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IEEE Guide for Application of Power Apparatus Bushings

Sponsor

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

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Abstract: Guidance on the use of outdoor power apparatus bushings is provided. The bushings are limited to those built in accordance with IEEE Std C57.19.00-1991. General information and recommendations for the application of power apparatus bushings, when incorporated as part of power transformers, power circuit breakers, and isolated-phase bus, are provided.
Keywords: circuit breakers, isolated-phase bus, power apparatus bushings, transformers

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Introduction

(This introduction is not part of IEEE Std C57.19.100-1995, IEEE Guide for Application of Power Apparatus Bushings.)

In August 1968, the ANSI C76 committee decided to separate ANSI C76.1 into three parts: The first (C76.1, presently IEEE Std C57.19.00-1991) part was to cover the general requirements and test procedures; the second (C76.2, presently IEEE Std C57.19.01-1991), to cover explicit ratings and dimensions; and the third (C76.3), to be an application guide. This document, IEEE Std C57.19.100-1995, is the application guide.

When the ANSI C76 committee was developing the first draft of the application guide, it was decided that the loading guide portion of the guide should be published for trial use before completion of the application guide. This would allow experience with its use and possible modifications prior to publication within the application guide. The trial-use loading guide was approved but not published before the disbanding of the ANSI C76 committee.

The Working Group on Bushing Application Guide was established by the Bushing Subcommittee of the IEEE Transformers Committee to take over the development and completion of the application guide so that it could be submitted for IEEE Standards Board approval and publication. IEEE published the trial-use loading guide in July 1989 as IEEE Std C57.19.101-1989. It was upgraded to a full-use guide on June 18, 1992, and designated as IEEE Std C57.19.101-1992. The current guide, IEEE Std C57.19.100-1995, is the application guide in its entirety, which includes the loading guide (clause 4), and hence, supersedes IEEE Std C57.19.101-1992.

The Working Group on Bushing Application Guide of the Bushing Subcommittee of the IEEE Transformers Committee had the following membership at the time the application guide was developed and approved:

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Guide for Application of Power Apparatus Bushings

1. Overview

1.1 Scope

Guidance on the use of outdoor power apparatus bushings is provided in this document. The bushings are limited to those built in accordance with IEEE Std C57.19.00-1991.[1]

1.2 Purpose

The purpose of this guide is to present general information and recommendations for the application of power apparatus bushings when incorporated as part of power transformers, power circuit breakers, and isolated-phase bus. The loading model developed in this guide is based on oil-impregnated, paper-insulated, capacitance-graded bushings. Similar loading models could be developed for other bushing constructions.

2. References

The following standards form a part of this guide to the extent specified in this document:

IEEE Std 1-1986 (Reaff 1992), IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation (ANSI).[2]

IEEE Std 4-1978, IEEE Standard Techniques for High-Voltage Testing (ANSI).[3]

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

IEEE Std C37.04-1979 (Reaff 1988), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

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[1]Information about references can be found in clause 2.

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[3]IEEE Std 4-1978 has been withdrawn; however, copies can be obtained from the IEEE Standards Department, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std C37.010-1979 (Reaff 1988), IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (including Supplement IEEE Std C37.010d) (ANSI).

IEEE Std C37.010b-1985, Supplement to IEEE Std C37.010-1979.

IEEE Std C37.010e-1985, Supplement to IEEE Std C37.010-1979.

IEEE Std C37.23-1987 (Reaff 1991), IEEE Standard for Metal-Enclosed Bus and Calculating Losses in Isolated-Phase Bus (ANSI).

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

IEEE Std C57.19.00-1991, IEEE General Requirements and Test Procedures for Outdoor Apparatus Bushings (ANSI).

IEEE Std C57.19.01-1991, IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings.

IEEE Std C57.92-1981 (Reaff 1991), IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers Up To and Including 100 MVA with 55 °C or 65 °C Winding Rise (ANSI).

3. Definitions

For definitions of terms used in this standard, see IEEE Std C57.19.00-1991 and IEEE Std 100-1992.

4. Thermal loading above nameplate rating for bushings applied on power transformers

4.1 General

The thermal loading capability of bushings varies with the way they are loaded, the way they are designed, and the ambient conditions in which they are applied.

4.1.1 Basis of rating and rationalization of thermal requirements rating

Capacitance-graded, paper-insulated bushings that, at rated current, meet the requirements of IEEE Std C57.19.00-1991 and earlier versions of that standard may be applied in either 55 °C or 65 °C rise transformers. IEEE Std C57.19.00-1991 and IEEE Std C57.12.00-1993 state that the temperature of the oil in which the lower end of the bushing is immersed shall not exceed 95 °C when averaged over a 24 h period. Transformer loading shall conform to IEEE Std C57.92-1981.

4.1.1.1 Operation above normal temperature

When operating a bushing at rated current in conjunction with a 65 °C average winding rise rated transformer, the hottest-spot temperature of the bushing is limited to a 65 °C rise over ambient or a 105 °C total temperature because of the use of temperature index 105 insulating paper for the bushing condenser. If it should be determined that a transformer develops a top oil rise of 65 °C at rated current when operating in a 40 °C ambient, the hottest-spot temperature of the bushing can be expected to exceed 105 °C. In addition, transformers can be expected to have bushing temperatures above 105 °C when loaded in accordance with IEEE Std C57.92-1981. In each instance, the normal life expectancy of the bushing will be shortened by the higher operating temperatures. The loss-of-life of a bushing will, like transformers, be a function of the actual temperature and the time operating at that temperature.

The severity of loss-of-life in a bushing can be minimized by installing bushings that have nameplate ratings greater than the transformer current ratings or by using bushings with special high-temperature insulation. An alternative is to operate the bushing with the higher inherent temperatures and accept a moderate degree of accelerated aging, as it is presently recognized for transformers. Refer to 4.4 to correlate bushing paper insulation aging with the bushing conductor hottest-spot temperature.

4.1.1.2 Factors influencing bushing aging

There are several factors that tend to decrease the severity of bushing aging. These are as follows:

a) The top oil rise of many transformers is significantly below 65 °C when the transformer is operated at nameplate loading. This is most likely to occur on forced oil-cooled (FOA) transformers.
b) Bushings are totally sealed from the atmosphere at the time of manufacture, thus preserving their dielectric and thermal integrity.
c) Bushing insulation is generally processed to a greater degree of dryness than transformer insulation, thus providing a lower power/dissipation factor, lower dielectric losses, and consequently prolonged life at any temperature.
d) The end-of-life of cellulose insulation in transformers may be governed by its ability to withstand mechanical forces that are associated with fault currents through the transformers. Cellulose insulation in bushings is not subjected to similar forces.
e) Although end-of-life of insulating materials is typically based on a given change in mechanical or chemical properties, no similar relationship for dielectric characteristics has been established. However, considering increased insulation power/dissipation factor and capacitance as important criteria, well-dried bushing cellulose material is probably equal in life expectancy to thermally upgraded (65 °C) transformer insulation.
f) The use of bushings with current ratings greater that the transformer current ratings as described in 4.1.1.1 reduces the temperature rise inside the bushing at rated transformer current.

4.1.2 Overload concerns

When a bushing is loaded above nameplate, it is exposed to the risks described in 4.1.2.1–4.1.2.5.

4.1.2.1 Pressure buildup

When load current through a bushing exceeds the nameplate rating, internal pressures can develop that could cause one or more of the sealing gaskets to leak or fail. This pressure increase is caused by the expansion of the insulating oil within the bushing. The rate of oil expansion is normally considered to be approximately 0.0725–0.0755% per °C temperature increase for temperatures ranging from 0–100 °C.

4.1.2.2 Gasket seals

Gasket materials will age according to the temperature adjacent to the gasket surface and the duration at that temperature. Usually gaskets will perform well at elevated temperatures; however, progressive changes in physical properties will occur when excessive temperatures are maintained for long durations. These changes could result in loss of seal and consequent loss of dielectric strength. Therefore, repeated occurrences at high temperature will require inspection for oil leaks and corrective actions where necessary.

4.1.2.3 Power/dissipation factor and capacitance

There are many reasons why insulation power/dissipation factor and/or capacitance may increase over the life of a bushing. In fact, some slight increase of power/dissipation factor can be tolerated. However degradation of that portion of the insulation that operates at greatly elevated temperature could result in a substantial increase in power/dissipation factor. An unusual increase in power/dissipation factor may become an indicator of the detrimental mechanical and electrical effects of loading beyond nameplate rating. Bushings that have been loaded beyond nameplate rating should be tested more frequently.

4.1.2.4 Dielectric performance at elevated temperatures

When bushing insulation is subjected to high electrical stress at elevated temperatures, the insulation power/dissipation factor increases due to increased dielectric loss. When the increase in dielectric loss exceeds the ability of the insulation to dissipate this increased loss, the temperature of the dielectric is further increased. Under some extreme conditions, thermal runaway may occur. This risk should be considered when the guide is applied.

Special capacitance-graded bushings built with insulation systems such as thermally upgraded paper rated higher than temperature index 105 insulation class are sometimes used in special applications. These insulation systems may have higher power/dissipation factors particularly at higher temperatures and may experience thermal runaway if loaded significantly beyond the nameplate rating. For specific information, the manufacturer should be contacted.

4.1.2.5 Stray magnetic flux

Additional heating may occur in bushings placed in the stray magnetic field of the windings and leads. The heating results from induced eddy current flowing in the metallic portions of the bushing below the mounting flange. The magnetic flux increases with the load current.

Induced fields can create high eddy current losses in tanks, flanges, and bus enclosures during overload conditions, causing them to reach high temperatures. High temperatures of the part itself may not be of concern, but the heat may transfer to the bushing causing high temperatures in the bushing, which are of concern.

4.1.3 Limitations

In order to coordinate the performance of bushings with the transformers in which they are mounted, the following limits are recommended for loading beyond nameplate rating:

a) Ambient air temperature: 40 °C maximum
b) Immersion oil temperature: 110 °C maximum
c) Maximum emergency current: Two times rated current of the bushing
d) Bushing hottest spot: The hottest spot of the conductor in contact with temperature index 105 insulation should be limited to 150 °C.
e) Air-end terminal connections: Although the air-end terminal connections do not greatly affect hottest-spot rise at rated current, they can become an important factor when loading beyond nameplate rating. Leads and connectors should be sized to meet the usual service conditions of IEEE Std C57.19.00-1991, 4.1(5).
f) Oil-end terminal connections: The large surface area of the connector fastened to the inboard end of the bushing tends to stabilize that point so that it generally has only a small rise over the oil temperature. However, the terminal rise, and indirectly the bushing hottest-spot rise, can also be influenced by the temperature of the lead connected to the terminal. Therefore, the inboard lead should be limited to an 80 °C rise over ambient air at rated current.

4.2 Temperature calculations for short-time loads above bushing rating

The hottest-spot temperature of a bushing is of importance when it is loaded under various conditions. The five key elements that affect the bushing hottest spot are the bushing current, the ambient air temperature, the immersion oil temperature, the air-end-connection temperature, and the oil-end-connection temperature. Easley and McNutt [B3] give an expression that contains each of these elements.

Accurate information about the end-connection temperatures and coefficients is usually not available. Therefore, this guide uses a more conservative method that requires information only about the bushing current, the ambient air temperature, and the immersion oil temperature to calculate the bushing hottest-spot temperature.

This method was developed from experimental data for bushings with no appreciable dielectric losses and no cooling ducts. Three constants are determined as described in 4.3.3. These constants are then used to estimate the steady-state and transient bushing hottest-spot temperatures. This method is usable within the limitations listed in 4.1.3.

Mathematical models for bushings with appreciable dielectric losses and/or with cooling ducts may be developed in the future and could be used in the same manner.

4.2.1 Steady-state hottest-spot temperature calculations

The steady-state temperature rise at the hottest spot of the conductor for bottom connected bushings with no appreciable dielectric losses and no cooling ducts is estimated with the following equation:

$$\Delta\theta_{HS} = K_1 I^n + K_2 \Delta\theta_o \tag{1}$$

where

$\Delta\theta_{HS}$ is steady-state bushing hottest-spot rise over ambient (°C)
$\Delta\theta_o$ is steady-state immersion oil rise over ambient (°C) (transformer top oil rise)
I is per unit load current based on bushing rating
n, K_1, and K_2 are constants that can be determined as described in 4.3.

Typical values of K_1 range from 15 to 32. Typical values of K_2 range from 0.6 to 0.8. The exponent n generally ranges between 1.6 and 2.0, with 1.8 being the most common value.

When a bushing is operated in the draw-lead mode, the thermal performance is dominated by an integral part of the transformer that is inserted through the tube of the bushing. This lead is not an integral part of the bushing, so the thermal performance cannot be directly related to a specific design of bushing that may also be operated in other transformers with different size draw-leads.

The temperature of the hottest spot of the conductor, when operated in the draw-lead mode, may be determined in the same manner, with I being the per unit load current of the draw-lead.

4.2.2 Transient hottest-spot temperature calculations

After changes in load current or ambient temperature occur, both the immersion oil temperature and bushing hottest-spot temperature will change with time from the initial to the final value in an exponential manner. Therefore, it is necessary to determine the initial and final transformer top oil temperature and the rate of change by the procedures established in IEEE Std C57.92-1981. After the changed per unit current I, the transformer top oil rise $\Delta\theta_o$, and the transformer top oil time constant τ_o have been established, the transient response of the bushing may be determined using K_1, K_2, n, and the bushing time constant t.

K_1, K_2, and n are the same constants and exponent used for the steady-state bushing calculations.

The bushing time constant τ is the length of time required for the temperature change to reach 63.2% of the final temperature change.

4.2.2.1 Iterative method

One method is to simulate the exponential rise by making a series of repeated calculations of the bushing hottest-spot temperature rise in successive time increments following Steps A–F.

where

T = elapsed time of the transient load (minutes)

Δt = an arbitrary time increment to divide the elapsed time of the transient load into steps for calculation (minutes)

t_1 = initial time at start of an increment (minutes)

t_2 = time when transformer oil $\Delta\theta_o$ reaches practical equilibrium (minutes)

τ = bushing time constant (minutes)

τ_o = oil time constant of transformer (minutes)

$\Delta\theta_{HS}(t_1)$ = bushing hottest-spot temperature rise at time t_1 (°C)

$\Delta\theta_{HS}(t_2)$ = ultimate bushing hottest-spot temperature rise as calculated from the steady-state equation (1) for the new load (°C)

$\Delta\theta_{HS}(T)$ = bushing hottest-spot temperature rise at the end of the transient load period

or

$\Delta\theta_{HS}(T) = \Delta\theta_{HS}(t_1 + \Sigma\Delta \mathrm{t})$ (°C)

$\Delta\theta_o(t_1)$ = immersion oil temperature rise as determined for time t_1 (°C)

$\Delta\theta_o(t_2)$ = ultimate immersion oil temperature rise as determined from IEEE Std C57.92-1981 for the new load conditions that apply during the transient load (°C)

$\Delta\theta_o(t_1 + \Delta t)$ = new immersion oil temperature rise at end of time increment $t_1 + \Delta t$, (°C), calculated as follows:

$$\Delta\theta_o(t_1 + \Delta t) = \Delta\theta_o(t_1) + [\Delta\theta_o(t_2) - \Delta\theta_o(t_1)][1 - \varepsilon^{-(\Delta t / \tau_o)}] \quad (2)$$

$\Delta\theta_{HS}(t_1 + \Delta t)$ = new bushing hottest-spot temperature rise at end of time increment $t_1 + \Delta t$, (°C), calculated as follows

$$\Delta\theta_{HS}(t_1 + \Delta t) = \Delta\theta_{HS}(t_1) + [\Delta\theta_{HS}(t_2) - \Delta\theta_{HS}(t_1)][1 - \varepsilon^{-(\Delta t / \tau_o)}] \quad (3)$$

— Step A: Determine initial bushing hottest-spot temperature rise at start of first increment, $\Delta\theta_{HS}(t_1)$, from equation (1) for prior per unit load I and $\Delta\theta_o(t_1)$.

— Step B: Determine new transformer immersion oil temperature rise at end of first increment, $\Delta\theta_o(t_1 + \Delta t)$, from equation (2).

— Step C: Determine the new ultimate bushing hottest-spot rise $\Delta\theta_{HS}(t_2)$ for the conditions which apply from equation (1) using $\Delta\theta_o(t_1 + \Delta t)$ from Step B.

— Step D: Calculate the new transient bushing hottest-spot rise $\Delta\theta_{HS}(t_1 + \Delta t)$ at the end of the time increment from equation (3) using $\Delta\theta_{HS}(t_1)$ and $\Delta\theta_{HS}(t_2)$ from Steps A and C.

— Step E: Use this new transient bushing hottest-spot rise $\Delta\theta_{HS}(t_1 + \Delta t)$ as the new $\Delta\theta_{HS}(t_1)$ for input to the subsequent incremental step.

— Step F: Repeat the incremental procedure of Steps A–E until the end of the transient load period ($\Sigma\Delta t = \mathrm{T}$).

See the example of figure 1.

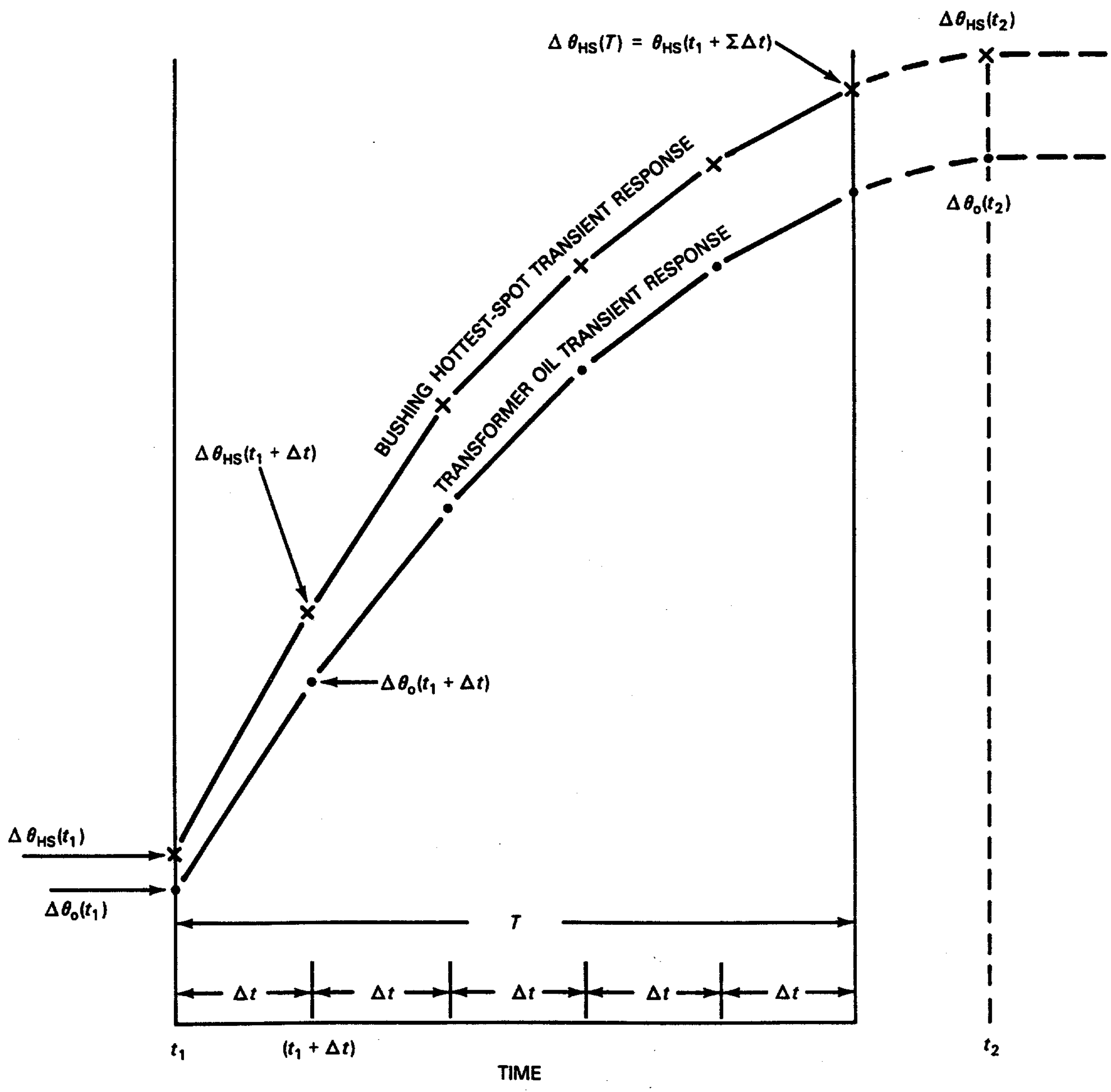

Figure 1—Bushing hottest-spot transient response

4.2.2.2 Single step method

A simpler but less precise method is to make a single step calculation using equation (4). This method yields a higher bushing hottest-spot temperature and therefore can be considered more conservative than the method in 4.2.2.1.

$$\Delta\theta_{HS}(T) = \Delta\theta_{HS}(t_1) + \{K_1 I^n + K_2[\Delta\theta_o(t_1) + (\Delta\theta_o(t_2) - \Delta\theta_o(t_1))(1 - \varepsilon^{-(T/\tau_o)})] - \Delta\theta_{HS}(t_1)\}\{1 - \varepsilon^{-(T/\tau)}\} \quad (4)$$

4.3 Test procedures for derivation of mathematical model

When performance is to be determined by test it is highly desirable that a uniform procedure be followed so that data may be accumulated on a consistent basis. These procedures are in no way to be construed as a mandatory design test for all bushings.

4.3.1 Procedure for performance testing of bottom-connected bushings

This procedure applies to bushings that comply with tables 3 through 7 of IEEE Std C57.19.01-1991.

a) Prepare the test unit by installing thermocouples on each terminal and in at least 4 locations not more than 30 in (762 mm) apart on the center conductor. The thermocouples may be attached directly to the outside of the conductor by removing portions of the insulation, or the thermocouples may make contact with the inside of a hollow conductor by means of a phosphor bronze thermocouple brush. The thermocouple leads may be threaded through the bottom end of a hollow center conductor, through a small hole in the top terminal, or brought out at some convenient location above the internal oil level.
b) Install a pressure gage in such a way that the additional gas space of the gage and connections will not exceed 0.5% of the normal gas space. Seal the test unit with the gas chamber charged with the proper gas at the sealing pressure. If the thermocouple connections of item a) have disturbed the sealing characteristics of the test unit, a duplicate unit may be prepared for pressure monitoring. If the test tank is of sufficient size to avoid proximity effects, the pressure unit may be mounted adjacent to and connected in series with the test unit. As an alternative, the pressure unit may be tested separately.
c) Mount the bushing on a suitable nonmagnetic metal plate that complies with the minimum size tabulated as follows:

Bushing mounting plate bolt circle		**Cover plate size (square or round)**		**Thickness**	
(in)	**(mm)**	**(in)**	**(mm)**	**(in)**	**(mm)**
6–9 1/4	152–235	18	457	1/4	6.4
13 1/4–15 3/4	337–400	24	610	1/2	13
21–25	530–635	36	910	5/8	16

d) Attach oil-end terminal connectors suitable for the rated current.
e) Attach air-end terminal connectors suitable for the rated current.
f) Attach air-end bus at least 3 ft (1 m) long, projecting from the terminal connector in a horizontal plane. The cross section of the bus should be such that at rated current the temperature rise at a location 3 ft (1 m) from the bushing should be at least 30 °C above ambient.
g) Attach thermocouples to the bus work connectors, mounting plate, and exterior of the bushing.
h) Mount the bushing so that the oil level complies with either 5.4.1 of IEEE Std C57.19.00-1991 or the level required in the actual bushing application after the steady-state test tank oil temperature has been achieved.
i) Heat and circulate the oil to maintain a minimum vertical temperature gradient over the bushing immersion depth without oil flow being directed at the test bushing.
j) The ambient environment should be indoor air between 10 °C and 40 °C.
k) Make load tests, as required, for obtaining the data necessary for a good statistical basis for a bushing mathematical model. Some suggested conditions are as follows:

I Current (pu)	$\Delta\theta_o$ Oil rise (°C)
0.0	55
0.7	55
1.0	55
1.25	55

I Current (pu)	$\Delta\theta_o$ Oil rise (°C)
0.0	70
1.0	70
1.5	70
2.0	70

l) Record temperatures at appropriate intervals until the thermal conditions become constant or until the measured temperatures do not increase by more than 1 °C for 2 h for bushings up through 900 kV BIL and not more than 1 °C for 4 h for bushings 1050 kV BIL and above.

m) Report initial and final values of conductor hottest-spot rise, top and bottom terminal connector rises, increase in pressure. Also report the bushing time and temperature readings.

4.3.2 Tests on draw-lead bushings

When the thermal performance of a bushing with a specific transformer lead is to be determined by test, a procedure similar to the applicable portions of 4.3.1 may be followed.

4.3.3 Derivation of model constants

Nominal values of the K_1, K_2, and n constants can be determined as follows:

a) Obtain a steady-state temperature profile at rated current with the bottom end immersed in hot oil by the procedure discussed in 4.3.1. This establishes $\Delta\theta_o(I=1\text{ pu})$ and $\Delta\theta_{HS}(I=1\text{ pu})$.

b) Reduce the current to zero and determine the steady-state temperature of the location that was the hottest spot at rated current. This establishes $\Delta\theta_o(I=0\text{ pu})$ and $\Delta\theta_{HS}(I=0\text{ pu})$.

c) The constants K_1 and K_2 can be calculated using the following equations:

$$K_2 = \Delta\theta_{HS}(I = 0\text{ pu})/\Delta\theta_o(I = 0\text{ pu}) \tag{5}$$

$$K_1 = \Delta\theta_{HS}(I = 1\text{ pu}) - K_2[\Delta\theta_o(I = 1\text{ pu})] \tag{6}$$

d) The exponent n can be calculated from additional tests using the following equation:

$$n = [1/\ln(I = X\text{ pu})]\ln\{[\Delta\theta_{HS}(I = X\text{ pu}) - K_2\Delta\theta_o(I = X\text{ pu})]/K_1\} \tag{7}$$

e) The bushing time constant can be determined by analysis of the time–temperature curves from the tests.

Additional tests as recommended in item k) will confirm the nominal values of constants K_1, K_2, and n or give additional data to refine the estimates by graphical or statistical means.

4.4 Thermal aging of nonthermally upgraded paper insulation

The paper insulation used in capacitance graded bushings is not thermally upgraded. The relationship of insulation deterioration to changes in time and temperature is assumed to follow an adaptation of the Arrhenius reaction rate theory, which states that the logarithm of insulation life is a function of the reciprocal of absolute temperature:

$$\log_{10}(\text{hours of life}) = (6972.15/T) - 14.133 \tag{8}$$

where

T = absolute temperature in °K (θ_{HS} + 273)

See figure 2 for a plot of this equation.

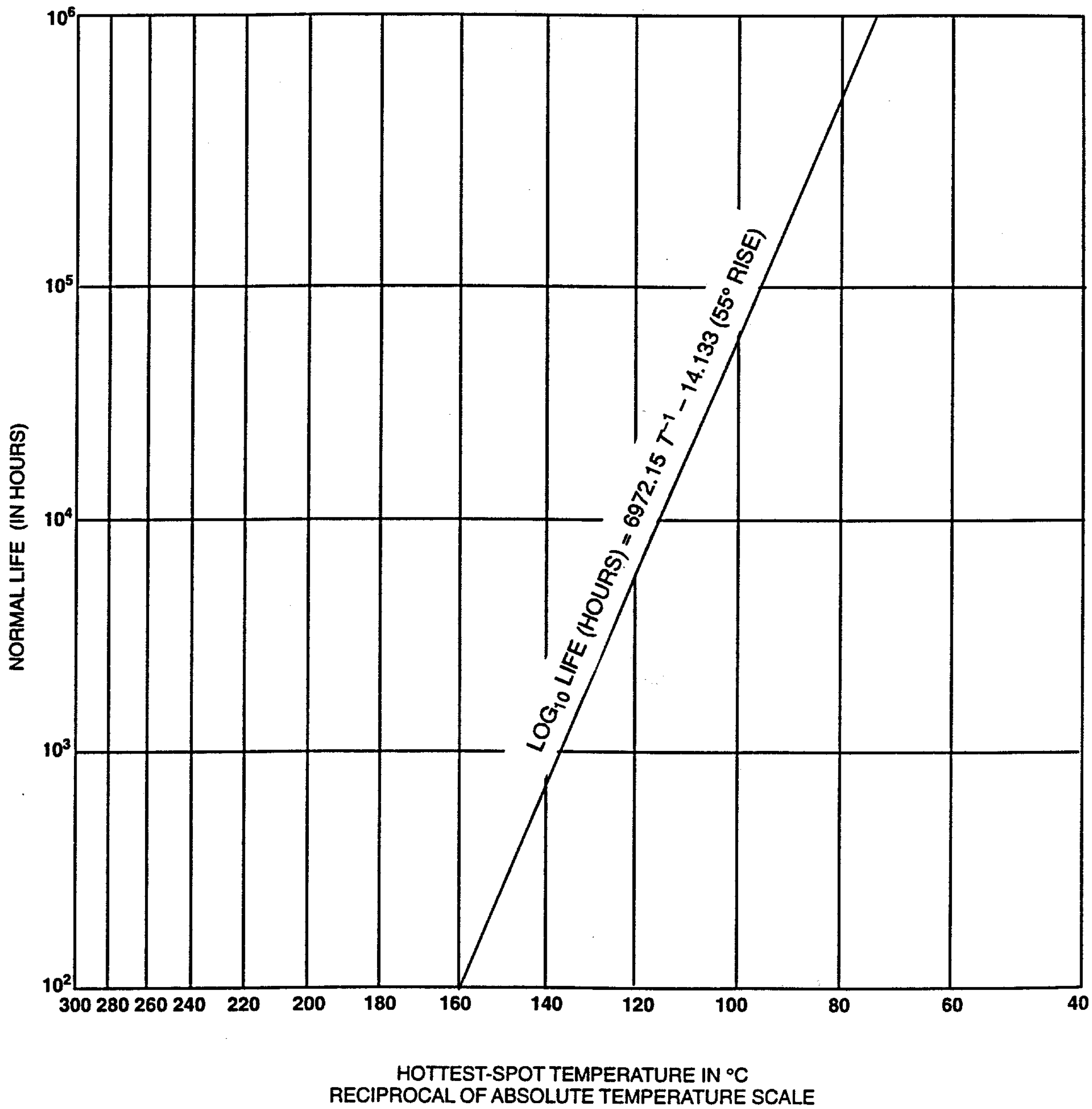

Figure 2—Life expectancy curve

5. Special considerations for application of bushings to power transformers

5.1 General

The temperature limits of bushings applied to power transformers can be exceeded by the transfer of heat from transformer components and accessories. If the thermal coordination of these sources is not correct, the bushing hottest-spot temperature may exceed 105 °C. The result may be accelerated aging. An additional concern is that the higher temperatures may deteriorate sealing gaskets. Potential sources of heat transferred to the bushing include the following:

a) Operation of bushings in transformers with top oil temperature rise greater than 55 °C.
b) Increased transfer of heat into the bushing from top oil in transformers with conservator oil preservation systems.
c) Improper thermal coordination of isolated-phase bus equipment (see clause 7).
d) Stray flux heating in the flange and other metallic bushing parts.

5.2 Loading of bushings with transformer top oil temperature rises between 55 °C and 65 °C

If a transformer has a top oil temperature rise greater than 55 °C but less than or equal to 65 °C, a bushing with a higher nameplate current rating than the transformer current rating may be applied by using an appropriate derating factor. If the bushing thermal constants are known, the derated current, I_d, may be determined from the following:

$$I_d = dI_r \tag{9}$$

where

I_d = derated current at new transformer top oil temperature rise $\Delta\theta_o$

$d = [(65 - K_2\,\Delta\theta_o)/K_1]^{1/n}$

I_r = bushing current rating

K_1, K_2, and n are as defined in 4.2 and 4.3

If the bushing thermal constants are not known, then the curve in figure 3, derived by setting $K_1 = 21$, $K_2 = 0.8$, and $n = 1.6$ in equation (9), may be used to determine d.

5.3 Application of bushings in transformers with conservator oil preservation systems

IEEE Std C57.19.00-1991 establishes bushing current ratings based on thermal tests run with the lower end of the bushing immersed to the minimum oil level, normally the bottom of the ground sleeve. When bushings are applied to transformers with conservator oil preservation systems, the bushing lower end is totally immersed in oil. If the transformer top oil temperature is higher than the bushing internal temperature, additional heat from the transformer oil will transfer into the bushing reducing its current-carrying capability. Consult the bushing manufacturer for appropriate derating factors for these applications.

6. Thermal loading for bushings applied on circuit breakers

Bushings applied on power circuit breakers will be subject to the requirements in IEEE Std C37.010-1979.

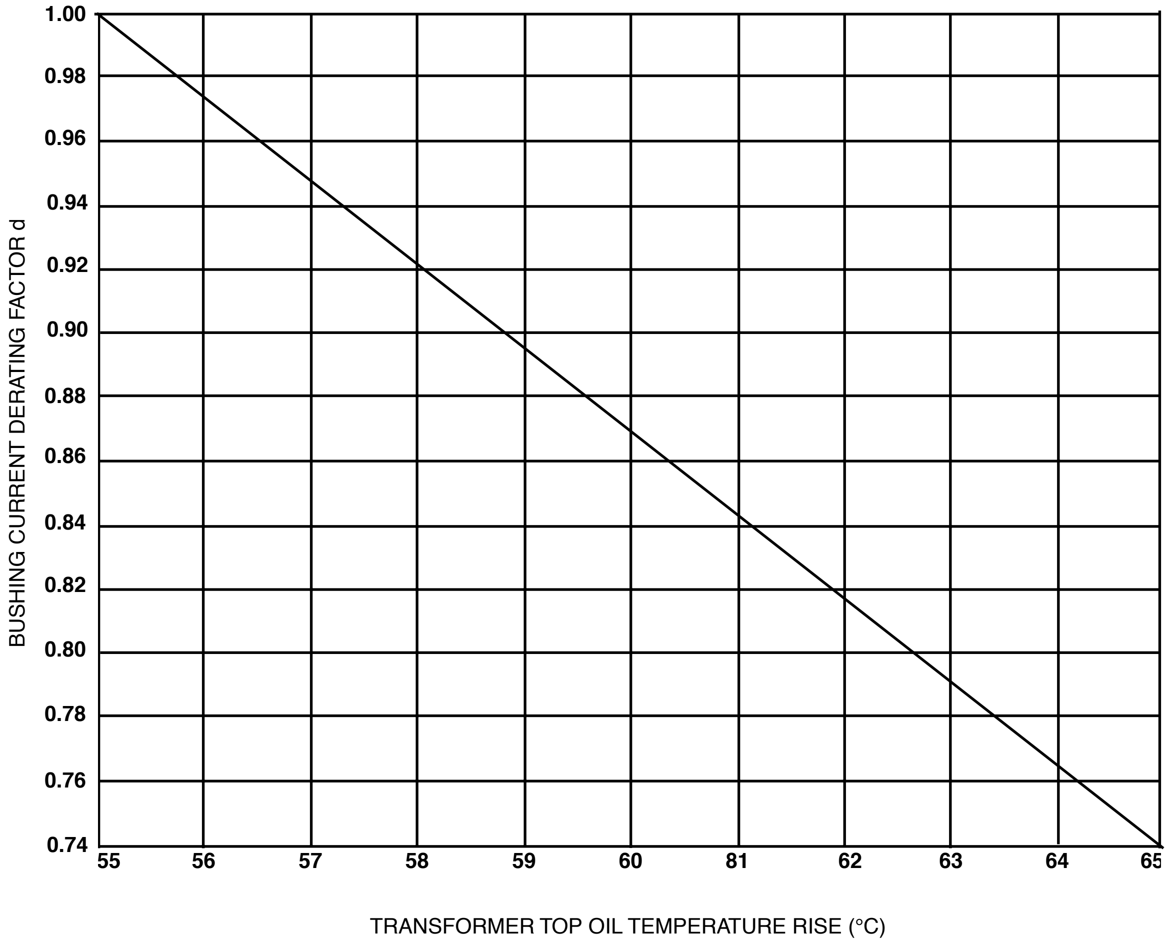

Figure 3—Bushing current derating factor for transformer top oil temperature rises between 55 °C and 65 °C

7. Thermal loading for bushings used with isolated-phase bus

7.1 Concerns for bushings used in isolated-phase bus

Bushings used with isolated-phase bus meeting the requirements of IEEE Std C37.23-1987 may be subjected to conductor and enclosure temperatures that violate the conditions specified in 4.1 of IEEE Std C57.19.00-1991. Table 1 of IEEE Std C37.23-1987 lists the temperature limits of isolated-phase bus conductors, enclosures, insulation, and terminations. After selecting the temperature rise rating of the conductor and enclosure, the user should identify this unusual service condition in the equipment specification.

7.2 Thermal coordination between the bushings and the isolated-phase bus

In order to ensure proper thermal coordination between the bushing and the bus, steps should be taken to reduce the temperature of the bus conductor, the surrounding medium, and the bus duct. Such steps could include the following:

a) Increase cross-sectional area of the conductor or the connection between the bushing and the conductor.
b) Use flexible cable or braids and silver-surfaced or tinned joints at the connection between the bushing and conductor.
c) Increase the cross-sectional area and the diameter of the bus enclosure surrounding the bushing.
d) Circulate forced air around the bushing or through the ventilated bus duct to keep the air temperature within the acceptable range.

As an alternative, bushings and gaskets suitable for high-temperature application can be considered, for instance bushings with aramid insulation, oil-filled bushings, or bushings with insulating materials other than oil-impregnated paper. Use of fluorocarbon or other high temperature gasket materials may sometimes be necessary.

Information on material temperature classification is covered in table 1 of IEEE Std 1-1986.

Information on temperature rises of bus systems is covered in IEEE Std C37.23-1987.

8. Allowable line pull (cantilever loading)

8.1 General (transformers and circuit breakers)

The continuous cantilever loading (i.e., line pull, wind loading, ice loading, etc.) applied to the bushing terminal should not exceed 50% of the test value, for the bushing ratings given in IEEE Std C57.19.01-1991, Table 8. The cantilever loading applied to a bushing terminal as a result of continuous cantilever loading plus dynamic or short-time loading (i.e., short-circuit forces, seismic but not including seismic forces generated by the mass of the bushing itself) should not exceed 85% of the bushing test value given in IEEE Std C57.19.01-1991, table 8. Cantilever loading should not exceed allowable values for the equipment in which the bushing is installed.

Consult the manufacturer for guidance when bushings are applied at angles exceeding 20 degrees from the vertical. This becomes very critical in bushings of 500 kV and above.

8.2 Circuit breaker applications

Bushings applied on circuit breakers should be capable of withstanding the forces specified in 6.2 of IEEE Std C37.04-1979.

9. Application of bushings in unusual service conditions

9.1 Contaminated environments

Standard bushing characteristics are specified for a standard clean environment. This promotes a common understanding between manufacturers and users of what bushing ratings mean.

Proper application of bushings in environments different from the standard requires knowledge of how bushing performance changes from one environment to another.

The purpose of this clause is to highlight those issues that need to be considered in applying bushings in varied environments.

9.1.1 Types of environments

Contaminated environments can be divided into the general types summarized in table 1.

9.1.2 Types of contaminants

9.1.2.1 Natural deposits

Natural deposits on bushings include such things as salts, dust, sand, etc., left on the bushings as the result of natural action. They may be airborne, waterborne, or left behind after the melting of snow and ice.

9.1.2.2 Automotive/industrial effluents

These are by-products put into the air as a result of industrial/commercial activity. They include particulates and gaseous materials that condense on bushing surfaces.

Table 1—General types of contaminated environments

Contamination level	Typical environments
Light	Areas without industries and with low density of emission-producing residential heating systems. Areas with some industrial or residential density but subject to frequent winds and/or precipitation. Agricultural areas (exposure to wind-borne fertilizer spray or crop-burning residues can lead to higher contamination levels). Mountainous areas. These areas are not exposed to sea winds or located near the sea. Typical measured *equivalent salt deposit density* (ESDD) levels are 0.03–0.08 mg/cm^2.
Medium	Areas with industries not producing highly polluting smoke and/or with average density of emission-producing residential heating systems. Areas with high industrial and/or residential density but subject to frequent winds and/or precipitation. Areas exposed to sea winds but not located directly on the coast. Typical measured ESDD levels are 0.08–0.25 mg/cm^2.
Heavy	Areas with high industrial density and large city suburbs with a high density of emission-producing residential heating systems. Areas close to the sea or exposed to strong sea winds. Typical measured ESDD levels are 0.25–0.6 mg/cm^2.
Extra heavy	Small areas subject to industrial smoke-producing thick conductive deposits. Small coastal areas exposed to very strong and polluting sea winds. Typical measured ESDD levels are above 0.6 mg/cm^2.

9.1.2.3 Other deposits

Other types of deposits such as agricultural residues can also occur as a result of specific types of activities in the vicinity of a bushing location.

9.1.3 Artificial contamination testing

A design or production test method that fully duplicates an actual environment where a bushing will be applied is usually not practical. Therefore, artificial test methods have been developed that are intended to provide a realistic assessment of the characteristic being tested (see references [B4] and [B8] for discussions of test methods). The three major categories of testing are discussed in 9.1.3.1–9.1.3.3.

9.1.3.1 Salt-fog

A bushing is energized at a constant test voltage and subjected to a salt-fog of controlled salinity. Typical salinity values range from 2.5–160 g of salt per cubic meter of fog solution. The fog is sprayed on the bushing through an array of nozzles with compressed air. The withstand salinity is the salinity at which there is a withstand in at least three of four 1 h test periods.

9.1.3.2 Wet-contamination

Artificial contamination is applied to a bushing by a spray or flow-coating method. Three to five minutes later, before the contaminant has time to dry, a test voltage is applied to the bushing. The voltage is either raised until the bushing flashes over or raised to a test value and held constant until the bushing flashes over or the contaminant dries out and all scintillation activity stops. The contaminant is a mixture of water and kaolin or other non-conductive material with a controlled amount of salt added.

A withstand value is sometimes determined by either three successful withstands without a flashover at a given test voltage or by statistical analysis of a number of trials.

This method has an advantage over the other methods in simplicity, ease of use and low test cost.

9.1.3.3 Clean-fog

A dry artificially contaminated bushing is subjected to clean fog and test voltage. In one variation, the fog is applied to the bushing and then it is energized. In the other variation, the bushing is energized and then the fog applied to it.

9.1.4 Natural contamination testing

The primary way to identify the types of natural contaminant on a bushing is through chemical analysis and testing. This is especially important for cases of industrial pollutants when the identity of the polluting agent is not immediately known. In addition, special tests can be used to quantify the effect of the contaminants on the electrical bushing characteristics.

The primary test for this purpose is the ESDD. This test is used to establish the conductivity of the water soluble deposits on a bushing surface in terms of the density of a standard soluble salt deposited on a surface that would produce the same conductivity.

A measured surface area on a bushing is washed in a known amount of water of very low conductivity. The resistivity of the wash water is then measured and the amount of sodium chloride (NaCl) needed to produce the same conductivity in the known quantity of wash water is calculated. The result is expressed as milligrams of NaCl per square centimeter of washed bushing surface area (mg/cm^2).

Additional information on this method is contained in Appendix 1C of IEEE Std 4-1978.

9.1.5 Countermeasures

The user will need to evaluate the following and any other options available to determine their suitability to the situation:

a) Install extra creep distance bushings. The following minimum creep values based on the bushing nominal line-to-ground kV rating are recommended. These values may need to be adjusted for factors such as shape, number of sheds, and bushing inclination.

Contamination	Creep distance
Light	28 mm/kV
Medium	35 mm/kV
Heavy	44 mm/kV
Extra heavy	54 mm/kV or greater

b) Apply protective coatings. Protective coatings can be applied to the surface of the bushings to improve their dielectric performance. There are temporary coatings, such as silicone grease, that require periodic replacement and permanent coatings that are nonremovable.

c) Install conductive glaze bushings. Consult manufacturer for specific application information.

d) Install composite insulated bushings with nonceramic, contamination-resistant external insulation. Consult manufacturer for specific application information.

e) Periodic cleaning of bushing surfaces. Bushings with known contamination cycles can be cleaned periodically as part of a maintenance program.

f) Eliminate air bushings. Installations can be designed to minimize the number of bushings exposed to atmospheric contamination.

9.2 High altitudes

Refer to IEEE Std C57.19.00-1991 for altitude correction factors.

10. Bushing maintenance practices

In-service maintenance frequency of bushings will normally vary according to circumstances and is generally combined with the inspection and maintenance of the associated equipment.

10.1 Mechanical maintenance and inspection

10.1.1 External porcelain

Inspect the porcelain for damage and pollution deposits. The following guidelines can be considered during the examination.

Small chips or breaks in the petticoats or sheds are generally of no concern. The exposed unglazed surface may be painted with a suitable paint to improve the appearance. Large breaks or chips may reduce the creep distance and may require bushing replacement.

Small cracks in the petticoats may be ground off to prevent further propagation. Large cracks may require bushing replacement.

Any damage to the main porcelain body would be a cause for concern and may require bushing replacement.

Bushings may be periodically cleaned by either hand-washing (de-energized installation) or by a suitable spray or jet method using low conductivity water.

Silicone-based greases and coatings can be applied to increase the time interval between cleanings. However, this treatment prevents normal rainfall from cleaning the porcelain surfaces.

10.1.2 Terminals

Inspect bushings for overheated connections when the unit is energized and loaded. Infrared cameras are sometimes used to detect overheated terminal connections. Loose connections should be tightened according to the bushing manufacturer's recommendations.

10.1.3 Mounting hardware

Inspect the mounting hardware for tightness.

10.1.4 Gaskets

Gaskets that are part of the bushing normally do not require replacement. Be sure that replacement gaskets between the bushing flange and the associated equipment are the right thickness and suitable material. Gasket stop rings, if used, should be in place.

Gaskets that are sensitive to ultraviolet radiation may deteriorate rapidly when exposed to combined sunlight, high humidity, and contamination. These materials should be avoided in these conditions. As an added precaution, gaskets in these conditions should be protected from exposure to sunlight.

10.1.5 Oil level

Loss of oil threatens the integrity of a bushing; therefore, any bushing that shows an abnormal oil level should be investigated as soon as possible. Follow the manufacturers recommendations in correcting the cause of the abnormal oil level and refilling the bushing.

The associated apparatus should be checked to ensure that the lower end of the bushing is immersed in oil to the proper level.

Special measures may be required to keep oil over internal insulation in bushings mounted at angles greater than 20 degrees from vertical.

10.1.6 Bushing taps

Inspect the bushing voltage and test taps for proper gaskets and grounding. The voltage tap compartments should be filled with insulating oil or compound when recommended by the bushing manufacturer.

10.2 Routine and special tests

10.2.1 Power/dissipation factor and capacitance

Bushing power or dissipation factor and capacitance should be measured when a bushing is first installed and also one year after installation. After these initial measurements, bushing power or dissipation factor and capacitance should be measured at regular intervals (3–5 years typical). The measured values should be compared with previous tests and nameplate values. Since power/dissipation factor varies with temperature, all measurements should be made at or corrected to 20 °C. Appropriate correction factors should be selected based on the manufacturer's recommendation and the user's experience.

Consult the manufacturer for temperature correction factors for cast insulation bushings. They normally require much higher correction factors than oil-impregnated paper-insulated bushings. This also means that extra care is required when making power or dissipation factor measurements on cast insulation bushings.

Any bushing that exhibits a history of continued power/dissipation factor increase should be scheduled for removal from service and further investigation. The bushing manufacturer should be consulted for guidance. If any bushing exhibits an increase in power or dissipation factor over a period of time, the rate of change of this increase should be monitored by more frequent tests. If the power or dissipation factor measurement of a bushing doubles from its initial reading, then the test frequency should be increased or the bushing should be removed from service. If the power or dissipation factor measurement triples the initial test reading, then the bushing should be removed from service.

Bushing capacitance should be measured with each power or dissipation factor test and compared carefully with both nameplate and previous tests in assessing bushing condition. This is especially important for capacitance-graded bushings where an increase in capacitance of 5% or more over the initial/nameplate value is cause to investigate the suitability of the bushing for continued service. The manufacturer should be consulted for guidance on specific bushings.

It is usually impossible to make absolute UST measurements of the bushing core capacitance and power factor of resistance-graded bushings because of the influence of the resistive glaze on the surface of the bushing porcelain. Differences in the glaze can cause significant variations in measurements between different bushings of the same voltage class and type. In some instances, the measured UST power factor may even be negative.

Standard practice during diagnostic testing of resistance-graded bushings is to record the measured UST values of capacitance and power factor for comparison with other measurements made on the same bushing. When there is evidence of a permanent increasing or decreasing trend in the measured values, the bushing manufacturer should be consulted for assistance in evaluation of the condition of the bushing.

10.2.2 Gas-in-oil

This test is not recommended as a routine test because it requires that the bushing be opened up and exposed to the outside atmosphere. This introduces the possibility of moisture entering the bushing while the bushing is open or after improper sealing of the opening.

The gas-in-oil test should only be used for diagnostic purposes on bushings that are suspect due to high power or dissipation factor measurements or other reasons. Gas-in-oil results should be compared with test results from other bushings and not with power transformer test results. The different mix of materials in bushings and in transformers will give different results. Experts with experience in interpreting bushing gas-in-oil tests should be consulted if help is needed.

The bushing manufacturer should be consulted for assistance in taking samples and interpreting results. The bushing oil level should be checked and adjusted if needed after oil samples are taken.

10.2.3 Dielectric tests

Bushing dielectric tests are sometimes performed in the field. Insulation dielectric strength generally depends on the level of insulation degradation. When dielectric tests are performed on service aged bushings, the following guidelines can help in determining the appropriate test levels:

a) Transformer bushings that will be removed from the transformer for testing should undergo 60 Hz tests at the 100% voltage test levels specified in IEEE Std C57.19.01-1991. This will minimize any problems that may develop during the testing of the transformer after the bushing is reinstalled.

b) Transformer bushings that will be tested while mounted in the transformer can only be tested at the lower of either the applicable bushing or transformer test levels. Test levels of 60 Hz should be limited to 1.5 times rated line-to-ground voltage or 85% of the withstand voltage level, whichever is lower. The voltage application should be limited to 1 min.

Partial discharges should be monitored during these tests to provide data for evaluating the condition of the bushing. IEEE Std C57.19.00-1991 gives additional information on partial discharge testing.

10.3 Bushing Storage

Recommended bushing storage practices vary from one manufacturer to another. Therefore, the user is advised to consult the manufacturer for information on the storage of a particular type of bushing.

Annex A

(informative)

Examples of calculation procedures for bushings applied on transformers

A.1 General information

This annex contains examples showing the use of calculation procedures given in this guide. In general, the conditions to be evaluated will include a period during which the bushing and transformer have reached a steady-state condition followed by a peak load period that may or may not reach steady-state conditions.

The load conditions and transformer parameters were obtained from actual operating data. The bushing parameters were obtained from published test data [B3].

The parameters for the bushings and transformer used in the examples are as follows:

a) Bushing coefficient $K_1 = 29.07$
b) Bushing coefficient $K_2 = 0.635$
c) Bushing time constant $\tau = 60$ min
d) Transformer oil time constant $\tau_o = 166$ min
e) Bushing exponent $n = 2$

A.2 Example 1

The equivalent load shape is 10 h at 0.64 pu followed by 14 h at 1.14 pu. The ultimate transformer oil temperature rises for the two load periods are 25.2 °C and 69.5 °C.

The duration of the initial load and the peak load periods are relatively long compared to the time constants of both the transformer and the bushing. This means that essentially constant conditions will be achieved in both periods. The average ambient temperature during the 10 h period is 27 °C and during the 14 h period it is 33 °C.

The rise above ambient of the hottest spot in the bushing can be calculated using equation (1) for each of the two load periods.

A.2.1 Load of 0.64 pu for 10 h

$$\Delta\theta_{HS} = 29.07 \times (0.64)^2 + 0.635 \times 25.2 = 27.9\ °C$$

hottest-spot temperature = 27 °C + 27.9 °C = 54.9 °C

A.2.2 Load of 1.14 pu for 14 h

$$\Delta\theta_{HS} = 29.07 \times (1.14)^2 + 0.635 \times 69.5 = 81.9\ °C$$

hottest-spot temperature = 33 °C + 81.9 °C = 114.9 °C

A.3 Example 2

The equivalent load shape is 1.22 pu for 11 h followed by 1.5 pu for 3 h. The ultimate transformer oil temperature rises for the two load periods are 78.2 °C and 115.7 °C, respectively. The average ambient temperature during the total of both load periods is 5.4 °C.

The rise above ambient temperature of the hottest-spot in the bushing can be calculated using equation (1) for the 11 h period since it is long compared to the bushing and transformer constants.

A.3.1 Load of 1.22 pu for 11 h

$$\Delta\theta_{HS} = 29.07 \times (1.22)^2 + 0.635 \times 78.2 = 92.9 \text{ °C}$$

hottest-spot temperature = 5.4 °C + 92.9 °C = 98.3 °C

The conditions during the peak load of 1.5 pu for 3 h will not reach steady-state conditions. Therefore, it is necessary to use the procedures in either 4.2.2.1 or 4.2.2.2.

A.3.2 Load of 1.5 pu for 3 h

The calculations in 4.2.2.1 are most easily performed using a digital computer or a programmable calculator. However, for the purpose of this example, manual calculations following the step-by-step procedure in 4.2.2.1 will be performed. Additional manual calculations will be made using equation (4) in 4.2.2.2. Finally, the results of both methods obtained by use of a digital computer will be tabulated.

The time interval chosen for the calculations is 5 min. The calculations using procedures from 4.2.2.1 are as follows:

a) *Step A1*. The initial hottest-spot rise is 92.9248 °C as determined in A.3.1.

b) *Step B1*. The oil temperature rise at the end of 5 min is

$$\Delta\theta_o(5 \text{ min}) = \{78.2 + 115.7 - 78.2\}\{1 - \varepsilon^{-5/166}\} = 79.312 \text{ °C}$$

Note that several significant figures are carried to improve the accuracy of the iterative calculations but are not to imply such a degree of accuracy in the final temperature rise.

c) *Step C1*. The ultimate hottest-spot rise based on conditions at 5 min is

$$\Delta\theta_{HS} = 29.07 \times (1.5)^2 + 0.635 \times 79.312 = 115.771 \text{ °C}$$

d) *Step D1*. The hottest-spot temperature rise at 5 min is

$$\Delta\theta_{HS}(5 \text{ min}) = 92.925 + \{115.771 - 92.925\}\{1 - \varepsilon^{-5/60}\} = 94.751 \text{ °C}$$

e) *Step A2*. The new hottest-spot rise is 94.751 °C.

f) *Step B2*. The oil temperature rise at the end of 10 min is

$$\Delta\theta_o(10 \text{ min}) = 79.312 + \{115.7 - 79.312\}\{1 - \varepsilon^{-5/166}\} = 80.392 \text{ °C}$$

g) *Step C2*. The ultimate hottest-spot rise based on conditions at 10 min is

$$\Delta\theta_{HS} = 29.07 \times (1.5)^2 + 0.635 \times 80.392 = 116.457 \text{ °C}$$

h) *Step D2*. The hottest-spot temperature rise at 10 min is

$$\Delta\theta_{HS}(10 \text{ min}) = 94.751 + \{116.457 - 94.751\}\{1 - \varepsilon^{-5/60}\} = 96.487 \text{ °C}$$

The steps can be repeated in the same manner until the entire 180 min time period has been covered.

The calculations using equation (4) from 4.2.2.2 for 180 min are as follows:

$$\Delta\theta_{HS}(180 \text{ min}) = 92.9248 + \{29.07 \times (1.5)^2 + 0.635[78.2 + (115.7 - 78.2) \times (1 - \varepsilon^{-180/166})] - 92.9248\} \times \{1 - \varepsilon^{-180/60}\} = 128.938 \text{ °C}$$

The computer output with complete results is shown in table 2.

Table 2—Sample computer data

Input data	Initial load current in pu = 1.22			
	Peak load current in pu = 1.5			
	Ultimate top oil temperature rise in °C = 115.7			
	K_1 = 29.07 K_2 = 0.635 n = 2			
	Duration of peak load in min = 180			
	Time increments in min = 5			
	Bushing time constant in min = 60			
	Transformer oil time constant in min = 166			

Results	**Elapsed time (min)**	**Top oil temperature rise (°C)**	**Hottest spot rise (°C)**	
			Per 4.2.2.1	**Per 4.2.2.2**
	0	78.2	92.9248	92.9248
	5	79.312 7	94.7515	
	10	80.392 3	96.4869	
	15	81.44	98.1368	
	20	82.456 5	99.7064	
	25	83.442 9	101.201	
	30	84.4	102.624	
	35	85.328 7	103.98	
	40	86.229 9	105.274	
	45	87.104 3	106.509	
	50	87.952 8	107.688	
	55	88.776 1	108.815	
	60	89.574 9	109.892	
	65	90.350 1	110.923	
	70	91.102 3	111.909	
	75	91.832 1	112.853	
	80	92.540 3	113.758	
	85	93.227 5	114.626	
	90	93.894 3	115.458	
	95	94.541 3	116.256	
	100	95.169 1	117.022	
	105	95.778 3	117.758	
	110	96.369 4	118.465	
	115	96.942 9	119.145	
	120	97.499 5	119.799	
	125	98.039 5	120.427	
	130	98.563 5	121.032	
	135	99.072	121.615	
	140	99.565 4	122.176	
	145	100.044	122.716	
	150	100.509	123.237	
	155	100.959	123.739	
	160	101.397	124.224	
	165	101.821	124.69	
	170	102.233	125.141	
	175	102.633	125.576	
	180	103.02	125.996	128.938
	180 Final	103 °C	126 °C	129 °C

Annex B

(informative)

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[4]IEC publications are available from IEC Sales Department, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse. 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.