

IEEE Standard for the Preparation of Test Procedures for the Thermal Evaluation of Solid Electrical Insulating Materials

IEEE Standards Coordinating Committee 4

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Insulation Systems

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Sponsor

**IEEE Standards Coordinating Committee 4 on
Insulation Systems**

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Abstract: The test procedures covered by this standard apply to the thermal endurance of solid insulating materials, including processed compositions of raw materials, before they are fabricated into insulating structures identified with specific parts of electrical equipment.

Keywords: destructive test, end-point criteria, IEEE 98™, nondestructive test, proof test, relative temperature index, solid insulating materials, temperature index, thermal aging, thermal endurance

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Introduction

This introduction is not part of IEEE Std 98-2016, IEEE Standard for the Preparation of Test Procedures for the Thermal Evaluation of Solid Electrical Insulating Materials.

IEEE Std 98-1986 reflected many of the concepts incorporated in IEC 60216-1974 while maintaining many of the practical considerations from the initial IEEE Std 98-1972™.

IEEE Std 98-2002 incorporated additional changes in the IEC 60216 Standards and introduced the Fixed Time Frame Method (FTFM) of sampling for the thermal evaluation of materials.

IEEE Std 98-2016 provides details on the purpose of temperature indices and relative temperature indices rating, on thermal aging, causes of variations in ovens, and how to overcome influence of oven characteristics. More details for proof test and examples of nondestructive tests and proof tests are provided. [Table B.1](#) has been revised for consistency with IEC 60216-2 [\[B1\]](#) and UL 746-B [\[B6\]](#). Annexes summarizing accepted sampling techniques and an Annex on accelerated aging have been added.¹

¹The numbers in brackets correspond to those of the bibliography in [Annex D](#).

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1. Overview

1.1 Scope

The test procedures covered by this standard apply to the thermal endurance of solid insulating materials, including processed compositions of raw materials, before they are fabricated into insulating structures identified with specific parts of electrical equipment.

Tests for specific types of insulating materials, such as wire enamel, varnish, sheet, tape, etc. are not within the scope of this standard.

1.2 Purpose

This standard provides principles for the development of test procedures to evaluate the thermal endurance of solid electrical insulating materials (EIMs) thermally aged in air. The test procedures use accelerated thermal endurance test(s), conducted in accordance with prescribed procedures herein. The thermal endurance value for a measured property can be assigned based on one of two following methodologies:

- Temperature index (TI), which establishes the temperature index value by means of a preselected time coordinate.

- Relative temperature index (RTI), which establishes the temperature index value by comparison of the performance of a new material to the performance of the same property of a known material. For RTI, there is no preselected time coordinate; the correlation time is determined based on the results of the known material under laboratory conditions.

Both TI and RTI are long-term thermal aging (LTTA) methodologies.

1.3 General

TI ratings are a means to compare long-term performance of materials when exposed to heat. TI ratings are assigned by performing the appropriate LTTA test on a material. The test results are plotted, and using the calculation method presented in IEEE Std 101, the TI rating is assigned by projecting to a preselected time coordinate.²

RTI ratings are a means to compare the long-term performance of materials when exposed to heat. RTI ratings are assigned by performing the appropriate LTTA test on a material. The test results of the candidate materials are compared to the performance of a known or reference material; hence the use of the word “relative.” The test results are plotted, and using the calculation method presented in IEEE Std 101, the RTI rating is assigned for the comparison. For RTI, there cannot be a preselected time coordinate as the time coordinate is established from the test results of the known or reference material.

A TI rating is assigned to a new EIM or a modification having no known relative comparison; whereas a RTI is assigned for a modification of an existing EIM wherein performance is well known. While a TI or RTI rating gives guidance on materials, it should not be taken to predict the relationship between temperature and life of an insulating material in service.

Thermal endurance tests provide a means for determining the rate at which important properties of insulating materials deteriorate irreversibly as a function of temperature and time. Such tests and the TI/RTI rating derived aid in selecting insulating materials for use in electrical equipment operating under a wide variety of service conditions.

The mechanical, chemical, and electrical properties of the materials when new should be evaluated separately by test methods not within the scope of thermal endurance test procedures. The properties as determined may indicate that one or more, or a combination of these will be the limiting factor in a particular application rather than thermal endurance.

A distinction between material tests and test to evaluate the performance of electrical insulation systems (EIS) is necessary because the details of the particular use of a material may not be known to its manufacturer. Because insulating materials are often used as EIS in combinations, test procedures should be developed to evaluate these combinations. General principles for designating the thermal capabilities of EIS are given in IEEE Std 1 [B4] with additional information on the topic in IEEE Std 99 [B5].³ For information on accelerated thermal aging, refer to [Annex C](#).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

²Information on references can be found in [Clause 2](#).

³The numbers in brackets correspond to those of the bibliography in [Annex D](#).

ASTM D5374, Standard Test Methods for Forced-Convection Laboratory Ovens for Evaluation of Electrical Insulation.⁴

ASTM D5423, Standard Specification for Forced-Convection Laboratory Ovens for Evaluation of Electrical Insulation.

IEEE Std 101™, IEEE Guide for the Statistical Analysis of Thermal Life Test Data.^{5,6}

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁷

destructive test: A test that results in the failure or breakdown of the test specimen.

diagnostic test: A test applied to a test specimen to determine if a measurable amount of thermal degradation has occurred.

non-destructive test: A test that is not known to cause any alteration, modification, or change to the material under test.

proof test: A test that is expected to result in measuring a breakdown or failure of the electrical insulation after a preselected level of decomposition of the insulation has occurred.

relative temperature index (RTI): The number expressed in degrees Celsius (°C) that corresponds to the calculated temperature index of the new (candidate) material when the performance of the candidate material is compared to an established material.

temperature index (TI): The number that corresponds to the temperature in degrees Celsius (°C) presented graphically but calculated mathematically from the thermal endurance relationship of an electrical insulating material at a specific preselected time.

temperature to failure: In the case of destructive tests using the fixed time frame method, this is the temperature on the aging curve from the plotted data at which the aging data crosses the end-point line.

thermal capability: The ability to withstand without failure the maximum short-time operating temperature and the long-time integrated degradative effect of temperature and time.

NOTE—Thermal capability constitutes a design limitation on the use of insulating materials in electrical and electronic equipment to the extent that both thermal softening (or other short-term effects) and long-term thermal aging (LTTA) affect functional properties.⁸

thermal endurance: The retention of important properties as functions of temperature and time.

time to failure: In the case of nondestructive tests, this is the time at which the specimen failed to pass the proof test, minus half the duration of the period just prior to failure. In the case of destructive tests using the fixed temperature method, this is the time on the aging curve from the plotted data at which the aging data crosses the end-point line.

⁴ASTM publications are available from the American Society for Testing and Materials (<http://www.astm.org/>).

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⁸Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

unaged test specimen: A specimen not exposed to any elevated thermal condition.

4. General considerations

The practice to assess the thermal endurance of insulating materials is to age the materials at higher temperatures than the intended service temperature and to conduct diagnostic tests at ambient temperatures to determine retention of properties. Refer to [Annex C](#).

Care is to be taken to match the approach of the test method to the expected operating life, operating temperature, and other factors. This standard is intended for evaluations for applications with an expected life of more than one year.

4.1 Results of thermal endurance tests

The results of thermal endurance tests can be described by the Arrhenius relationship between the logarithm of time to a certain degree of property change and the reciprocal of the absolute temperature, K, as shown in [Figure 1](#). This relationship is often used for extrapolating the times to the same degree of property change at lower temperatures. Performing a thermal endurance test at three or more temperatures serves a double purpose: first, the confidence limits of the extrapolation are improved and, second, a check is provided of the basic assumption that a linear relationship exists between the logarithm of time and the reciprocals' absolute temperature. This linearity may not exist if there is more than one dominant deterioration mechanism in the range of aging temperatures. An extrapolation of the results may not be justified if this check is negative.

The two following methods are used to establish thermal endurance ratings:

- a) TI where the rating is established by projection of the accelerated thermal aging pattern to a specific preselected number of hours
- b) RTI where the rating is established by comparison of the performance of the candidate insulating material to the performance of a known insulating material

For TI, the aging curve may be extrapolated (see [7.3](#)) to a preselected length of time, which is specified in the thermal evaluation procedure for a particular insulating material. The TI for that material is the number that is equal to the value of the temperature obtained from the life-temperature curve at the arbitrarily specified time. Common preselected correlation times are 20 000 h and 40 000 h. However, the preselected correlation time can be any value or several preselected lengths of time agreed to by all interested parties. [Figure 2](#) shows a representation of how the TI data from the aging experiment is plotted.

The aging curve gives the most complete information about the results of an accelerated thermal aging test.

For RTI, the performance of the candidate material is compared to the performance of the established material. The RTI value assigned is calculated to the correlation time (usually expressed in hours) of the reference material. Refer to [Figure 3](#).

4.2 End-point criteria

The TI/RTI of a material is determined by end-point criteria based on the material's ability to withstand stresses such as electric field, mechanical (tensile, flexural and/or impact), etc., or is based on changes in a property of the material. All the properties of a material subjected to the heat aging do not deteriorate at the same rate and consequently, TI/RTI ratings should be obtained for all properties related to possible modes of failure of the material in service. A material should be expected to be assigned more than one TI/RTI derived from the measurement of different properties.

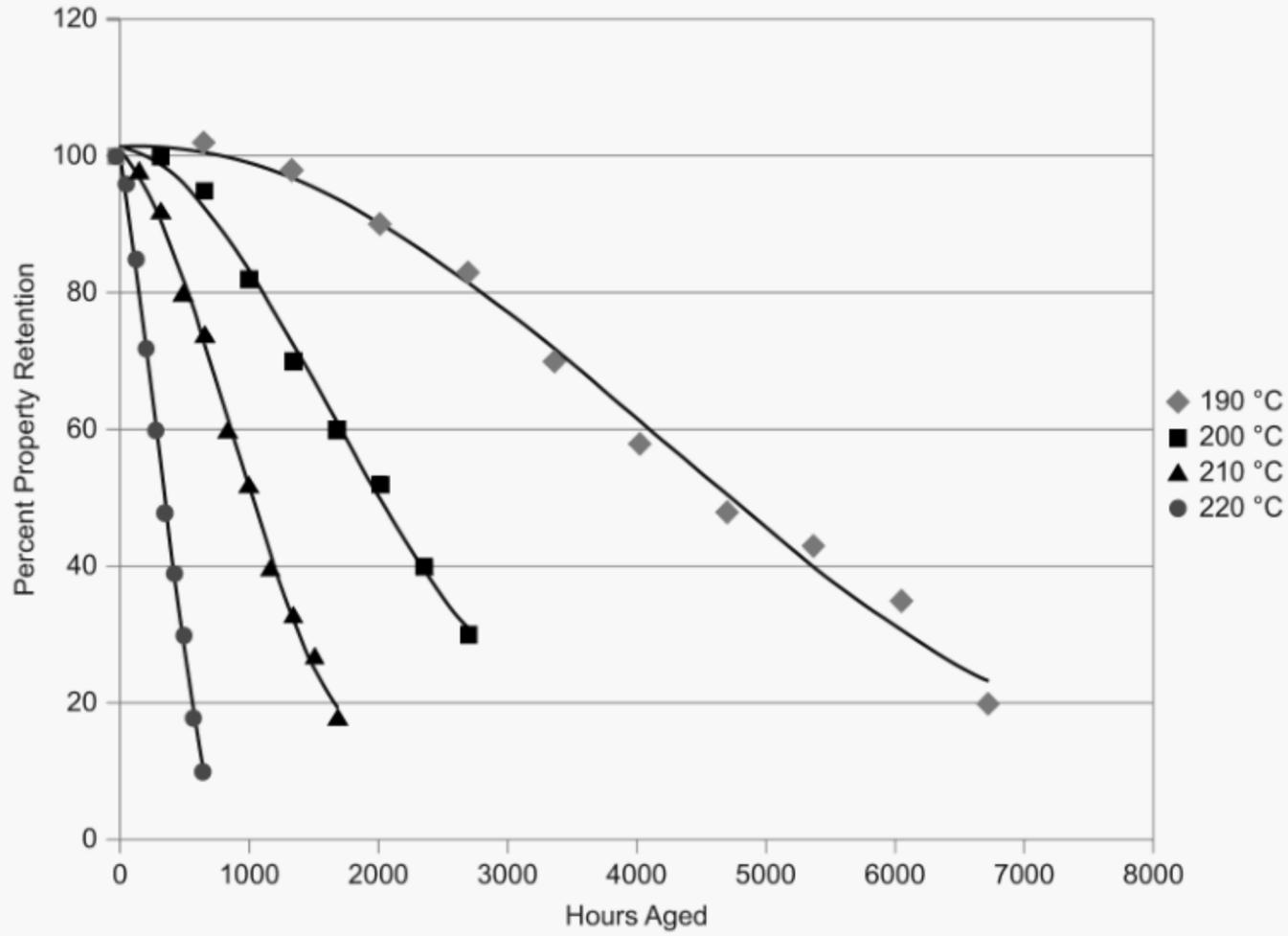


Figure 1—Illustration of property retention in a thermal evaluation

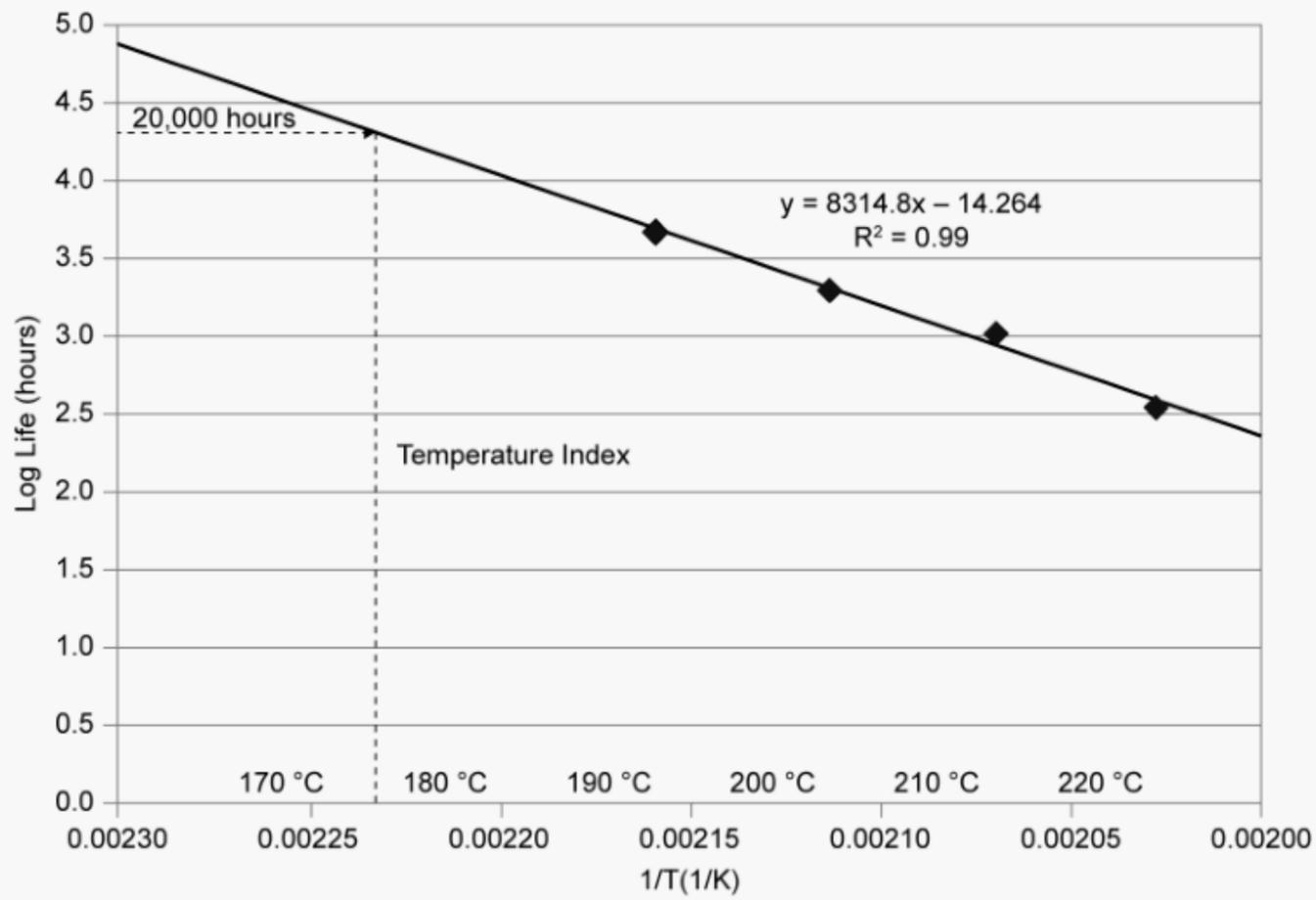


Figure 2—Temperature Index

4.3 Test procedures and conditions

Different procedures have been and are being developed to evaluate the thermal degradation of solid EIMs,

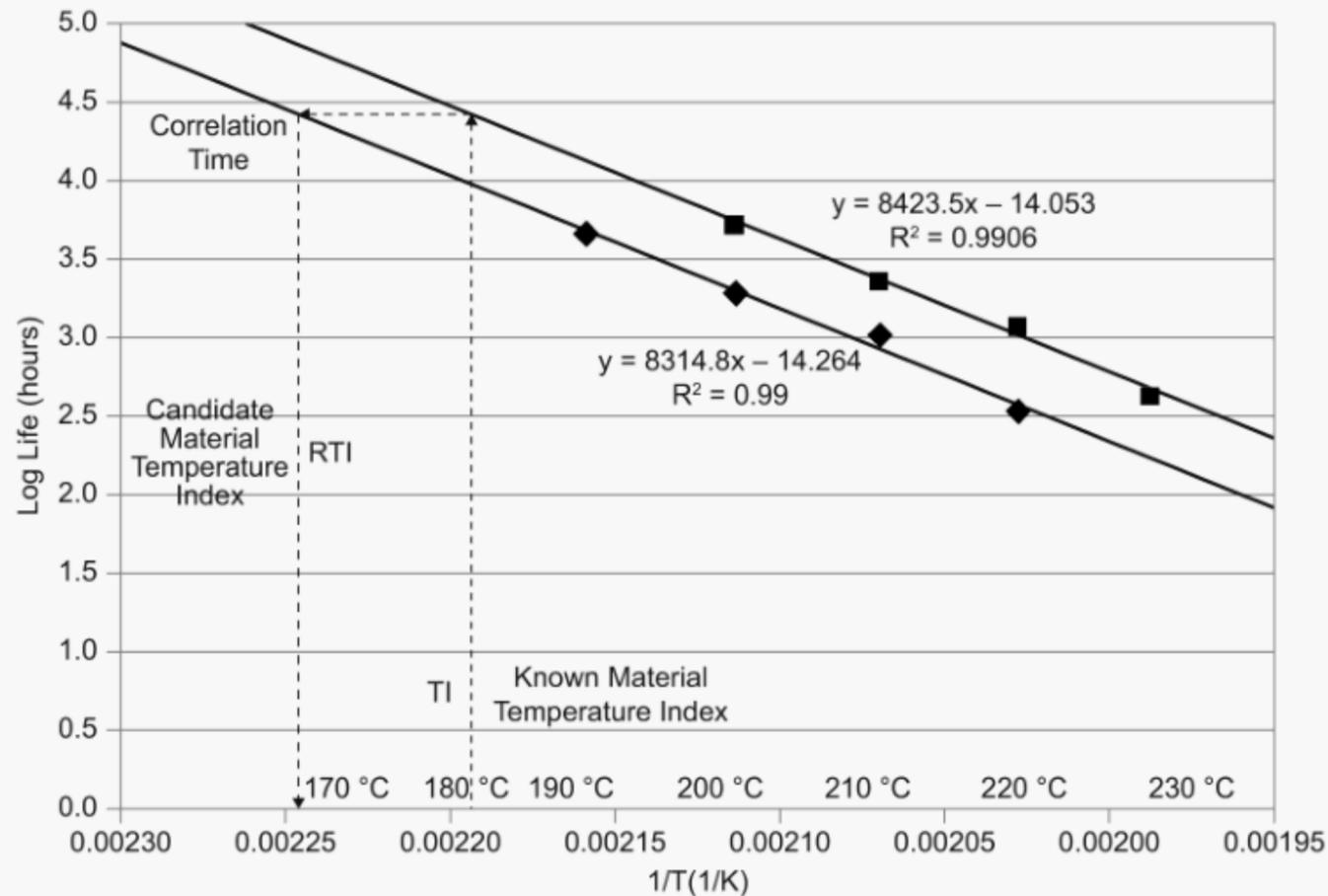


Figure 3—Relative Temperature Index Calculation

films, and papers, as well as impregnating varnishes and resins. Experience has shown that the use of some insulating materials in combination can influence one another during the thermal aging process. This interaction may modify the related thermal life as compared with the material tested alone. For example, the thermal life of enameled magnet wire may be either increased or decreased, depending upon the insulating impregnating varnish/resin used to impregnate windings containing the enameled wire. Metals in contact with insulating materials may also affect the thermal aging of the materials.

4.4 Variability

It is recognized that insulating materials will be used under widely different conditions. Factors such as voltage stress, irradiation, mechanical shock and vibration, environmental condition, and chemical contamination shall be carefully considered. The test procedure may be modified to provide methods for evaluating the effects of these factors as the material deteriorates thermally. Because materials are used in many different applications and in equipment operating under varying degrees of severity, care shall be taken not to over emphasize any one of these factors.

Experience has shown that the results of thermal endurance tests for comparable insulating materials may vary between different manufacturers and from lot to lot. Experience also indicates that thermal degradation often will be more pronounced for some materials when tested in certain shapes or in thin sections. The choice of specimen shape and thickness may therefore affect the test results and cause variations that may be greater than variations introduced by slight differences in sample preparation, handling, and test technique. For this reason, rigorous specifications in a test procedure will not prevent variations in test results. More importantly, if requirements that are too strict are specified, the tests may be costly and impractical for general use. In any case, the test method should give reliable results consistent with the inherent variations in the material under test and should provide data free from bias of the tester.

5. Use of thermal evaluation data

The procedures covered by this standard provide data on the long-time characteristics of insulation materials, which give the designer and development engineer information for the selection of materials.

A TI/RTI should not be used by itself to determine the limitations for the acceptable use of an insulating material in service. However, if a material is used in isolation from others, and if test and specimen parameters are directly comparable to service conditions, then a determination of an operating temperature may be reasonable. In such cases, the results of tests on familiar, widely used materials may be compiled for convenient reference so that comparisons between new and old material can be made.

Great care shall be exercised in the publication and interpretation of TI/RTI values for specific materials as the derivation of the TI described in 7.4 will usually be influenced by the characteristics of the aging ovens. Some of the variations caused by ovens used can be related to air circulation velocity, air changes, uniformity of the temperature throughout the oven chamber, sensitivity, or accuracy of the electronic controller.

Use of the RTI helps to overcome such difficulties because it involves a comparison with tests on a material of established service experience under precisely the same test procedure in the same ovens. These test procedures require thermal aging of the new material and the comparison material within the same time frame of the thermal evaluation. When possible to place both the new and the known material in the same aging oven, this procedure removes the influence of variations in the oven during the period of time in which the materials were in the same oven. If the oven operating conditions are not modified or changed, it can be expected that usage of the same oven for thermal aging continues to compensate for oven variations even when the materials are placed into the same oven at different times.

6. Experimental procedure guidelines

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

6.1 Selections of test methods

Each test procedure should specify the test methods to be applied to the specimens to obtain end points of aging. The test method and the end point should be appropriately selected to indicate significant deterioration of the insulating material.

The tests shall determine properties that can be measured with reasonable accuracy such as dielectric strength, insulation resistance, dissipation factor, flexural or tensile strength, elongation, impact strength, and flame retardancy.

The test chosen should evaluate a property that is likely to be of significance in practice and, when possible, should be a well-established national or international method of test.

A selection of accepted test methods for determining thermal endurance properties of electrical insulating materials is given in [Table 1](#). A summary of accepted sampling techniques is provided in [Annex A](#) (fixed time frame method) and [Annex B](#) (fixed temperature).

When it is desired to determine the thermal endurance of materials aged in atmospheres other than air (such as nitrogen or other gas or liquid), the test procedure shall give details of such special tests.

6.2 Selection of end points

Each test procedure shall fix a clearly defined end point. There are two ways in which the end point may be defined, as follows, both of which are equally acceptable:

- a) As a percentage increase or decrease in the measured value from the original value. The original value of the property is defined, unless otherwise specified, as the average value of at least 10 specimens after exposure to the lowest aging temperature for $48\text{ h} \pm 6\text{ h}$.
- b) As a fixed value of the property.

Care must be taken to select an end point that is meaningful for the evaluation of a material. A selection of end-point criteria is given in Table 1. In some cases, other end-point criteria may be better suited for a specific material or a specific purpose and should be specified in the test procedure of a specification for that material.

NOTE—For example, a material with low dielectric strength may be unable to be aged to 50% of initial dielectric strength. If the end-point value is below the dielectric strength of air, it cannot be reached until the sample fails mechanically. In this situation, a minimum dielectric value above the air breakdown value must be used as the end point. A number of standards use 300 V/mil for this purpose.

Table 1—Examples of insulating materials with recommended test properties and end points

Insulating materials	Recommended properties	Recommended end points		IEC/ISO test method	ASTM test method
		Preferred	Alternate		
Rigid materials	Flexural strength	50%	25%, 75%	ISO 178	ASTM D790
	Loss of mass – molded, cast	3%	5%, 10%	IEC 60455-2	—
	Loss of mass – laminate, fiber	5%	3%, 10%		
	Tensile strength	50%	25%, 75%	ISO 527-2	ASTM D638
	Charpy impact strength – molded, cast	50%	25%, 75%	ISO 179-1	ASTM D6110
	Tensile impact strength – molded, cast	50%	25%, 75%	ISO 8256	ASTM D1822
	Dielectric breakdown voltage	50%	25%, 75%	IEC 60243-1	ASTM D149
Elastomers	Tensile Stress at 100% extension	50%	25%, 75%	ISO 37	—
	Elongation at break	50%	25%, 75%	ISO 37	—
	Dielectric breakdown voltage	50%	25%, 75%	IEC 60243-1	ASTM D149
Semi-rigid materials	Bursting strength	50%	25%, 75%	ISO 2759	—
	Tensile strength	50%	25%, 75%	ISO 1924	—
Paper, paper based or woven materials	Tensile strength	50%	25%, 75%	IEC 60394	ASTM D882
	Dielectric breakdown voltage	50%	25%, 75%	IEC 60243-1	ASTM D1830
Pressure sensitive tapes	Dielectric breakdown voltage	50%	25%, 75%	IEC 60454-2	ASTM D149
	Loss of mass	10%	5%, 20%	IEC 60454-2	—
Flexible film and film based materials	Tensile strength	30%	10%, 50%	ISO 527-3	ASTM D882
	Elongation at break	50%	25%, 75%	ISO 527-3	—
	Dielectric breakdown voltage	2.5 kV	1 kV, 4 kV	IEC 60454-2	ASTM D1830
	Loss of mass	10%	5%, 10%	IEC 60454-2	—

Table continues

Table 1—Examples of insulating materials with recommended test properties and end points (continued)

Insulating materials	Recommended properties	Recommended end points		IEC/ISO test method	ASTM test method
		Preferred	Alternate		
Flexible insulating sleeveings	Elongation at break	50%	25%, 75%	IEC 60684-2	—
	Tensile stress at 100% extension	2 times initial	—	IEC 60684-2	—
	Dielectric breakdown voltage	50%	25%, 75%	IEC 60243-1	—
Flexible material combinations	Tensile strength	50%	25%, 75%	ISO 9124	ASTM D882
	Dielectric breakdown voltage	50%	25%, 75%	IEC 60243-1	ASTM D1830
Resin based reactive compounds	Flexural strength	50%	25%, 75%	ISO 178	ASTM D1932
	Loss of mass – unfilled	5%	3%, 10%	—	—
	Loss of mass - filled	3%	5%, 10%	—	—
Impregnating compounds and varnishes	Bond strength	22N	—	IEC 61033/B	ASTM D2519
	Dielectric breakdown voltage	3kV	—	IEC 60455-2	ASTM D3251
	Loss of mass	10%	—	IEC 60455-2	—
	Flexural strength	50%	25%, 75%	ISO 178	ASTM D1932
Coating compounds	Loss of mass	10%	5%, 10%	IEC 60455-2	—
	Dielectric breakdown voltage	3kV	—	IEC 60455-2	ASTM D3251
Insulation on conductors	Dielectric breakdown voltage	0.3–1.2 kV	—	IEC 60172	ASTM D1676

6.3 Preparation of test specimens

When not included in the test method, test procedures shall contain instructions for preparing test specimens. Include drawings and photographs when applicable.

Using the test methods selected in 6.1, specimens in an unaged condition shall be tested to verify that specimens are of uniform quality and that test results are typical of the material to be tested.

6.4 Number of test specimens

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

It is recommended that additional unaged specimens from a batch of material be allocated for future contingencies such as the need to test at additional temperatures in case of nonlinearity of data (see 7.3).

6.4.1 Number of specimens for nondestructive test

In most cases, a group of 10 specimens for each exposure temperature is an adequate sample size. Examples of nondestructive tests are as follows:

- a) Dissipation factor
- b) Dielectric constant/capacitance
- c) Resistivity: surface or volume
- d) Insulation resistance

Nondestructive properties can be used to find when a measured property undergoes a significant change, which can be the indicator of the onset of thermal decomposition.

6.4.2 Number of specimens for proof test

In most cases, a group of 10 or 11 specimens for each exposure temperature are an adequate sample size. A proof test is commonly selected when cost or other factors could increase project cost and time; the proof test approach is intended to minimize the number of test specimens needed. Examples of proof tests are as follows:

- a) Breakdown voltage of magnet wire (winding wire)
- b) Breakdown voltage of impregnating resins/varnishes applied over magnet wire (winding wire)

Both of these test methods evaluate the retained electrical insulation property using a preselected voltage value.

6.4.3 Number of specimens for destructive test

The number of specimens (N) is determined as follows in Equation (1):

$$N = (a \times b \times c) + d \quad (1)$$

where

- a is the number of specimens in a test group undergoing identical treatment at one temperature and discarded after determination of a property (usually five)
- b is the number of aging times at one temperature
- c is the number of aging temperatures
- d is the number of specimens in the group used to establish the initial value of the property

6.5 Establishment of initial property value

Randomly select specimens for the determination of the initial property value. Before determining the property value, condition these specimens for two days ($48 \text{ h} \pm 6 \text{ h}$) by exposure to the lowest aging temperature. This initial property value shall be used for the duration of the test even when the range of aging temperatures must be expanded or modified.

Unless otherwise stated in the test method for determining the diagnostic property, the initial value is the arithmetic mean of the test results.

6.6 Temperature exposures and times

Each test procedure shall recommend temperatures and times to which test specimens shall be subjected.

Two different sampling techniques may be employed to select the aging temperatures and exposure cycle times for a specific test procedure:

- a) Fixed time, variable temperature (for more details, see [Annex A](#))
- b) Fixed temperature, variable time (for more details, see [Annex B](#))

One of the commonly used procedures of thermal aging is to expose the specimens for a given period of time to the temperature conditions, known as an aging cycle. After exposure to temperature, the specimens are then subjected to the appropriate test procedure. The temperature-diagnostic factor exposure is referred to as a full

test cycle and is repeated until the end point is reached. However, thermal aging is sometimes applied continuously, and the diagnostic factors are applied periodically.

When any specimens are undergoing a proof test, the same specimens are expected to be cycled several times in the same aging condition, known as cyclic testing. When cyclic testing is used, there should be a rational relation between length of cycle, exposure temperature, and expected operating temperature. The length of the aging cycle at each exposure temperature should be selected to approximate one-tenth of the expected specimen life by this test. Values of thermal aging cycles may be established for specific equipment. The time or temperature may be adjusted to make the best use of test facilities.

For many EIM programs, the minimum length of thermal aging test time is recommended to be a minimum of 5000 h at the lowest aging temperature. However, for some types of equipment in certain categories of applications, a time other than 5000 h may be preferable. This selection of the minimum length of thermal aging time should be determined by the proper technical committee, or by written agreement between the parties involved prior to the start of the thermal aging and selection of the aging temperatures.

6.7 Aging ovens

The reliability of the test results depends upon the precision of the measured aging temperature and the accuracy to which it is maintained during testing. Even slight temperature variation may considerably influence life.

For this reason during aging, the oven temperature should be recorded and the actual average temperature during the aging period for each set of samples should be determined and used in the determination of the TI and RTI, not the oven set point. For fixed temperature aging, the average must be determined for all of the aging periods. For the fixed time frame aging, each set of aging times could have a different average temperature.

Two types of temperature variation shall be considered: variation with time (both cyclic and long-term drift) and variation at different locations in the oven. The thermal aging ovens that are used in the aging program shall comply with ASTM D5374 and ASTM D5423 and shall be capable of providing at least a minimum of five air changes per hour.

6.8 Procedure for aging

Three types of tests may be used to evaluate endurance of an insulating material:

- a) Nondestructive test.
- b) Proof test: It is expected that as thermal decomposition continues, the performance being measured/evaluated will fall below the preselected value and a failure or breakdown of the material under test will be determined.
- c) Destructive test: Each test specimen is destroyed during the evaluation of the property under test and cannot be placed back under thermal aging.

Establish the exposure temperatures and times in accordance with the instructions of 6.6 (see also [Annex A](#) or [Annex B](#)).

Prepare a number of specimens following the instructions for the selected test method and sampling procedure. If necessary, determine the initial value of the property as specified in 6.5. Divide the specimens by random selection into as many groups as there are exposure temperatures and/or times.

Place one group of specimens for exposure in each of the ovens complying with 6.7, maintained as closely as possible to the temperatures selected. The oven temperature shall be recorded.

NOTE—Electronic controllers can hold oven temperatures to within ± 1 °C (± 1 K) for oven temperatures up to 250 °C or higher.

The actual average temperature determined during the aging period for each test group is used in the determination of the TI and RTI.

6.8.1 Procedure using a nondestructive test

Unless stated otherwise in the selected test method, at the end of each aging cycle, remove the group of specimens from the oven and allow the group to cool to room temperature. Apply the appropriate test to each specimen and then return the group to the oven from which they came, at the same temperature as before, and expose for a further aging cycle. Continue the test cycles of temperature exposure, cooling, and application of the test until the individual specimens fail when the preselected end-point value for the property under test has been applied and reached.

6.8.2 Procedure using a proof test

Specimens for testing shall be selected randomly from the group of specimens that have successfully withstood screening by the proof test.

At the end of each aging cycle, remove all specimens from the aging oven. Allow the specimens to cool to room temperature and then subject each specimen to the proof test. Return specimens that withstand the proof test to the oven from which they were removed and expose for an additional aging and test cycle.

If the test results show that the time to the end point is likely to be reached in ten cycles of exposure, there is no need to alter the cycle time originally selected. If the results do not show this, the cycle time may be changed so that the median results may be expected in at least seven cycles provided this change in cycle time is made before the fourth cycle.

When there is concern that the handling or conditioning related to each full cycle could cause damage to the test specimens other than the intended thermal decomposition, a beneficial approach is to hold one or more unaged specimens. Subject the unaged test specimen(s) to the same evaluation proof test value. If the unaged specimen(s) shows failure when tested, it confirms the handling or conditioning factors have a significant influence in the test results and the project should be reevaluated to determine if the selected test method is the appropriate one to be used. If no failure occurs in the unaged specimen(s), it supports the handling and conditioning factors are not significant in the evaluation.

6.8.3 Procedure using a destructive test

For each aging oven, select at random a test group of the assigned number of specimens (see [Annex A](#) or [Annex B](#)). At the completion of each aging cycle, remove only the number of specimens to be tested. After the removal, allow those specimens to cool to room temperature prior to testing, unless otherwise specified.

Specimens are normally discarded after the test, unless they are retained for other tests or to provide a visual chronological record.

Continue to remove at the selected cycle times until the property being measured has reached the specified end point and at least one average measured value beyond the end point has been reached.

7. Evaluation

7.1 Numerical analysis of thermal aging data

The methods of analyzing the data obtained should be described in detail in the test procedure. Regression analysis, based on the method of least squares, is the preferred procedure as detailed in IEEE Std 101. This

method provides the parameters necessary for expressing the aging time and temperature relationship in mathematical form.

7.2 Times/temperatures to end-point criterion

For each group of specimens at a given temperature, a property value after each aging period is obtained. From these values, it is necessary to determine either the time or temperature required to reach the end-point criterion.

7.2.1 Nondestructive tests

The value of the property measured on each specimen after aging is plotted as a function of the logarithm of time. The point at which this graph intersects the horizontal line corresponding to the end-point criterion is taken as the time to the end point of the specimen. The time to end point of the temperature group is the mean of the specimens' time.

7.2.2 Proof tests

Unless otherwise specified, the time to failure at each temperature for the group of specimens exposed at that temperature is taken as the median value of the times to failure of the individual specimens.

For example, a specimen passes the proof test application for cycles 1, 2, 3, 4, and 5 but fails on cycle 6. The life assigned to this specimen is the total number of hours accumulated during the combined first five aging cycles, plus one-half of the number of hours of aging cycle 6. If each aging cycle is 100 h, the first five cycles would have accumulated a total of 500 h. Adding half of the number of hours for cycle 6, the life assigned would be 550 h. This procedure is performed to determine the life for each individual test specimen. The life assigned to the group of specimens being aged as a set at a single aging temperature is calculated in accordance with the specific instructions of the test method being used to evaluate the specific property of the material under test.

7.2.3 Destructive tests

For the fixed time frame procedure (see [Annex A](#)), a graph of property values at each fixed exposure time is plotted against temperature. A straight line corresponding to the selected end point, which may be either a specified value or a percentage of the original value, is drawn on the graph. The point where the curve drawn from the plotted points crosses the straight line, indicating the end point, is read as the measured temperature to failure at each exposure time.

For the fixed temperature procedure (see [Annex B](#)), a graph of property values determined at the end of each exposure period is plotted against time of exposure. The straight line corresponding to the selected end point, which may be either a fixed value or a percentage of the original value, is drawn on the graph. The point where the curve drawn from the plotted points crosses the straight line, indicating the end point, is read as the measured time to failure at each exposure temperature.

7.3 Extrapolation of the data

For the fixed time frame method, the temperatures to reach the end point at each fixed time are plotted on a graph with the logarithm of time as the ordinate and the reciprocal of the absolute temperature, K , as the abscissa.

For the fixed temperature method, the times to reach the end-point temperature are plotted on a graph identical to the one in the fixed time frame method. If nonlinearity is apparent in the thermal endurance curve or is defined by a statistical analysis, testing at additional temperatures is recommended.

Regression analysis using the analytical procedures outlined in IEEE Std 101 is the preferred method of drawing the thermal endurance graph. In some cases, a straight line drawn to visually fit the data points is satisfactory. IEEE Std 101 also outlines methods to determine whether the data is linear and to calculate the confidence limit of the thermal endurance graph at chosen temperatures or time. Computer programs exist for this purpose. The data points shall always be shown even with computer plots.

If nonlinearity is apparent in the thermal endurance curve, testing at additional temperatures is recommended. The selection of additional temperatures must be based on the pattern of the original test data, the application, and requirements of the end product.

In practice, values between 20 000 h and 40 000 h have been selected as the time for which the corresponding temperature on the extrapolated thermal endurance curve gives the nominal value of the TI. It is the responsibility of the appropriate standardizing body to define the time upon which the TI of specific insulating materials is to be based.

7.4 Determination of temperature index (TI)

The TI is deduced from the graph at the desired time, and the number of thousands of hours shall prefix the index. For example, in [Figure 2](#), the TI at 20 000 h is expressed as follows:

TI 20kh/173

An alternative procedure is to include in the test a material of recognized service experience in the same ovens, and plot the thermal endurance graph for both materials on the same sheet. Find the point on the graph for the known material that corresponds to its recognized service temperature, and then use this time for obtaining the TI of the second material.

CAUTION

Caution in the use of this procedure is called for when the thermal endurance graphs have significantly different slopes.

When the TI is determined in this way, it is called the RTI. For example, in [Figure 3](#), the RTI of the candidate material is as follows:

RTI/171

Care shall be taken that the increments for expressing TI and RTI are not too small so as to avoid the impression that a high degree of precision is inherent in the procedure or that very fine discrimination can be made among insulating materials. One scheme, which has been used in UL 746-B [B6], utilizes the following graduations:

- 5 °C increments up to 130°C
- 10 °C increments from 130 °C to 180 °C, except to include 155 °C
- 20 °C increments over 180 °C

Different thermal endurance curves may be obtained when different failure (end-point) criteria are used. It is desirable, therefore, to describe the TIs with the end-point criteria shown parenthetically. For example:

- TI (tensile strength)
- TI (voltage breakdown)

— TI (impact strength)

8. Test report

The test report shall include the following, in all cases:

- a) The description of the tested material (including the reference material if an RTI is derived)
- b) The nature and magnitude of additional exposure factors, if used
- c) The property investigated to evaluate the thermal aging and the individual values obtained
- d) The test method used for the determination of the property (for example, by reference to a national or international standard)
- e) The nature and magnitude of the failure
- f) End point selected
- g) Actual aging temperatures
- h) Tables of test data
- i) The thermal endurance graph and, where applicable, the graphs of the variation of property versus time
- j) The TI expressed in accordance with 7.4 of this standard

Annex A

(normative)

Fixed time frame method sampling

It can be difficult to know or select the right or best temperatures for a long-term thermal aging (LTTA) test. The fixed time frame method (FTFM) of sampling is based on fixing the time (aging intervals) as the controlled variable while aging temperature is the dependent variable.

The FTFM utilizes standard test specimens and test methods. The end-of-life values are the same as for the fixed-temperature method of sampling.

The recommended first step in FTFM is a broad temperature screening test. The balance of the test is organized using the results of the screening test.

A.1 Screening test

- a) As a general guideline in selecting the aging temperatures to be used in the screening test, select six or more aging temperatures starting approximately 40 °C above the expected TR/RTI value of the candidate material. The aging temperatures should be at increments of 10 K.
- b) For RTI evaluations, the reference material shall also be aged. The selected aging temperatures for the reference and the candidate materials are not required to be identical, but there should be overlap of several of the aging temperatures to assist in the comparison and analysis of the candidate material. Selection of the aging temperatures may need to be different for the reference and candidate materials due to melt temperatures or other essential conditions.
- c) The aging temperatures must span the end-of-life value for the property being evaluated in the screening test. It is recommended that the results of four consecutive aging temperatures be used in calculating the temperature coordinate at which the end-of-life value is found. In order to achieve this, it is essential that the results obtained at one of the aging temperatures have a measured property value above the end-of-life value, and at least one below the end-of-life value.
- d) An appropriately sized set of specimens shall be placed into each aging oven selected for the screening test. The preferred time, fixed time interval, for the screening test is 552 h. All sets of specimens aged at all temperatures selected for the screening test are removed, conditioned, and tested at the completion of the time selected for the screening test.

Based on the end-of-life value, select four or more sequential aging temperatures that span the end-of-life value meeting the requirement that at least one value is above and one is below the end-of-life value.

- e) Calculate the average percentage of retention of the property being evaluated after aging at each temperature. For each set of specimens, use the initial value of property in accordance with 6.5 of this standard as the reference value for determining the percent of retained property. This calculation provides a set of temperature-percent retention values. Using the four sequential percent retention values meeting the condition in item c, calculate the temperature at which the end of life can be assigned. The end-of-life retention values shall be based on a linear regression through the set of four or more temperature-percent retention values.
- f) The calculated end-of-life value is the temperature assigned to the fixed time of the aging interval. This time-temperature value is one of the fixed coordinates needed for the analysis and calculation of the TI or RTI value. This time-temperature can be designated as time interval (for example, T552h).

- g) The screening test provides both a time-temperature coordinate, as well as a profile of the thermal decomposition of the material being tested.

A.2 Completion of the test

- a) Based on the results of the screening test, the remainder of the needed specimens is placed under aging for testing at additional fixed-time intervals to be selected. A minimum of four fixed-time intervals should be used in the calculation of the TI or RTI value.

Because most long-term heat-aging projects have a 5000 h minimum time requirement, the preferred group of fixed-time intervals is:

- 1) 552 h (from the screening test)
- 2) 1008 h
- 3) 2016 h
- 4) 3528 h
- 5) 5040 h

Select a minimum of four of these intervals. For programs with the 5000 h minimum requirement, the 5040 h interval must be included.

In each case, four consecutive aging temperatures are to be used at each selected fixed-time interval. It is recommended that more than four aging temperatures be used for each interval, but only four sequential temperatures are to be selected for the calculation at each interval.

- b) Analyze the data obtained at four or more fixed-time intervals using the procedures given in [Clause 7](#) of this standard.

Annex B

(normative)

Fixed temperature method of sampling

A selection of aging temperatures and cycle durations for a thermal endurance test is shown in [Table B.1](#). The row in [Table B.1](#), corresponding to the estimated TI/RTI, shows suggested aging cycles in days at oven temperatures that appear at the head of the respective columns. The following recommendations and suggestions are useful in establishing aging temperatures and times.

B.1 Exposure temperature guidelines

The highest exposure temperature should result in a median time to end point between 100 h and 500 h.

The exposure temperatures selected are preferred to be at intervals of 10 K. However, based on the chemistry of the material test, the temperature separations of 15 K or 20 K may be preferred.

Selection of exposure temperatures involves estimating or knowing beforehand the approximate value of the TI/RTI of the material to be tested. If this information is not available, screening tests as described in [Annex A](#) may be performed to predict a value of TI/RTI.

For RTI evaluations, the reference material shall also be aged. The selected aging temperatures for the reference and the candidate material are not required to be identical, but when possible, there should be an overlap of at least two temperatures.

B.2 Exposure temperatures

B.2.1 Cycling aging

For proof test and nondestructive tests, exposure cycles should be selected so as to give approximately the same number of cycles before the failure at each temperature. It is suggested that the exposure time at each temperature be selected so as to subject the specimens to approximately 10 heating and cooling cycles.

B.2.2 Continuous aging

For destructive tests, the aging of each tested group is continuous and therefore, the length and number of time intervals between testing are not as important. However, it is recommended that the planned number of groups of test specimens at each temperature be at least five, with ten being preferred. The time interval between tests of groups of specimens should be planned so that at least two groups of specimens are available before the time-to-end point, so that at least one group is available after the time-to-end point.

If relatively long test periods are selected initially, approximately half of the groups of specimens can be held back and placed in the aging oven at the end of the second or third cycle. When failures take place after a long period of aging, the groups of test specimens held back are to be used to define the time to failure more accurately with relatively short exposure times.

The end of insulation life is assumed to have occurred at the midpoint of the exposure time between two consecutive applications of diagnostic factors: the one during which failure was observed and the last prior application of diagnostic factors with no failures.

Table B.1—Illustration of exposure temperature and cycle duration

Estimated value of TI in range (°C)	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310
95-104	28	14	7	3																
105-114		28	14	7	3															
115-124			28	14	7	3														
125-134				28	14	7	3													
135-144					28	14	7	3												
145-154						28	14	7	3											
155-164							28	14	7	3										
165-174								28	14	7	3									
175-184									28	14	7	3								
185-194										28	14	7	3							
195-204											28	14	7	3						
205-214												28	14	7	3					
215-224													28	14	7	3				
225-234														28	14	7	3			
235-244															28	14	7	3		
245-254																28	14	7	3	

NOTE—This table is illustrative only; other tables are in use. The appropriate equipment technical committee can choose test ranges, exposure temperatures, and length of cycles suitable for their particular equipment. They may find it convenient, for example, to replace the temperature range by a specific limiting temperature to make the time per cycle in weekly multiples, or to adjust the aging temperature for laboratory convenience.

Annex C

(informative)

Accelerated aging of an electrical insulating material

C.1 General

Accelerated aging provides useful information that can be used to indicate potential long-term performance (operating life) of an end product based on testing completed in a reduced time frame.

Accelerated aging simulates normal wear conditions over the service life by subjecting the material to more rapid thermal decomposition by testing at elevated temperatures and more frequent or severe stresses to measure the change in material property over a much shorter duration of time.

C.1.1 Thermal aging and material properties

In thermal aging, the properties of a material deteriorate at different rates. Select specific properties to be evaluated and the tests to evaluate the change in those properties. Aging temperatures should be chosen so that the dominant deterioration mechanism is in the range of test temperatures. Interim test intervals should be chosen to be significant enough to detect initial presence of failures. Select a sufficient number of test samples for statistically validating results for each test interval. The time to the end point of aging is an exponential function of temperature that can be expressed linearly assuming thermal degradation is dominated by a single deterioration mechanism. In the event of nonlinearity, unaged samples should be tested at additional temperatures - based upon the pattern of the original data, the property of the material under evaluation and failure mode.

C.1.2 Evaluating end-product operating life

For end products that have an expected operating life of longer than a year(s), the evaluation of the possible life of the product under real world conditions would require a year(s) of time; hence the need for accelerated aging for applications with an expected long operating life. The test methodology needed to be able to evaluate an end product can be approached by multi-factor testing in real world conditions, or by separating the overall program into steps or stages. To evaluate the end product can be expensive and time consuming, leading to the benefit of testing laboratory models. Part of the stepped approach is to evaluate the electrical insulation system (EIS) of interest for the end product, and/or the end product in a reasonable period of time, and EIMs for use within the product.

Once the EIS level of accelerated aging is understood, it is easier to then extend the concept to the evaluation of EIMs.

C.1.3 Accelerated aging

For example, the results of an accelerated aging project give insight into potential life of an EIS or an end product of several years under expected operating conditions. The accelerated aging aspect of the test program is expected to be completed in a year or less. Based on the structure of the project and the selection of the reference, the potential life can be estimated for 5 years, 10 years, 20 years, or longer. Since different applications have different levels of the combined real-world stresses, not all tests for the different applications should be expected to project the same expected operating life potential. Each segment of the industry must adjust any projection to fit within reasonable limits.

C.2 Background

All performance and safety requirements originate with the end product and its application. All EIS and EIM testing came along many decades after end product testing had been in place. End product testing has been part of the industry since the beginning of the commercialization of electricity. EIS and EIM testing did not become a major part of the industry until the 1950s and more recent.

EIS and EIM testing is to be used as a means to evaluate alternate, new or replacement materials into existing (known) end product evaluations. The origination of EIS and EIM testing was not to convey that this level of testing/evaluation by itself can provide the information needed to predict the potential life of any end product. The intent was to use the established or known life of the end product, and to merge or combine the EIS or EIM test results to substitute a new or alternate EIS or EIM for the original.

EIS and EIM testing were not intended to be the starting point for the decision process needed by the end product manufacturing companies.

Annex D

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] IEC 60216-2, Electrical insulating materials – Thermal endurance properties – Part 2: Determination of thermal endurance properties of electrical insulating materials – Choice of test criteria.⁹

[B2] IEC 60216-5, Electrical insulating materials – Thermal endurance properties – Part 5: Determination of relative thermal endurance index (RTE) of an insulating material.

[B3] IEC 60216-6, 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.

[B4] IEEE Std 1™, Recommended Practice – General Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation.¹⁰

[B5] IEEE Std 99™, Recommended Practice for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electrical Equipment.

[B6] UL 746-B, Standard For Safety Polymeric Materials – Long Term Property Evaluation.¹¹

⁹IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch>). IEC publications are also available in the United States from the American National Standards Institute (<http://www.ansi.org/>).

¹⁰IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

¹¹UL standards are available from Underwriters Laboratories (<http://www.ul.com/>).

Consensus

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