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(Revision of
IEEE Std 1-1986)

IEEE Recommended Practice—General Principles for Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation

Sponsor

IEEE Standards Coordinating Committee 4, Insulation Systems of the IEEE Power Engineering Society

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Abstract:
This recommended practice is intended to serve in the preparation of standards that are principally concerned with the thermal endurance of EIM and simple combinations of such materials, with the establishment of limiting temperatures of EIS, and with the provision of general principles for thermal classification of EIS.
Keywords:
aging factors, EIM, EIS, electrical insulating material, electrical insulating system, electrical properties, electrical stress, environmental stress, factor of influence, hottest-spot temperature, mechanical properties, mechanical stress, observable temperature rise, relative temperature index, temperature index, temperature limits, thermal aging, thermal evaluation, voltage stress

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Introduction

(This introduction is not a part of IEEE Std 1-2000, IEEE Recommended Practice—General Principles for Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation.)

There is general agreement from experience that a number of service stresses influence the service life of electrical insulation in electric equipment. The purpose of IEEE Std 1-2000 is to provide guidance for the preparation of thermal-aging test procedures to determine the temperature index (TI) of electrical insulating materials (EIM) and the thermal class of electrical insulation systems (EIS).

The main changes from IEEE Std 1-1986 are as follows:

a) The title was changed from a "Standard" to a "Recommended Practice" to be consistent with the predominant verb used in the text, "should."
b) The table of thermal classification, now Table 3, was modified to include both numerical and letter designations and all currently recognized temperature classes.
c) The multifactor testing portion of Clause 8 has been deleted because it is beyond the scope of this recommended practice, which covers temperature limits.

This revision has been made with the intent of harmonization with IEC 60085-1984, Thermal evaluation and classification of electrical insulation, and IEC 60505-1999, Evaluation and qualification of electrical insulation systems. This work was done by a working group of IEEE Standards Coordinating Committee 4 (SCC4), Insulation Systems. The members of the SCC4 working group are also technical experts of IEC TC 98, Electrical Insulation Systems. TC 98 plans to draft a revision to IEC 60085-1984.

At the time this revision was completed, the SCC4 working group had the following membership:

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Contents

IEEE Recommended Practice— General Principles for Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation

1. Overview

These principles are intended to serve in the preparation of IEEE and other standards that deal with the selection of temperature limits and the measurement of temperature for specific types of electric equipment. They include an outline of the fundamental considerations and a review of the elements to be considered in applying the principles to specific cases.

1.1 Scope

Guiding principles are included for the development of test procedures for

— Thermal evaluation of electrical insulating materials (EIM)
— Thermal evaluation of electrical insulation systems (EIS)
— Thermal classification[1] of EIS for rating electric equipment

The principles are presented in the following order:

— Clause 4, General concepts
— Clause 6, Evaluation of the thermal capability of EIM
— Clause 7, Limiting temperatures and their measurement for EIS
— Clause 8, Thermal evaluation of EIS

In the application of these principles, variations are necessary to suit the widely different types of equipment and service conditions that are considered in equipment standards. When specific equipment, IEEE, or other

[1]Historically, the term *thermal classification* has been used in reference to both insulation systems and to electric equipment. Therefore, for clarity, thermal classification should always be used in combination with the word *system* or *equipment*, for example, Class 155 System.

recognized standards based on these principles are available, they should take precedence over this recommended practice.

1.2 Purpose

This recommended practice is intended to serve in the preparation of standards that are principally concerned with the thermal endurance of EIM and simple combinations thereof, with the establishment of limiting temperatures of EIS, and with the provision of general principles for thermal classification of EIS.

2. References

This recommended practice should be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revisions apply.

IEC 60085-1984, Thermal evaluation and classification of electrical insulation.[2]

IEEE Std 98-1984 (Reaff 1993), IEEE Standard for the Preparation of Test Procedures for the Thermal Evaluation of Solid Electrical Insulating Materials.[3]

IEEE Std 99-1980 (Reaff 2000), IEEE Recommended Practice for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electrical Equipment.

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

IEEE Std 943-1986 (Reaff 1992), IEEE Guide for Aging Mechanisms and Diagnostic Procedures in Evaluating Electrical Insulation Systems.

3. Definitions

For this recommended practice, the following terms and definitions apply. *The Authoritative Dictionary of the IEEE Standards Terms* [B3][4] should be referenced for terms not defined in this clause.

3.1 General definitions

3.1.1 aging: The irreversible change of the properties of an electrical insulating material (EIM) or electrical insulation system (EIS) due to action of one or more factors of influence.

3.1.2 aging factor: A factor of influence that causes aging.

3.1.3 electrical insulating material(s) (EIM): Material suitable for providing electrical isolation between parts at different voltages. It may be a solid, liquid, or gas.

[2]IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, 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, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[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://standards.ieee.org/).

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

3.1.4 electrical insulation system(s) (EIS): An insulating structure containing one or more electrical insulating materials (EIM) together with associated conducting parts employed in electric equipment (an electrotechnical device).

3.1.5 estimated life (performance): The expected service life derived from either service experience or the results of tests performed in accordance with appropriate evaluation procedures or both, as established by the responsible technical committee.

3.1.6 factor of influence: A stress imposed by conditions of operation, environment, or test that affects the life of an electrical insulating material (EIM) or electrical insulation system (EIS).

3.1.7 service condition: A combination of factors of influence and duty that are to be expected in a specific application of an electric device.

3.1.8 service requirement: Specified factors of influence, intended performance, and duty of an electric device.

3.1.9 simple combination of [electrical] insulating materials (EIM): A number of insulating materials, which together make possible the evaluation of any interaction between them. Magnet (winding) wire insulation and varnish are illustrative.

3.1.10 thermal aging: The aging that takes place at an elevated temperature due to chemical reactions.

3.1.11 useful service life: The length of time (usually in hours) for which an electrical insulating material (EIM), electrical insulation system (EIS), or electric equipment performs in an adequate or specified fashion.

3.2 Definitions related to electric equipment

3.2.1 ambient: The medium (for example, air, gas, liquid, or earth) in which electric equipment operates.

3.2.2 ambient temperature: The temperature of the ambient medium.

3.2.3 hottest-spot temperature (hot spot): The highest temperature attained in any part of the electrical insulation system (EIS) of electric equipment. (Difficulties in its determination are encountered. See Clause 4.)

3.2.4 hottest-spot temperature allowance: The designated difference between the hottest-spot temperature and the observable insulation temperature. Suggested values are commonly used in standards. (The value depends on many factors, such as size and design of the equipment, and should be determined by thermal analysis and/or calculations based on fundamental loss and heat transfer principles and substantiated by testing on prototype equipment or full-size models).

3.2.5 limiting ambient temperature: The highest (or lowest) ambient temperature at which electric equipment is expected to give specified performance under specified conditions, for example, rated load.

3.2.6 limiting hottest-spot temperature: The highest temperature attained in any part of the electrical insulation system (EIS) of electric equipment, which is operating under specified conditions, usually at maximum rating and the upper limiting ambient temperature.

3.2.7 observable insulation temperature: The temperature of the electrical insulation system (EIS) in electric equipment, which is measured in a specified way, for example, with a thermometer, embedded thermocouple, or resistance detector or by winding resistance or other suitable procedure.

3.2.8 observable temperature rise: The difference between the observable temperature of an electrical insulation system (EIS) and the ambient temperature.

3.3 Definitions related to the evaluation of thermal capability

3.3.1 accelerated test: A functional test applying accelerated aging to shorten test time.

3.3.2 candidate EIS or EIM: The electrical insulation system (EIS) or electrical insulating material (EIM) under evaluation to determine its service capability.

3.3.3 diagnostic factor: A variable or fixed stress, which is applied to an electrical insulating material (EIM) or electrical insulation system (EIS) to establish the degree of aging without influencing the aging process.

3.3.4 EIM temperature index (TI): The lowest value of a range of temperature indices for electrical insulating material (EIM).

3.3.5 end-point criterion: A selected value of either property or changed property that defines the end of the life of an electrical insulating material (EIM) or electrical insulation system (EIS) in a functional test.

3.3.6 functional test: A procedure to obtain information about suitability of an electrical insulating material (EIM) or electrical insulation system (EIS) under specified conditions.

3.3.7 halving interval (HIC): The number that corresponds to the interval, in °C, determined from other thermal endurance relationships and expresses the halving of the time-to-end-point centered on the temperature of the temperature index (TI) or relative temperature index (RTI). For graphical derivation, the time corresponding to TI or RTI and one half that value usually produces an acceptable approximation.

3.3.8 proof test: A means of evaluation in which an arbitrary fixed level of a diagnostic factor is applied periodically. In this case, the number of failures among multiple test specimens (rather than the magnitude of the diagnostic factor; see 3.3.3) defines the end point of the test.

3.3.9 reference EIM or EIS: An evaluated and established electrical insulating material (EIM) or electrical insulation system (EIS) with either a known service experience record or a known comparative functional evaluation as a basis.

3.3.10 relative temperature index (RTI): The temperature index (TI) of a candidate electrical insulating material (EIM) that corresponds to the accepted TI of a reference EIM. A reference EIM shall be established by a full aging program.

3.3.11 temperature index (TI): The number that corresponds to the temperature, in °C, presented graphically, but calculated mathematically from the thermal endurance relationship of an electrical insulating material (EIM) at a specified time. (The TI is not used for equipment.)

3.3.12 test object: A piece of original equipment; or a representation (model) of equipment, a component, or part of equipment, including the electrical insulation system (EIS) intended for use in a functional test.

3.3.13 thermal classification of EIS. A standardization designation of the temperature capability of the electrical insulation system (EIS) in electric equipment, as defined by the appropriate technical committee. It may be determined by experience or test and expressed by letters or numbers. It is preferable to make comparisons at a particular temperature, for example, 130 °C, 155 °C, or over a range of temperatures.

3.3.14 thermal endurance graph: The graphical expression of the thermal endurance relationship in which time to failure is plotted against the reciprocal of the absolute test temperature.

3.3.15 thermal endurance relationship: The expression of aging time to failure as a function of test temperature in an aging test.

4. General concepts

The temperature limits for electric equipment should be selected so that the equipment results in a satisfactory life under normal operating conditions. In addition, permissible emergency temperature limits and corresponding ratings may be established, including the durations and frequencies of emergency or the peak-load operation to which these limits apply. In the establishment of temperature limits, the following statements should be recognized:

a) The ambient temperature is unlikely to be maintained at its minimum or maximum value for long periods.

b) Load cycles may consist of periods during which the load may be above or below rated.

4.1 Temperature measurement

Standards for electric equipment usually specify temperature rise rather than maximum temperature. However, it is beyond the scope of this recommended practice to specify the permissible temperature rise of insulated parts or prescribe the methods by which such temperature rises are determined. In normal practice, the maximum temperature (hottest spot) attained by an insulated part is seldom measured directly. The permissible temperature rise is generally specified, therefore, to be less than the difference between the temperature recognized in this recommended practice (Table 1) and the temperature of the ambient air or other cooling medium.

The method of measurement to be used for determining the temperature rise of insulated parts should be prescribed in the standards for the equipment.

When specifying permissible temperature rises and measurement methods in standards for electric equipment, it is generally useful to consider construction factors, such as method of cooling, although these factors are normally not included in the standard proper.

4.2 Additional aging factors

The ability of an EIM or EIS to fulfill its function is also affected by the presence of other aging factors. These factors will vary from one type of equipment, or application, to another, but may include electrical stresses, mechanical stresses, and ambient (environmental) stresses. Mechanical stresses imposed upon the system and its supporting structure by vibration and differential thermal expansion may become of increasing importance as the size of the apparatus increases. Electrical stresses will be more significant with high-voltage apparatus or with equipment exposed to voltage transients. Moisture in the equipment environment and the presence of dirt, chemicals, radiation, or other contaminants may have an injurious effect. All such factors should be taken into account in establishing the standards of temperature limits for particular classes of apparatus.

4.3 Limits of temperature

In choosing temperature limits suitable for specific equipment and particular conditions, the general concepts in 4.3.1 through 4.3.8 may be applied.

4.3.1 Electrical and mechanical properties of EIM

The electrical and mechanical properties of EIM are temperature dependent. In many applications where organic-based materials are used, the melting point should be higher than the maximum operating temperature in service. In most polymeric insulating materials, a sharp transition from solid to liquid does not occur and softening increases as the temperature increases. Many polymeric insulating materials will undergo a second order transition from a partially crystalline or hard glassy state to a softer, rubbery, or viscous state when exposed to rising temperatures and will experience marked changes in properties over a narrow temperature range. In these cases, the functionally important softening temperature, which is generally known as the glass transition temperature, may relate to the mechanical stresses imposed in service and the amount of deformation and creep that can be tolerated. Limits for the loss of these properties may be developed through systems tests or service experience.

Dielectric loss may also be temperature dependent so that, in high-voltage equipment, the dielectric loss alone at elevated temperatures may lead to a thermal runaway condition.

4.3.2 Effect of high temperature on electrical and mechanical properties of EIM

Marked changes in the electrical and mechanical properties of EIM also occur progressively as a result of prolonged exposure to high temperature. The materials may soften, lose weight, or become brittle; and the chemical composition and structure may change. The effects of high temperature may differ widely, depending upon the particular environmental conditions. While infant mortality may occur with equipment, insulation does not usually fail because of immediate breakdown at some critical temperature, but rather as a result of gradual deterioration with time.

4.3.3 Temperature limit for EIS

The limiting temperature at which an EIS may be operated depends upon the degree and intermittency of the loading, the degree of reliability required, and the length of life desired. A specific material as part of a system may be satisfactory for use at different limiting temperatures, depending upon the type and size of equipment in which it is used and the kind of service to which the equipment is subjected.

The temperature limit for an EIS may not be directly related to the thermal capability of the individual materials included in it. In an EIS, the thermal performance of an EIM may be improved by the protective character of other materials used with it. On the other hand, problems of incompatibility between materials may decrease the appropriate temperature limit of the system from that of the individual materials.

4.3.4 Thermal aging

The electrical and mechanical properties of insulating materials and insulation systems may be influenced in different ways and to different degrees as a function of temperature and with thermal aging. In some cases, the electrical properties and mechanical strength of insulating materials initially improve as thermal aging progresses. However, elongation to rupture generally progressively decreases with thermal aging so that embrittlement finally leads to cracking and may contribute to electrical failure.

Thus, how long insulation is serviceable depends not only upon the materials used, but also upon the effectiveness of the physical support for the insulation and the severity of the forces tending to disrupt it. Even though portions of insulation structures may have become embrittled under the influence of high temperature, successful operation of the equipment may continue for years if the insulation is not disturbed.

Because of the effect of mechanical stress, the forces of thermal expansion and contraction may impose temperature limitations on large equipment even though higher temperature limits proved satisfactory in small equipment when similar insulating materials were used.

4.3.5 Equipment life—environmental issues

The life of equipment is dependent to a considerable extent upon the degree of exclusion of oxygen, moisture, dirt, and chemicals from the interior of the insulating structure. At a given temperature, therefore, the life of equipment may be longer if the insulation is suitably protected than if it were freely exposed to industrial atmospheres. The use of chemically inert gases or liquids, as cooling or protective media, may increase the temperature capability of an insulation system.

4.3.6 Equipment life—operational issues

The life of equipment also depends upon the care it receives during manufacture, transportation, storage, and installation and upon maintenance during operation. Successful operation cannot be expected of insulation that has been damaged or displaced.

4.3.7 Insulation life

The rate of physical deterioration of insulation under thermal aging increases rapidly with an increase in temperature. A fairly precise method of determining insulation life at elevated temperature is provided by the concept that the logarithm of the insulation life is a function (often linear) of the reciprocal of the absolute temperature. A straight line plot of aging data indicates that the nature, or order, of the chemical reaction causing aging remains unchanged. Departure from linearity normally suggests that the type of chemical reaction is changed. When the logarithms of the hours of life, found by thermal evaluation tests at three or more different temperatures, are plotted against the reciprocals of the absolute temperatures, they will usually, but not always, form a straight line. Individual time-temperature life curves for different insulating materials and insulation systems should be determined by thermal evaluation tests.

4.3.8 Ambient temperature

The ambient temperature directly affects the temperature attained by equipment in operation.

5. Basic considerations in the preparation of standards

The desired life of electric equipment depends upon the initial investment, reasonable maintenance, needed reliability, obsolescence, importance of size, weight, and other factors. In considering such factors, predominant conditions rather than extreme requirements should be used as a basis for standards. For some types of equipment and service, the user may expect a life of 30 years or more with a high degree of reliability. For other types of equipment a life of only a few years, or a few hours, may be satisfactory.

5.1 Service experience

The great variety of physical factors and economic considerations entering into the problem of standardization makes it essential to give much weight to experience. Standard values that are entirely safe for extreme conditions or that allow for improbable combinations of unfavorable factors will result in products too costly for the majority of applications and consequently will not be respected. No laboratory or factory test can fully simulate the many combinations of temperatures, loads, mechanical stresses, voltage surges, and environmental conditions met in service. The response to test or service conditions will also change as insulation ages, often in a complex manner. To what extent extreme conditions may be discounted, without incurring unreasonable maintenance, can only be determined by practical experience over considerable time.

5.2 General principles for temperature limits

The temperature limits generally used for electric equipment are the results of long experience and have proved to be reasonably satisfactory. The general principles outlined in this recommended practice suggest that major changes in existing standards should be made only when they are indicated to be desirable in the light of new test data, availability of new or improved materials, additional operating experience, new measurement techniques, or changes in service requirements.

The following important trends were considered in preparing these principles:

a) Reliance on accelerated life tests, as provided in IEEE Std 99-1980, to determine appropriate limiting temperatures and suitable applications for a complete EIS or individual EIM.
b) The availability of many candidate EIS and EIM with characteristics and appropriate applications that shall be determined by tests.
c) The great expansion in many areas of application (such as equipment for nuclear energy, aerospace, computers, and other electronic applications; industrial and domestic air conditioning; and domestic appliances of many kinds), which are increasing the varieties of special-purpose equipment supplied by the electrical industry and increasing the ranges of temperature considered in their operation.
d) The continuing and greater use of enclosed types of equipment, often operating in controlled gases or liquids.
e) A trend toward operating some electric equipment at, or close to, limiting insulation temperature.
f) A trend toward operating some electric equipment for short-time duty periods at higher-than-normal temperature so that the average rate of thermal deterioration over the total elapsed time is consistent with the desired life expectancy.

The various standards for different types of electric equipment should be correlated to ensure that the thermal performance and life expectancies of associated elements in a complete electric system will be consistent under short-time overload and emergency conditions and in normal service. However, it is important to allow freedom in using different temperature limits for individual types of equipment and for specific applications in accordance with their individual requirements.

5.3 Purpose of life testing

A principal purpose of the development and use of test procedures for life-testing EIS and EIM is to enable more accurate estimates to be made of the life expectancy of equipment under particular service conditions. In the course of time it will be desirable to correlate further the various standards to achieve more consistent life expectancies for associated equipment and be better suited to give the desired degree of reliability.

Only carefully evaluated service experience or adequately accepted tests provide the basis for rational thermal classification of electric equipment, EIS, and temperature index (TI) determination of EIM.

6. Evaluation of the thermal capability of EIM

In the evaluation of thermal endurance of EIM and simple combinations of EIM, other aging stresses or factors (that is, mechanical, electrical, and environmental) may be limitations in determining the life of a material in service. While knowledge of the response of a material to these other factors and their interaction with thermal aging may be important in particular cases, no general classification method exists for those capabilities.

6.1 Thermal aging

The process of thermal-aging an EIM is complex, and the mechanisms vary with different materials and under different service conditions. Typical mechanisms include the following:

a) Loss of volatile constituents, such as low molecular-weight component initially present or formed in the aging process.
b) Oxidation that can lead to molecular cross-linking, chain-scission, embrittlement, and the production of volatile components.
c) Continuous molecular polymerization that may increase physical and electrical strength at first, but may subsequently lead to decreased flexibility, embrittlement, and early failure under mechanical stress.
d) Hydrolytic degradation in which moisture reacts with the insulation under the influence of heat, pressure, and other factors to cause molecular deterioration.
e) Chemical breakdown of constituents with formation of products that act to degrade the material further, such as hydrochloric acid. (Such processes, once started, may become autocatalytic.)

Because different EIM react in different ways to the various aging processes, predicting the thermal performance from the chemical composition of the material is essentially impossible. Rapid advances in polymer chemistry have produced EIM so numerous and complex that simple chemical description has become almost completely meaningless. Consequently, the traditional procedure of dividing EIM into several thermal classes based upon broad descriptive statements according to general chemical composition is inadequate, should be deprecated, and has been discounted and discontinued.

6.1.1 Process of thermal aging

In general, the thermal-aging process leads first to increased strength, but subsequently to loss of strength and embrittlement. In some cases, thermal aging may cause softening, particularly in closed spaces where the insulation is exposed to the effects of its own products of degradation. Often the electrical properties improve as thermal aging progresses. Electrical failure usually takes place only after mechanical failure occurs, either immediately or after moisture and contaminants penetrate the cracked structure.

6.1.2 Thermal life

The thermal life of EIM in electric and electronic equipment may depend to a large extent upon the way in which the materials are applied and the conditions to which they are exposed. Exclusion of moisture, particles, and dirt; the presence of an inert ambient atmosphere; limitation of mechanical and electrical stresses; and freedom from mechanical or thermal shock tend to increase the life of EIM and EIS in which they are used. When oxidation mechanisms are important factors, the geometry of the materials (that is, thickness) may be significant.

Other factors being equal, thermal degradation is accelerated as the temperature is increased. For many EIM, the life is an exponential function of the reciprocal of the absolute operating temperature over a limited range of temperatures.

However, for some materials,[5] such simple relationships do not hold. In the case of thermoplastic materials or those that lose strength markedly at elevated temperatures, the softening point, rather than the thermal stability, may limit the temperature capability.

[5]A different type of chemical breakdown takes place in some material, such as polyvinyl chloride; the formation of hydrochloric acid may be autocatalytic after exhaustion of the stabilizer (acid absorber).

6.2 TI and relative temperature index (RTI) of an EIM

A useful characteristic of an EIM, the TI is determined by a thermal-aging test. The RTI for a candidate material is determined by conducting comparative thermal-aging tests with a reference EIM for which considerable test and service experience has been obtained.

The TI and the RTI provide a technical basis for comparing the thermal capability of EIM. The RTI affords better reproducibility with fewer errors from experimental factors, such as often introduced by aging ovens. Neither the TI nor the RTI can be related directly to the appropriate operating or service temperature, which depends on many factors including environment, service severity, and the design of the EIS in which the material is used.

6.2.1 Thermal endurance graph

For comparison, it is frequently of interest to know the slope of the thermal endurance graph. Although many measures of the slope can be derived, the most practical one is the halving interval (HIC), which is the number corresponding to the interval, in °C, determined from the thermal endurance relationship between the time at the TI (for example, 20 000 h) and half that time (10 000 h, to continue the example). See 3.3.11 and Figure A.1.

NOTE—The HIC is a measure derived from the slope of the thermal endurance graph. It is not a constant, but varies with temperature when the thermal endurance relationship is linear. In many practical cases, the error incurred by using the HIC within the temperature range of interest remains within acceptable limits.

The characterization of the material, thus, consists of either a TI-HIC or RTI-HIC.

6.2.2 Temperature classification

The TI is a value obtained by test, which may be used as a guide and does not imply a thermal classification or a limitation on use in equipment. It is used most suitably for comparing EIM that have been evaluated under controlled conditions. Temperature classification for the purpose of rating electric machines should be defined in terms of the thermal endurance of the EIS.

Where possible, the TI and the RTI are based upon results obtained from standard test procedures for determining the thermal endurance. Where standard test procedures are not developed, the TI and the RTI may be assigned based on a relevant test, provided that the test method and the end point are described. Determination by test is described in 6.3. A TI may also be determined from service experience as described in 6.4.

6.2.3 Temperature index (TI)

An EIM may be assigned more than one TI, each of which is based upon different properties, environmental conditions, or material geometry (such as thickness). For example, an EIM can be assigned a TI based upon retention of mechanical properties after aging. Thus the TI describes performance characteristics that provide the designer with information for the selection of materials based upon engineering data, rather than arbitrary classification.

Conditions encountered in the use of insulation (such as voltage stress, partial discharge, mechanical stress, and environmental factors) may degrade and limit the life of some EIM irrespective of thermal degradation. These effects and the physical and chemical properties of EIM should be evaluated separately to ensure suitability for a particular application. The evaluation of these other aging factors is beyond the scope of this recommended practice although the development of such standards are encouraged. However, other factors of influence (for example, voltage stress) may be combined with thermal aging (possibly in nonlinear, cumulative fashion) to determine the TI under the applied environment.

6.3 Determination of TI for EIM by test

The many factors to be considered and the philosophy underlying the development of EIM test procedures for determining the TI are described in detail in IEEE Std 98-1984.

The test procedures for EIM cannot take into account all of the many different influences that affect the life of insulation in different equipment and applications. The useful life of an EIM in a particular electric or electronic equipment may be quite different from the life determined by testing the EIM alone. The life of an EIM used in one type of electric equipment may be different from the life of the same EIM applied in another type of equipment. The suitability of EIM in electric equipment, and in combination with other materials, is determined by experience or by tests on the EIS.

The test procedures for EIM will, however, provide thermal-life data that can be used to compare the RTI of EIM. Using a relevant test procedure, the test life of a reference EIM as a function of temperature can be determined. Because the normal temperature of a reference EIM will have been established by service experience, its life-temperature characteristic, determined by test, provides a comparative basis for establishing the RTI of a candidate EIM.

The severity of the tests and their duration are arbitrarily chosen for convenience, accuracy, and economy in testing. Therefore, the life expectancy under test conditions may be shorter than, and may have no uniform relation to, the life expectancy of the EIM in actual service. EIM of a given TI may be used as components of complete insulation systems that are assigned widely different limiting temperatures, depending upon the results of thermal evaluation tests of the EIS.

Appropriate technical or standards groups may wish to establish the test time for establishing the temperature indices.

6.3.1 Statistical criteria

Thermal-aging tests evaluate the thermal capability of EIM. Normally, test results at several higher temperatures are extrapolated to lower temperatures. The TI or RTI for EIM is derived by applying mathematical operations, including appropriate statistical analysis, to the test data. Care needs to be exercised so that projections, estimations, extrapolations, and other procedures are based on a valid statistical analysis. However, the derivation of a TI often should be permitted even if all of the statistical criteria, such as linearity and equality of variances, are not satisfied. In this way, the loss of useful information, obtained with a substantial economic investment, can be avoided. In this case, the TI or RTI should include a notation that specified statistical requirements have not been met.

Detailed considerations for the preparation of test procedures for the thermal evaluation of EIM are given in IEEE Std 98-1984, and the statistical aspects are considered in IEEE Std 101-1987.

6.3.2 Acceleration of thermal-aging tests

Acceleration of thermal-aging tests is obtained by intensifying the test parameters. Rules enabling estimation of the acceleration factor can be deduced when the mechanism of the aging process is known (for example, that the logarithm of lifetime is proportional to the reciprocal absolute temperature).

For long-life applications, a high acceleration is desired to obtain a relatively short test time, but the correlation between test and reality becomes increasingly uncertain with increasing acceleration.

6.4 Determination of material TI by experience

Thermal-aging tests of EIM, as described in Clause 4, provide quantitative data. However, the relationship of such data to the life of electric or electronic equipment is always to some degree qualitative. For this reason, the TI for EIM is expressed simply as a number that provides a useful basis for comparison, but is not a design temperature value.

Making thermal-aging tests on every EIM to represent every condition of use is not practical or even possible. On the other hand, the service life of electric and electronic equipment provides the most significant basis for determining the thermal capability of EIM. The analysis and evaluation of service life is difficult and time consuming. Truly quantitative information is seldom obtained. Moreover, the equipment user with the most direct and immediate knowledge of service life may not transmit such information adequately to the equipment manufacturer or to the maker of EIM. Nevertheless, after several years of intensive use, a qualitative knowledge of the thermal capability of an EIM is developed. More often such knowledge is based on comparison with reference EIM. Thus it becomes possible to compare the thermal capabilities of a candidate EIM to a reference EIM and thereby group the candidate in preferred temperature categories.

The determination of a material temperature class for an EIM from service experience is qualitative. Such factors are difficult to define or to specify. The adequacy of such a determination depends on the amount of experiences and the reliability of the source.

A knowledge of the chemical nature and structure of EIM by experienced individuals provides additional information for the comparison of thermal capability. Such experience alone does not provide an adequate basis for establishing a material temperature class, but it may supplement other information.

Experience becomes most useful for establishing material temperature classes for EIM when service experience, the knowledge of chemical structure, and tests on materials are compared and interrelated. To establish a reliable material temperature class by experience, data should be collected from many sources; these data need to be evaluated by experienced individuals.

7. Limiting temperatures and their measurement for EIS

Limiting temperatures for EIS used in equipment should be established from results of thermal-life tests and service experience. The requirements for EIS and the limiting temperatures assigned to them should be suited to the equipment considered and should be based on obtaining a desired life expectancy.

7.1 Derivation of temperature rise

Steps to determine limits of observable temperature rise for standardization are as follows:

a) Classify EIS by experience or by accelerated life tests.
b) Select a value of limiting ambient temperature.
c) Subtract the limiting value of ambient temperature from the limiting insulation temperature to obtain the limiting value of insulation temperature rise.
d) Decide on a hottest-spot allowance.
e) Derive an observable temperature rise to be used for assigning a rating under standard conditions of test.

These five steps are illustrated in Figure 1.

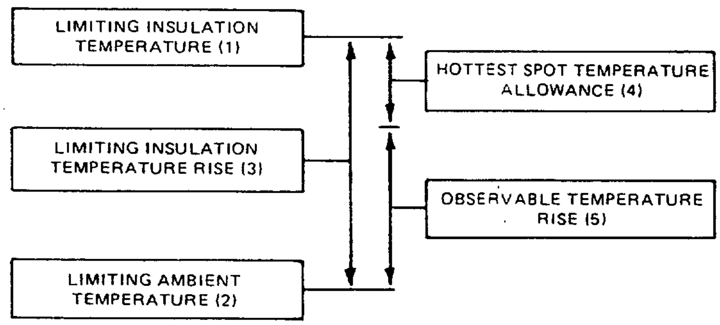

Figure 1—Derivation of a value of limiting insulation temperature for equipment rating

Alternatively, the limiting value of observable temperature rise may be selected first on the basis of economic or other considerations. The five steps of the procedure should then be carried through in the reverse order to find the corresponding hottest-spot temperature and to determine from life-test data the insulation required to give the desired expectancy in service.

7.1.1 Limiting insulation temperature

The limiting insulation temperature of an EIS may be established by test or by service experience with the particular EIS.

The limiting insulation temperature is useful as a point of reference or benchmark and is of primary importance in selecting the practical limits of observable temperature rise that are included in specific equipment standards for rating and testing. It is not usually measurable in the ordinary course of testing or operating electric equipment. The limiting insulation temperature rise is a performance parameter to be met by the manufacturer of the electric equipment.

7.1.2 Ambient temperature

The time, location, and methods of measurement should be standardized for each type of equipment under consideration.

Experience indicates that ambient outdoor-air temperatures at most locations where electric equipment is operated seldom exceed 40 °C. The average outdoor-air temperature during a 24 h period is usually 5 °C to 10 °C lower than the maximum. For the purpose of assigning a rating when the temperature of the outdoor air is taken as the ambient, 40 °C normally is chosen as the value of the maximum ambient temperature. When daily average ambient air temperature is specified, 30 °C is generally recommended.

For self-ventilated (self-cooled) equipment, the ambient temperature is the average temperature of the air in the immediate neighborhood of the equipment.

For self-ventilated equipment operated in an enclosure as a complete unit, the ambient temperature is the average temperature of the air outside the enclosure in the immediate neighborhood of the equipment.

For equipment with a heat exchanger that is not integral with the equipment, the ambient temperature is that of the ongoing cooling medium to the equipment.

For equipment completely buried in the earth, the ambient temperature is the temperature of the earth near the equipment, but sufficiently remote so it is not affected by the dissipated heat. It also is the temperature of the earth adjacent to the equipment when the equipment is not contributing heat to the surrounding medium.

7.1.3 Hottest-spot temperature allowance

Limiting values of insulation temperature rise are not usually applicable for standards for rating EIS testing because the observable temperature rise is less than the actual temperature rise by an amount that may be widely different for equipment of various types and sizes. Some factors that cause the observable temperature rise to be different are as follows:

a) Inaccessibility of the hottest spot
b) Nonuniformity of cooling
c) Kind and thickness of insulation
d) Form of winding
e) Rate of heat flow
f) Relative locations of heat generation and dissipation
g) Method of temperature measurement

Under varying load conditions, the time lag of the measured temperature behind the actual temperature is also an important factor.

Experience and reasoning indicate that an embedded temperature detector, properly placed, should give the highest obtainable temperature indication. Temperature measurements by the resistance method give the average temperature of the winding, which should be lower than the temperature obtained by a well-placed embedded temperature detector.

In view of these variable factors, no single value of the hottest-spot temperature allowance will apply exactly to different types or sizes of equipment. Therefore, the organization responsible for each standard covering each specific type of equipment should select the hottest-spot allowance method of temperature measurement most appropriate for the conditions and should determine the limiting observable temperature rise from this value. The hottest-spot temperature rise should be determined by thermal analysis and/or calculations based on fundamental loss and heat transfer principles and substantiated by testing on prototype equipment or full-size models. In addition to the observable temperature rise, hottest-spot temperature rise should be a performance parameter to be met by manufacturers of electric equipment.

7.1.4 Observable temperature rise

To arrive at the observable temperature rise for use in a particular standard, it is necessary to ascertain the method or methods of temperature determination that are most suitable. It is desirable, where practicable, to standardize on one method for each type and size of equipment so that measurements are comparable.

The selection of an observable temperature rise for rating or testing a particular type of equipment depends largely upon practical experience obtained in the application and upon the considerations mentioned in Clause 4. Different values may be appropriate for different types of equipment using the same EIM. For example, for small, low-voltage coils, higher temperature rises are recognized comparative to insulating conductors (cable) in general, using the same EIM. Also, low-voltage, firmly contained mica-flake insulated coils have been found suitable in service at significantly higher temperatures than are suitable for large, high-voltage coils.

Further, some EIM enclosed in a nitrogen atmosphere have been found to withstand higher temperatures than they do in air.

In selecting the final value of temperature rise for a particular type of equipment and service, it is important to recognize the need for uniformity and simplicity among the various standards. The least number of different values of temperature rise and methods of measurement should be adopted as practical.

It is recommended that values of observable temperature rise be selected from Table 1.

Table 1—Suggested values of observable temperature rise, °C

30	60	100	160
35	65	115	180
40	70	120	200
45	75	130	220
50	80	140	240
55	90	150	

Temperature-rise values permissible in service may differ from values established for rating purposes. Such conditions may be defined by service factors, by recommendations in operating guides, or by standards for assembled equipment that are different from the standards for individual components.

7.2 Methods of temperature determination

Five fundamental methods of temperature determination that are in use are listed in Table 2. Specific methods of temperature determination are the responsibility of the equipment subcommittees.

7.2.1 Other temperature-measuring devices

A variety of other methods or instruments, or both, are available or under development for temperature measurement such as thermal sensors and fiberoptic temperature measurement. Thermal imaging (infrared cameras) has been widely used as a nondestructive test technique to monitor thermal loads.

7.2.2 Selection of methods of temperature determination

The applied thermocouple method is suitable for measuring the temperature of surfaces that are accessible to thermocouples. The contact thermocouple method is suitable for measuring temperatures of bare-metal surfaces such as those of commutator bars and slip rings. The resistance method is suitable for measuring the temperature of insulated windings. For windings of low resistance, special precautions are necessary to obtain accurate results.

The embedded temperature detector method is suitable for measuring the temperature at designated interior location as specified in the standards for some kinds of equipment such as large rotating machines.

7.2.3 Accuracy of the hottest-spot temperature allowance on the capability of measuring the internal temperatures

Stators and similar equipment can usually be measured with a good degree of confidence; however, it is impossible to ensure that the hottest-spot temperature is determined. A large number of measurement points in the vicinity of probable hottest-spot temperature locations may provide temperature data closer to the hottest-spot temperature. Therefore, a different hottest-spot temperature allowance is used in comparison to when a small number of temperature points are taken.

Table 2—Methods of temperature measurement

Method	Description of method
Thermometers	Thermometers potentially provide the least accuracy. The method of fixation to the surface on which temperature is to be measured is critical. They should be limited to applications where only general information is required. The thermometer method of measuring surface temperature is based on the determination of temperature by thermometers or other suitable temperature measuring instruments when applied to the hottest parts accessible without alteration of the structure. NOTE—When the thermometer method of temperature determination is called for, it is intended that the temperature-measuring instrument used should indicate substantially the same temperature as obtained by a liquid-in-glass thermometer in the same location.
Applied thermocouple	The applied thermocouple method is based on the determination of temperature by thermocouples or other suitable temperature-measuring instruments of comparable size when applied to the hottest parts accessible to thermocouples in locations normally inaccessible to liquid-in-glass thermometers. NOTE—Depending upon the thickness of insulation separating thermocouples from current-carrying conductors, thermocouples may give readings comparable to those obtained by the resistance method or may give considerably lower readings, characteristic of the thermometer method. Accordingly, in the measurement of winding temperatures by thermocouples, the method shall be defined as the applied thermocouple method only if the thermocouples are applied directly to the conductors or are separated from the metallic circuit only by the integral insulation of the conductor itself.
Contact thermocouple	The contact thermocouple method is based on the determination of the temperature by the application of pointed prods made of dissimilar metals, to an exposed metal surface so that the metal whose temperature is to be measured forms part of a thermocouple circuit.
Resistance	The resistance method is based on the determination of the average winding temperature by comparing the resistance of a winding at the temperature to be determined with the resistance at a known temperature.
Embedded temperature detector	The embedded temperature detector method is based on the determination of temperature by thermocouples, or resistance temperature detectors, or other temperature-measuring devices built into the equipment, either permanently or for testing, in specified locations.

7.3 Effects of altitude

Equipment is usually rated for use at an altitude not exceeding a value specified in the standards.

The reduced air density at high altitudes causes an increased temperature rise in all equipment cooled wholly or partially by free or forced convection. This effect may or may not be compensated for in whole or in part by the lower ambient temperatures usually found at the higher altitudes. The effect of reduced air density is greatest on equipment cooled principally by forced convection of a substantially constant volume of air. This is usually the case of a constant-speed, self-ventilated, open or air-cooled enclosed machine or a machine cooled by an external constant-speed fan or blower.

The increase in temperature rise with altitude as determined in various investigations varies from approximately 1% per 303 m for certain air-cooled equipment, where a large part of the cooling is by radiation, to approximately 5% for other machines where the cooling is almost entirely by forced-air convection. Generally, the increase in temperature rise with altitude may be neglected in the operation of standard equipment up to 1000 m in altitude. For some stationary equipment for which the percentage increase is low, it may be negligible at any altitude normally encountered.

8. Thermal evaluation of EIS

The basic philosophy of this recommended practice may be applicable for any application that uses dielectric materials, that is, rotating machines, transformers, switchgear, circuit boards, electronic devices, insulated wire, and cables.

Historically, functional evaluation of EIS has primarily been based on thermal stresses. This evaluation has frequently been made using models containing the candidate EIS or comparison to a reference EIS. In addition to the EIS, test objects contain the associated electric and mechanical parts needed to simulate the conditions found in equipment. For thermal-aging tests, stresses (other than thermal) have normally been used only as diagnostic aids to help determine when thermal aging of the EIS has reached the point where it is unreliable when exposed to normal levels of these other stresses.

Thermal functional evaluation of EIS has been and continues to be a useful test. However, with many types of equipment, other aging stresses or factors (for example, mechanical, electrical, and environmental) may be dominant and significantly influence service life. This recommended practice covers test procedures where thermal stress is the main cause of aging. Other standards describe test procedures where other stresses are the main cause of aging, such as IEEE Std 1043-1996 [B4] for electrical aging, IEEE Std 1310-1996 [B5] for thermal cycling, and IEC 60505-1999 [B2] for all aspects of functional testing of EIS in models or equipment, including multifactor testing, where the stress level of more than one aging factor is accelerated.

8.1 Temperature classification of EIS

Thermal aging of insulation is an important factor in the life of electric equipment. Such aging makes insulation more vulnerable to the various other degrading stress exposures encountered in service.

Experience has shown that the thermal life characteristics of composite EIS for particular equipment cannot be reliably inferred solely from information concerning component materials. To ensure satisfactory service life, insulation specifications need to be supported by service experience or life tests. Accelerated life tests are used as comparative methods to evaluate systems, thus shortening the period of service experience required before they can be used with confidence. Tests on complete EIS, representative of each type of equipment, are necessary to confirm the performance of materials for their specific functions in the equipment.

The electrical insulation of equipment may be made up of many different components selected to withstand the widely different electrical, mechanical, thermal, and environmental stresses occurring in different parts of the structure. The duration an EIS will be serviceable depends on the effectiveness of the physical support for the insulation, the severity of the forces acting on it and the materials themselves, and the service environment. Therefore, the length of useful life of the EIS depends on the arrangement of individual components, their interactions upon one another, the contribution of each component to the electrical and mechanical integrity of the system, and the process used in manufacturing the equipment.

8.2 EIS classes

Most equipment standards have previously classified the insulation in one or more EIM classes and include appropriate limiting temperature-rise standards for equipment using each of these classes. Although this classification has nominally been by material classes, the wide divergence in expected performance and in both observable temperature and hottest-spot temperature between different types of equipment using the same material indicates that the real classification was by EIS.

Insulation system classes may be designated by letters, numbers, or other symbols and may be defined as assemblies of EIM in association with equipment parts (see Table 3). EIS class temperature is not directly related to equipment operating or service temperature or to service life. These systems may be assigned an EIS temperature rating based on service experience or on an accepted test procedure that can demonstrate an equivalent life expectancy. Reference EIS have generally been service-proven. Candidate EIS may be evaluated by accepted test procedures and, when so evaluated, should have equal or longer thermal endurance than a service-proven reference EIS of the same class at the prescribed test conditions. A candidate EIS may also be classified in a higher class by test if it has equal or greater thermal endurance at appropriately higher test temperatures when compared to a reference EIS under the same test conditions. If no suitable reference EIS exists or if it is a new application, then comparison should be made to a set of reference operating conditions defined for the target application.

Table 3—Thermal classification of EIS

Thermal classification	Class temperature, °C
A	105
E	120
B	130
F	155
H	180
N	200
R	220
S	250
C	>250

8.3 Thermal evaluation test procedures for EIS

The members of each technical committee are responsible for developing test procedures suitable for the temperature-life evaluation of the EIS used in their equipment. These test procedures should be in general accord with the principles outlined in this recommended practice. However, they may differ for the various types of equipment, in whatever ways are appropriate, to allow for differences in EIS and for the many conditions to which the equipment is exposed in service. A principle objective of these test procedures is to enable the performance of candidate and reference EIS to be compared directly in a practical way and in a reasonable time, thus providing a sound basis for introducing candidate EIS into service.

The test for the evaluation of EIS should be chosen so that each component of the system will perform under the test conditions in a manner similar to its operation in service. However, the severity of the tests should be substantially greater than the conditions encountered in service to enable the performance of the system to be determined in a reasonable time. Prolonged exposure to high temperature is the single accelerated aging factor employed in these tests. Other factors, such as exposure to moisture and voltage, are chosen to develop and disclose promptly any significant weakness or deterioration of the EIS. So far as practicable, the atmospheric and other environmental conditions should be similar to those usually encountered in service. When such conditions are made more severe, at the discretion of the responsible technical committee, the effect on acceleration of the test should be considered and IEC 60505-1999 [B2] should be consulted.

The chief criterion of life expectancy is the elapsed time-at-temperature, whether the temperature is the result of continuous or cyclic loading, overload, or operation at other than normal ambient temperature.

8.3.1 Acceleration of thermal-aging procedures

The test temperature-exposure conditions should be chosen to cover a reasonable range of temperatures to facilitate reasonable extrapolation of data. The severity of the test exposures should be selected to provide reasonable acceleration and positive determination of insulation system life. In evaluating and comparing life expectancies determined by tests, the regression analysis methods given in IEEE Std 101-1987 should be employed.

8.3.2 Test procedure outline

For uniformity and standardization, technical committees should use the following outline in preparing the test procedures for the thermal evaluation of the EIS used in the equipment. IEEE Std 99-1980 explains in more detail the following essentials:

a) Purpose
b) Scope
c) Definition of reference EIS or reference operating conditions
d) Models—construction and number
e) Thermal aging
f) Humidification
g) Associated structural materials
h) Mechanical stress
i) Electrical stress
j) Special environments
k) Method of cooling
l) Test sequence
m) Length of test cycle
n) Failure criteria
o) Mathematical treatment of thermal-aging data
p) Interpretation of thermal life expectancy
q) Specification of minimum life expectancy and variability
r) Form and method for reporting results

8.3.3 Test report

The test report should include the following:

a) Description of the applicable evaluation standard

b) Description of the candidate EIS

c) Description of the
   1) Reference EIS, including service experience to demonstrate its assigned thermal classification, or
   2) Reference operating conditions for the specific application

d) Description of test object (model of production part)

e) Description of any preconditioning

f) Test temperature and cycle time at each temperature

g) Diagnostic treatments, tests, and measurements

h) Test sequence and duration and number of samples

i) End-point criteria selected

j) Aging curves and end points

k) Statistical analysis of results per IEEE Std 101-1987

l) Classification statement for candidate EIS

Annex A

(informative)

Illustration of thermal endurance graph, TI, RTI, and HIC

The TI for an EIM is deduced from the graph, at the selected time. For example, in Figure A.1, the TI at 20 000 h is expressed as TI 20 kh/128, and in Figure A.2, the RTI at 20 000 h for the candidate material is expressed as RTI 20 kh/135.

The number of hours so used shall prefix the index.

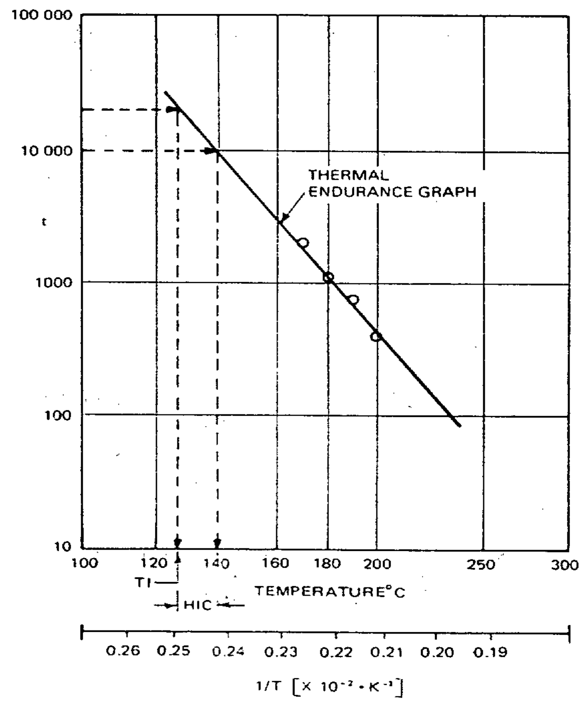

Figure A.1—Thermal endurance graph, TI, and HIC

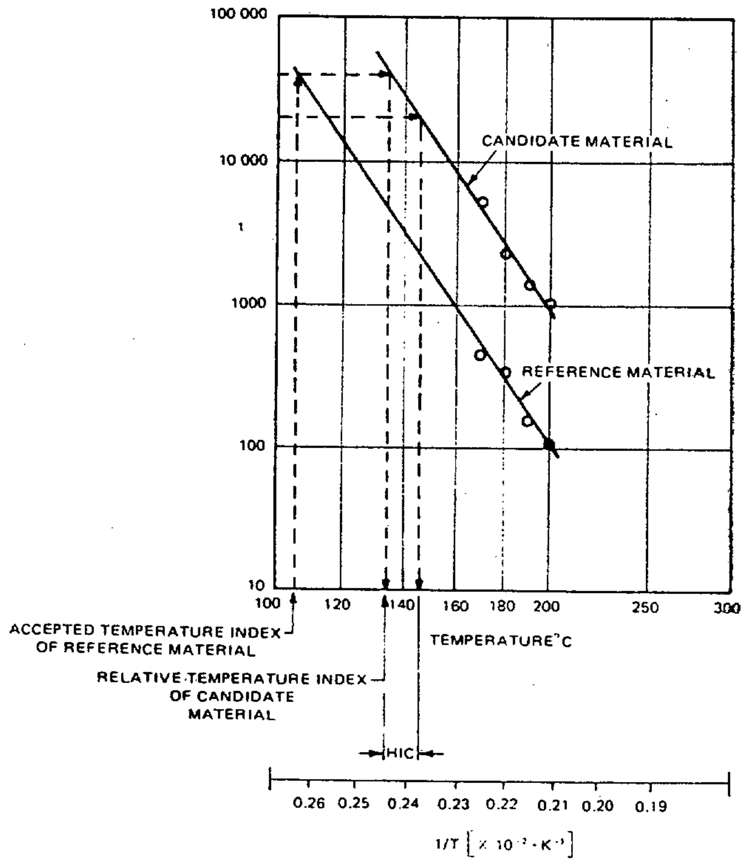

Figure A.2—RTI and HIC

Annex B

(informative)

Bibliography

[B1] For an annotated bibliography, refer to Brancato, E. L., "Insulation Aging, a Historical and Critical Review," *IEEE Transactions Electrical Insulation*, vol. EI-13, no. 4, Aug. 1978, pp. 308–317.

[B2] IEC 60505-1999, Evaluation and qualification of electrical insulation systems.

[B3] IEEE 100, *The Authoritative Dictionary of the IEEE Standards Terms,* Seventh Edition.

[B4] IEEE Std 1043-1996, IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils.

[B5] IEEE Std 1310-1996, IEEE Trial-Use Recommended Practice for Thermal Cycle Testing of Form-Wound Stator Bars and Coils for Large Generators.

