced air circulation oven which is capable of maintaining the temperature of the specimens under test within 2 °C of the selected exposure temperature.

The exposure times are selected to subject the test specimens to approximately 10 cycles at each temperature before the time to failure is reached.

Table 3 – Recommended exposure times in days per cycle

Exposure or ageing temperature (°C)	Estimated temperature index						
	105-109	**120-130**	**150-159**	**180-189**	**200-209**	**220-239**	**240-249**
320	–	–	–	–	–	–	1
310	–	–	–	–	–	–	2
300	–	–	–	–	–	1	4
290	–	–	–	–	–	2	7
280	–	–	–	–	1	4	14
270	–	–	–	–	2	7	28
260	–	–	–	1	4	14	49
250	–	–	–	2	7	28	–
240	–	–	–	4	14	49	–
230	–	–	–	7	28	–	–
220	–	–	1	14	49	–	–
210	–	1	2	28	–	–	–
200	–	2	4	49	–	–	–
190	1	4	7	–	–	–	–
180	2	7	14	–	–	–	–
170	4	14	28	–	–	–	–
160	7	28	49	–	–	–	–
150	14	49	–	–	–	–	–
140	28	–	–	–	–	–	–
130	49	–	–	–	–	–	–
120	–	–	–	–	–	–	–

Thermal endurance values obtained from test specimens subjected to an average of less than eight or more than twenty cycles at the exposed temperature may not be reliable and should not be used to predict the temperature rating of the enamelled wire. Therefore, a shorter or longer cycle time than those given in Table 3 may be chosen for certain exposure temperatures, to ensure that the average number of cycles to failure falls within this range.

After the specimens have been subjected to a particular cycle, the time may be appropriately increased or decreased to control the number of cycles required to reach the time to failure.

Test specimens shall be exposed to a minimum of three and preferably four exposure temperatures. The lowest temperature, recommended at 20 °C above the desired thermal class, shall be one which results in a time frame to failure of more than 5 000 h. The highest exposure temperature shall have a value of at least 100 h to be considered a valid data point. Exposure temperatures should not be more than 20 °C apart. The accuracy of the temperature index predicted from the results will improve as the exposure temperature approaches the temperature to which the insulation is exposed in service.

7 Test voltage and its application

The voltage to be applied shall be an AC voltage and shall have a nominal frequency of 50 Hz or 60 Hz of an approximately sine-wave form, the peak factor being within the limits of $\sqrt{2}$ ± 5 % (1,34 to 1,48). The test transformer shall have a rated power of at least 500 VA and shall provide a current of essentially undistorted waveform under test conditions.

To detect failure, the overcurrent indication device shall operate when a current of 5 mA or more flows through the high-voltage circuit. The test voltage source shall have a capacity to supply the detection current (5 mA or more) with a maximum voltage drop of 10 %.

The test specimens are removed from the ovens and cooled to room temperature. Each specimen shall be subjected to a proof voltage according to the average thickness of the enamel as specified in Table 3 for specimens according to 5.1.1 and in Table 4 for specimens according to 5.1.2. In the case of self-bonding wires, the self-bonding layer is included in the increase in diameter due to the insulation.

Table 4 – Proof voltage for tape-wrapped round and for enamelled or tape-wrapped rectangular wire

Increase in dimension due to the insulation (mm)		Voltage (rms)
Over	Up to and including	
0,035	0,050	300
0,050	0,065	375
0,065	0,080	450
0,080	0,090	550
0,090	0,100	650
0,100	0,115	700
0,115	0,130	750
0,130	0,140	800
0,140	0,150	850

The proof voltage shall be applied to the test specimens for approximately 1 s.

NOTE A relatively short time of application of the test voltage minimizes the effects of corona and dielectric fatigue.

Care shall be taken in all cases to avoid mechanical damage to the test specimens. The specimens that fail the proof test can be discarded and the remaining specimens returned to the oven for another temperature exposure.

8 Calculations

8.1 Specimen failure time

The failure time of an individual specimen at one exposure temperature is determined by calculating the mid-point between the total hours of exposure temperature at which the specimen failed the proof voltage and the total hours of exposure of the previous cycles. This assumes that the specimen would probably have failed the proof voltage at some point in the middle of the last temperature exposure cycle. Thus, the specimen failure time is the sum of the total hours at the time to failure, minus half the hours of the last exposure cycle.

8.2 Time to failure

The time to failure of a set of specimens at one exposure temperature shall be calculated by using either the median value or the logarithmic mean value. For many materials, the median value is statistically valid. In most cases, use of the median will significantly reduce testing time, since the test ceases once the median value has been obtained.

When using the median value, the time to failure is calculated as follows:

Where there are a total number of n specimens in a set of specimens, the time to failure of the set equals:

a) the specimen failure time of specimen number $(n + 1)/2$; if n is odd;

b) the mean value of the specimen failure times of specimen number $n/2$ and $(n + 2)/2$; if n is even.

For instance, if n is 12, the time to failure of the set would be the mean value of the specimen failure times of the sixth and the seventh specimen. For convenience, it is suggested that when the median value is used for calculating the time to failure of the set, the total number of specimens of a set be odd, thus simplifying calculation.

When using the logarithmic mean value, the time to failure is calculated by dividing the sum of the logarithms of the specimen failure times of the set by the total number n of specimens in the set. The antilogarithm of this mean value is the time to failure of the set.

8.3 Linearity of data

To avoid misleading extrapolations (see 8.4), the correlation coefficient shall be calculated as shown in Annex B, to provide a measure of linearity.

If the correlation coefficient r is equal to or greater than 0,95, the data are said to be linear and the data points will be reasonably close to a straight line. In the event that the correlation coefficient is less than 0,95, the data are said to be non-linear and an additional test shall be performed at a temperature below the lowest previous temperature.

The new temperature point may be 10 °C below the previous lowest temperature point. When re-calculating the temperature Index and correlation coefficient, one temperature point may be deleted, starting with the highest temperature, for each new temperature point obtained.

The data will be linear if the thermal deterioration of the enamelled wire or the varnished enamelled wire appears as one chemical reaction. Non-linearity may indicate that:

a) two or more reactions which have different activation energies (slopes) are predominant at different temperatures within the testing range; or
b) errors have been introduced through the sampling technique and/or the testing procedure.

Non-linear data shall not be used for extrapolation.

8.4 Calculating and plotting thermal endurance and temperature index

Thermal endurance is graphically presented by plotting the time to failure (see 8.2) versus its respective exposure temperature on graph paper having a logarithmic time scale as the ordinate and the reciprocal of absolute temperature as the abscissa. The exposure temperatures at 2 000 h and 20 000 h are estimated based on the first order regression calculation presented in Annex A. A regression line is drawn through these two points on the graph, which represents the thermal endurance of the enamelled winding wire (see Figure 9).

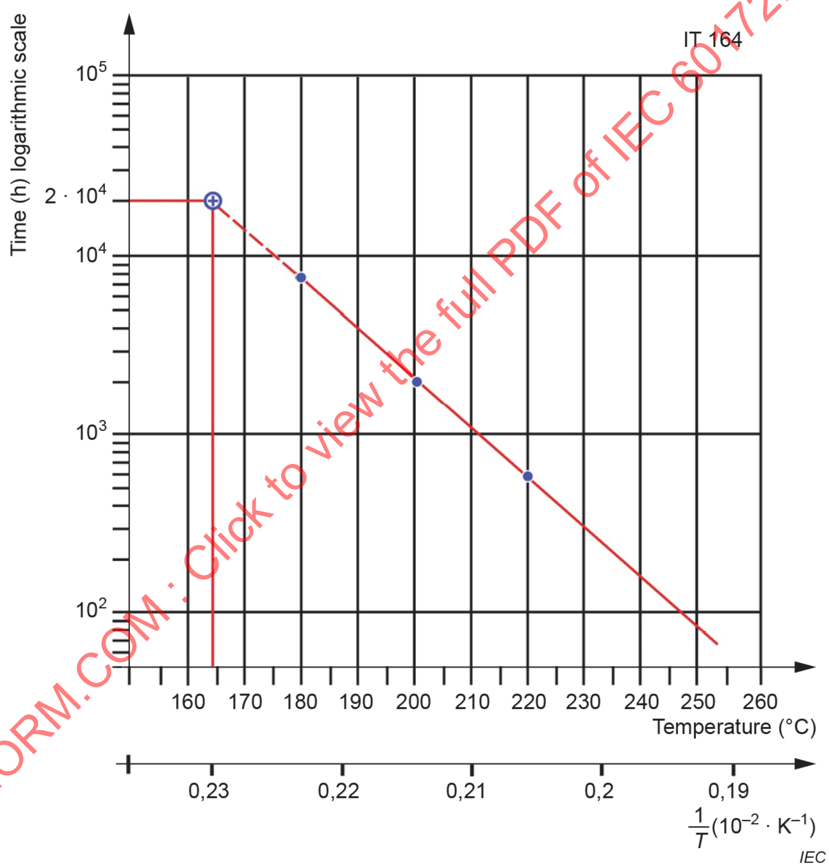

Figure 9 – Thermal endurance graph – Temperature index

The temperature index of the enamelled wire is the number corresponding to the temperature in degrees Celsius at which the regression line intersects the 20 000 h line. It is listed without reference to degrees Celsius.

If further statistical analysis of the data is necessary, reference may be made to IEC 60216-3.

9 Report

The report of the results shall contain the following information as a minimum:

a) identification or description of the wire enamel, grade and the type of conductor (e.g. copper, aluminium, etc.);

b) identification or description of the impregnating varnish and varnishing process;

c) time to failure of each set of specimens at each exposure temperature;

d) a graph of the first order regression line through the time to failure values;

e) the temperature index (TI);

f) the correlation coefficient, r.

Annex A
(normative)

Method for calculation of the regression line

Annex A presents a method for quickly plotting the regression line for thermal endurance data. This method may be used for any number of measurements at various test temperatures. If information concerning the confidence limits is required, a more detailed analysis shall be made in accordance with IEC 60216-3.

It has been established that many insulations deteriorate in such a manner that the following formula applies:

$$L = Ae^{B/T} \tag{A.1}$$

where:

L	=	insulation endurance in hours;
T	=	absolute temperature in kelvins;
A, B	=	constants for each insulation, and
e	=	base of natural logarithms.

Formula (A.1) may be expressed as a linear function by taking logarithms:

$$\log_{10} L = \log_{10} A + (\log_{10} e) \cdot \frac{B}{T} \tag{A.2}$$

Let:

Y	=	$\log_{10} L$;
a	=	$\log_{10} A$;
X	=	$1/T$;
b	=	$(\log_{10} e)\ B$.

Then:

$$Y = a + bX \tag{A.3}$$

Thus, data from testing at higher temperatures may be plotted on $\log_{10}$ L versus 1/ T graph paper and a straight line extrapolated to lower temperatures. However, since the nature of logarithmic plots does not allow accurate extrapolation by the method of drawing the best apparent straight line through the data points, a more rigorous method shall be used for greater accuracy and uniformity. By using the method of least squares, the constants a and b may be derived in terms of the experimental data obtained. These equations are as follows:

$$a = \frac{\sum Y - b \sum X}{N} \tag{A.4}$$

$$b = \frac{N\sum XY - \sum X \sum Y}{N\sum X^2 - (\sum X)^2} \qquad \text{(A.5)}$$

where:

X	=	$1/T$ = reciprocal of the test temperature in kelvins (θ °C + 273 °C);
N	=	number of test temperatures used;
Y	=	$\log_{10} L$ = logarithm of time to failure;
Σ	=	summation of N values.

Knowing the constant a, and the slope b of the regression line, the temperature at any required life value may be calculated as follows:

$$Y = a + bX$$

$$T = \frac{1}{X} = \frac{b}{Y - a} \qquad \text{(A.6)}$$

$$\text{Temperature at 20 000 h in °C} = \frac{b}{4{,}3010 - a} - 273 \qquad \text{(A.7)}$$

(temperature index)

$$\text{Temperature at 2 000 h in °C} = \frac{b}{3{,}3010 - a} - 273 \qquad \text{(A.8)}$$

To simplify the handling of the test data used in Formulae (A.4) to (A.8), it is suggested that the steps for a sample calculation be followed as outlined below (see Table A.1 and Table A.2):

a) In column 1, list the temperatures in °C, as illustrated in Table A.2, at which a set of specimens was tested;

b) In columns 2 and 3, list the reciprocals (X = 1/T) and the reciprocals squared (X^2 = 1/T^2) of the above test temperatures converted to kelvins (see also Table A.1);

c) In the column 4, list the time to failure L, in hours, of each set of specimens, and in the column 5, list the $\log_{10}$ of the values in the fourth column ($Y = \log_{10}L$);

d) In column 6, list the products of X and Y;

e) Provide summation for columns 2, 3, 5 and 6 and enter the summation (indicated by Σ) at the bottom of the respective column;

f) Indicate the number N of times to failure on the worksheet;

g) Using the values obtained in steps e) and f), compute b (Formula (A.5)) and a (Formula (A.4)) in that order. The constant a will always be negative;

h) Using constants a and b, calculate the temperature in degrees °C at 20 000 h (Formula (A.7)) and at 2 000 h (Formula (A.8));

i) Plot the above two temperature points from step h) on a $\log_{10}$L versus 1/T graphing system and draw the regression line through them as shown in Figure A.1. It is recommended that this graph supplement the minimum test report information required in Clause 9;

j) Plot the times to failure L at their respective temperatures on the same graph.

Table A.1 – Commonly used test temperatures in degrees Celsius and the corresponding kelvins with its reciprocal and reciprocal squared values

θ (°C)	T (K)	X = 1/T (K^{-1})	$X^2 = 1/T^2$ (K^{-2})
105	378	$2,646 \times 10^{-3}$	$6,999 \times 10^{-6}$
120	393	$2,545 \times 10^{-3}$	$6,475 \times 10^{-6}$
125	398	$2,513 \times 10^{-3}$	$6,313 \times 10^{-6}$
130	403	$2,481 \times 10^{-3}$	$6,157 \times 10^{-6}$
140	413	$2,421 \times 10^{-3}$	$5,863 \times 10^{-6}$
150	423	$2,364 \times 10^{-3}$	$5,589 \times 10^{-6}$
155	428	$2,336 \times 10^{-3}$	$5,459 \times 10^{-6}$
165	438	$2,283 \times 10^{-3}$	$5,212 \times 10^{-6}$
175	448	$2,232 \times 10^{-3}$	$4,982 \times 10^{-6}$
180	453	$2,208 \times 10^{-3}$	$4,873 \times 10^{-6}$
185	458	$2,183 \times 10^{-3}$	$4,767 \times 10^{-6}$
190	463	$2,160 \times 10^{-3}$	$4,665 \times 10^{-6}$
200	473	$2,114 \times 10^{-3}$	$4,470 \times 10^{-6}$
210	483	$2,070 \times 10^{-3}$	$4,287 \times 10^{-6}$
220	493	$2,028 \times 10^{-3}$	$4,114 \times 10^{-6}$
225	498	$2,008 \times 10^{-3}$	$4,032 \times 10^{-6}$
230	503	$1,988 \times 10^{-3}$	$3,952 \times 10^{-6}$
240	513	$1,949 \times 10^{-3}$	$3,800 \times 10^{-6}$
250	523	$1,912 \times 10^{-3}$	$3,656 \times 10^{-6}$
260	533	$1,876 \times 10^{-3}$	$3,520 \times 10^{-6}$
270	543	$1,842 \times 10^{-3}$	$3,392 \times 10^{-6}$
280	553	$1,808 \times 10^{-3}$	$3,270 \times 10^{-6}$
300	573	$1,745 \times 10^{-3}$	$3,048 \times 10^{-6}$
320	593	$1,686 \times 10^{-3}$	$2,844 \times 10^{-6}$
NOTE Calculations for X^2 are based on non-rounded values.			

Table A.2 – Sample calculation

Column 1 Temperature (°C)	Column 2 X = 1/T	Column 3 X^2 = 1/T^2	Column 4 L (h)	Column 5 $Y = \log_{10}L$	Column 6 $XY = (\log_{10}L)/T$
170	2,257 73 × 10^{-3}	5,095 57 × 10^{-6}	5 600	3,748 19	8,460 92 × 10^{-3}
185	2,183 41 × 10^{-3}	4,767 26 × 10^{-6}	2 600	3,414 97	7,456 27 × 10^{-3}
200	2,114 16 × 10^{-3}	4,469 69 × 10^{-6}	1 500	3,176 09	6,714 78 × 10^{-3}
215	2,049 18 × 10^{-3}	4,199 14 × 10^{-6}	640	2,806 18	5,750 37 × 10^{-3}
Σ	8,604 09 × 10^{-3}	18,531 66 × 10^{-6}		13,145 43	28,382 34 × 10^{-3}

N = 4

$$b = \frac{N\sum XY - \sum X \sum Y}{N\sum X^2 - (\sum X)^2} = \frac{4x28{,}38234x10^{-3} - 8{,}60409x10^{-3}x13{,}14543}{4x18{,}53166x10^{-6} - 8{,}60409x10^{-3}x8{,}60409x10^{-3}} = 4413$$

$$a = \frac{\sum Y - b\sum X}{N} = \frac{13{,}14543 - 4413x8{,}60409x10^{-3}}{4} = -6{,}20610$$

Temperature at 20 000 h in degrees °C = $\frac{b}{Y-a} - 273$

$$\frac{4413}{4{,}3010 + 6{,}20610} - 273 = 147\ ^\circ\text{C}$$

Temperature at 2 000 h in degrees Celsius = $\frac{b}{Y-a} - 273$

$$\frac{4413}{3{,}3010 + 6{,}20610} - 273 = 191\ ^\circ\text{C}$$

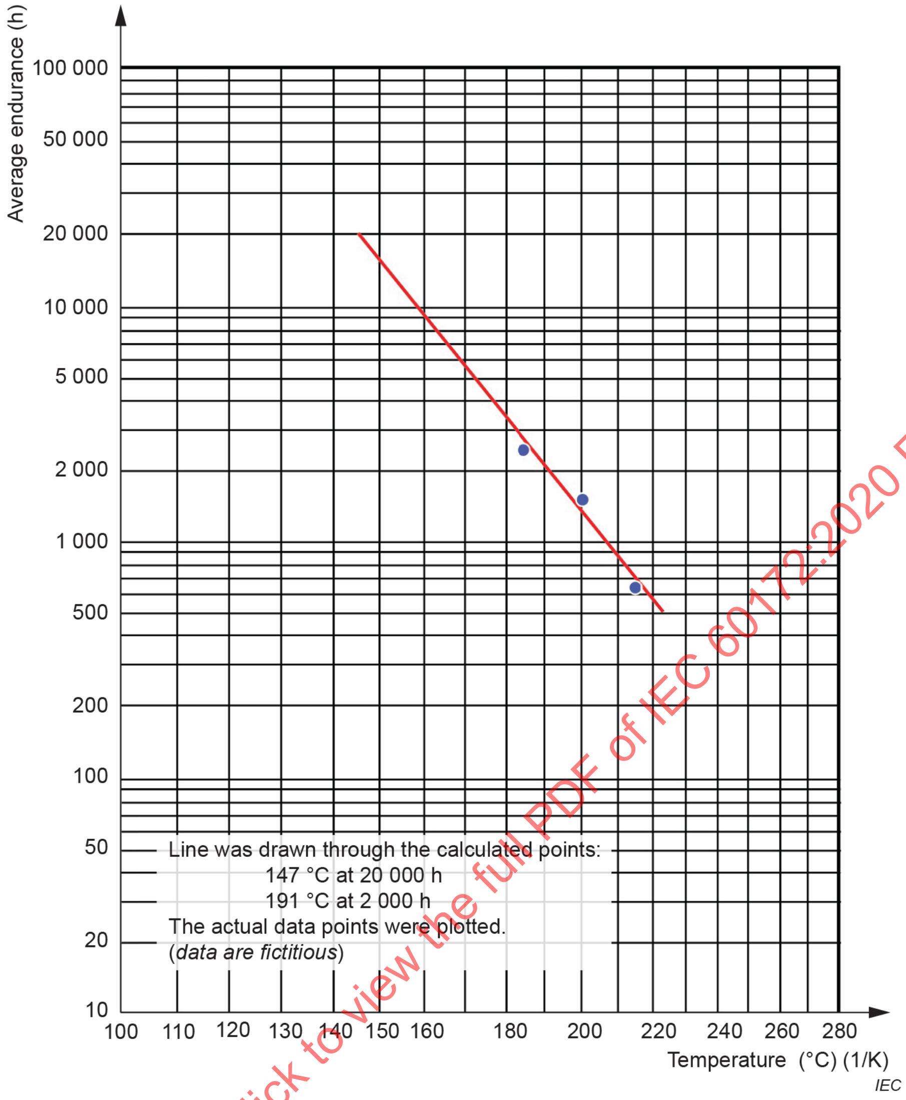

Figure A.1 – Plot of regression line based on sample calculation (Table A.2)

Annex B
(normative)

Correlation coefficient

The correlation coefficient r is a measure of the amount of relationship between variables.

When r = 1,0, a perfect association between the variable exists, and when r = 0, a completely random relation exists.

$$r=\sqrt{\frac{aY+bXY-N(Avg\,Y)^2}{Y^2-N(Avg\,Y)^2}} \qquad \text{(B.1)}$$

where:

a	=	Y intercept of the regression line;
b	=	Slope of the regression line;
X	=	$1/T$ = reciprocal of the test temperature in kelvins (8 °C + 273 °C);
N	=	number of test temperatures used;
X, Y	=	the variables.

Using the example data in Table A.2 in Annex A, the correlation coefficient is calculated according to the following formula:

$$\sqrt{\frac{a\Sigma Y+b\Sigma XY-N(\text{Avg}\,Y)^2}{\Sigma \text{Y}^2-N(\text{Avg}\,Y)^2}}=0{,}996 \qquad \text{(B.2)}$$

If the correlation coefficient r is equal to or greater than 0,95, the data is said to be linear and the data points will be reasonably close to a straight line.

In the event that the correlation coefficient is less than 0,95, the data is said to be nonlinear and additional tests at other test temperatures are required. It is recommended that the new temperature point be 10 °C below the previous lowest temperature point.

When recalculating the temperature index and correlation coefficient, it is permissible for one temperature point to be deleted, starting with the highest temperature, provided that there are still three valid data points.

The data will be linear if the thermal deterioration of the film insulated wire or the varnished film insulated wire appears as one chemical reaction. Nonlinearity possibly indicates the following:

a) Two or more reactions that have different activation energies (slopes) are predominant at different temperatures within the testing range; or

b) Errors have been introduced through the sampling technique or the testing procedure, or both.

It shall be noted that nonlinear results provide useful engineering data when plotted on the thermal endurance graph even when the data cannot be extrapolated appropriately to give a temperature index (TI).

Bibliography

IEC 60317 (all parts), *Specifications for particular types of winding wire*

IEC 60455-3-5, *Resin based reactive compounds used for electrical insulation – Part 3: Specifications for individual materials – Sheet 5: Unsaturated polyester based impregnating resins*

IEC 60464-3-2, *Varnishes used for electrical insulation – Part 3: Specifications for individual materials – Sheet 2: Hot curing impregnating varnishes*

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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MÉTHODE D'ESSAI POUR LA DÉTERMINATION DE L'INDICE DE TEMPÉRATURE DES FILS DE BOBINAGE ÉMAILLÉS ET ENVELOPPÉS DE RUBAN

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La Norme internationale IEC 60172 a été établie par le comité d'études 55 de l'IEC: Fils de bobinage.

Cette cinquième édition annule et remplace la quatrième édition parue en 2015. Cette édition constitue une révision technique.

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

– révision du 3.1, définition d'indice thermique;
– révision du 3.3, durée de fonctionnement avant défaillance;
– révisions du 5.1.1 à des fins de clarification et pour limiter la plage des dimensions de fils à laquelle l'essai s'applique;

– révisions à des fins de clarification du 5.1.2 relatif au fil de section circulaire enveloppé d'un ruban et au fil de section rectangulaire émaillé ou enveloppé d'un ruban;
– révision de l'Article 9 afin d'ajouter le coefficient de corrélation, r au rapport.

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

FDIS	Rapport de vote
55/1876/FDIS	55/1893/RVD

Le rapport de vote indiqué dans le tableau au ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette Norme internationale.

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MÉTHODE D'ESSAI POUR LA DÉTERMINATION DE L'INDICE DE TEMPÉRATURE DES FILS DE BOBINAGE ÉMAILLÉS ET ENVELOPPÉS DE RUBAN

1 Domaine d'application

La présente Norme internationale spécifie, conformément aux dispositions de l'IEC 60216-1, une méthode pour l'évaluation de l'indice de température du fil émaillé, imprégné ou non imprégné avec un matériau d'imprégnation, et du fil de section circulaire ou rectangulaire, enveloppé de ruban, dans l'air à la pression atmosphérique, en contrôlant périodiquement les variations de réponse aux essais de tension d'épreuve en courant alternatif. Cette méthode ne concerne pas le fil avec revêtement fibreux ou le fil recouvert de rubans contenant des fibres non organiques.

NOTE Les données obtenues au moyen de cette méthode d'essai fournissent à l'ingénieur d'étude et de développement les informations pour sélectionner le fil de bobinage et obtenir une meilleure évaluation des systèmes isolants et des essais d'équipement.

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 60216-1, *Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 1: Méthodes de vieillissement et évaluation des résultats d'essai*

IEC 60216-3, *Matériaux isolants électriques – Propriétés d'endurance thermique – Partie 3: Instructions pour le calcul des caractéristiques d'endurance thermique*

3 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 http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1
indice de température
IT
nombre permettant la comparaison entre les caractéristiques de température et de temps d'un matériau isolant électrique ou d'une simple association de matériaux en fonction de la température en degrés Celsius obtenue par extrapolation du tracé d'Arrhenius de durée de vie en fonction de la température pour une durée de vie de 20 000 h

Note 1 à l'Article: Dans le cas de systèmes d'isolation, l'indice de température peut être déduit de l'expérience en service connue ou d'une évaluation fonctionnelle comparative connue d'un système d'isolation de référence évalué et établi en tant que base.

[SOURCE: IEC 60050-212:2010, 212-12-11, modifiée – La Note 1 a été intégrée à la définition et une durée de vie de 20 000 h a été précisée.]

3.2
durée de vie de l'éprouvette
temps en nombre d'heures à la température d'exposition pendant lequel une éprouvette résiste à l'essai diélectrique

3.3
durée de fonctionnement avant défaillance
temps en nombre d'heures de fonctionnement avant défaillance calculé à partir de la valeur moyenne de l'éprouvette ou de la valeur moyenne logarithmique des durées de vie d'un groupe d'éprouvettes soumises à une température d'exposition, conformément au 8.2

4 Résumé du mode opératoire

Un groupe d'éprouvettes conformes à l'Article 5 est soumis à un cycle d'essais. Ce cycle comprend une période d'exposition à la chaleur à une température indiquée à l'Article 6, suivie par une épreuve sous tension à la température ambiante conformément à l'Article 7.

Ce cycle est répété jusqu'à obtenir un nombre suffisant d'éprouvettes défaillantes. La durée de fonctionnement avant défaillance est calculée conformément à l'Article 8. L'essai est réalisé à trois températures ou plus. Une droite de régression est calculée conformément au 8.4 et les valeurs de durée de fonctionnement avant défaillance sont reportées sur un graphique d'endurance thermique en fonction de la température d'exposition.

La température, en degrés Celsius, correspondant au point d'intersection de la droite de régression avec l'ordonnée d'endurance à 20 000 h représente l'indice de température du fil de bobinage en essai.

5 Éprouvettes d'essai

5.1 Préparation

5.1.1 Fil de section circulaire émaillé sans ruban

Cette méthode s'applique aux fils de section circulaire émaillés qui ne sont pas enveloppés d'un ruban. L'indice thermique peut être déterminé en évaluant un fil de section circulaire émaillé sans ruban d'un diamètre nominal du conducteur de 0,224 mm jusques et y compris 2,65 mm.

NOTE Pour les fils de bobinage émaillés de section circulaire, l'expérience a démontré que les diamètres nominaux de conducteurs de 0,800 mm jusques et y compris 1,60 mm conviennent généralement aux manipulations et à l'essai.

L'utilisation des fils dont le diamètre nominal du conducteur est compris entre 0,280 mm et 0,500 mm est admise lorsque la plage de dimensions spécifiée est limitée à 0,500 mm ou moins.

Le grade de l'isolant utilisé pour la détermination de l'indice thermique doit être le grade 2 ou grade 2B pour les fils de bobinage avec une couche thermoadhérente.

Les éprouvettes doivent être préparées de la façon suivante:

a) Une éprouvette de fil d'environ 400 mm de long doit être torsadée sur elle-même, sur une distance de 125 mm avec un appareil comme cela est représenté à la Figure 1. La force (poids) exercée sur les deux fils pendant la torsion et le nombre de tours sont spécifiés dans le Tableau 1.

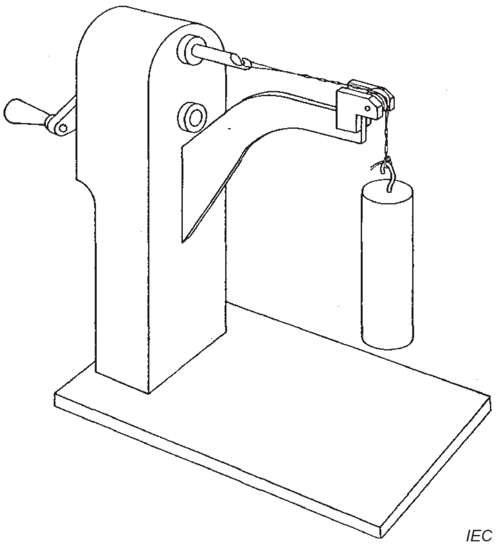


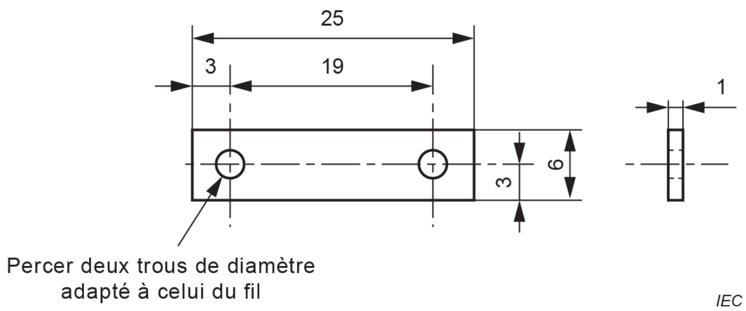
Figure 1 –Dispositif pour la réalisation des éprouvettes de fil émaillé de section circulaire

Tableau 1 – Force et nombre de tours des éprouvettes

Diamètre nominal mm		**Force exercée sur les deux fils** N	**Nombre de tours par** **125 mm**
De	**Jusques et y compris**		
0,224	0,25	0,85	33
0,25	0,35	1,7	23
0,35	0,50	3,4	16
0,50	0,75	7,0	12
0,75	1,05	13,5	8
1,05	1,50	27,0	6
1,50	2,15	54,0	4
2,15	2,65	108,0	3

b) Les séparateurs peuvent être préparés suivant la Figure 2. Des matériaux isolants, thermiquement stables, tels que la céramique ou les stratifiés silicone – fibre de verre peuvent être utilisés. Les séparateurs sont marqués d'une lettre ou d'un numéro d'identification approprié.

Dimensions en millimètres

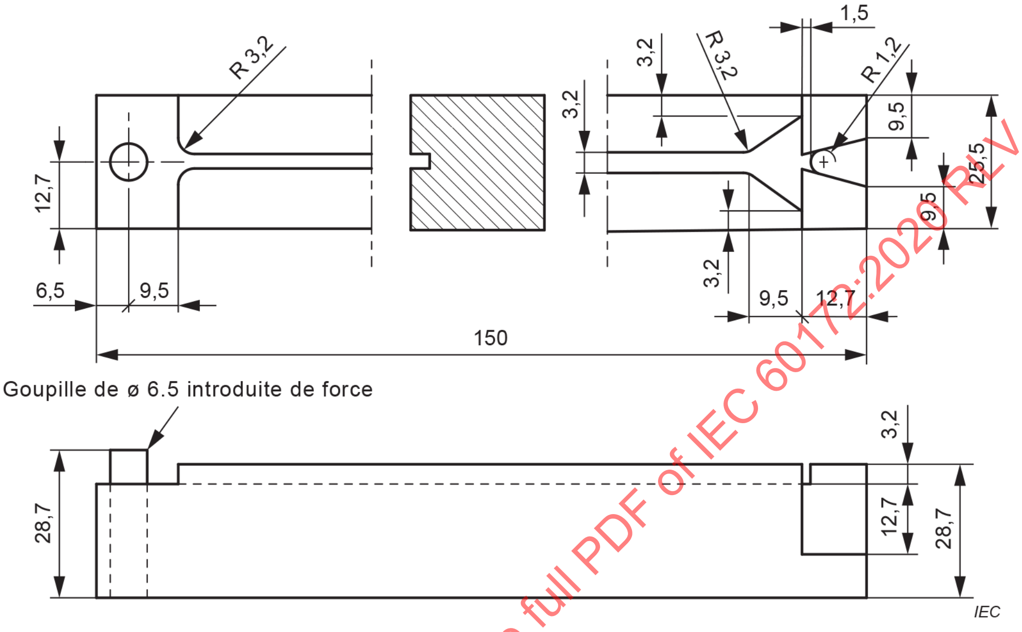


Matériau: Stratifié silicone – fibre de verre

Figure 2 –Séparateur

c) Les éprouvettes peuvent être mises en forme dans un gabarit dont un dessin est représenté à la Figure 3. Une éprouvette est placée dans le gabarit et un séparateur est placé entre les fils de sortie de la torsade et poussé jusqu'à la butée, comme cela est représenté à la Figure 4. Les fils de sortie sont ensuite repliés parallèlement entre eux de façon à maintenir le séparateur en place. Le gabarit permet d'obtenir des éprouvettes plus uniformes. Les séparateurs ne sont pas nécessaires si un porte-éprouvettes est utilisé.

Dimensions en millimètres



R = Rayon de courbure

Figure 3 – Gabarit pour la préparation des torsades

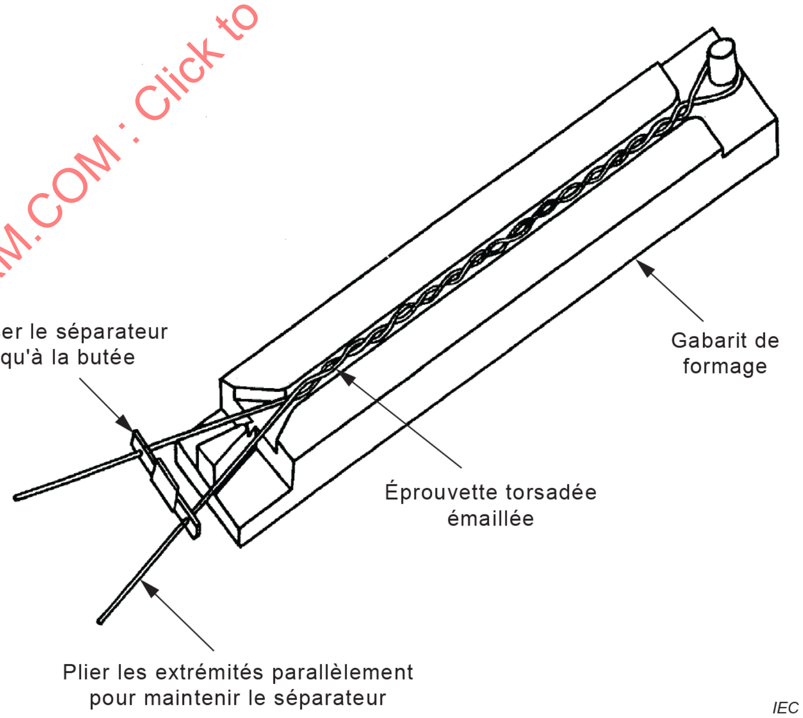


Figure 4 – Éprouvette disposée dans le gabarit de formage

d) La boucle à l'extrémité de la section torsadée doit être coupée en deux endroits (et non un seul) afin d'obtenir un espacement maximal entre les extrémités coupées comme cela est représenté à la Figure 5. À cette extrémité ou à l'extrémité non torsadée, tout formage réalisé sur les fils de manière à assurer un écartement approprié entre eux doit éviter toute courbure aiguë ou détérioration de l'isolation.

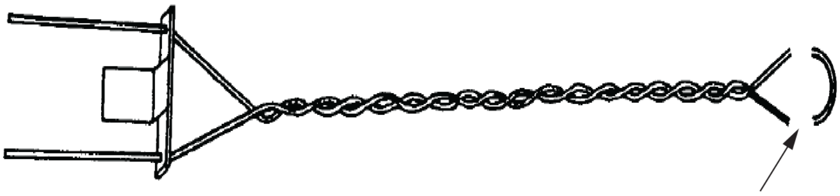


Figure 5 – Éprouvette réalisée, boucle coupée

Pour assurer l'homogénéité du groupe d'éprouvettes, il est recommandé de les soumettre, sans observer de claquage, à une tension d'essai qui correspond à trois fois la valeur indiquée dans le Tableau 2 pendant 1 s avant de démarrer le cycle d'exposition thermique.

Tableau 2 – Tension d'essai pour le fil émaillé de section circulaire

Accroissement du diamètre dû à l'isolant (mm)		Tension (valeur efficace)
De	Jusques et y compris	
–	0,015	300
0,015	0,024	300
0,024	0,035	400
0,035	0,050	500
0,050	0,070	700
0,070	0,090	1 000
0,090	0,130	1 200

5.1.2 Fil de section circulaire enveloppé d'un ruban et fil de section rectangulaire émaillé ou enveloppé d'un ruban

Cette méthode s'applique à toute dimension appropriée de fil de section circulaire enveloppé d'un ruban ou rectangulaire émaillé enveloppé d'un ruban.

Il est recommandé de sélectionner un fil présentant des dimensions qui réduisent le plus possible la force de courbure nécessaire pour former l'éprouvette, car un fil de grande raideur donne des éprouvettes avec de faibles surfaces de contact fil-à-fil.

Les éprouvettes doivent être préparées de la façon suivante:

a) Deux éprouvettes droites de fil de 250 mm de longueur chacune doivent être prélevées de la bobine de livraison.

b) 10 mm à 15 mm d'isolant doivent être retirés sur l'une des extrémités de chaque éprouvette afin d'assurer un contact électrique.

c) Chaque éprouvette doit être formée dans un gabarit, comme cela est représenté à la Figure 6. Cela produit au centre une partie droite de 150 mm environ avec des extrémités courbes, qui assurent l'écartement nécessaire aux deux extrémités de l'éprouvette finale.

Dimensions en millimètres

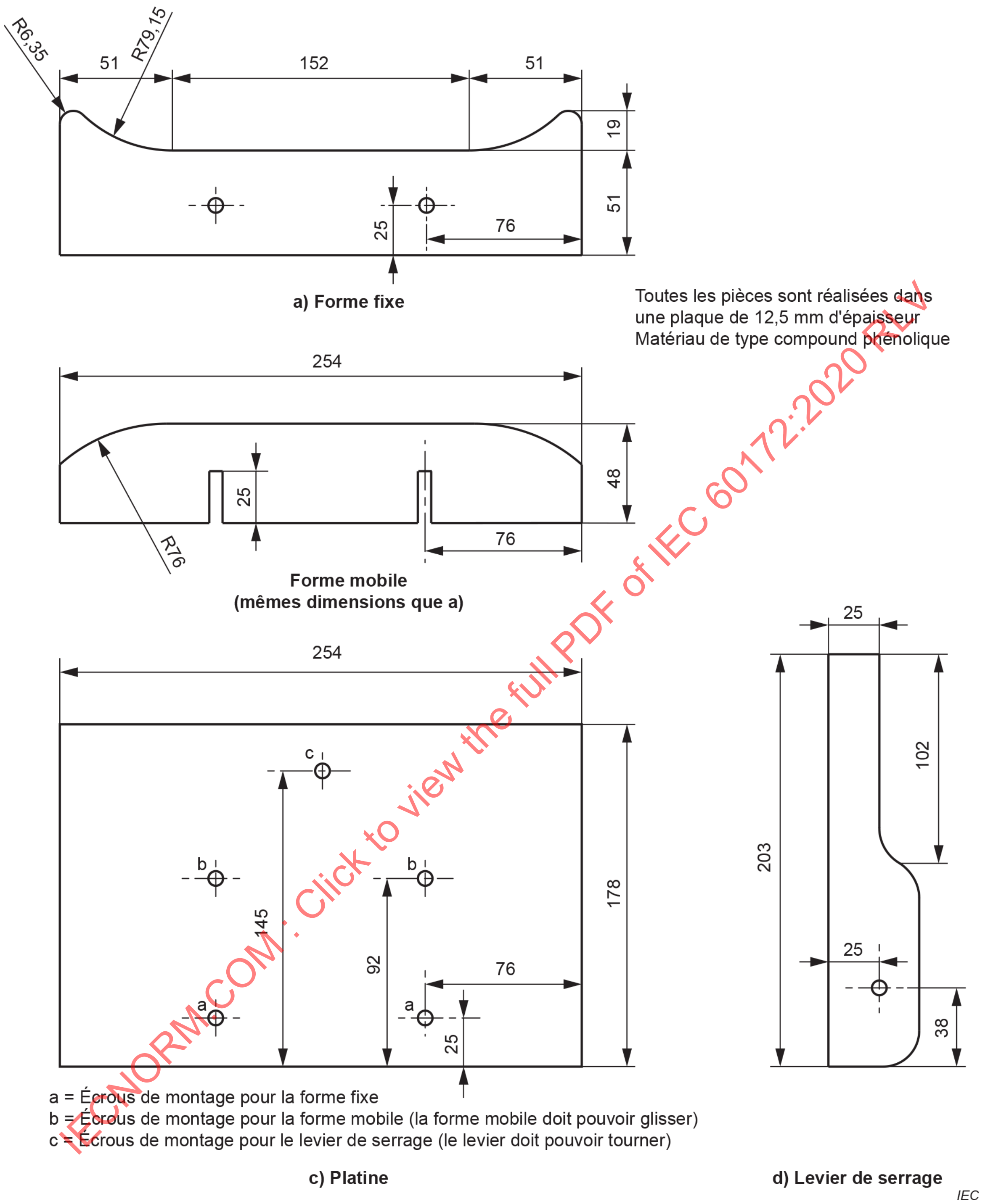


Figure 6 – Gabarit pour le formage d'un gros fil de bobinage, essai diélectrique

d) Les deux éprouvettes formées doivent être placées dos-à-dos et enveloppées fortement serrées avec de la fibre de verre sur la partie droite centrale de l'éprouvette, comme cela est représenté à la Figure 7.

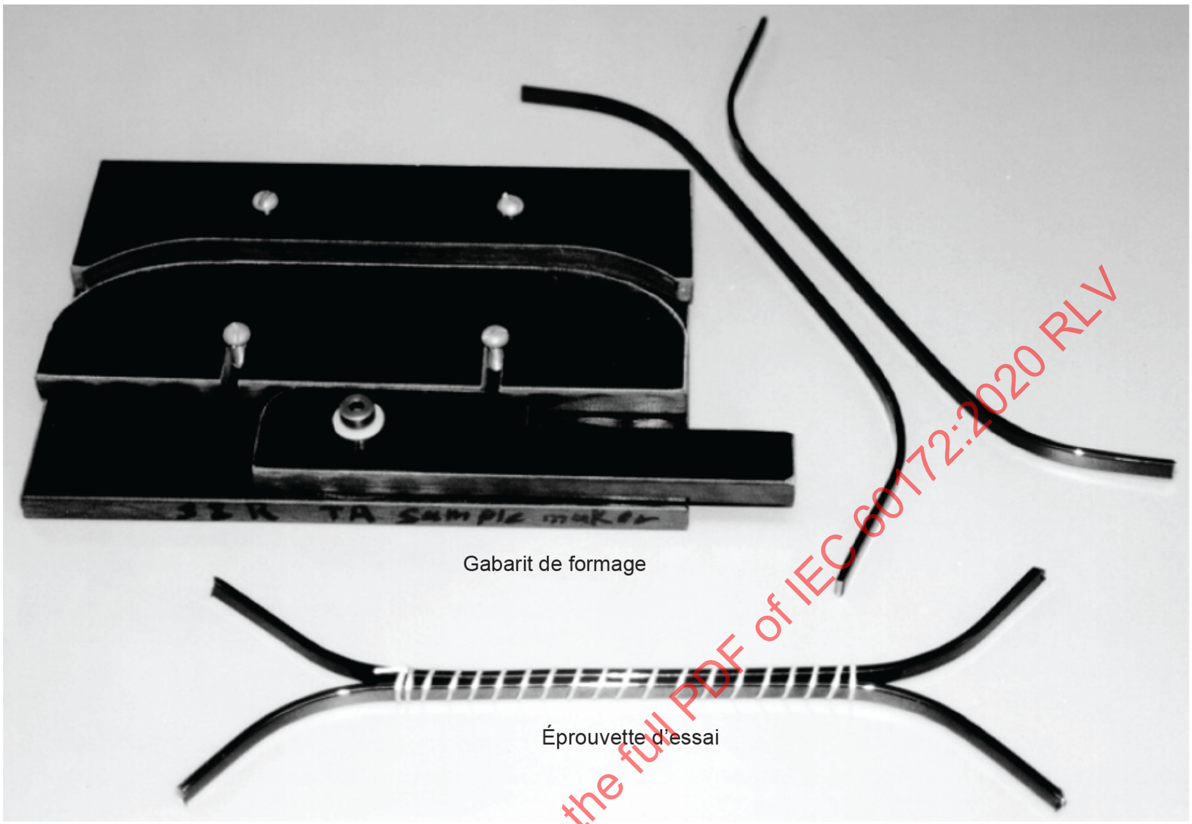


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Figure 7 – Gabarit de formage et éprouvette d'essai

Il faut veiller à ce que la partie droite centrale présente un contact très serré entre les deux éprouvettes.

Après ligature, l'accentuation des courbures des extrémités doit être évitée. Une précuisson de l'éprouvette avant l'essai ou l'imprégnation élimine les contraintes et le faïençage; elle peut donc être souhaitable pour certains matériaux.

e) Avant de démarrer les cycles d'exposition thermique, l'éprouvette doit être soumise à l'essai de tension alternative de 1 000 V.

5.2 Imprégnation

Le fil isolé conforme à l'IEC 60317 et les matériaux d'imprégnation conformes à l'IEC 60455-3-5 ou à l'IEC 60464-3-2 peuvent réagir l'un sur l'autre pendant le processus de vieillissement thermique.

NOTE 1 L'essai d'éprouvettes imprégnées permet d'évaluer la compatibilité de l'isolant du fil avec un matériau d'imprégnation. Les indices de température de différentes combinaisons peuvent ainsi être comparés.

L'interaction entre l'isolant du fil et le matériau d'imprégnation peut augmenter ou réduire la vie thermique relative quand cette combinaison est comparée à la vie du fil soumis à l'essai sans imprégnation. Avec des éprouvettes imprégnées, cette méthode d'essai peut donc donner une indication de l'endurance thermique d'une combinaison d'isolant de fil et de matériau d'imprégnation.

Si une imprégnation est exigée, la méthode suivante doit s'appliquer: