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(Revision of
IEEE Std C57.100-1986)

IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers

Sponsor

**Transformers Committee
of the
IEEE Power Engineering Society**

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IEEE-SA Standards Board

Abstract: A test procedure is established to provide a uniform method for investigating the effect of operating temperature on the life expectancy of liquid-immersed transformers. The test procedures are intended to provide data for the selection of a limiting hottest-spot temperature for rating purposes, provide data which may serve as the basis for a guide for loading, and permit the comparative evaluation of a proposed insulation system with reference to a system that has proven to be acceptable in service.
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Introduction

(This introduction is not part of IEEE Std C57.100-1999, IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers.)

This standard is intended to establish test procedures for evaluating the insulation systems of liquid-immersed transformers. The electrical insulation of transformers is subject to many electrical, mechanical, and thermal stresses occurring in different parts of the structure. How long the insulation system will be serviceable depends on the effectiveness of the physical support for the insulation and the severity of the forces acting on it, as well as on the materials themselves and the service environment. Therefore, the length of useful life of the insulation system depends on the way that its individual components are arranged, their interactions upon each other, the contribution of each component to the electrical and mechanical integrity of the system, and the way the transformer is manufactured and maintained.

Experience has shown that the thermal life characteristics of composite insulation systems cannot be reliably inferred solely from information concerning individual component materials. To assure satisfactory service life, transformer designs need to be verified by service experience or accelerated life tests. Tests on complete insulation systems, representative of each transformer design, are necessary to confirm the performance of materials for their specific functions in the transformer.

During the preparation of prior editions of this standard, manufacturers built and tested more than one hundred complete distribution transformers. The results of these tests, while not specifically published, confirmed the practicality of the test procedures in this standard for liquid-immersed distribution transformers.

It was recognized by prior working groups that a need existed for a similar test procedure for power transformers. To fulfill this need, two projects on “Basic Transformer Life Characteristics” were completed by the Electric Power Research Institute (EPRI) in 1982. The goal was to find a way to evaluate the effect of overload on the insulation life of power transformers. Testing was performed on insulated coils, models, and model assemblies. The information obtained from these EPRI projects was used to extend the test procedures in this standard to power transformers. It was recognized by the working group that the effect of bubbles is a factor during overloading. However, the objective of this standard is to evaluate the effect of operating temperature on the life expectancy and not to test for the effect of bubbles that may occur during, or following, overloads.

The correct value for end point dielectric tests has been a subject of debate for many years, and it is very difficult to arrive at the correct value. At one extreme are those who believe that useful life ended only when the transformer was unable to carry rated load at rated voltage. At the other extreme are those who believe that transformers that could not sustain the standard tests given to new transformers were unfit for further use, since they believe that the probability of failure on abnormal currents or voltage would then be high. For distribution transformers, the consensus was that the end point test level should be 65% of the values specified for a new transformer. For power transformer models, the consensus was that the end point test level should be 65% of the design level. Since such tests, presumably, are intended to insure serviceability of the apparatus, the 65% should be adequate for end point tests.

Manufacturers occasionally must make changes in the insulation used in transformers. This occurs due to the development of a new material or a change in vendors. In some cases, a preferred material will no longer be available, or a preliminary evaluation of the potential of a new insulation system is needed. Therefore, it is reasonable to permit a reduced scale thermal test to determine that the change will not reduce the life of the transformer. For these reasons an annex to this procedure has been added defining a sealed tube aging test.

This test procedure was produced by the IEEE Working Group on Thermal Evaluation of Power and Distribution Transformers which had the following membership:

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Contents

IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers

1. Overview

1.1 Scope

This test procedure is intended to give a direct evaluation of the thermal aging characteristics of the composite insulation system of a liquid-immersed distribution or power transformer. The evolution of bubbles or their effect on dielectric strength is not considered. It is to be noted that the liquid in which the transformer is immersed is to be considered a part of the insulation system.

It is the intent of the procedure to provide that each component of the insulation structure operate during the test under conditions that are, as nearly as possible, the same as those that it would encounter in service. Thus, it is intended that each component be evaluated in accordance with its actual function.

1.2 Purpose

The objective of this test procedure is to establish a uniform method for investigating the effect of operating temperature on the life expectancy of liquid-immersed transformers. The purposes of this standard are as follows:

a) Provide data for the selection of a limiting hottest-spot temperature for rating purposes. Acceptable thermal aging performance may be assumed if the hottest-spot temperature, at rated load as defined in IEEE Std C57.12.00-1993,[1] demonstrates a minimum life expectancy of at least 20.5 y (180 000 h) as determined by this test procedure;

b) Provide data that may serve as the basis for a guide for loading; and

c) Permit the comparative evaluation of a proposed insulation system with reference to a system that has proven to be acceptable in service. The minimum life expectancy curve to be used for comparison purposes is given by Equation (1) and displayed in Figure 1.

[1]Information on references can be found in Clause 2.

$$LIFE = EXP^{\left[\frac{15\,000}{T + 273} - 27.064\right]} \quad (1)$$

where

LIFE is the life in hours
T is the hottest-spot temperature in ºC

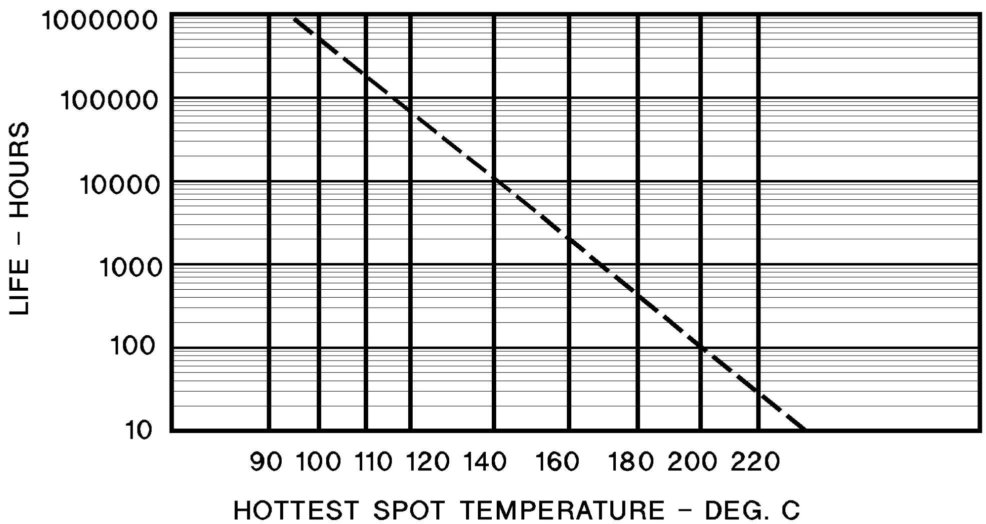

Figure 1—Minimum life expectancy curve for liquid-immersed distribution, power, and regulating transformers rated in accordance with IEEE Std C57.12.00-1993, 65 °C average rise, 80 °C hottest-spot rise

2. References

This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

ASTM D-4243-86 (Reaff 1993), Standard Method for Measurement of Average Viscometric Degree of Polymerization of New and Aged Electrical Papers and Boards.[2]

IEEE Std 1-1986 (Reaff 1992), IEEE General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation.[3]

IEEE Std 99-1980 (Reaff 1992), IEEE Recommended Practice for the Preparation of Test Procedure for the Thermal Evaluation of Insulation Systems for Electric Equipment.

IEEE Std 101-1987 (Reaff 1995), IEEE Guide for the Statistical Analysis of Thermal Life Test Data.

[2]ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).

[3]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.90-1999, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.91-1995, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

3. Aging influences

The primary aging factors employed in this procedure are temperature and time. Since few transformers operate for extended periods at constant temperatures, provision is made for thermal cycling in this procedure.

It is recognized that environmental conditions, such as corrosive atmosphere and excessive vibration, may affect actual service life. It seems appropriate to evaluate such extraneous influences separately from the effects of temperature, and they are not included in this procedure.

4. Minimum life expectancy

The load on most transformers is cyclic, with both daily and annual cycles. For this reason, the peak thermal loading (that which develops the highest temperature in the transformer windings) occurs on relatively few days during the year and for a relatively small portion of each of these days. Thus, the cumulative time at or above the rated hottest-spot temperature is considerably less than the total elapsed time. Further, it is generally agreed that thermal degradation of insulation is a function of both temperature and time at the temperature. Consequently, the life expectancy (elapsed time) in actual service will be very much greater than the life determined by the essentially continuous loading procedure prescribed in this standard.

Experience and experimental evidence indicate that an insulation system capable of operating 180 000 h, (approximately 20.5 y) at rated hottest-spot temperature should give satisfactory life expectancy under the normal operating conditions described in the preceding paragraph.

5. Criteria for end of life

In this test, the life of a particular test specimen is considered to be ended when thermal degradation has progressed to a point such that the specimen cannot withstand any one of a series of tests intended to simulate the abnormal currents or voltages that are commonly experienced in actual service. The degradation or aging is produced by a series of temperature cycles, each consisting of a specified time at a specified hottest-spot temperature followed by a return to approximately ambient temperature. Such a series of temperature cycles, followed by end-of-life tests, will hereafter be referred to as a *test period*.

Since it is impractical to determine the exact point in the test period procedure when the sample reached the level at which it could not withstand the end-point tests, its life at the test temperature should be considered to be the duration of one test period multiplied by the number of periods to failure less one half of one period.

Because of the nature of this test, the word *failure*, as used herein, assumes a special connotation. It is used here to describe an insulation breakdown such that a service outage would result if it occurred in the field. Consequently, some of the criteria of failure that are commonly used in tests on new transformers do not apply. For example, minor disturbances in the oscillograms obtained on impulse tests, or increases in the leakage current on applied potential tests are not necessarily indicative of failure as defined here. Specific instructions for the treatment of such marginal cases are given in 9.3.

If a test sample should fail prematurely, that is, long before its anticipated life expectancy and if subsequent examination conclusively shows the failure to be the result of defects in material or workmanship rather than thermal degradation, failure of this sample may be ignored in determining the test results and another sample substituted for it.

6. Test temperatures

The accuracy of an evaluation will increase as the number of test temperatures increases, but its cost will also increase. In general, tests should be made at the maximum number of temperatures that can be justified economically with the following qualifications:

a) When insufficient previous information exists regarding the shape of the life expectancy temperature curve for the system being evaluated, tests should be made at a minimum of three temperatures selected as recommended in IEEE Std 99-1980. If the results are not such as to permit the necessary extrapolation with confidence, tests at additional temperatures should be made; and
b) When the shape of the life expectancy temperature curve is known, evaluation tests at a single temperature may be adequate. Such tests may be of value, for example, in experimental studies or in demonstrating that a minor change in the system has not, in fact, altered its life expectancy. They must be used with caution and never for the evaluation of new materials in highly stressed areas. The test temperature should be the minimum consistent with obtaining results in a reasonable length of time.

7. Test specimens and procedures

7.1 Distribution transformers

Test samples should be complete transformers and should be typical of the design being evaluated insofar as insulation structure and processing, liquid content, and manner of sealing are concerned. A minimum of three samples should be tested at each test temperature.

The test procedure involves subjecting the test samples to repeated test periods consisting of the following two parts:

a) Exposure to elevated temperature while excited at rated voltage; and
b) Application of end-point tests to determine end of life, as defined in Clause 5.

7.2 Power transformers

It will normally be impracticable to test full-size transformers for thermal evaluation of their insulation systems. However, transformer experts believe that model winding configurations utilizing typical conductors, insulation, and supporting structures can provide performance representative of power transformer thermal endurance. The models are based on the assumption that the conductor turn insulation is subjected to the most critical thermal degradation that limits the transformers' dielectric and/or through-fault withstand.

The models shall be calibrated and monitored to establish accurate thermal gradients and hottest-spot temperatures so that correlation of time and temperature can be established over the duration of the aging period. Preliminary models should be tested to dielectric breakdown and through-fault displacement in order to establish the model rating. The model rating is the benchmark for establishing the “end point” test levels.

It is recommended that the test tanks containing the aging models use a conservator (or other constant pressure) liquid preservation system. Experience has demonstrated that temperature cycling of models with a gas blanket liquid preservation system may introduce gas into the insulation and result in premature dielectric failure. (See Electric Power Research Institute [B3][4] and McNutt and Kaufmann [B11].)

The test procedure, like the procedure for distribution transformers, involves subjecting the samples to repeated test periods consisting of the following two parts:

a) Exposure to elevated temperatures by circulating current through the windings, i.e., the conductor resistance provides the heat source; and
b) Application of end-point tests to determine end of life, as defined in Clause 5. Dielectric tests should be performed at or near room temperature and at an appropriate time after aging to assure that free gasses evolved at higher temperatures will not affect the test results.

8. Test period

8.1 Hottest-spot test temperature

The test temperature, measured in degrees Celsius, should be produced by circulating alternating current of rated frequency through the windings and should be maintained constant within ±1.5% during the aging period in all samples. It should be the temperature indicated by a sensing means located at the hottest spot within the insulation structure.

One method of meeting these requirements is to construct a monitor unit identical to the test samples, except that it has a thermocouple embedded in the transformer winding at the hottest insulation spot. The thermocouple leads are brought out of the sample through a suitable sealed plug in the tank to an appropriate measuring and control device. To ensure equal current in all samples, corresponding windings of all test samples and those of the monitor unit are connected in series. Other methods of controlling hottest-spot temperature in the test samples may be used, if desired.

8.2 Temperature of liquid

During the aging period, the liquid temperature should be allowed to attain its natural value as determined by the transformer design unless this will produce a fire or explosion hazard. To avoid these hazards, forced-air cooling of natural convection cooled (ONAN) transformers is permissible for the sake of consistency with other test points; however, the amount of artificial cooling should be no more than that required to hold the top liquid temperature in the test samples to a safe temperature. In the presentation of test data, points obtained with artificial cooling should be so identified.

8.3 Duration of test period

The duration of each test period should be approximately 10% of the anticipated life expectancy of the sample at the test temperature with two permissible exceptions as follows:

[4]The numbers in brackets correspond to those of the bibliography in Annex B.

a) When the test period thus determined is long, it may be desirable to perform a set of end-point tests before the end of the first test period in order to eliminate samples with gross defects before the test has proceeded too far; or

b) If no failure has occurred by the end of the tenth test period, the length of succeeding periods may be increased to increase the number of hours at temperature obtained per unit of elapsed time.

8.4 Cycling

At least four times during each test period, and also prior to making end-point tests, the power supply to the test samples should be disconnected and the samples allowed to cool to a top liquid temperature between 25 ºC and 40 ºC.

8.5 Calculation of aging caused by heating and cooling

Some aging will occur during the heating and cooling periods involved in each temperature cycle so that the actual life will be somewhat greater than the total elapsed time at temperature as defined in Clause 5. In general, aging during the cooling period will be a negligible fraction of the total aging per cycle.

Aging during the heating period (and the total duration of the test program) will be substantially reduced if the initial value of the load current is chosen as 1.5 to 2.0 per unit of the value required to maintain the hottest-spot temperature at the desired value. It will then also be a negligible fraction of the total aging per cycle.

A rough calculation of the error involved in neglecting the aging during transient heating and cooling should be made using the method and equations found in Clause 5 of IEEE C57.91-1995, as well as using the planned load cycle, the known thermal characteristics of the test specimen, and an aging curve based on previous tests or anticipated test results. If the error, so calculated, exceeds 5%, either

a) The preheating rate should be further accelerated to reduce the error below 5%; or

b) The hottest-spot temperature should be monitored during a typical temperature cycle and actual correction computed using the above appropriate references and the uncorrected life-expectancy data obtained from the test results. This correction should then be added to the results obtained, using Clause 5 of IEEE C57.91-1995.

9. End-point tests

9.1 Distribution transformers

At the end of each test period, each sample should be given the following end-point tests in the following order:

a) Short-circuit test (symmetric) at 25 times rated current for 2 s[5]
b) Full-wave impulse test at 65% of the values specified for a new transformer[6]
c) Applied potential test at 65% of the values specified for new transformers[7]
d) Induced potential tests at 130% of rated voltage for 7200 cycles[8]

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[5]See IEEE Std C57.12.90-1999.
[6]See IEEE Std C57.12.00-1993 and Table 4 for specified test values for new transformers.
[7]See footnote 4.
[8]See footnote 4.

9.2 Power transformers

At the end of each test period, each sample should be given the following end-point tests in the following order:

a) Short-circuit test. The current level should apply stresses to the windings that are representative of those experienced in the full size transformers represented by the model. The short-circuit duration should be at least 1 s and provide an asymmetrical offset of at least 130% of symmetrical; and

b) The dielectric test should be at least 65% of the design level of the model. Design level is defined as 70% of the mean breakdown voltage between turns, turn sections, or layers, as appropriate to the model. Either two applications of full-wave impulse test voltage or two applications of a 1 min low-frequency test voltage are acceptable for end-point tests.

9.3 Abnormalities

If a major abnormality occurs on any of these tests, the unit should be considered to have failed.

In marginal cases, as defined in Clause 5, the unit may be returned to life test with the provision that, should a definite failure occur on the next series at end-point tests, the reported end of life should be as of the preceding test period.

10. Test results

The tests specified herein are of an accelerated nature as compared to normal service. Hence, extrapolation of the life-temperature relationship obtained by the tests will usually be necessary. Furthermore, some variation in the life of individual samples tested at the same temperature is to be expected. The evaluation procedure must demonstrate the attainment of a minimum life expectancy of 180 000 h at the continuously rated hottest-spot temperature. Three methods for presentation of test results are as follows:

a) When all units have been tested to failure and the test results are sufficiently consistent, statistical analysis as indicated in IEEE Std 101-1987 may be employed. Rated hottest-spot temperatures and life-expectancy claims should be based on the resulting lower 95% confidence bound;

b) When the difference between the elapsed times to failure of the tested samples at the various test temperatures is so great as to make statistical analysis of the test results impractical, a relationship between life expectancy and temperature may be assumed. This relationship should be of the form described in IEEE Std 101-1987 and should be so selected that no failure at any test temperature should have occurred at less than five times the life expectancy indicated by the assumed relationship for distribution transformers, and two times for power transformers (see NOTE below). Such a relationship should be designated as minimum life expectancy and may be used to establish maximum rating temperature, or as the basis for guides for loading; or

c) When the purpose of the evaluation tests is solely to demonstrate that the tested design has achieved a pre-selected minimum life expectancy, the tests should continue until the total elapsed time at each test temperature is at least five times the pre-selected value at that temperature for distribution transformers, and two times for power transformers (see NOTE below). If no failure (as qualified in Clause 5) has occurred by this time at any test temperature, demonstration of the pre-selected minimum life expectancy may be claimed.

The report of tests made under this standard shall clearly identify the method that was employed.

NOTE—The 5:1 ratio of elapsed time at test temperature for distribution transformers, and 2:1 ratio for power transformers, between minimum time to failure and the pre-selected, or assumed life expectancy, is intended to allow for the effects of a limited number of samples and the necessity for some extrapolation. This criteria is believed to be conservative. The ratios are based on demonstrated withstand of actual tests of distribution transformers, and model power transformers.

11. Applicability of test results

While the effects of electrical and mechanical stresses on the life expectancy of an insulation structure have not been clearly established, it seems reasonable to expect that failure may occur sooner if these stresses are high rather than if they are low. Furthermore, the temperature distribution through structures of different design may be different at the same hottest-spot temperature. For these reasons, caution should be exercised in applying the results of thermal evaluation tests to designs other than those actually tested. In particular, when it is intended that an evaluation apply to a number of different transformer ratings, the test samples preferably should be of the rating in which the design stresses are the highest.

12. Other tests

When the transformer or models fail, or tests are complete, the Degree of Polymerization (DP) measurement according to ASTM D-4243-86 of material samples from the hottest-spot region is recommended as a supplementary test, to determine its correlation with transformer aging. The DP test is recommended with the goal of eventually using it as a criterion as a main, or alternative, test in the future.

The DP measurement, while applicable to cellulose insulation materials, is not necessarily applicable to other polymeric materials, such as polymeric enamels or aramid papers. For materials not cellulosic in composition there may be other tests which have more relevant correlation to the aging process. Although there are no proven tests which have been correlated with thermal aging and tensile strength reduction, several techniques are available which would be more relevant than DP for synthetic polymers. Possible suggestions would be measurement of “average molecular weight” or “molecular weight distribution,” or other comparisons such as results obtained from Differential Scanning Calorimeter (DSC) or Thermal Gravimetric Analysis (TGA).

Annex A

(normative)

Standard test procedure for sealed tube aging of liquid- immersed transformer insulation

A.1 Purpose

Manufacturers occasionally must make changes in the insulation, or treatment, used in their transformers. This occurs due to the development of a new material, a change in vendors, or due to the unavailability of a preferred material. If the change is minor, it is reasonable to permit a reduced scale thermal test to determine that the change does not reduce the life of the transformer.

It is therefore appropriate to perform a *sealed tube aging procedure*. This procedure is also an effective method for making a preliminary evaluation of the potential of a new insulation system. A sealed tube aging procedure is more rapid, less expensive, and provides samples with a controlled thermal history. It is also more amenable to the exploration of the materials and their condition during aging.

The procedure involves aging the new materials within sealed tubes. It requires that the tested material include all other significant materials used in the system. Also, for comparison, the test program should include samples of the materials used in the present system.

A.2 Test samples

The test tubes are typically of stainless steel, but alternatively may be of glass. The tubes are typically about 28 cm long with an inside diameter of 4.0 cm, and a wall thickness of 5.0 mm. The tubes have gasketed screw-on caps and may be fitted with a valve for venting.

The insulation shall be dried to approximate the treatment that is used for a full scale transformer. A minimum moisture content of 0.25% and a maximum of 0.50% by weight of solid insulation is required as measured by the Karl Fischer method.

The insulation in each tube should be apportioned to approximate their relative content in a full-scale transformer. An appropriate air or gas space should be left in each tube, and a minimum of four samples shall be aged at each temperature.

A.3 Test period

The samples shall be aged at a minimum of three temperatures selected as recommended in IEEE Std 99-1980. An oven or liquid bath may be used to age the samples. The temperatures and aging time should be selected to approximate the Arrhenius curve appropriate for the system.

A.4 Determination of life

New materials that have not been thermally qualified by complete system life tests in transformers or transformer models shall be qualified for use in an insulation system designed for operation at a specified rated hottest-spot temperature by means of the sealed tube aging test described in previous clauses. It shall be demonstrated that paper materials retain at least 50% of initial tensile strength at an extrapolated life of 65 000 h at the rated hottest-spot temperature. Tests of wire enamel shall demonstrate retention of at least 80% of its initial dielectric strength at an extrapolated life of 65 000 h at the rated hottest-spot temperature. To extrapolate from test temperatures to the rated hottest-spot temperature, the aging tests must be performed over a sufficiently wide temperature range to establish the "A" and "B" constants in the equation

$$LIFE = EXP^{\left[\frac{B}{T + 273} - A\right]} \quad \text{(A-1)}$$

where

LIFE is the life in hours
T is the aging temperature in ºC

It is recommended that DP test measurements be made according to ASTM D-4243-86, for cellulose materials as a supplementary test for correlation with the mechanical test results.

A.5 Comparative evaluation

When this procedure is utilized for qualifying cellulose insulation for substitution in transformers rated in accordance with IEEE C57.12.00-1993, 65 ºC average rise, 80 ºC hottest-spot rise, the tested life shall be equal to or exceed the life expectancy curve displayed in Figure A.1, which is defined by equation A-2.

$$LIFE = EXP^{\left[\frac{15\,000}{T + 273} - 28.082\right]} \quad \text{(A-2)}$$

where

LIFE is the life in hours
T is the aging temperature in ºC

When wire enamel insulation is evaluated, the same life expectancy curve is used except the test criteria is 80% of initial dielectric strength.

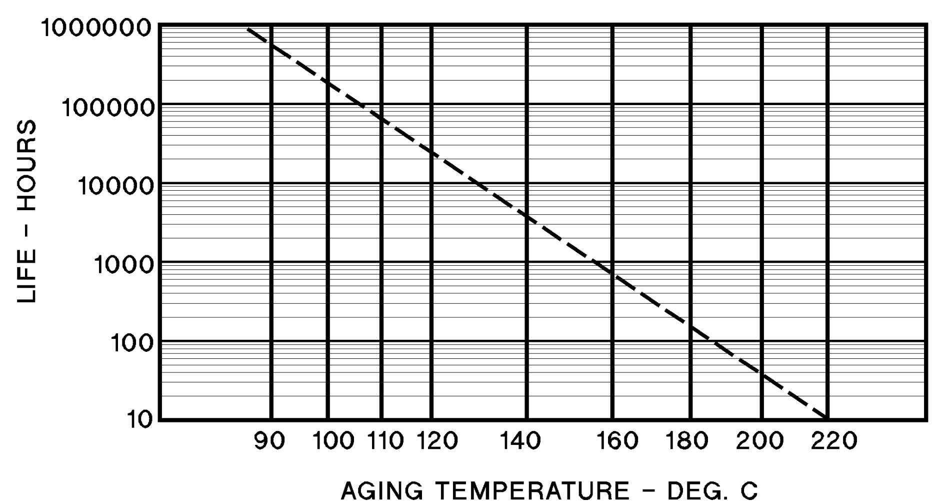

Figure A.1—Minimum life expectancy curve for sealed tube tests of liquid-immersed cellulose insulating materials (50% reduction of tensile strength)

Annex B

(informative)

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