



IEEE Standard for Test Procedure for Thermal Evaluation of Insulation Systems for Liquid-Immersed Distribution, Power, and Regulating Transformers

STANDARDS

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std C57.100™-2022
(Revision of IEEE Std C57.100-2011)



IEEE Standard for Test Procedure for Thermal Evaluation of Insulation Systems for Liquid-Immersed Distribution, Power, and Regulating Transformers

Developed by the

Transformers Committee
of the
IEEE Power and Energy Society

Approved 3 December 2022

IEEE SA Standards Board

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Abstract: A series of test procedures to provide uniform methods for investigating the effects of operating temperature on the life expectancy of liquid-immersed transformers or insulation systems is provided. 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.

Keywords: aging, distribution transformers, IEEE C57.100™, life tests, liquid immersed, power transformers, sealed tube, test procedures, thermal evaluation

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Introduction

This introduction is not part of IEEE Std C57.100™-2022, IEEE Standard for Test Procedure for Thermal Evaluation of Insulation Systems for Liquid-Immersed Distribution, Power, and Regulating 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 electrical, mechanical, and thermal stresses occurring in different parts of the structure. How long the insulation system is serviceable depends on the transformer design and the severity of the stresses 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 operated.

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

In IEEE Std C57.100™-2011 [B18],⁶ significant changes were made to supplement the transformer model testing that were the basis for prior versions of this standard to allow for simplified testing of systems of insulation materials for transformers. This simplified testing was outlined in Annex A, Annex B and Annex C of IEEE Std C57.100-2011 [B18]. As a result of widespread use of these new methods, this revision has reorganized the testing to use these materials tests into the main part of the standard and to move the seldom used transformer model testing to normative annexes. In addition to the movement of the materials tests to the main body of this standard, there was a significant amount of work to enhance the methodology previously outlined in the Annex to take advantage of industry experience with these tests in the intervening time.

Further developments have also been added as annexes for this version to provide information on the basis for ratios of materials specified in the materials testing, the introduction of a new enamel wire test for evaluation as part of the insulation system, as well as conducting screening tests to help set up aging programs. Another addition to this document provides information as to how to modify insulation systems that have previously been tested according to this standard. Finally, [Annex D](#) was added to provide a test procedure for qualifying suppliers of thermally upgraded papers.

⁶The numbers in brackets correspond to those of the bibliography in [Annex H](#).

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IEEE Standard for Test Procedure for Thermal Evaluation of Insulation Systems for Liquid-Immersed Distribution, Power, and Regulating ~~Power~~ Transformers

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1. Overview

1.1 Scope

This standard applies to the insulation systems used in all liquid-immersed distribution and power transformers. This standard provides test procedures to evaluate the thermal aging characteristics of insulation systems used in liquid-immersed distribution or power transformers. The dielectric liquid is part of the insulation system.

1.2 Purpose

The objective of this test procedure is to establish uniform methods for investigating the effects of operating temperature on the life expectancy of liquid-immersed transformer insulation systems. The results of these test procedures are expected to be as follows:

- a) Provide the basis for the selection of a limiting hottest-spot temperature for rating purposes

- b) Provide life curves that may serve as the basis for a guide for loading
- c) Permit the comparative evaluation of a proposed insulation system with reference to an industry- proven system [\(IPS\)](#) that has been shown to be acceptable in service

1.3 Word usage

[The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted \(*shall equals is required to*\).^{7, 8}](#)

[The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required \(*should equals is recommended that*\).](#)

[The word *may* is used to indicate a course of action permissible within the limits of the standard \(*may equals is permitted to*\).](#)

[The word *can* is used for statements of possibility and capability, whether material, physical, or causal \(*can equals is able to*\).](#)

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.

⁷[The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.](#)

⁸[The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.](#)

[ASTM D828, Standard Test Method for Tensile Properties of Paper and Paperboard Using Constant-Rate-of- Elongation Apparatus.](#)⁹

[ASTM D982, Standard Test Method for Organic Nitrogen in Paper and Paperboard.](#)

ASTM D1676, ~~“Standard Test Methods for Film-Insulated Magnet Wire. ”~~

[ASTM D3487, Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus.](#)

[ASTM D5374, Standard Test Methods for Forced-Convection Laboratory Ovens for Evaluation of Electrical Insulation.](#)

[ASTM D5423, Standard Specification for Forced-Convection Laboratory Ovens for Evaluation of Electrical Insulation.](#)

[IEC 60450, Measurement of the average viscometric degree of polymerization of new and aged cellulosic electrically insulating materials.](#)¹⁰

[IEC 60814, Insulating liquids—Oil-impregnated paper and pressboard—Determination of water by automatic coulometric Karl Fischer titration.](#)

IEC TS 62332-1, ~~—~~Electrical Insulation Systems (EIS)—Thermal evaluation of combined liquid and solid components—Part 1: General requirements.[†]

⁹[ASTM publications are available from the American Society for Testing and Materials \(https://www.astm.org/\)](https://www.astm.org/)

¹⁰[IEC publications are available from the International Electrotechnical Commission \(https://www.iec.ch/\)](https://www.iec.ch/). IEC publications are also available in the United States from the American National Standards Institute (<http://www.ansi.org>).

[†]~~IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA.~~

IEEE Std C57.12.00™, IEEE Standard [for](#) General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers. [11.12](#) ~~2,3~~

IEEE Std C57.12. ~~80~~ 90™, IEEE Standard [Terminology](#) ~~Test Code~~ for [Power and](#) ~~Liquid-Immersed~~ Distribution, ~~Power, and Regulating~~ Transformers.

IEEE Std C57.91™, IEEE Guide for Loading Mineral-Oil-Immersed Transformers [and Step-Voltage Regulators](#).

[ISO 1924-2, Paper and board—Determination of properties—Part 2: Constant rate of elongation method \(20 mm/min\).](#)¹³

[3. Definitions, acronyms, and abbreviations](#)

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary* [Online](#): ~~Glossary of Terms & Definitions~~ should be [consulted](#) ~~referenced~~ for terms not defined in this clause. [14](#) ⁴

[candidate system \(CS\): the yet to be qualified system under thermal evaluation to determine its thermal class. It shall be composed of:](#)

¹¹ ² IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>). ~~445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).~~

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¹³ ISO publications are available from the ISO Central Secretariat (<https://www.iso.org/>). ISO publications are also available in the United States from the American National Standards Institute (<https://www.ansi.org/>).

¹⁴ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

⁴ ~~The IEEE Standards Dictionary: Glossary of Terms & Definitions is available at <http://shop.ieee.org/>.~~

- a) A functionally equivalent solid insulation material to the cellulose pressboard tested in the industry- proven system (IPS).
- b) A functionally equivalent solid insulation material to the thermally upgraded kraft paper tested in the IPS.
- c) An electrical insulating liquid.
- d) Same size and type of core steel as tested in the IPS.
- e) Same size and type of conductor as tested in the IPS.

In addition, the CS insulation materials physical properties (e.g., thickness, density), and mechanical properties (e.g., starting tensile strength) shall be as close as possible to those of the IPS. Materials with similar physical characteristics and mechanical properties, as well as functional equivalence in application, offer a fair comparison between a CS and the IPS. Modifications to an already qualified CS shall be addressed by the guidance in Annex C.

industry-proven insulation system (IPS): Decades of operating equipment manufactured using an insulation system including thermally upgraded kraft paper, cellulose ~~cellulosie~~ pressboard, Polyvinyl Formal (PVF) coated magnet wire, and mineral oil has shown that a minimum life expectancy of at least 20.5 years (180 000 h ~~hours~~) may be assumed if the hottest-spot temperature, at rated load as defined in IEEE Std C57.12.00₇ is maintained. Important to life expectancy of this proven insulation system is ~~includes~~ a manufacturing process that includes proper ~~,which provides initial drying of to a moisture content of 0.25% to 0.50% moisture by weight, and after processing,~~ the solid insulation, proper processing of the liquid insulation, and proper sealing of the equipment to reduce ~~system will be sealed to prevent~~ the ingress of air (oxygen) and moisture.

The minimum life expectancy curve from IEEE Std C57.12.00 to be used for comparison purposes is repeated here by Equation (1) and displayed in Figure 1.

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

where

$LIFE$ is the life in hours

e is the base of natural logarithms

T is the aging temperature in °C

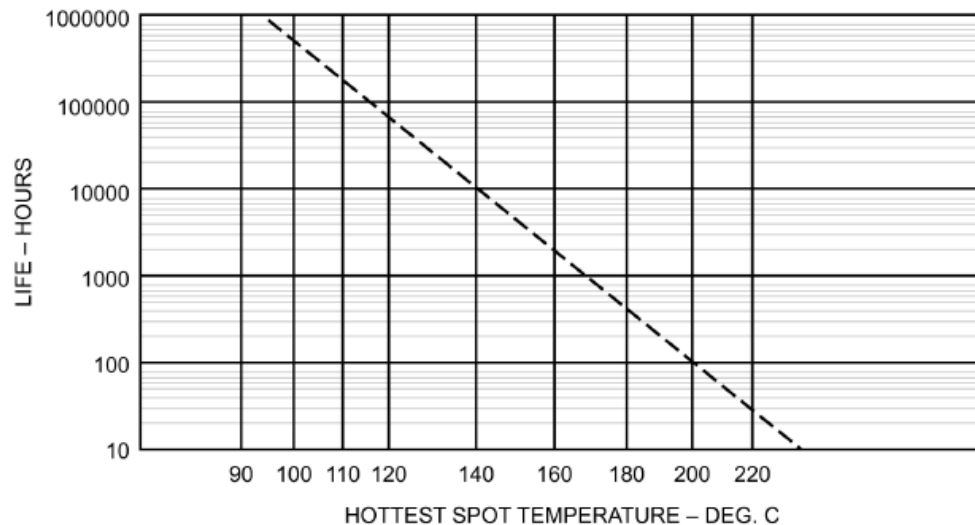


Figure 1—Minimum life expectancy curve for liquid-immersed distribution and power transformers as defined in IEEE Std C57.12.00, 65 °C average rise, 80 °C hottest-spot rise

In addition to the insulation materials mentioned earlier, aging tests performed using this standard shall include core steel and conductor material as part of the IPS as well, to provide basic representation of the primary materials contained in the active part.

To fully and specifically define all IPS materials to be used in the aging tests described in this standard, and in order to help produce consistent results across test laboratories, the IPS is further defined in Table 1.

Table 1—IPS materials to be used in thermal aging testing

Material	Description	Density, g/cm ³	Recommended Thickness, mm	Nitrogen content, %*	Minimum. MD tensile strength, MPa
Cellulose pressboard	Precompressed 100% sulfate wood pulp (kraft) pressboard	≥ 1.0	1.0	—	100
Thermally upgraded kraft paper	High density thermally upgraded 100% sulfate wood pulp (kraft) paper	≥ 1.0	0.125	1.3–2.6	75
Mineral oil	Unused inhibited Type II mineral oil, per ASTM D3487	—	—	—	—
Core steel	Grain oriented electrical steel	—	—	—	—
Conductor	Bare copper**	—	5.0–7.0	—	—

(New)

*As measured by ASTM D982 or by the Dumas method.

**Copper has a higher catalytic effect for insulation system degradation than aluminum. For this reason, copper shall be used in these insulation system tests rather than using aluminum. This does not prevent the use of aluminum conductor in transformers whose electrical insulation systems were tested using copper conductor.

To further define and also qualify the thermally upgraded kraft (TUK) paper component of the IPS as being thermally upgraded, the TUK paper shall additionally meet the definition of thermally upgraded paper described in IEEE Std C57.12.80 and the qualification testing requirements described in Annex D.

3.2 Acronyms and abbreviations

BV breakdown voltage

CS candidate system or candidate insulation system

DP degree of polymerization

IPS industry-proven system

MD machine direction

PVF polyvinyl formal

RS relative saturation

RTI relative thermal index

TUK thermally upgraded kraft

4. Relative thermal index aging testing

4.1 General

The thermal class of a candidate system (CS) shall be determined by the test procedures defined in this standard, which establishes the thermal index associated with the maximum hottest spot temperature for which the insulation system is expected to provide normal life. The thermal index of a CS is determined relative to the IPS; thus, the test is generally referred to as a Relative Thermal Index (RTI) test. This RTI test procedure uses failure of the solid insulation during accelerated aging in the liquid insulation as a determining factor in defining the hottest spot temperature capability, or thermal index, of the insulation system, since solid insulation failure often defines the life of a transformer. The result of the RTI test is rounded down to the nearest value in Table 2 and is designated as the thermal index. The thermal class of the insulation system is then determined from the designated thermal index and is defined as 10 °C higher than the thermal index. The 10 °C higher difference between thermal class and thermal index is due to the difference in ambient temperatures. The thermal index is based on an average ambient of 30 °C, and the thermal class is based on the maximum ambient of 40 °C. See Table 2 for a list of potential insulation system thermal classes and the associated hottest spot temperatures and thermal indices.

Table 2—Potential insulation system thermal classes

Thermal class	Thermal index/hottest spot temperature °C
105	95
120	110
130	120
140	130
150	140
155	145
160	150
170	160
180	170
190	180
200	190

(New)

4.2 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. For the transformer tests sealed tube test procedure and the dual temperature test~~ described in Annex A and, Annex B ~~and Annex C~~, ~~cyclical loading is not part of the standard test method.~~

It is recognized that other conditions, such as oxygen, moisture, pressure, headspace gas volume, amounts and ratios of materials, and mechanical stresses can also affect actual service life. In the aging tests described in this standard, these other conditions are either controlled or limited in order to achieve consistent results.

~~It is recognized that environmental conditions, such as corrosive atmosphere and excessive vibration, can affect actual service life. It seems appropriate to evaluate such extraneous influences separately from the effects of temperature, and they are therefore not included in this procedure. However, for all insulation system testing covered under this requirement, moisture content of the insulation system should be monitored at the beginning of the testing, as it should be representative of the upper limit of factory oil processing equipment (typically in the range of 0.25 to 0.50% moisture by weight of the solid).~~

4.3 Minimum life expectancy

The load on most transformers is cyclic, with both daily and annual cycles. For this reason, the peak thermal loading (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 the length of time at that ~~the~~ temperature. Consequently, the life expectancy in actual service may potentially be ~~differ~~ greatly longer than ~~from~~ the life determined by the essentially continuous thermal exposures ~~loading procedure~~ prescribed in this standard.

Experience and experimental evidence indicate that an insulation system capable of operating 180 000 h ~~hours~~, (approximately 20.5 years) at a constant rated hottest-spot temperature should give satisfactory life expectancy under the normal life expectancy loading ~~operating~~ conditions described in IEEE Std C57.12.00 and IEEE Std C57.91.¹⁵ ~~the preceding paragraph.~~

4.4 Criteria for end-of-life

In a transformer, the life of an insulation system ends when the degradation of the solid insulation has progressed to a point such that it fails dielectrically, thermally, or mechanically. The point of failure is considered end-of-life.

¹⁵Information on references can be found in Clause 2.

For the insulation system materials tests described in this standard, a wide variety of test parameters could be considered for evaluation, and correspondingly a wide variety of end-of-life criteria chosen. Examples of this wide variety are shown in IEEE Std C57.91 and include 50% tensile strength, 25% tensile strength, and 200 degree of polymerization (DP). Each of these example criteria demonstrate an absolute value for end-of-life, and likely would provide a different result in any aging program. Thus, in order to help avoid this potential confusion, in this standard, the test results from the aging conducted using the IPS determines the relative value for end-of-life criteria for the CS. The selected relative end-of-life criteria shall be reached by both the IPS and CS.

This would mean that the end-of-life criteria for a solid insulation material (e.g., paper, film, pressboard) in the CS shall be compared to the functionally equivalent material in the IPS. For such solid insulation materials, tensile strength, expressed as percent retained tensile strength, is the recommended primary end- of-life test criteria. DP has traditionally been another test criterion for solid insulation materials; however, it is recommended to be only a secondary method because it cannot be performed on materials other than those composed of 100% cellulose, and because DP can only be indirectly but not precisely correlated to the mechanical strength of the material. Tensile strength is preferred as it is a direct measurement of the mechanical integrity remaining in the material.

For the liquid insulation material in the CS and IPS, there are currently no specific thermal test end-of-life criteria, but this topic is being studied and results may be appropriate to include in future versions of this standard.

For wire enamels, which may also be evaluated as part of the insulation system, dielectric breakdown strength of twisted pair wires tested before and after thermal aging, following the ac breakdown voltage (BV) test as per ASTM D1676 (500 V/sec rate of voltage rise), is the recommended end-of-life criteria. Details of a specific modified test for use in determining the thermal class of enameled conductors used in liquid-immersed transformers may be found in Annex E, which summarizes a procedure described in Prevost, Levin, Greaves, and Biggie [B29].

Evaluating the thermal capability of an insulation system and determining the relative thermal index (RTI) and thermal class can be performed by conducting a sealed tube aging test or a dual-temperature aging test. Many laboratories are familiar with the sealed tube test, and Clause 5 outlines a procedure for using this test for determining the thermal class of a CS. For insulation system testing where excessive liquid temperatures might be a concern, a dual temperature test as outlined in Clause 6 may be more appropriate.

5. Sealed tube aging test

5.1 Purpose

The sealed tube (i.e., sealed vessel) aging test represents the most common test for thermal evaluation of insulation systems for liquid immersed transformers, due to its relative practicality, simplicity, and cost effectiveness. It allows for an effective way to perform a relative thermal endurance comparison between two insulation systems, and to qualify the thermal class of a CS relative to a known IPS.

This sealed tube aging test further described in the remainder of this clause is followed by the three-point test procedure outlined in Clause 7.

5.2 General requirements

The following general requirements apply to sealed tube aging tests:

- a) Tested insulation materials for any specific insulation system, either the IPS or CS, shall come from the same batches (liquids, papers, pressboards, etc.) where there are common materials in both systems.
- b) All other materials in the aging test vessels (transformer core steel, copper, enameled wire if used, etc.) shall be of the same type/grade and from the same source.
- c) The control aging test vessels (at aging time "0") shall be processed and prepared in the same way as all other vessels, in order to get consistent initial un-aged results.

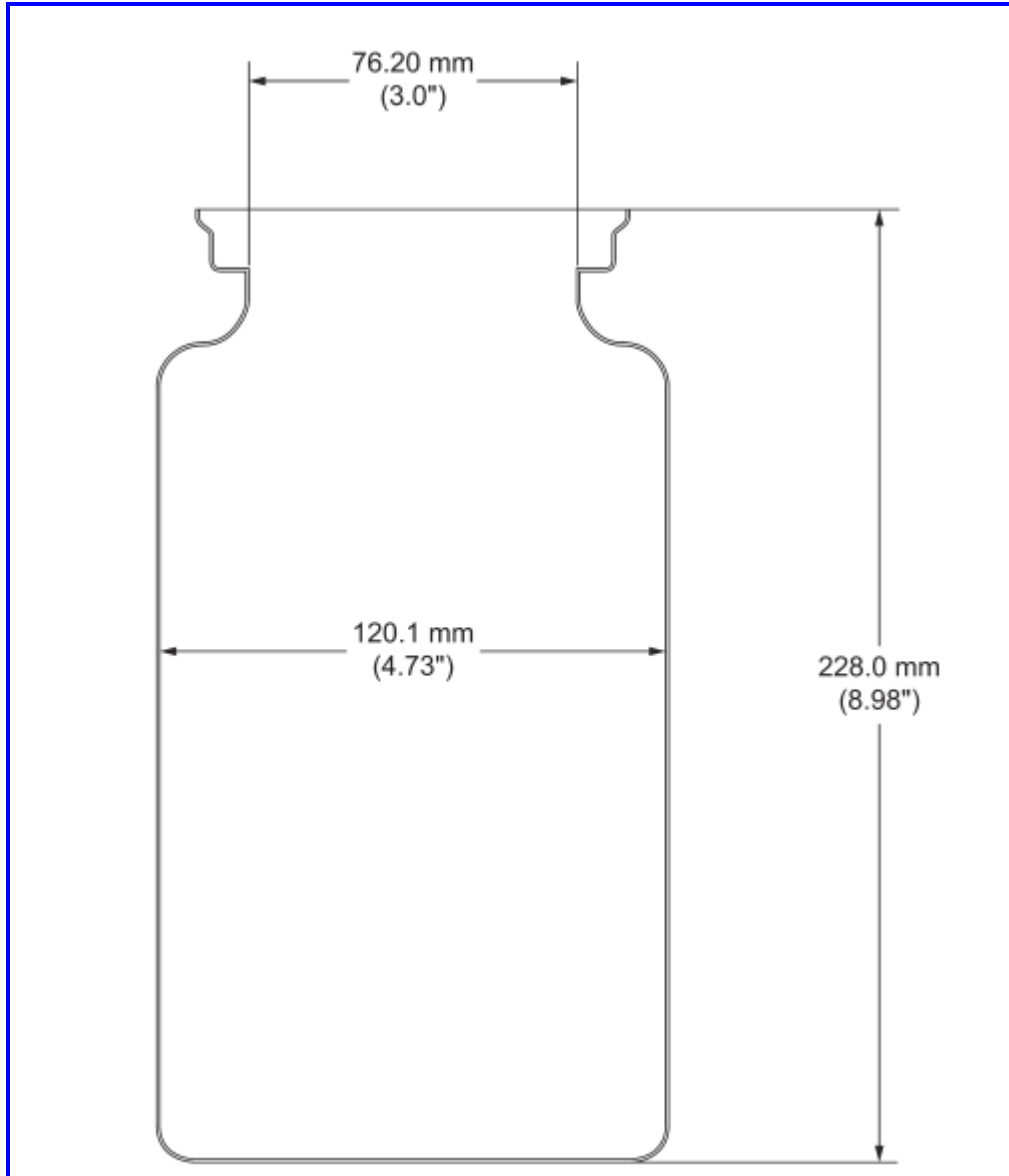
- d) For each temperature tested, prepare at least one, but preferably two or more, additional aging test vessels, where the time to stop the aging test for those vessels is left to be determined based on the results of the tests on the vessels from the previous aging times.

5.3 Test equipment

5.3.1 Test vessels

Test vessels used for sealed tube aging tests shall meet the following requirements:

- a) Test vessels shall be made of stainless steel, have a gasketed seal able to withstand the temperature and environment being tested, and be of at least one-liter capacity.
- b) Suggested test vessel design is a “2 liter” stainless steel container detailed in Figure 2, along with the associated hardware, including: lid with installed pressure relief valve, lid clamp, and single-use high- temperature sealing gasket compatible with the insulating liquid, as shown in Figure 3.



(New)

Figure 2 – Suggested test vessel design “2-liter” stainless steel container



(New)

Figure 3—“2 liter” stainless steel container with associated hardware, including lid with installed pressure relief valve, lid clamp, and single-use high-temperature sealing gasket compatible with the insulating liquid

- c) During this test, it is normal to generate internal pressure; thus, a pressure relief valve is required for safety reasons. Pressures as high as 1380 kPa (200 lb/in²) have been recorded in test, so precautions should be taken in case the pressure relief valve fails.
- d) In addition to safety reasons, pressure relief valves also help to keep pressure inside the test vessels consistent, which has been shown to be an important factor in the consistency of accelerated aging test results.

- e) In order to balance the benefits of controlled pressure, but not releasing pressure too often such that gasses and moisture potentially escape the test vessel, a nominal 70 kPa, ± 14 kPa (10 lb/in², ± 2 lb/in²) pressure relief valve with high temperature sealing gasket compatible with the insulating liquid shall be used. The pressure relief valve shall be equipped with high temperature sealing gasket compatible with the insulating liquid and the aging temperatures.
- f) The ratio of the “total test vessel volume: total liquid & solid volume” shall be 1.2:1.0, at room temperature, for aging temperatures up to and including 200 °C, in order to set a consistent headspace gas volume in the vessels. For higher temperatures, the calculated thermal expansion of the liquid shall be considered, and the ratio adjusted accordingly. For example, the test vessel in Figure 2 called a “2 liter” vessel can practically hold a total volume of 2.3 L, so the combined volume of the liquid and solid materials for aging testing should be $2.3/1.2 = 1.92$ L.

Open test vessels, such as for simulating free breathing liquid preservation systems, are not included in this standard due to the safety hazard of testing liquids at temperatures above their flashpoints where additional oxygen is available. In the case of a sealed test, the amount of available oxygen is limited.

NOTE—Oxygen is known to increase aging of insulation systems, so a test with air would be expected to be more severe than one sealed with nitrogen.¹⁶

5.3.2 Ovens

The following requirements apply for the ovens used in sealed tube aging tests:

- a) Type I ovens, as specified in ASTM D5423, shall be used.
- b) Ovens should be calibrated according to ASTM D5374.

¹⁶Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

- c) The oven temperature uniformity shall be monitored to determine variability according to ASTM D5374. As outlined in ASTM D5423, the oven shall have a degree of uniformity of ± 2.5 °C at temperatures between 80 °C to 180 °C and of ± 3 °C for temperatures from greater than 180 °C to 300 °C. For aging temperatures above 300 °C please refer to the ASTM D5423 for the appropriate temperature uniformity.

5.4 Test samples

To standardize the ratio of materials used in sealed tube aging tests, one set of material ratios is provided in Table 3. An example calculation of material quantities for the suggested test vessel design “2-liter” stainless steel container, based upon the set of material ratios listed in Table 3, is listed in Table 4.

Table 3—Single combined set of material ratios for sealed tube aging tests (by volume)

	Ratio (by volume)
Total test vessel volume: total liquid and solid insulation volume	1.2: 1.0
Liquid insulation: solid insulation	13.1: 1.0
Pressboard: paper	2.0: 1.0
Core steel and bare copper surface area (cm ²): kg of fluid	12.6: 1.0*

(New)

*Core steel and bare copper to liquid ratio not by volume, but rather by surface area (cm²): kg of liquid.

Table 4—Example calculation of material quantities for the new suggested test vessel design “2-liter” stainless steel container based on the ratios from Table 3

	Volume, cm ³
“2-liter” vessel	2300
Total liquid and solid insulation	1917
Liquid insulation	1781
Solid insulation	136
Pressboard	91
Paper	45
Core steel (cm ²)	22*
Bare copper surface area (cm ²)	22*

(New)

*Core steel and bare copper surface area are calculated from the given volume of liquid converted to weight of liquid using the following material density (g/cm³): IPS mineral oil, 0.895.

The single set of material ratios in Table 3 is a combined representation of both power transformer and distribution transformer insulation systems. The reason for a single combined set of ratios, versus having separate distribution and power transformer material ratios as in the previous version of this standard, is that material ratios have a significant effect on the results. Therefore, having separate different ratios requires having separate different tests, which yield different results for the same system of materials. As the main purpose of this standard is to compare the thermal endurance of different insulation systems relative to each other, and not to have two different results for the same insulation system, one single combined set of material ratios shall be used. In addition, one set of ratios saves the time and effort to do two or more sealed tube aging tests on the same insulation system.

In addition to the ratio of liquid to solid insulation being important, as was described in the previous version of this standard, the ratio of pressboard to paper has also been found to be important. Therefore, Table 3 prescribes a specific pressboard to paper ratio as well. A ratio for core steel and bare copper has also been included in Table 3.

The background for the selection of these specific ratios, including examples, maybe found in Annex F.

As mentioned earlier, and in addition to the ratio of materials, the CS insulation materials physical properties (e.g., thickness, density), and mechanical properties (e.g., starting tensile strength) shall be as close as possible to those of the IPS. Materials with similar physical characteristics and mechanical properties, as well as functional equivalence in application, offer a fair comparison between a CS and the IPS.

5.5 Test sample preparation and testing

5.5.1 Solid insulation preparation

Preparation includes pre-cutting of all solid insulation to required size for analysis after aging (e.g., cutting tensile specimens to required dimensions beforehand, as attempting to cut them after aging may negatively impact the results) and placing all the required solid materials into individual aging test vessels.

5.5.2 Liquid insulation preparation

Dry and de-gas insulating liquids using vacuum processing equipment. Criteria for final dried liquid water content as measured by parts per million (ppm) or relative saturation (RS) are:

- a) *Mineral oil*: less than 2 ppm (3.3% RS) after drying, and no more than 6 ppm (10% RS) after filling the aging test vessels.
- b) *Natural ester liquid*: between 25 ppm to 35 ppm (2.5% RS to 3.5% RS) after drying, and no more than 40 ppm (4% RS) after filling the aging test vessels.
- c) *Synthetic ester liquid*: between 30 ppm to 40 ppm (1.2% RS to 1.5% RS) after drying, and no more than 50 ppm (2% RS) after filling the aging test vessels.

All of the above water concentration levels (ppm or RS) are values measured at room temperature.

5.5.3 Metal preparation

Metal surfaces (e.g., core steel and bare copper) shall be cleaned with laboratory grade isopropyl alcohol ($\geq 99\%$ purity).

5.5.4 Test vessel preparation

Thoroughly clean test vessels from residual substances and debris and perform a final rinse with laboratory grade isopropyl alcohol ($\geq 99\%$ purity).

5.5.5 Oven preparation

Pre-heat aging test ovens to the respective required temperatures of the test.

5.5.6 Solid insulation dry-out, test vessel liquid filling, sealing, and loading into oven

The following procedure shall be used:

- a) Aging test vessels, minus covers, and gaskets shall be assembled with all required solid materials, i.e., solid insulation and metals, prior to the solid insulation being dried in order to approximate the treatment that is used for a full-scale transformer.
- b) The assembled aging test vessels shall be dried at 115 °C under hot air and/or vacuum until solid insulation materials reach a minimum water content of 0.1% and a maximum of 0.3% by weight as measured by the Karl Fischer method (modified IEC 60814, excluding the “degreasing” process).
- c) Dry covers and gaskets separately in an air circulating oven set to 115 °C for a minimum 8 h.
- d) Test vessels shall be removed from the drying oven shortly before the liquid filling procedure.

e) Complete preparation of assembled test vessels, liquid, and covers and gaskets in parallel immediately prior to liquid filling.

f) The components shall remain at approximately the respective processing temperatures.

g) Liquid filling procedure:

1) Option #1:

i) Remove already assembled test vessel from the air oven and immediately and continuously flush with dry nitrogen.

ii) Fill test vessel with liquid while introducing nitrogen blanket for a minimum of 1 min after filling, and until sealing.

2) Option #2:

i) Fill already assembled test vessel with liquid under vacuum using equipment designed to do this.

ii) Remove filled test vessel from the vacuum oven and immediately and continuously flush with dry nitrogen for a minimum of 1 min, and until sealing.

h) Sealing procedure: Seal test vessel with the gasket and cover.

NOTE—Flushing with nitrogen should be done continually from the time the vessel is removed from the oven until the time it is sealed.

i) Immediately place the test vessel into the pre-heated aging oven. Test vessels should be placed vertically, evenly spaced off the oven floor and apart from each other, and not touching the oven walls, in order to reduce uneven heating and hotspots.

j) After the loading of all vessels into any one oven has been completed, register the time that the oven again reaches the set test temperature. This is the starting time for the test.

- k) Control test vessels are not placed in the oven. Open control vessels for sampling after 24 h, but before 48 h after sealing the vessel. Follow the same procedure as outlined in 5.5.7 starting with c).

5.5.7 Sample extraction and testing

After aging the vessel in the oven for the prescribed time and temperature, the following procedure shall be used to take and test samples:

- a) Remove test vessel from the oven.
- b) Wait until the test vessel reaches ambient temperature (minimum 24 h, but no later than 48 h after removing from the aging oven) before opening and collecting the samples.
- c) Certain time critical tests, e.g., water content, shall be performed immediately after opening the test vessel.
- d) Tensile test samples shall be gently blotted using a dry cloth to remove excess liquid (do not chemically remove the liquid) and shall be placed at 23 ± 2 °C, $50 \pm 2\%$ RH condition, for a minimum of 24 h prior to testing. Tensile strength should be measured according to ISO 1924-2 or ASTM D828. As the quantity of available solid insulation tensile test samples depends on the test vessel size (per 5.3.1) and the standard material ratios (per 5.4), the preferred minimum number of tensile test samples is 10, or as many as are available for the given material in the test vessel used. For example, a 1-L test vessel may not allow 10 pressboard tensile samples.
- e) Other tests, such as DP, are not time critical and may be tested afterwards. If DP is also tested as a secondary end-of-life criterion, DP should be measured according to IEC 60450. The minimum number of DP test samples is two per material tested.
- f) If necessary, hermetically sealed liquid samples shall be stored away from direct light at a temperature no higher than 25 °C for future testing.

It is important to use the same test method for testing both the IPS and CS.

~~Annex C~~

~~(normative)~~

6. ~~Materials testing standard test procedure for~~ Dual-temperature sealed tube aging ~~test of liquid-immersed transformer insulation~~

6.1 Purpose of test

Sealed tube testing as described in [Clause 5](#) ~~Annex B~~ has been shown to be a simple, easy-to-implement test, especially for solid and liquid components of similar thermal capability. When one of the components of the insulation system has a higher temperature capability than the rest of the system, aging at a single temperature as is conducted in the sealed tube test is constrained by the lower temperature component. For this reason, a dual-temperature sealed tube test was developed, and has been described in IEC [TS 62332-1](#).

This thermal evaluation test procedure utilizes a dual-temperature arrangement to independently control the hottest spot temperature of the conductor insulation from the top oil temperature of the insulation system. This allows different combinations of materials used in a liquid-immersed [transformer](#) ~~power or distribution transformers~~ to be evaluated because the evaluation temperatures are independent of each other and can be established based on the relative thermal capabilities of the individual components of the system (solid and liquid).

6.2 General requirements

The following general requirements apply to dual-temperature sealed tube aging tests:

- a) Tested insulation materials for any specific insulation system, either the IPS or CS, shall come from the same batches, e.g., liquids, papers or pressboards, where there are common materials in both systems.

- b) All other materials in the aging test vessels (transformer core steel, copper, enameled wire if used, etc.) shall be of the same type/grade and from the same source.
- c) The control aging test vessels (at aging time "0") shall be processed and prepared in the same way as all other vessels, in order to get consistent initial un-aged results.
- d) For each temperature tested, prepare at least one, but preferably two or more, additional aging test vessels, where the time to stop the aging test for those vessels is left to be determined based on the results of the tests on the vessels from the previous aging times.

6.3 Test equipment

6.3.1 Aging vessels

Each aging vessel is constructed out of stainless steel, the size to be determined by the size of the insulation test piece assembly. The cell volume should also consider the fluid expansion space required for the dielectric liquid at the top liquid temperature. The two ends of the cell shall be fitted with removable, sealable bolt-on covers. The test object is mounted within the aging vessel.

Ports shall be provided for the following:

- Liquid sampling
- Pass-through of electrical circuits for heating the insulated conductor loop
- Monitoring and control elements (such as thermocouples)
- Rods for liquid heating
- Gas blanketing and associated pressure relief system

The design of the aging cell shall be configured to maintain the thermocouples controlling the liquid and the solid component of the test objects immersed in the liquid under all aging temperatures.

6.3.2 Heat sources

In this dual-temperature sealed tube test, there are two independent sources of heat which replace the ovens used in the sealed tube test described in in Clause 5. The first source is in the insulated conductor loop though which circulates alternating current to generate heat, the temperature which is controlled to the hottest spot temperatures noted in the aging temperatures listed in Clause 7. For the dual nature of the test set up, the second heat source is a pair of immersion heaters mounted to one of the face plates of the aging vessel, with the temperature controlled independently to a level that is cooler than the insulated conductor loop. For example, in the experiment described in 7.2 (IPS end-of-life test), the conductor loop would be controlled at 150 °C, 165 °C and 180 °C for three sets of aging vessels each, but for all three, the top oil temperature shall be controlled at 105 °C.

An over-temperature protection device shall be provided, responding to the temperature sensors in both the liquid and the test assembly in each cell. The sensors for the over-temperature protection shall be independent of the sensors for temperature control.

6.3.3 Gas blanketing system

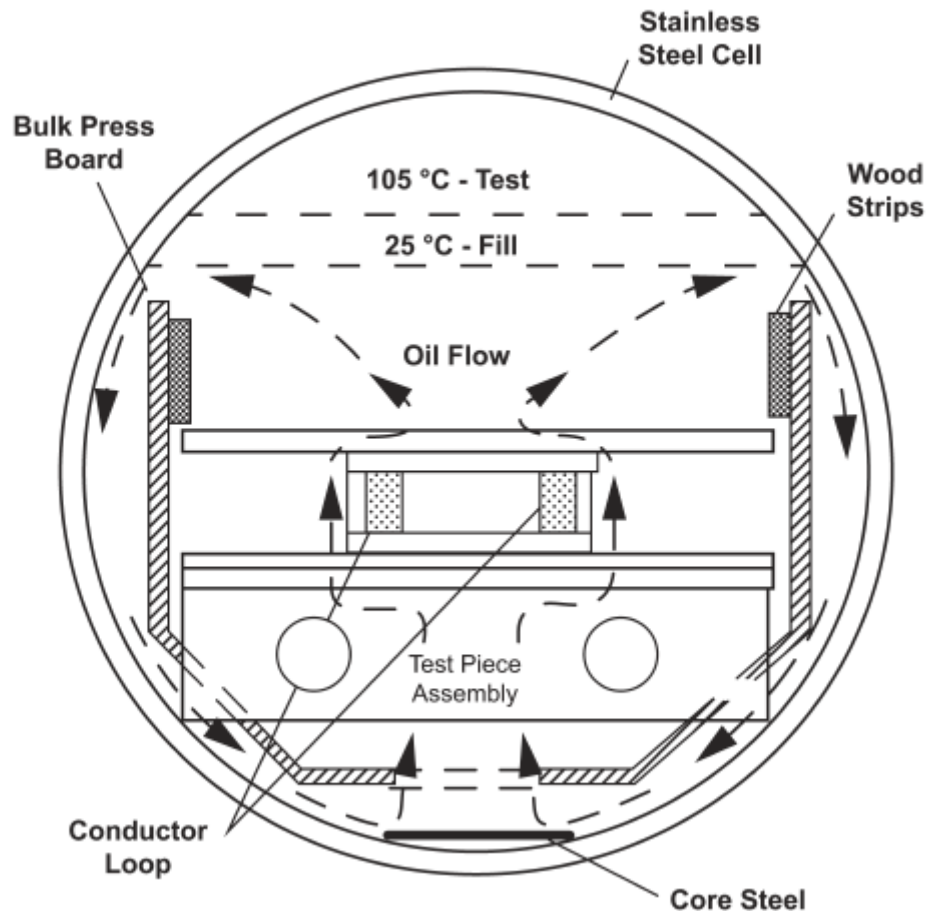
A gas blanketing system shall be provided which simulates the insulation system used by transformer manufacturers. This can be a sealed nitrogen system, which maintains a gas blanket over the liquid in the cell for the purpose of eliminating the possibility of oxidation of the liquid, or it could be a system simulating a desiccated air system. In each case, the gas blanket in each cell shall be regulated to maintain a positive pressure.

As with the sealed tube test described in Clause 5, in order to balance the benefits of controlled pressure, but not releasing pressure too often such that gasses and moisture potentially escape the test vessel, a nominal 69 kPa, ± 14 kPa (10 lb/in², ± 2 lb/in²) pressure relief valve with high temperature sealing gasket compatible with the insulating liquid shall be used.

NOTE—At this point, industry experience with this test method has only conducted testing with a sealed nitrogen system, though due to the lower bulk liquid temperatures this method allows, alternative sealing methods might be possible. It would be expected that the transformer life tested using air as a sealing method would demonstrate shorter absolute life than one tested with nitrogen blanket, however what the effect on the relative performance of a CS versus the IPS is unknown.

6.4 Test samples

For the purpose of this test method, the limiting hottest spot temperature for the solid insulation is assumed to be present in conductor insulation. The insulated conductor loop shown in Figure 4 shall ~~C.1 will~~ be insulated with material to be used in the insulation system under evaluation, and shall ~~will~~ be evaluated as is ~~was~~ described in Clause 7 A.4.2. For this conductor insulation, elevated temperatures should be produced by circulating alternating current of rated frequency (50 Hz or 60 Hz) through the conductor loop. To facilitate the technical evaluation of the conductor insulation, precut tensile strips should be installed in direct contact with the conductor loop so the strips are exposed to the controlled temperature of the conductor loop. For the insulating liquid, the top oil temperature shall be maintained at the same temperature for all of the hottest spot temperatures used for determining the life curve. This temperature shall then determine the maximum top oil temperature for the insulation system under evaluation. For the IPS ~~industry-proven-system~~, this temperature should be 105 °C, as outlined in Table 9 of IEEE Std C57.91-2011.



(Copyright © 1996 IEEE, McNutt, Prevost, and Whearty [B25])

Figure 4—Dual-temperature test set-up

As with the sealed tube test procedure outlined in Clause 5, a uniform ratio of materials should be applied in both the IPS and CS evaluations. Because of the unique design of the test set-up for dual temperature testing, the precise ratios outlined in Table 3 may not be possible but could be used as a starting point in developing such a model incorporating the test piece assembly, with the insulated conductor loop as well as the bulk pressboard pieces. The ratios of materials selected in this case may be limited so that the thermal gradient required for the dual temperature control is reached. Once this set up has been established for the design that is limiting (likely the higher temperature CS model), this set up should be duplicated for the IPS evaluation. The actual ratio of materials used should be documented in the final test report.