



IEEE Standard for Thermal Evaluation of Insulation Systems for Dry-Type Power and Distribution Transformers

STANDARDS

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std C57.12.60™-2020
(Revision of IEEE Std C57.12.60-2009)



IEEE Standard for Thermal Evaluation of Insulation Systems for Dry-Type Power and Distribution Transformers

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Transformers Committee
of the
IEEE Power and Energy Society

Approved 30 January 2020

IEEE SA Standards Board

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Abstract: A uniform method is established for determining the temperature classification for the insulation systems for dry-type power and distribution transformers. These insulation systems are intended for use in transformers covered by IEEE Std C57.12.01™ and IEEE Std C57.12.91™ as they apply to dry-type transformers whose highest voltages exceed nominal 600 V.

Keywords: IEEE C57.12.60™, insulation systems, model transformer coils, resin-encapsulated transformers, solid-cast transformers, thermal evaluation

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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PDF: ISBN 978-1-5044-6472-7 STD24068
Print: ISBN 978-1-5044-6473-4 STDPD24068

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Introduction

This introduction is not part of IEEE Std C57.12.60-2020, IEEE Standard for Thermal Evaluation of Insulation Systems for Dry-Type Power and Distribution Transformers.

This standard is a revision of IEEE Std C57.12.60™-2009, and it represents the state of the art in methodology for evaluating insulation systems for dry-type power and distribution transformers with high-voltage ratings greater than 600 V. In the time since the last revision, there has been a significant amount of interest in such systems testing, and other standards bodies have developed or are developing testing standards with similar characteristics. This revision has tried to take into account the best parts of these other test methods to build on what has been developed over the years within IEEE, starting with IEEE Std 65™-1956 [B5]¹ that first lead to IEEE Std C57.12.56™-1986 [B10] and later to IEEE Std C57.12.60™-1998 [B11].

Areas of significant change from IEEE Std C57.12.60-2009 include the following:

- Modified table for suggested aging conditions
- Design screening test procedures
- Detailed dielectric testing procedures
- Detailed description for making changes to existing insulation systems

Informative annexes were also added to provide guidance on the selection of aging temperatures as well as a second annex that outlines a procedure for adding optional partial discharge testing to the testing protocol as a diagnostic tool.

NOTE—The dielectric test methods described in this standard are based on relevant IEEE standards. For customers considering use of this test methodology using different dielectric test methods, such as those outlined in IEC standards, those methods should be followed for the complete test program, and they should be agreed to in advance.²

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

²Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

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IEEE Standard ~~Test Procedure~~ for Thermal Evaluation of Insulation Systems for Dry-Type Power and Distribution Transformers, ~~Including Open-Wound, Solid-Cast, and Resin-Encapsulated Transformers~~

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1. Overview

1.1 Scope

This test procedure for the thermal evaluation of insulation systems of dry-type power and distribution transformers, ~~including both open-wound technology and solid-cast / encapsulated technology~~ is to be used for determining the temperature classification and modification of the insulation systems. This standard shall apply to all dry-type transformers with a voltage of 601 V or higher in the highest voltage winding except as follows:

NOTE—Where IEEE standards do not exist for the transformers mentioned above or for other special transformers, this standard may be applicable as a whole or in parts subject to agreement between the parties responsible for the application and for the design of the transformer.

1.2 Purpose

The purpose of this test procedure is to establish a uniform method for the following:

- a) Acquiring ~~Providing~~ data used to determine ~~for the selection of~~ the temperature classification of an ~~the~~ insulation system³;
- b) Acquiring ~~Providing~~ data that may be used as a basis for a loading guide, such as IEEE Std C57.96™³;
- c) Modifying an established electrical insulation system
- e) ~~Comparative evaluation of different insulation systems.~~

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).^{4,5}

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).

^{3,4} Information on references can be found in Clause 2.

⁴ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁵ The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

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.

[ANSI C57.12.55, American National Standard for Transformers—Used in Unit Installations, Including Unit Substations—Conformance Standard.](#)⁶

ASTM D5374, Standard Test Methods for Forced-Convection Laboratory Ovens for Evaluation of Electrical Insulation.⁷

[ASTM D5642, Standard Test Method for Sealed Tube Chemical Compatibility Test.](#)

ASTM E104, Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions.¹

IEEE Std 1™, IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation.^{8,9 2,3}

IEEE Std 101™, IEEE Guide for the Statistical Analysis of Thermal Life Test Data.

⁶ANSI publications are available from the American National Standards Institute (<http://www.ansi.org/>).

⁷ASTM publications are available from the American Society for Testing and Materials (<http://www.astm.org/>), ~~100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA.~~

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IEEE Std 259™, IEEE Standard Test Procedure for Evaluation of Systems of Insulation for Dry-Type Specialty and General-Purpose Transformers.

IEEE Std C57.12.01™, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers ~~Including Those With Solid-Cast and/or Resin-Encapsulated Windings.~~

IEEE Std C57.12.58™, IEEE Guide for Conducting a Transient Voltage Analysis of a Dry-Type Transformer Coil.

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.91™, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers.

[IEEE Std C57.96™, IEEE Guide for Loading Dry-Type Distribution and Power Transformers.](#)

IEEE Std C57.98™, IEEE Guide for Transformer Impulse Tests.

3. Definitions, abbreviations, and acronyms

3.1 Definitions

[For the purposes of this document, the following terms and definitions apply. For other terms, the standard transformer terminology in IEEE Std C57.12.80 shall apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.](#)¹⁰

aging cycle: [A measure of the time spent at a target temperature for the purpose of accelerated aging of insulation.](#)

chemical compatibility test (CCT): [Sealed tube test procedure, as defined in ASTM D5642, which is designed to evaluate the chemical compatibility of all components of an insulation system.](#)

cold exposure: [Test specimens are exposed to cold temperatures once per aging cycle as part of the diagnostic procedures used to evaluate the thermal capability of the tested insulation system.](#)

¹⁰ [IEEE Standards Dictionary Online is available at: http://dictionary.ieee.org.](http://dictionary.ieee.org)

correlation coefficient (R^2): A measure of how well a predictive model fits the aging data from a thermal evaluation experiment.

electrical stress path: Dielectric failure paths in the representative small-scale model coils representing turn to-turn, layer-to-layer, disk-to-disk, section-to-section, winding-to-winding, and winding-to-ground.

enhanced sealed tube (EST) evaluation: A sealed tube test procedure that is conducted under enhanced conditions (higher temperature, longer time) and with more detailed evaluations versus the chemical compatibility test (CCT) procedure.

full-size transformer coils: Full-size transformer coils capable of meeting the requirements of IEEE Std C57.12.01 and passing testing per IEEE Std C57.12.91, which are selected for use as test objects in this procedure.

humidity conditioning: Humidification of the test coils as part of the diagnostic procedures used to evaluate the thermal capability of the testing insulation system.

instrumented control coil: A coil used that is of the same coil design, including all materials, as the full-size transformer coils used in the circulating current evaluation method that is imbedded with sufficient thermal sensors to accurately determine the hottest spot of the winding during the aging process. This instrumented control coil shall experience the same current as the full-size transformer coils but is not to be subjected to dielectric testing, cold exposure, or humidity conditioning. If the coil is in good operating condition, it may be used for multiple aging temperatures or test programs as long as it is the same coil design.

insulation system: An assembly of insulating materials in a particular type, and sometimes size, of equipment.

In most cases, this combination of insulating materials is also known as an electrical insulation system (EIS).

representative small-scale model coils: Model coils that represent the insulation components used in the tested insulation system and allow for sequential testing of the appropriate electrical stress paths required within the model.

test laboratory ambient conditions: The ambient conditions of the laboratory environment where the dielectric testing is performed shall be between 10 °C and 40 °C with no limitation on humidity. The temperature and humidity during the dielectric testing should be recorded.

thermal index: An index that allows relative comparisons of the temperature rating of an insulation system with a defined life expectancy based on the specified test procedure.

3.2 Abbreviations and acronyms

BIL full wave impulse

FEA finite element analysis

TVA transient voltage analysis

4. Basic considerations

4.1 General

This test method is based on the retention of the dielectric properties based on basic impulse insulation level and induced voltage ~~by impulse testing~~. Therefore, it is most applicable to ~~high-voltage~~ windings in excess of 600 V. For this reason, a low-voltage winding of 600 V or less is excluded from this test procedure, except where necessary to perform an induced test or to provide a ground plane for the high-voltage winding. In the latter case, the low-voltage winding may be simulated by any suitable method. When a test is required on the low-voltage winding, it should be tested according to IEEE Std 259⁴, using 40 000 h as a minimum acceptable basis to determine the thermal index. If the low-voltage winding exceeds 600 V line-line and is substantially different in construction from the high-voltage winding, then a separate test shall ~~must~~ be performed that adequately models the low-voltage winding. The preferred method for this test procedure is to use full-size transformer coils; however, an alternative method using representative small-scale coils is also provided.

NOTE—An alternative method for testing low-voltage windings below 600 V would be to test per this document at a 1.2 kV level and scale down the voltage using the method described in 8.6.

4.2 Intent of test methods

The intent of these test methods is to define uniform end-of-life criteria for the thermal evaluation of a medium-voltage, dry-type transformer insulation system during accelerated aging, which is accomplished by elevating the hottest spot temperature of a winding or electrically equivalent model well above normal and then extrapolating to a 40 000 h lifetime. The expectation is that this extrapolation is equivalent to the expected 180 000 h transformer lifetime due to the severity of the accelerated aging. The methods then test ~~have~~ each component of the insulation system dielectrically ~~tested~~ under conditions that are, as nearly as possible, the same as the conditions in the actual transformer. Thus, each component ~~of the components~~ is evaluated in accordance with its actual function.

4.3 Aging factors

Although the primary aging factors are temperature and time, the criterion of failure of these high-voltage insulation systems is assumed to be voltage related to the initial dielectric strength or to the rated basic impulse voltage level. Therefore, the time-to-failure of the system is determined during the accelerated thermal aging by its ability to withstand prescribed proof-test voltages applied after each thermal aging cycle (see 6.4.2 and 7.6.2 ~~4.8~~).

The Arrhenius relationship is the theoretical basis for this test procedure.

Test methods specified in this test procedure are of an accelerated nature. Therefore, an Arrhenius extrapolation of the time-to-failure obtained at the test temperatures (log of life ~~versus~~ vs. 1/absolute temperature) is required ~~in order~~ to obtain the temperature classification for normal operation. As the conditions of this accelerated testing are unusually severe, extrapolation of the data ~~should~~ will indicate a shorter time-to-failure than would be obtained in actual service use. Due to the lack of a universally accepted standard transformer insulation system, it is not possible to compare insulation systems with a standard system via the Arrhenius approach. It is expected that the extended use of this procedure ~~may~~ will make such a comparison possible. Until then, a reference time of 40 000 h to failure shall be used as a minimum acceptable basis for establishing a temperature classification. See item c) 4) in Clause ~~2~~ 5.

4.4 Data treatment

~~In order~~ To make sure that valid results are obtained that are free of bias and suitable for comparative studies, the test data shall be reduced statistically and the results shall be reported according to Clause ~~2~~ 5.

Tests shall be carried out in accordance with Clause 5; except when the thermal degradation characteristics have been previously determined by using the procedures in this standard, in which case the methods ~~Method 1,~~ described in Clause 8 shall ~~4.1.1; however, Method 2, described in 4.1.2,~~ may be used ~~where applicable~~.

Ideally, the extrapolations ~~described~~ indicated in Clause ~~9 should~~ in Clause 5 shall be applied only for failures occurring ~~that occur~~ in the same part of the insulation ~~insulating~~ system. During the testing, the failure mode of each test sample shall be documented. When multiple modes of failure are present within a group of test samples (see 6.1 and 7.1 for quantities of samples in a group), additional samples shall be tested until there is a common failure mode in the number of samples described in 5.2. The temperature classification shall be extrapolated from this set of samples with a common failure mode. ~~If failures occur in more than one part of the system, data for each mode of failure shall be treated separately.~~

For test samples designed with multiple independent test configurations, it is possible that different configurations may fail at different times. In the case of these types of test samples, testing to failure may be conducted for all configurations and separate temperature classifications may be extrapolated for each configuration. If multiple extrapolations are conducted for such test samples, these extrapolated values shall be documented. However, only ~~Similarly, The temperature classification shall be determined by separate extrapolation for each mode of failure, and~~ the lowest extrapolated temperature ~~value obtained~~ shall be used as ~~representing~~ the temperature classification of rating for the insulation complete system.

4.5 Decision on intended performance

Before the screening test or thermal aging program can begin, the scope and breadth of the test plan shall first be determined. The following list of targets is a suggested starting point and is not all inclusive:

- Insulation system temperature class
- Maximum nominal system voltage
- Minimum/maximum physical size of transformers
- Type of conductors to be tested (aluminum/copper)
- Coil winding geometry and method
- Types and thicknesses of solid insulation and varnish/epoxy to be evaluated
- Maximum voltage stresses used in design

5. Aging program requirements – new insulation system

5.1 General

~~4. Test procedures~~

~~4.1.1 Method 1~~

This method shall be used when no reference insulation system life curve is available for comparison. This new insulation system shall be evaluated with a minimum of three different temperatures with a minimum separation of 10 °C between adjacent aging temperatures. Additionally, there shall be a minimum separation of 30 °C between the lowest and the highest aging temperature in the complete test program. At each aging temperature, a set of test objects (full-size transformer coils or representative small-scale model coils) shall be tested to failure
~~Suggested temperatures are given in Table 1. At least three samples (when using small scale coils), or at least 12 samples (when using representative models), in addition to control samples used for temperature monitoring, shall be tested at each of three (or more) different temperatures. Suggested temperatures are given in Table 1. Details of model construction and test procedure are covered in 4.2 through 4.8.~~

Additionally, the highest aging temperature shall result in a minimum mean time-to-failure of 100 h. The lowest aging temperature shall result in a minimum mean time-to-failure of 5000 h, and the correlation coefficient (R^2) of the equation shall be equal to or greater than 0.95. If the 5000 h minimum is not reached, exceptions shall be allowed when this mean time-to-failure is greater than 4700 h and the correlation coefficient is greater than 0.97 or if this mean time-to-failure is greater than 4300 h and the correlation coefficient is greater than 0.99. Suggested times and temperatures are given in Table 1. The aging periods and temperature, together with the dielectric stress level, should be chosen to reach the anticipated average test life in 5 to 10 aging cycles for each set of test objects. Details of model construction and test procedure are covered in 6.1 for full-size transformer coils and in 7.1 for representative small-scale model coils ~~4.2 through 4.8.~~

Table 1—Suggested temperature and exposure time guidance ~~guide~~

Time period per aging cycle	Aging temperature for EIS with anticipated thermal class of °C (assuming 40 000 h correlation time)									
	90	105	120	130	155	180	200	220	240	250
504 h to 840 h	120	135	150	160	185	210	230	250	270	280
336 h to 504 h	130	145	160	170	195	220	240	260	280	290
168 h to 336 h	140	155	170	180	205	230	250	270	290	300
72 h to 168 h	150	165	180	190	215	240	260	280	300	310
24 h to 72 h	160	175	190	200	225	250	270	290	310	320

(New)

Model coil group temperature designations	Estimated time per cycle (in hours)	Hottest-spot temperature (in °C) or equivalent for system expected to operate at temperature class					
		105	130	150	180	220	250
X	336	135	165	195	230	275	310
Y	96	150	180	215	250	300	340
Z	24	165	200	235	270	325	375

(Deleted)

NOTE 1—The various temperatures ~~temperature~~ and times shown in Table 1 do not describe any actual insulation system but are intended only as a guide in selecting aging temperature and times. The Table 1 temperatures and times cannot be expected to yield the same endpoints for all insulation systems.

NOTE 2—As discussed in IEEE Std C57.96, there is a general consensus that a temperature increase of 6 °C for solid-cast and 10 °C for resin-encapsulated transformers doubles the aging rate. This table provides suggested temperature and exposure times for both equipment types and, as such, must provide a range of both times and temperatures to cover both types. Care should be taken to set up the test plan to meet the minimum aging times and temperature ranges based on the expectation of the aging result for the specific insulation system under evaluation. More detail on this selection is provided in Annex C.

5.2 Thermal aging test coil samples

Thermal aging test samples shall consist of either full-size transformer coils or representative small-scale model coils. The procedure for evaluation of the insulation system using full-size transformer coils is detailed in Clause 6. The procedure for evaluation of the insulation system using representative small-scale model coils is detailed in Clause 7.

These procedures outline design screening tests, quality control tests, as well as the testing performed during the aging process. It is suggested that, when the test coils are being produced, an extra set be manufactured and stored in test laboratory ambient condition in the event one or more coils do not pass the design screening tests. Once the design of the test coil has been finalized, it may also be useful to have an extra set of the final designed test coils available in case one or more coils do not pass the quality control screening tests.

5.3 Design screening tests

5.3.1 General

Prior to the manufacture of the sample design test coils, screening tests should be performed as described in 6.2 for full-size transformer coils and shall be performed as described in 7.4 for representative small-scale model coils to evaluate design and construction of the test coil and provide an early indicator to potential performance during the thermal aging process. If the design screening tests indicate that any intended measurable property may not be achievable, the test coils may be redesigned and the design screening tests repeated.

The two properties to be evaluated during the design screening tests are thermo-mechanical and dielectric breakdown. Since these tests are destructive, the coils created for this clause should not be used as test samples for thermal aging. Other properties may be evaluated during the screening tests, but this evaluation would require additional test coils.

If the design screening tests are not performed, the test parameters outlined in 5.1 may not be met. If the samples are aged at too high of a temperature, the requirement of having the aging times of 100 h at the highest aging temperature or 5000 h at the lowest aging temperature may not be met. If the samples are aged at too low of a temperature, the samples may never fail and the aging program may not be able to be completed in a reasonable time. Similarly, if the dielectric screening tests are not conducted, using too low of a proof voltage could result in a lack of failures and using too high of a voltage would result in aging times that are too short.

NOTE—Conducting the design screening test does not guarantee a successful test, it only improves the likelihood of the testing reaching a successful conclusion.

5.3.2 Pre-aging diagnostic purpose

The test results obtained during the pre-aging diagnostic screening test are used to determine whether the insulation system used in the design and construction of the prototype coils is likely to achieve the desired thermal rating.

The purpose of the design screening tests outlined in 6.2 and 7.4 is to evaluate the following parameters:

- a) Determine the maximum thermal aging temperature level
- b) Determine the maximum dielectric performance via testing to failure by using the applicable tests, such as impulse, applied, and induced voltage tests

A minimum of one new, unused prototype coil should be used for each evaluation described. Detail is provided in 6.2 and 7.4 to determine the number of samples required for these optional diagnostic screening tests.

5.4 Conductor size and shape

This test procedure evaluates the electrical insulation system of the coil design, not the current carrying capacity of the conductor in a production coil. The windings for test shall be made with an appropriately sized conductor that allows for the repeatable production of coil samples and incorporates the insulation thickness selected.

5.5 Conductor type

The preferred conductor type for all samples is copper. An insulation system tested with copper conductor is appropriate for use with either copper or aluminum conductors. The inverse of this is not true; an insulation system tested with an aluminum conductor shall not be used for applications using a copper conductor. The thermal aging of the conductor surface is different between copper and aluminum, which can influence the expected thermal performance. Changes to conductor type are discussed in 8.5.

6. Full-size transformer coils

6.1 Coil design

~~4.2 Test samples~~

~~4.2.1 Sample design considerations~~

~~Test samples may consist of one of the following alternatives:~~

~~Small-scale transformer coils:~~ These test samples should be actual full-size transformer coils capable of meeting the requirements of IEEE Std C57.12.01 and passing the testing per IEEE Std C57.12.91. Coils shall be ~~working coils,~~ selected to represent the transformer range intended for commercial use. The coils may ~~should~~ be any production size as long ~~small~~ as they ~~practical while still large enough to~~ provide the typical minimum air clearances and solid insulation thickness for the voltage class represented. The physical size of the test coil should approximate a standard 500 kVA to 750 kVA three-phase transformer coil. ~~After screening (see 4.3),~~ The coils are ~~will be~~ tested to determine their functional life through the accelerated aging process at elevated temperatures. Since full-size ~~small-scale~~ transformer coils best represent the candidate insulation system, groups of four sample coils shall be tested at no less than three different temperatures. One coil in each set of four shall be designated as an instrumented ~~the~~ control coil.

~~4.8.1 General~~

For full-size transformer coils, the dielectric design shall be evaluated by using impulse, applied voltage and induced voltage testing. The location of the failure shall be recorded by failure mode, as follows:

~~Initial screening and periodic endpoint dielectric tests shall be conducted according to Method A or Method B, as applicable. These methods are described in 4.8.2 and 4.8.3. Dielectric tests shall be applied while the samples are in the humid condition. The order of the tests, when applicable, shall be as follows:~~

- a) Turn-to-turn

- b) Layer-to-layer
- c) Disk-to-disk
- d) Section-to-section
- e) Winding-to-winding
- f) Winding-to-ground

6.2 Optional design screening test—full-size transformer coils

The screening tests are used to establish as many parameters of the program as possible prior to the start of the full thermal aging and to confirm the thermal aging prototype coils are in proper working order. Once the screening tests outlined in this clause have been completed, the coils shall then be referred to as test coils.

6.2.1 Pre-aging diagnostics

From a transient voltage analysis (TVA) test performed per IEEE Std C57.12.58 or finite element analysis (FEA) of the transformer windings for the winding type being evaluated, determine the maximum percentage of the rated full-wave impulse (BIL) voltage that would be experienced for each potential failure mode as listed in 6.1. Refer to B.5 for historical descriptions of where highest stress points are expected to occur for certain winding types.

The calculated voltage stress levels from this analysis should be compared with the range of transformers that are produced using this insulation system to make sure the tested full-size transformer coil is representative of a whole range.

6.2.2 Thermo-mechanical screening test

This test is intended to determine the maximum aging temperature sustainable by the prototype coils.

Exposure to elevated temperature may be accomplished by circulating electric current in the windings of the test sample, by the use of suitable ovens, or by combinations thereof. It is recommended that circulating electric current be used for the aging of full-size transformer coils, but any of these three methods may be used.

Each cycle shall last for 24 h, and the initial test temperature should be no higher than the maximum temperature in Table 1 for the targeted insulation system temperature class. If thermal performance is uncertain, then starting at the midpoint temperature from Table 1 is suggested. After heat exposure, the sample is allowed to return to laboratory ambient conditions before being evaluated for physical degradation. Examples of physical degradation may include, but not be limited to, the following:

- Visible cracking
- Dullness
- Melting
- Delamination or separation
- Extreme color change
- New odors

If no physical degradation is observed, the sample(s) is subjected to an additional heating cycle at 10 °C higher than the previous in a stepwise fashion up to the highest temperature listed for the target insulation system in Table 1.

If physical degradation occurs at a temperature below the maximum temperature listed for the target insulation system, it is likely that the insulation system is lower than the targeted system. If the maximum temperature listed in Table 1 is achieved, then the prototype coil shall undergo postheating cold exposure (6.4.3), humidification (6.4.4), and dielectric testing (6.4.5) at rated nameplate values. If the prototype coil passes all the electrical testing, then the maximum thermal aging temperature should match the last heating temperature. If it fails, then the maximum thermal aging temperature should be 10 °C lower than the last heating temperature.

NOTE—Since there has been no successful dielectric test of aged prototype coils under this last scenario, it may be prudent to conduct the postheating cold exposure (6.4.3), humidification (6.4.4), and dielectric testing (6.4.5) after each 24 h heating cycle, whether physical degradation is observed or not; otherwise this portion of the screening test would need to be repeated with a second new unused prototype coil. Testing after every heating cycle is a suggestion, not a requirement for the thermal-mechanical screening test.

If the prototype coil passes all of the electrical testing, additional thermal evaluations at even higher temperatures may be valuable for consideration of a higher temperature insulation system, but it would be recommended to perform the electrical testing after each successful thermal evaluation to identify the highest aging temperature at which the dielectric tests can still be passed.

6.2.2.1 Aging by ~~circulating~~ electric current

This method typically applies to full-size transformer coils. This method may require more than one prototype coil depending on the method used to monitor the temperature of the hottest spot in the windings.

When ~~Where~~ exposure to elevated temperature is accomplished by circulating electric current in the windings of the test sample, the coils ~~corresponding electrical elements of all samples~~ shall be connected in series to have the same current circulated in the like elements.

The means for making small adjustments to the current through individual samples may be provided to aid in achieving the desired temperatures. Individual enclosures for the test models may be used to maintain test temperatures. However, the physical arrangement of the prototype coils ~~samples~~ with respect to each other shall be such as to promote equality of temperature in all samples.

Any suitable method may be used for monitoring the temperature of the [prototype coils](#) ~~samples~~ during the temperature exposure. [Annex B provides detailed information that may provide useful information related to this testing.](#) The following method is recommended: one [prototype coil](#) ~~test sample~~ in a group shall be equipped with thermocouples and shall be used for temperature monitoring purposes only. The number and location of thermocouples shall be such as to give an accurate indication of the hottest-spot temperature and an adequate knowledge of the temperature distribution within the [prototype coil](#) ~~sample in order~~ to satisfy the conditions specified below. [This prototype coil is also referred to as an instrumented control coil.](#)

The temperatures in all [prototype coils](#) ~~samples~~ shall be monitored by one or more thermometers or thermocouples located on each sample. The relative position of the thermometers or thermocouples shall be the same for all samples, including the control sample. The monitored temperatures on individual test and control samples shall have a degree of uniformity of $\pm \text{ } \pm / - 2$ °C at temperatures [up to 180](#) ~~under 300~~ °C and $\pm \text{ } \pm / - 3$ °C for temperatures [from greater than 180 °C to](#) ~~over~~ 300 °C, for the same monitored locations. [The tolerance for aging temperatures above 300 °C shall be determined by the involved parties.](#)

The intent is to maintain constant test temperatures at the hottest spots within the sample as measured by the monitoring thermocouples. Thus, the hottest-spot temperature of each [winding](#) ~~shall of the windings will~~ be nearly the same.

For solid cast designs, the heat-up rate of the [prototype coils](#) ~~test samples~~ should be controlled and monitored to prevent premature coil cracking. It should be cautioned, however, that an excessive heat-up time [adds](#) ~~will add~~ aging time to the samples that [is](#) ~~will~~ not [to](#) be included in the total aging time.

The aging cycle [begins](#) ~~will begin~~ only when the monitored control sample has reached the prescribed aging temperature. The aging cycle [terminates](#) ~~will terminate~~ at the point in time when the control sample drops more than 3 °C below the aging temperature. [Should the aging cycle be interrupted for any reason, including a power outage, only the time within this temperature band shall be counted for calculation of aging time. Depending on when the aging cycle is interrupted, the aging cycle can either be restarted or terminated to conduct the diagnostic test cycle as if a full cycle had been conducted.](#)

Temperature exposure shall be conducted in a ~~relatively clean, draft free~~ area having a controlled air flow, and the samples may be covered to exclude dirt as long as the cover does not artificially alter the heating profile of the prototype coils.

6.2.2.2 Aging by hot air ovens

This method may also be used with full-size transformer coils. The prototype coils ~~Each group of samples~~ shall be thermally aged in a ~~separate~~ hot-air-circulating oven that has been stabilized at the prescribed temperature. The samples shall be kept in these ovens for the required duration ~~known durations (cycles)~~ before further treatments.

The oven temperature uniformity shall be monitored to determine variability according to ASTM D5374. The oven shall have a degree of uniformity of $\pm 2^\circ\text{C}$ at temperatures up to 180°C and of $\pm 3^\circ\text{C}$ for temperatures from greater than 180°C to 300°C , with the tolerance for aging temperatures above 300°C to be determined by the involved parties.

One unmarked prototype coil sample (control sample) in each oven shall be equipped with a thermocouple to determine the temperature of all the samples in that oven, and shall be used for monitoring purposes only. The thermocouple shall be placed in the location of the coil that reaches the oven temperature last. Once this thermocouple has reached the selected aging temperature, the time shall be logged and used as the start of the thermal aging cycle ~~This control sample is in addition to the 12 test samples. The oven must be large enough to hold all 13 sample coils. The oven temperature uniformity shall be monitored to determine variability according to ASTM D5374. The oven shall have a degree of uniformity of $\pm 2^\circ\text{C}$ among the measured points in the oven at temperatures under 300°C , and $\pm 3^\circ\text{C}$ for temperatures over 300°C .~~

The aging cycle begins ~~will begin~~ only when the monitored control sample has reached the prescribed aging temperature. The aging cycle terminates ~~will terminate~~ at the point in time when the control sample drops more than 3°C below the aging temperature. This would occur when the oven doors are opened and/or when the oven is turned off. Should the aging cycle be interrupted for any reason, including a power outage, only the time within this temperature band shall be counted for calculation of aging time. Depending on when the aging cycle is interrupted, the aging cycle can be either restarted or terminated to conduct the diagnostic test cycle as if a full cycle had been conducted.