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Nuclear Maintenance Applications Center: Dry-Type Transformer and Reactor Application and Maintenance Guide

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Nuclear Maintenance Applications Center: Dry-Type Transformer and Reactor Application and Maintenance Guide

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Abstract

This report is focused on dry-type transformers used in unit secondary substations of nuclear power plants for power delivery purposes. This report does not cover instrument transformers, nor is it specifically for transformers used in grounding circuits, although these usages are addressed in Section 3.

The primary purpose of this report is to inform the engineer or technician who has been assigned responsibility for secondary unit substation transformers in a nuclear station's power system.

Fundamentals of dry-type power transformer design, construction, shipping, installation, and maintenance are covered to improve the knowledge base of plant personnel as it relates to the issues involved in applying and maintaining dry-type transformers.

Various dry-type transformer designs with distinctive characteristics are on the market. It is recommended that, before procuring a transformer, the engineer/technician review their application(s), as well as the characteristics of the dry-type transformer designs, to ensure adequate service and life when selecting replacement transformers.

There is a significant amount of information relevant to dry-type transformers, and many of the documents related to this equipment are referenced herein. Additional details with regard to specific issues can be located in the reference documents that are listed in this report.

Because dry reactors have certain characteristics in common with dry-type transformers, they are also considered in this report for characteristics/issues relating to their applications and recommended maintenance. Considerations specifically pertinent to reactors are under headings labeled accordingly.

Keywords
Dry type
Electrical
Maintenance
Transformer
Unit substation
Ventilated

Table of Contents

Section 1: Introduction 1-1
1.1 Scope and Purpose of Report 1-1
1.2 Key Points 1-1
1.3 Historical Perspective 1-3
1.4 Dry-Type Versus Liquid-Filled 1-4
1.5 Organization of the Report 1-5

Section 2: Design and Construction 2-1
2.1 Basic Transformer Design 2-1
2.2 Characteristics of Transformers 2-3
2.2.1 Capacity 2-3
2.2.2 Voltage Ratings 2-5
2.2.3 Deenergized Voltage Taps 2-5
2.2.4 Basic Impulse Insulation Level 2-5
2.2.5 Impedance 2-5
2.2.6 Regulation 2-6
2.2.7 Winding Temperature Rise 2-6
2.2.8 Hottest Spot Temperature Rise 2-6
2.2.9 Nameplate Information 2-6
2.3 Description of Major Parts of a Transformer 2-9
2.3.1 Enclosure 2-9
2.3.2 Active Part (Core and Windings) 2-12
2.3.3 Insulation Systems 2-18
2.3.4 Accessories 2-20
2.4 Principal Considerations in the Design and Construction of Transformers for Nuclear Plants 2-21
2.4.1 Power Quality 2-22
2.4.2 Radiation 2-23
2.4.3 Seismic 2-23
2.4.4 Temperature 2-23
2.4.5 Airborne Contaminants—Choosing a Transformer 2-23

2.5 Coatings and Sealants....2-23
2.5.1 Conventional Vacuum-Pressure Impregnation....2-24
2.5.2 Vacuum-Pressure Encapsulated/Resin-Encapsulated....2-24
2.5.3 Solid Cast....2-25
2.5.4 Processes Applicable to Sheet Windings in Cast Coil Transformers....2-26
2.6 Cooling Classes....2-27
2.6.1 Self-Cooled....2-27
2.6.2 Forced-Cooled....2-28
2.6.3 Double-Rated....2-28
2.6.4 Nonventilated....2-28
2.6.5 Sealed-Tank....2-29
2.6.6 SF6 GA Transformers....2-29
2.7 Reactor Design and Construction....2-29

Section 3: Application of Dry-Type Transformers and Reactors....3-1
3.1 Location in the Power System....3-1
3.2 Special Applications....3-2
3.2.1 Nuclear Safety-Related....3-3
3.2.2 Unusual Operating Conditions....3-3
3.3 Non-Safety-Related Applications....3-4
3.4 Spill Containment and Fire Protection....3-5
3.5 Transformer Protection....3-5
3.6 Installation Environment....3-7
3.7 Space and Access....3-7
3.8 Transformer Loading....3-8
3.9 Sound....3-8
3.10 Enclosures....3-8
3.11 Transformer Selection, Sizing, and Loading....3-9
3.11.1 Transformer Cooling....3-9
3.11.2 Transformer Sizing....3-11
3.11.3 Specification....3-12
3.12 Reactor Applications....3-13
3.12.1 Application Issues....3-14

Section 4: Aging, Degradation, and Failures....4-1
4.1 Infant Mortality....4-2
4.2 Aging....4-2
4.2.1 General Discussion....4-2
4.2.2 Aging as Related to Operation Beyond Hottest Spot Temperature Rating....4-3

4.3 Various Operational Stressors 4-5
4.3.1 Dielectric Stress 4-6
4.3.2 Structural Stress 4-6
4.3.3 Thermal Stress 4-7
4.3.4 Electromagnetic Stress 4-8
4.4 Summary of Industry Experience 4-8
4.4.1 INPO Database (Licensee Event Report, Equipment Performance Information Exchange, and Operating Experience Database) 4-9
4.4.2 NRC 1E Notices, Bulletins, and Circulars 4-11
4.5 Failure Review 4-12
4.6 Stressors, Aging Mechanisms, and Potential Failure Modes 4-13
4.7 Degradation Effect on Components 4-16
4.7.1 Core 4-16
4.7.2 Windings 4-16
4.8 Failure Mechanisms 4-17
4.8.1 Short-Circuit Failure 4-17
4.8.2 Thermal Aging 4-18
4.9 Summary 4-18

Section 5: Maintenance 5-1
5.1 Overview 5-1
5.2 Cooling System 5-1
5.3 Power Factor Versus Insulation Resistance 5-2
5.4 Applicable Industry Standards 5-2
5.4.1 Recommended Practice for Electrical Equipment Maintenance 5-2
5.4.2 Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type General-Purpose Distribution and Power Transformers 5-2
5.4.3 Maintenance Testing Specifications for Electric Power Distribution Equipment and Systems 5-3
5.4.4 Transformer Maintenance (U.S. Department of Interior, Bureau of Reclamation) 5-3
5.4.5 Dry-Type Transformers for General Applications 5-5
5.5 Insurance Recommendations 5-6
5.6 Summary of Maintenance Recommendations 5-6
5.6.1 Routine Maintenance 5-6
5.6.2 Special (Nonroutine) Maintenance 5-9
5.7 Troubleshooting 5-15

Section 6: Installation and Replacement 6-1
6.1 Considerations for Retirement 6-1
6.1.1 Service Issues 6-2
6.1.2 Other Replacement Issues 6-2
6.2 Factory Inspections 6-3
6.3 Factory Testing 6-4
6.4 Receiving and Handling.....6-6
6.4.1 Receiving Inspection.....6-6
6.4.2 Receiving Tests 6-7
6.5 Storage of Spare Transformers and Reactors 6-8
6.6 Final Inspection Prior to Energizing 6-8
6.7 Startup Testing 6-9

Section 7: References 7-1

Appendix A: IEEE Standards A-1
A.1 Standards Applicable to Dry-Type Transformers..... A-1
A.2 EPRI Report A-2
A.3 NRC Documents (NUREGs, IE Notices, Bulletins, and Circulars) A-2
A.4 Other Document A-3

Appendix B: Glossary of Terms and Acronyms.....B-1
B.1 Glossary of Terms B-1
B.2 Other Definitions B-3
B.3 Acronyms B-4

Appendix C: Summary of Key Points.....C-1

Appendix D: Harmonics and K-Factor Transformers D-1

List of Figures

Figure 2-1 Transformer principles 2-1
Figure 2-2 Typical nameplate.....2-9
Figure 2-3 An indoor ventilated enclosure 2-10
Figure 2-4 Outdoor ventilated enclosures 2-10
Figure 2-5 A sealed-tank enclosure 2-12
Figure 2-6 A simple illustration of a laminated core 2-13
Figure 2-7 Step-lap mitered core joints 2-14
Figure 2-8 Low-voltage sheet wound coil 2-15
Figure 2-9 Disk winding, schematic 2-16
Figure 2-10 Disk winding, photo 2-16
Figure 2-11 Helical winding 2-17
Figure 2-12 Example of a VPI transformer—inside a sealed-tank enclosure 2-24
Figure 2-13 A resin-encapsulated transformer winding.....2-25
Figure 2-14 An example of a solid cast dry-type transformer 2-26
Figure 2-15 Sketch of an iron-core reactor.....2-30
Figure 2-16 Example of a dry-type gapped core reactor 2-30
Figure 2-17 Sketch of air-core reactors.....2-31
Figure 2-18 Example of an air-core reactor 2-31
Figure 3-1 One-line diagram showing typical locations of dry-type transformers 3-2
Figure 3-2 A typical dry-type transformer protection schematic.....3-6
Figure 4-1 Life expectancy curve—base 10 4-4
Figure 4-2 Life expectancy curve—base e 4-5

List of Tables

Table 2-1 Dry-type transformer standard base kVA ratings 2-4
Table 2-2 Guideline for nameplate information 2-7
Table 2-3 Limits of temperature rise for continuous rated dry-type transformer windings 2-19
Table 2-4 Examples of materials used in insulation systems 2-19
Table 2-5 Transformer cooling classes.....2-27
Table 2-6 Dry-type transformer self-cooled and forced-air-cooled ratings.....2-28
Table 3-1 Self-cooled continuous loading on basis of average ambient temperature.....3-10
Table 3-2 Continuous per unit loading capability as a function of ambient temperature.....3-10
Table 3-3 Dielectric strength correction factors for altitudes greater than 1000 m (3300 ft) 3-11
Table 4-1 Stressors, aging mechanisms, and potential failure modes 4-14
Table 5-1 Transformer insulation resistance test voltage.....5-3
Table 5-2 Dry-type transformer maintenance summary 5-4
Table 5-3 Audible sound levels for dry-type transformers 15,000-V nominal system voltage and below.....5-8
Table 5-4 Summary of transformer maintenance recommendations.....5-10
Table 5-5 Summary of reactor maintenance recommendations.....5-14
Table 5-6 Troubleshooting guide 5-16
Table D-1 Typical load K-Factors D-2

Section 1: Introduction

1.1 Scope and Purpose of Report

This report contains information pertinent to the application and maintenance of dry-type general-purpose, distribution, and power dry-type transformers of the following types:

- Ventilated, self-cooled, and fan cooled, for indoor and outdoor application
- Totally enclosed, nonventilated, self-cooled, for indoor or outdoor application
- Sealed-tank, gas-filled for indoor or outdoor application, self-cooled
- Steel-core and air-core reactors, with or without enclosures (to the extent applicable)

This report does not directly apply to the following types of transformers:

- Instrument transformers
- Rectifier transformers
- Voltage regulators
- Specialty transformers

This report is informative to personnel with the responsibility for applying and maintaining dry-type transformers and reactors in service at nuclear power plants. Information includes application issues relating to the specification of transformers and reactors, design and construction, maintenance issues, inspection, testing, and failure modes that are considered important for an expectancy of a reasonable service and/or for life extension.

1.2 Key Points

Throughout this report, key information is summarized in Key Points. *Key Points* are bold lettered boxes that succinctly restate information covered in detail in the surrounding text, making the Key Point easier to locate.

The primary intent of a Key Point is to emphasize information that will allow individuals to take action for the benefit of their plant. The information included in these Key Points was selected by the consultants and utility personnel who prepared and reviewed this report.

The Key Points are organized according to three categories: Operation and Maintenance (O&M) Costs, Technical, and Human Performance. Each category has an identifying icon, to draw attention to it when quickly reviewing the report. They are as follows:



Key O&M Cost Point
Emphasizes information that will result in overall reduced costs and/or an increase in revenue through additional or restored energy production.



Key Technical Point
Targets information that will lead to improved equipment reliability.



Key Human Performance Point
Denotes information that requires personnel action or consideration in order to prevent personal injury, prevent equipment damage, and/or improve the efficiency and effectiveness of the task.

Appendix C contains a listing of all Key Points in each category. The listing restates each Key Point and provides references to its location in the body of the report. By reviewing this listing, users of this report can determine whether they have taken advantage of key information that the writers of the report believe would benefit their plants.

1.3 Historical Perspective

When William Stanley installed the first practical ac power distribution system in Great Barrington, Massachusetts, in 1886, he (or, rather his employer, George Westinghouse) was in a heated battle over whether electrical usage in the United States would go the way of ac or dc. Westinghouse's competitor (Thomas Edison) already had a growing business in providing dc power to light streets and to power houses/businesses. It could be said that the ability to transform ac tipped the balance of favor to George and William. During the winter of 1886–1887, about a dozen dry-type transformers were constructed to step the dynamo's output of 500 volts (V) down to 100 V for use in that first experiment. Twenty-five years later, Stanley observed the following:

> As I look back on the plant now I tremble for the safety of the inhabitants of Great Barrington while these experiments were being tried. We did not have oiled insulation or oiled cloth in those days, but separated our primary and secondary circuits with shellacked paper and various other substances of an equally fragile nature; but all went well with the system, no accidents occurred, and no dangers, other than a small fire, were reported. [1]

Since that time, there has been much advancement in dry-type transformer technology (even beyond oiled paper and oiled cloth), including the use of high-temperature insulation materials, such as meta-aramids (for example, Nomex[1]), mica, and porcelain, and also many active part design innovations for efficiency and cost reduction.

[1] *Nomex* is a registered trademark of E. I. du Pont de Nemours and Company.

1.4 Dry-Type Versus Liquid-Filled

Liquid-filled transformers have dominated the market for out-of-doors applications (such as pole-top and pad-mounted transformers), largely because of their lower cost. However, dry-type transformers are a typical cost-effective choice for indoor applications, and they often are applied outdoors as well.



Key O&M Cost Point
When spill and fire protection considerations are included, dry-type transformers are typically less costly to install and to maintain.

Dry-type transformers and reactors are designed to provide their function while representing a low risk of environmental contamination and a low risk of fire. The following are some advantages of choosing dry-type transformers and reactors for applications that would otherwise be subject to fire and/or spill concerns:

- Low environmental risk (no vaults or firewalls required)
- No liquid leakage or rupture (no containment required)
- Less weight (lower installed cost of base/foundation)
- Non-explosive and high resistance to flame (minimum fire hazard)
- Absence of oil, allowing for higher operating temperature transformers
- Lower installed cost (as compared with liquid when spill and fire protection are considered)
- Reduced maintenance requirements (no oil or pumps to manage)



Key Technical Point
Locating dry-type transformers close to loads represents lower line losses and less line voltage drop with which to contend.

Dry-type transformers and reactors contain no liquids. Therefore, they represent very low fire risk and require no catch basins, fireproof vaults, firewalls, special waste disposal considerations, or venting of gases. The absence of these concerns makes these dry-type devices candidates for locating inside of buildings (close to the loads), which represents lower line losses and less line voltage drop with which to contend.

Over the years, there have been many advances in the design, manufacturing, and application of dry-type transformers and reactors. Sealed enclosures allow gas-insulated transformers to operate in an environment that is physically isolated from harsh conditions that include dust, chemicals, moisture, and so forth. Cast coils, while being provided in ventilated and nonventilated enclosures, isolate the windings from the surrounding environment while allowing the cooling advantage of ventilated enclosures. Encapsulated windings provide a similar isolation but to a lesser degree.

1.5 Organization of the Report

This report is organized in seven sections and four appendices, as follows:

- Section 1 introduces and summarizes the scope and purpose of the report and describes its organization.
- Section 2 covers transformer design, standard requirements, materials, and operating parameters associated with construction.
- Section 3 covers various issues relating to applications.
- Section 4 covers industry documents detailing failures associated with aging and degradation mechanisms.
- Section 5 describes recommended predictive tests and preventive maintenance plans.
- Section 6 covers installation and replacement.
- Section 7 provides a list of references.
- Appendix A includes applicable standards and Nuclear Regulatory Commission (NRC) documents.
- Appendix B provides a glossary and a list of abbreviations and acronyms.
- Appendix C provides a summary of Key Points.
- Appendix D covers harmonics and K-Factor transformers.

Section 2: Design and Construction

2.1 Basic Transformer Design

Power transformers serve a vital function in the operation of modern ac power systems. In fact, one of the primary advantages of ac power (over dc) is the capability of efficiently transforming power at different voltage levels for efficient transmission to load locations. A transformer accomplishes this by converting alternating electrical power into an alternating magnetic field. Figure 2-1 illustrates a typical two-winding transformer with an iron core. When an alternating voltage is applied to one of these windings (generally, by definition, the primary), a current will flow, which sets up an alternating magnetomotive force and, therefore, an alternating flux in the core. By exposing a secondary coil to this same field, the magnetic energy is again converted into current and voltage in the secondary coil.

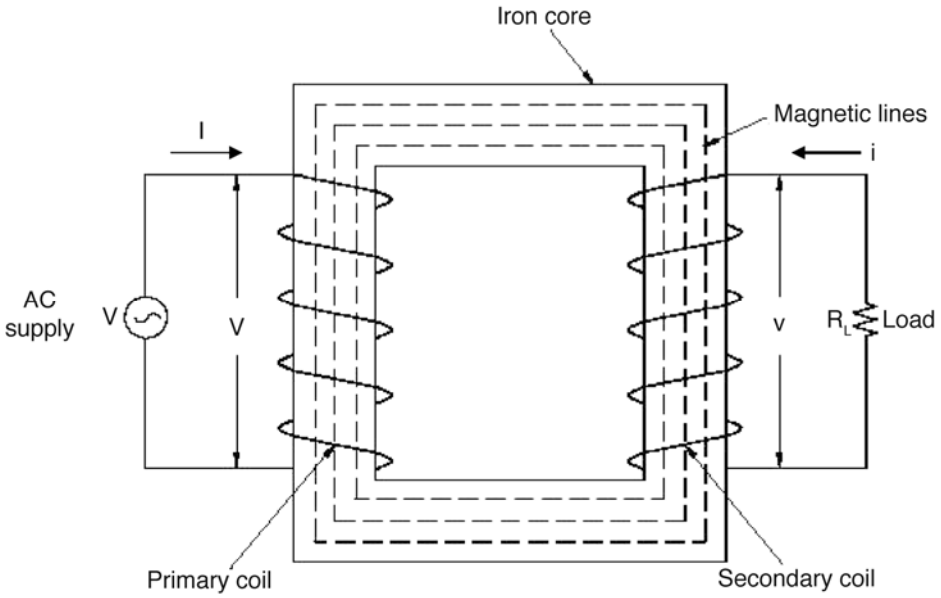


Figure 2-1
Transformer principles

The relationship between the induced voltage and the flux is given by reference to Faraday's law, which states that its magnitude is proportional to the rate of change of flux linkage, and Lenz's law, which states that its polarity is such as to oppose that flux linkage change if current were allowed to flow. This is normally expressed in the form

$$e = N(d\varphi/dt)$$

However, in the practical transformer, it can be shown that the voltage induced per turn is

$$E/N = K\Phi_m f$$

where

K is a constant (for sinusoidal voltage: 4.44)

Φ_m is the maximum value of flux (in Webers) linking that turn

f is the system frequency in hertz.

Most transformer designers are concerned with the volts per turn and the flux density in the core when designing the transformer. The term Φ_m can be rewritten as

$$\Phi_m = B_m A \times 10^{-6}$$

where

B_m = maximum value of flux density in the core, tesla

A = net cross-sectional area of the core, mm^2.

There are several basic principles and voltage–current relationships by which ac power is transformed. The relationship of voltage and current for the input (primary) and output (secondary) of ideal transformers (losses and regulation neglected) is as follows:

$$V I = v i$$

where

V= primary voltage

v = secondary voltage

I = primary current

i = secondary current

and

$$I = \frac{n}{N} x\, i \qquad\qquad V = \frac{N}{n} x\, v$$

where

N = number of electrical turns in primary winding

n = number of electrical turns in secondary winding.

The power of these simple basic relationships will be obvious when one realizes the cost and practical advantage of using the electromagnetic properties of a power transformer to convert power of a circuit from lower voltage (and higher current) to a higher voltage (and lower current) for efficient transmission across the distance of a power transmission line. At the same time, the voltage–current relationships can be again converted (transformed) to drop voltage to a usable level at the other end of the line, so as to put the power to practical use. Of course, it must be said that when losses and regulation are considered, the relationships become somewhat more complex, because such issues as core and winding heating and voltage drop (regulation) are introduced. However, the basic principle stands.

2.2 Characteristics of Transformers

Some important characteristics of dry-type transformers are as follows:

- Capacity
- Deenergized voltage taps
- Impedance
- Winding temperature rise
- Voltage ratings
- Basic impulse level (BIL)
- Regulation
- Hottest spot temperature

2.2.1 Capacity

The kVA rating of the transformer is an indication of its capacity to transform power without overheating. As a result of advances in the development of insulation and core steel materials and advances of transformer design and design tools, dry-type transformers of larger capacity (kVA) and voltage are being manufactured. Dry-type transformers are available at capacities of up to 30 MVA and up to 40 kV (250 BIL).

Table 2-1 shows the kVA ratings for single- and three-phase transformers.

Table 2-1
Dry-type transformer standard base kVA ratings [2]

Single-Phase	Three-Phase
1	15
3	30
5	45
7.5	75
10	112.5
15	150
25	225
37.5	300
50	500
75	750
100	1,000
167	1,500
250	2,000
333	2,500
500	3,750
833	5,000
1,250	7,500
1,667	10,000
2,500	12,000
3,333	15,000
5,000	20,000
6,667	25,000
8,333	30,000
10,000	—

It should be noted that transformers are rated in kVA rather than in kW to account for core heating when operated at power factors other than a power factor of 1.0. A typical power factor applicable to a nuclear generation station's auxiliary system is from 0.8 to 1.0. For operation with a power factor lower than 0.8, transformer derating can be required to avoid overheating the core.

2.2.2 Voltage Ratings

The primary voltage rating of the transformer represents the continuous operating voltage that the transformer is designed to have applied to its primary terminals. The secondary voltage rating is the voltage output that will result (under a no-load condition) when the rated primary voltage is applied. The high-voltage winding typically includes voltage taps brought out to allow connection choices that represent alternative ratings for the high voltage (see Section 2.2.3).

2.2.3 Deenergized Voltage Taps

To adjust for a higher or lower primary (input) voltage than expected or to adjust the resulting secondary (output) voltage, dry-type transformers typically are provided with voltage taps in the high-voltage winding. These taps are brought out of the winding for interconnection in such a way as to select/adjust the turns ratio of the transformer. For dry-type transformers, these tap connections are usually on each phase; therefore, one must take care that, when tap connections of one phase are changed, the others must be changed to match. An exception to this description is the sealed-tank design, which requires a mechanical de-energized tap changer (DETC) that is operable from outside of the tank. Whether manual taps or a DETC is provided, typical tap range is +/-5% of nominal, usually consisting of two 2.5% taps at full capacity above normal and two 2.5% taps at full capacity below normal. **Note**: under-load tap changers are not typically provided for dry-type transformers and are not included herein.

2.2.4 Basic Impulse Insulation Level

The BIL of a transformer is the peak level of voltage that a transformer is designed to tolerate when that voltage is an impulse from lightning. The standard wave for the factory testing for this characteristic is a 1.2 x 50 μs wave shape—that is, the front of the wave is characterized by a 1.2μs time to crest (peak), and the tail of the wave is characterized by a time of 50μs (from start of the wave) to drop to 50% of peak. During factory testing, positive impulses are to be applied to dry-type transformers to avoid strikes to ground.

2.2.5 Impedance

The impedance of a transformer is a result primarily of the physical geometry of the windings—especially as they relate to each other. The impedance of the transformer is an important characteristic and has implications with regard to operation, such as losses, regulation, and fault current limits. The standard tolerance allowed for nominal guaranteed impedance is +/-7.5% for a two-winding transformer and +/-10% for a transformer with three or more windings.

2.2.6 Regulation

Regulation, which is related to impedance and losses, is a characteristic that determines the voltage of the secondary resulting from a constant voltage input to the primary—at various power factors. In an unloaded condition, the voltage out can be predicted accurately by the turns ratio (the ratio of primary versus secondary turns). However, for a loaded transformer (for a given input voltage), to determine output voltage at a particular operating power factor, one must include consideration for percentage regulation, which is a tested value reported in the Certified Test Report. A typical percentage regulation at 0.8 power factor is 5%–8%. Therefore, for this case, output voltage will be 5%–8% lower than predicted by the ratio of turns.

2.2.7 Winding Temperature Rise

The temperature rise of a transformer is the average temperature of the winding (measured by winding resistance), less the ambient—therefore, the term *rise* (above ambient), under full load condition.

2.2.8 Hottest Spot Temperature Rise

Typically, the hottest point in the winding is the main concern for insulation aging. However, the precise location of this point cannot be accurately determined. Therefore, the value of the hot spot is determined for each transformer design by calculation. Hottest spot temperature rise is the highest temperature in the winding (less the applicable ambient) under loaded condition.

2.2.9 Nameplate Information

Nameplates on transformers serve an important function in identifying basic characteristics of the transformers upon which they are mounted. The nameplate should be made of stainless steel or some other durable material that will stand the test of time and be legible many years after the transformer is delivered for service. Table 2-2 provides a list, with footnotes, of the minimum items required to be included. It can be found in IEEE (*Institute of Electrical and Electronics Engineers*) Standard C57.12.01-2005 [2].

Table 2-2
Guideline for nameplate information [2]

Nameplate Information
Serial number[a]
Class (AA, AS/FA, etc.)[b]
Number of phases
Frequency
Power ratings[c]
Voltage ratings[de]
Tap voltages[f]
Temperature rise in °C, by individual winding if different
Polarity (single-phase transformers)
Phasor diagram (polyphase transformers)
Percent impedance[g]
Basic lightning impulse insulation levels (BILs)[h]
Approximate weight in pounds and kilograms[i]
Connection diagram[j]
Name of manufacturer
Installation and operating instruction reference
The words "dry-type transformer"
Conductor material
Step-up transformer suitability, if involved[k]

[a]The letters and numerals showing the power rating, serial number, and voltage ratings shall have a minimum height of 3.2 mm (0.125 in), whether engraved or stamped. The height of other letters and numerals shall be optional for the manufacturer.

[b]Where the class of transformer involves more than one kilovolt-ampere rating, all ratings shall be shown. Provisions for future forced-cooling equipment shall be indicated.

[c]See Footnote a and Footnote b.

[d]The voltage ratings of a transformer shall be designated by the voltage ratings of each winding separated by dashes. The winding voltage ratings shall be designated as specified in Figure 2 and Figure 3. If the transformer is suitable for Y connection, the nameplate shall be so marked, except that, on a twowinding single- phase transformer that is insulated for Y connection on both windings, the nameplate shall show the Y voltage on the high-voltage side only for such transformers having high-voltage ratings of above 600 V.

[e]See Footnote a.

[f]The tap voltages of a winding shall be designated by listing the winding voltage of each tap, separated by a slant (/), or shall be listed in tabular form. The rated voltage of each tap shall be shown in volts, except that for transformers 500 kVA and smaller with taps in uniform 2-1/2% or 5% steps that may be shown as percentages of rated voltage. The taps shall be identified on the transformer nameplate by means of letters in sequence or Arabic numerals. The numeral 1 or the letter A shall be assigned to the voltage rating providing the maximum ratio of transformation with tap changers for de-energized operation. The normal position shall be designated by the letter N for load-tap changers. (See IEEE Std C57.12.80.) The raised range positions shall be designated by numerals in ascending order, corresponding to increasing output voltage, followed by the suffix

R, such as 1R and 2R. The lower range positions shall be designated by numerals in ascending order, corresponding to decreasing output voltage, followed by the suffix L, such as 1L and 2L. The rated currents of all windings at the highest kilovolt-ampere, and on all tap connections, shall be shown for transformers 501 kVA and larger.

[g]The percent tested impedance of two-winding transformers over 500 kVA shall be given on the tested rated voltage connection and at rated self-cooled power. For transformers with more than two windings, the percent impedance shall be given between each pair of windings. The voltage base shall be stated following each percent impedance figure, and if the transformer has more than one kilovolt-ampere rating, the rated power base shall be given.

[h]Full-wave BIL rating, in kilovolts of line terminals, shall be designated as in the following example:

- High-voltage winding 60 kV BIL
- Low-voltage winding 10 kV BIL
- If a neutral terminal is assigned a BIL rating, it shall be similarly described.

[i]For transformers rated 30 kVA or less, the weight may be omitted from the nameplate. Supplemental data shall be available showing the approximate weight of the transformer for ratings smaller than those for which data are shown on the nameplate. The total approximate weight shall be shown for transformers larger than 30 kVA up to 500 kVA. The following approximate weights shall be shown for transformers larger than 500 kVA:

- Core and windings
- Total

[j]All winding terminations shall be identified on the nameplate or on the connection diagram. A schematic view shall be included. All termination or connection points shall be permanently marked to agree with the schematic identification. In general, the schematic view should be arranged to show the low-voltage side at the bottom and the H1 high-voltage terminal at the top left. (This arrangement may be modified in particular cases, such as multi-winding transformers equipped with terminal chambers, potheads, or transformers having terminal locations not conforming to the suggested arrangements.) Indication of potential transformers, potential devices, current transformers, and winding temperature devices, when used, shall be shown. Polarity and location identification of current transformers shall be shown if used for metering, relaying, or line-drop compensation. (Polarity need not be shown if current transformers are used for winding-temperature equipment or fan control.) All internal leads and terminals that are not permanently connected shall be designated or marked with numerals or letters in a manner that will permit convenient reference and will obviate confusion with terminal and polarity markings. Winding-evelopment diagrams shall use symbols as described in IEEE Std 315. Any winding grounds shall be indicated.

[k]If the transformer is larger than 500 kVA and is suitable for step-up operation, the nameplate shall so state.

Each transformer should have a stainless steel or otherwise corrosion-resistant nameplate, secured to the case with corrosion-resistant fasteners.

Figure 2-2 is an example of a typical transformer nameplate.

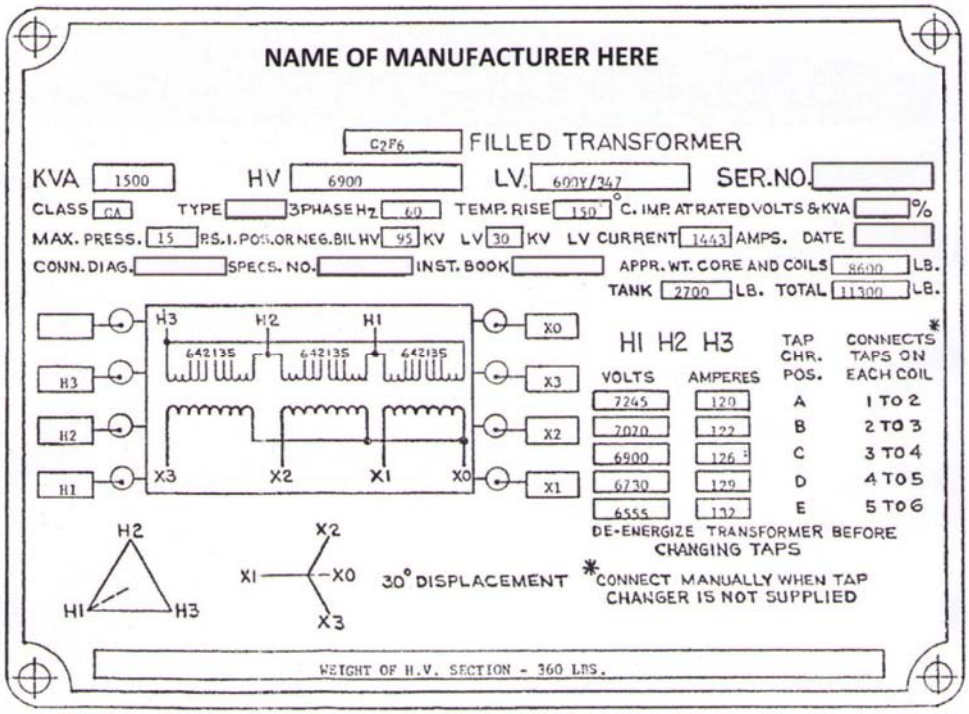


Figure 2-2
Typical nameplate [2]

2.3 Description of Major Parts of a Transformer

Transformers typically consist of the following four major portions:

- Enclosure
- Active part
- Insulation
- Accessories

2.3.1 Enclosure

As covered briefly with regard to cooling classes of dry-type transformers, enclosures are of various types, depending upon the application needs and the environment in which the transformer is installed. It should be noted that, for forced-air transformers, the fans are usually mounted under the coils to boost the natural convection flow through the cooling ducts.

2.3.1.1 Ventilated Enclosure

The ventilated enclosure includes an allowance for ambient air to be drawn into openings on/near the bottom of the enclosure and to be exhausted by openings near the top. To limit the dust and other airborne debris that might otherwise enter the enclosure, provisions for filters might be included. For installations

subject to water falling or spraying (whether indoors or out), outdoor enclosures should be chosen. For this case, deflector shields can be added or the ventilating grills can be of a special design to prevent water entry. The transformer within this type of enclosure might (or might not) include forced-air cooling. If forced-air cooling is provided, the fans are typically installed under each coil to boost air flow in the cooling ducts. See Figures 2-3 and 2-4 for illustrations of ventilated enclosure and fan cooling.



Figure 2-3
An indoor ventilated enclosure (center panel removed)



Figure 2-4
Outdoor ventilated enclosures



Key O&M Cost Point
Ventilated dry-type transformers are typically smaller and less costly than nonventilated dry-type transformers.

Because ventilated enclosures provide direct exchange of air with outside air, ventilated transformers are typically smaller (and less costly) than nonventilated transformers.

2.3.1.2 Nonventilated Enclosure

Where some isolation of the transformer's active part from airborne debris or contaminants is desired, the nonventilated enclosure (neither openings nor grills included) can be specified. Although some air leakage into and out of this enclosure can occur, there are no intentional provisions for air exchange. Nonventilated enclosures appear the same as ventilated enclosures, only without ventilating grills.

2.3.1.3 Sealed Tank (Gas-Filled)

Where maximum isolation from its surrounding environment is desired, the active part can be housed in a sealed tank, with a pressurized gas included as a dielectric medium and a vehicle for heat transfer from the active part to the tank walls. Some gas-filled (sealed-tank) designs are pressurized with nitrogen, while others are filled with one of several formulations of dielectric Freon[2]. Freon is chosen for this application because of its superior dielectric and heat transfer characteristics, as compared with nitrogen or air. However, greenhouse-gas concerns caused the Freon gases commonly used at the time to be pulled from the market in the 1980s, and the acceptable replacement gas is significantly more costly. Needless to say, Freon-filled transformers are no longer available on the market, but there are many remaining in service.

Whether Freon-filled or nitrogen-filled, sealed-tank transformers are self-cooled only, because internal fans would be inaccessible for maintenance or inspection. Another distinction of the sealed-tank enclosure is the necessity of bringing main conductors out of the sealed-tank using air-to-air bushings. Also, whereas other dry-type designs allow for hardwired links for changing tap connections, capability of tap changing (if provided) for the sealed-tank design requires a DETC, with an operating shaft penetrating the tank. For high-voltage bushing terminal connections, a sheet metal high-voltage terminal compartment is provided. For low voltage, a compartment is provided or provisions are included for close-coupling the transformer to a low-voltage switchgear lineup or bus duct.

Figure 2-5 is an example of a sealed-tank enclosure.

[2] *Freon* is a registered trademark of E.I. du Pont de Nemours & Company.

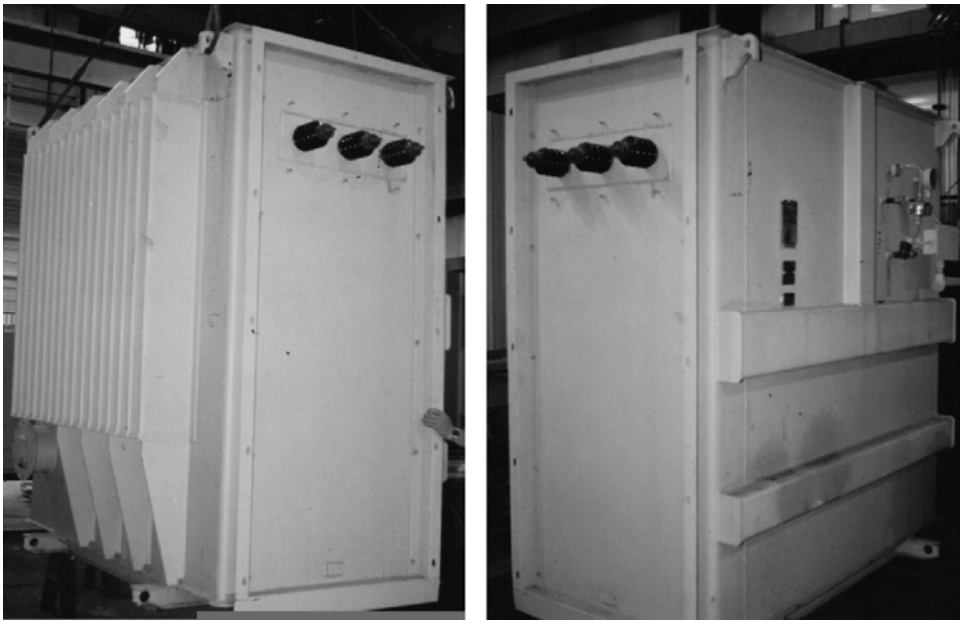


Figure 2-5
A sealed-tank enclosure (front and back)

2.3.2 Active Part (Core and Windings)

The active part of a transformer consists primarily of the core, coils (windings), leads, bus, clamps, and braces that make up the electromagnetic portion of the transformer. It should be noted that active parts (sometimes referred to as *core* and *coil assemblies*) are available in two basic designs, although only one applies to dry-type power transformers. The two types are shell-formed and core-formed.

A very brief description of shell-formed design is to say that wound coils are suspended and core is built up around and through them. Therefore, the core forms a shell around the coils. Although there are shell-formed instrument transformers and shell-formed large power (liquid-filled) transformers, this design is not practical for small and medium power transformers.

Core-formed design involves cylindrical or rectangular coils being wound in preparation for installation onto appropriate limbs of an E-section of core (or equivalent with another number of limbs). The E-section is a completed core with the top yoke removed. See Figure 2-6 for an illustration of the core.

A description of each major part of a core-form transformer follows.

2.3.2.1 Core

Modern transformer cores consist of grain-oriented magnetic steel. The core steel is thin insulated pieces called *laminations*, which are used to minimize circulating current within the core and between laminations. This steel is cut/stacked into the appropriate number of legs that, along with the top and bottom yokes, make up the magnetic loops as appropriate for the particular transformer being manufactured. Figure 2-6 shows a laminated core.

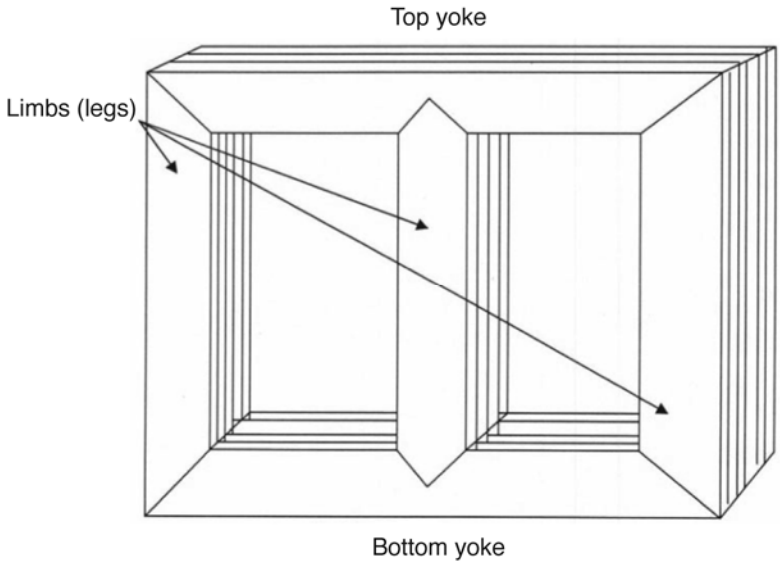


Figure 2-6
A simple illustration of a laminated core

Small power transformers will be of butt-lap design for efficiency of construction. Butt-lap joints consist of packs (or books) of one size that butt the next piece. The significance of the butt-lap design is that, although it provides ease of assembly, this joint is not as efficient at transferring flux from limb to yoke (or vice versa). Therefore, increased losses will result in higher joint temperatures (relative to core temperature). For larger sized transformers, the assembled core is made up of mitered joints (each lamination cut on the bias to form a joint) and step-lap construction (a joint design to minimize heating as flux transitions from one piece to the other). In the step-lap design, each book consists of a number of different lamination lengths, providing very efficient flux transfer (as compared with butt-lap). Figure 2-7 shows step-lap mitered core joints.

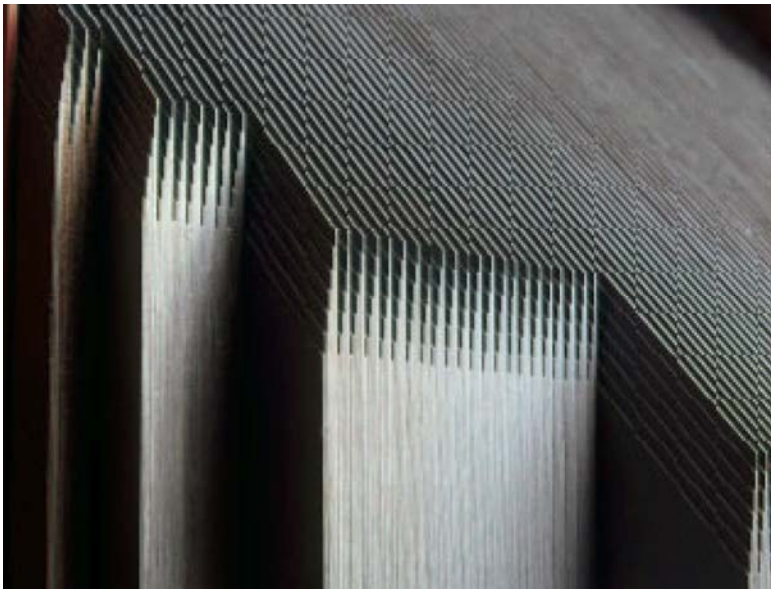


Figure 2-7
Step-lap mitered core joints
Used with permission from ABB

Core limbs/legs (the sections of core that extend through the windings) for small transformers typically consist of single-width laminations so that, when stacked, the cross section is a square or a rectangle and (for small transformers) the windings are rectangular to match. For larger transformers, various widths of laminations are used to form a stacked limb of circular cross section. This design allows for a more efficient fill of the space within a circular-wound winding.

Cores for larger transformers are insulated from the case and ground with a single point brought out and grounded intentionally. This provides a point of test to ensure that a second grounded point has not developed. A second grounded point would allow for circulating currents through the grounded frame system, with resulting increased losses and heating.

2.3.2.2 Winding Designs

Various designs are chosen for the windings of transformers based upon cost optimization, ratings of the transformer, short-circuit duty, impedance requirement, and so forth. Some of these basic designs are discussed as follows:

Sheet/strip winding. This is the most common design for low-voltage windings in small and medium power transformers today. Typically, it is used with rectangular windings, but it is sometimes included as the low voltage of circular-wound transformers. For this design, a full sheet of copper or aluminum (or several strips wound together that make up a full sheet), along with insulation, is wound on a high-density pressboard tube. The sheets (or strips) are simply wound (along with the paper that will insulate the turns from each other) around a form. The winding and form (when the coil is completed) will slip down onto

the leg of the core. The winding turns are counted from the first turn (closest to core) to the last turn (farthest from the core). An advantage (other than cost savings) of this design is that the winding's electric center (an important characteristic with regard to short-circuit duty) self-adjusts (by a shift in current density) to align with the wire-wound high-voltage winding's electric center. Therefore, the axial (vertical) short-circuit forces are theoretically eliminated. Transformers using this type of winding often have little or no coil bracing for vertical support. Figure 2-8 shows a low-voltage sheet wound coil.



Figure 2-8
Low-voltage sheet wound coil
Used with permission from ABB

Layer winding. This winding consists of insulated round or rectangular wire and turns that are simply wound from top of the cylinder to the bottom and then back (some designs are wound from the top to the bottom, and then a run-back takes the conductors back to the top to begin the next turn). This design is optimum for windings with a relatively small current rating. Axial spacers are inserted between some layers to provide ducts for heat removal.

Circular or rectangular windings can be typically found in transformers with up to 2500 kVA capacity; however, for windings greater than 2500 kVA, the designer typically will use circular windings.

Disk winding. This winding is formed basically by winding from the core out, forming a disk and then either by providing a drop-down to begin another disk from next to the core out or by shifting the conductors over and reverse-winding the alternate disks (from the outside inward). Radial spacers are installed between disks to provide dielectric clearances and a path for air to get between disks for removing heat. Figures 2- 9 and 2-10 show disk winding.

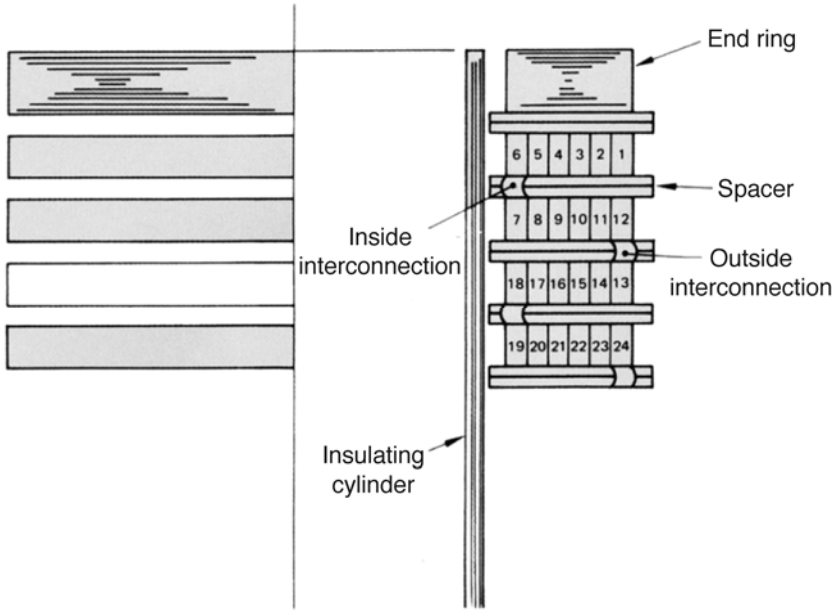


Figure 2-9
Disk winding, schematic
Used with permission from SPX Waukesha

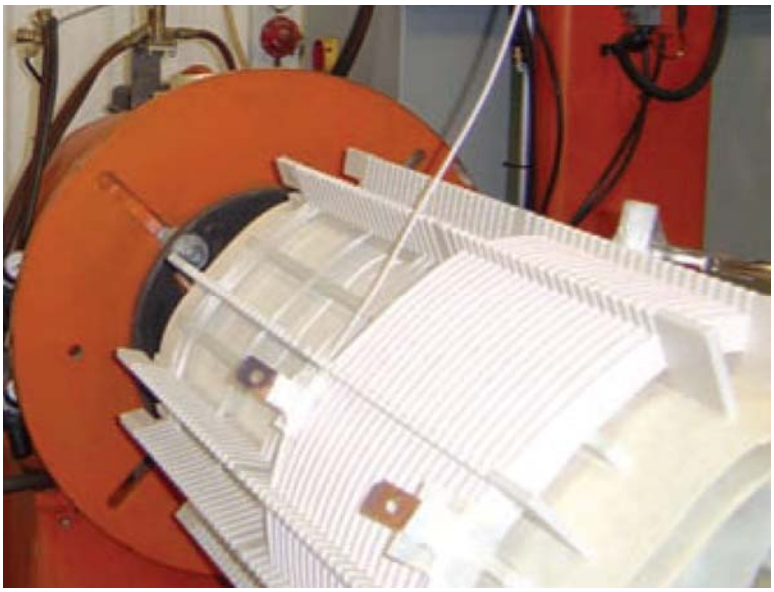


Figure 2-10
Disk winding, photo
Used with permission from ABB

Helical winding. For windings that must carry very large currents, a helical design is typically the choice. This winding starts at one end of the form, and a large bundle of rectangular, individually paper wrapped wires are pulled together to form a mass of conductors with an appearance much like the disk wound described previously. The mass of conductors is wound around the form with an appropriate number of radial spacers inserted between each turn as it comes around. The turns of this winding are counted from top to bottom, because each bundle represents a turn. Perhaps an appropriate analogy is to say that the bundle of conductors spirals around the center point much like a mechanical spring. Although most cast coil windings are of disk construction, winding turns are arranged (in the casting) for optimum balance of dielectric, thermal, and manufacturability concerns. Figure 2-11 shows a helical winding.

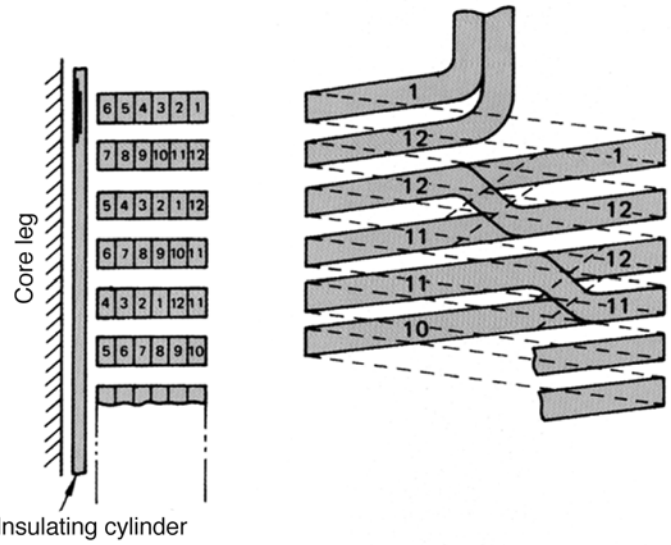


Figure 2-11
Helical winding
Used with permission from SPX Waukesha

The preceding basic types of windings are common in open wound transformers. Because of special physical restraints and opportunities, cast coils do not necessarily conform to these traditional winding types.

Circular Versus Rectangular Coils

Most small dry-type transformers include cores that are stacked with one width of steel, forming a core that has a rectangular cross section for limbs and yokes. The coil that is fitted around each limb is typically rectangular (conforming to the core), as well. Most of the cooling duct area is installed in the front and back of this coil, with little or no duct space in the core window or on the ends. This technique results in an oval shape to the outer radius of the coils. The area between coils is usually stuffed out so that each coil restrains its neighbor from being forced out (to a more rounded shape) in the event of a through fault.

Key O&M Cost Point
The choice of rectangular winding for the high-voltage coil and sheet winding for the low-voltage coil will be the least costly option.

The rectangular design allows for substantial cost savings from reduced core steel, tank steel, and oil volume. Rectangular design used to be confined to approximately 2000 kVA and smaller, primarily because of short-circuit concerns. However, during the past several decades, this design has become available in increasingly higher capacities and voltage ratings with manufacturers citing design improvements resulting from short-circuit testing and analyses. For example, on larger rectangular transformers, heavy plates are bolted or welded on the ends of the active part to provide restraint to those areas for the event of a through fault. The application of sheet-wound low-voltage windings provides (at least theoretically) no axial short-circuit forces.

For a given set of ratings for a dry-type transformer, the choice of rectangular wound high-voltage coil with a sheet low-voltage coil will be the least costly option.

2.3.2.3 Leads, Clamps, and Braces

Key Technical Point
Conductors must be braced and insulated to maintain dielectric integrity while withstanding a short circuit.

For three-phase (and most single-phase) transformers, individual windings must be interconnected in order to simplify the customer's connections. Each winding's neutral lead must be combined and routed to a common connection area (usually adjacent to line terminals). Winding leads must be connected together to form a delta configuration. Terminals for series/multiple windings must be brought out to a convenient area for the customer to make his or her choices. Depending upon operating amperes and operating voltage, as well as short-circuit duty, these interconnecting conductors can be made up of leads (cables) or bus—with clamps and braces designed accordingly. Of particular concern for short-circuit duty are leads or bus routings that run parallel to each other. Clamps and braces must withstand dielectric stresses, as well as short-circuit duty. An important point to be made is that conductors must be braced and insulated so as to maintain dielectric integrity while withstanding a short circuit.

2.3.3 Insulation Systems

Key Technical Point
To extend the thermal life of a transformer with a 220°C insulation system, allow only an 80°C or 110°C temperature rise.

Insulation systems for dry-type transformers are available at various temperature ratings that must be coordinated with the thermal design of the transformer. For all but the smallest power transformers, the very typical thermal rating (allowable temperature) is 220˚C, otherwise known as *H class*. The basis for this temperature is assuming a 150˚C winding rise for the transformer, a (maximum peak) 40˚C ambient, and a 30˚C hottest spot rise (over average winding rise). (Therefore, 40˚C+150˚C+30˚C = 220˚C). Because the primary contributor to thermal aging of a transformer is its insulation system, the theoretical thermal life of the transformer can be increased by specifying a 220˚C insulation system and a winding rise lower than 150˚C (for example, an 80˚C or 110˚C rise). On the other hand, to purchase the least costly transformer, specify a 150˚C rise for a 220˚C insulation system.

Key O&M Cost Point
Purchase the least costly transformer, specify a 150°C rise for a 220°C insulation system.

Temperature rise limits for continuously rated dry-type transformer windings are shown in Table 2-3.

Table 2-3
Limits of temperature rise for continuous rated dry-type transformer windings [2]

Insulation System Temperature Class (°C)	Winding Hottest-Spot Temperature Rise (°C)	Average Winding-Temperature Rise by Resistance (°C)[a]
130	90	75
150	110	90
180	140	115
200	160	130
220	180	150

[a]Higher average winding temperature rises by resistance can apply if the manufacturer provides thermal-design test data substantiating that temperature limits of the insulation are not exceeded.

Table 2-4 contains some examples of solid materials used in insulation systems of dry-type transformers.

Table 2-4
Examples of materials used in insulation systems [2]

Solid Insulating Materials	Binding Insulating Materials
Mica	Polyester resins
Porcelain	Epoxy resins
Glass	Silicone elastomers
Glass fibers	Silicone resins
Aramid sheets/fibers	Polyamide resins
Cast epoxy	Polyester—imides
Cast silicone	
Polyamide sheet	
Polyester film	

Note: the lists of materials in this table do not purport to be complete. They are only intended to identify generically some typical insulating materials for illustrative purposes.

Dry-type power transformers use only high-temperature solid insulation materials for application in the windings, such as mica and Nomex sheets, porcelain and epoxy blocks, Nomex wire wrap, and fiberglass sticks.

2.3.3.1 Freon

It should be noted that the Environmental Protection Agency (EPA) has imposed restrictions on the use of some dielectric Freon gases because of greenhouse gas concerns. When some Freon gases are leaked to the atmosphere, they are believed to be harmful to the environment. Therefore, Section 608 of the EPA's Clean Air Act of 1990 (and subsequent amendments) requires that leaks of certain Freon gases be repaired within 30 days (with some exceptions) and prohibit continuing leaks beyond a maximum allowable leak rate, based on percentage of total volume that would be released in a year's time.

Two Freon gases commonly found in sealed-tank transformers are Freon 115 (C_2F_5CL) and Freon 116 (C_2F_6).

Since Freon 115 and Freon 116 were removed from the market, C_3F_8 has been used as an environmentally acceptable substitute for repressurizing sealed tanks.

2.3.4 Accessories

Optional accessories that are available for dry-type transformers, listed by transformer type, are as follows:

- General-purpose (small power) transformers:
  - Weather shields
  - Wall mounting brackets
- Medium power transformers (open-wound and cast coil):
  - Provisions for jacking
  - Provisions for lifting
  - Fans
  - Hottest spot indicator
  - Thermal controls for fan operation
  - Weather shields or outdoor enclosure
  - Current transformers
  - Neutral grounding resistors
  - Surge arrestors
- Medium power transformers (sealed tank):
  - Provisions for jacking
  - Provisions for lifting
  - High-voltage and low-voltage bushings
  - High-voltage terminal compartment
  - Low-voltage terminal compartment or flange connection
  - Hottest spot indicator
  - Gas thermometer
  - Current transformers

- Neutral grounding resistors
- Surge arresters
- Pressure/vacuum gage with alarm relay
- DETC

2.4 Principal Considerations in the Design and Construction of Transformers for Nuclear Plants

In nuclear power plants, dry-type transformers are often used as vital components of the auxiliary systems, stepping down voltages to provide power to medium- and low-voltage switchgear and motor control centers, which provide power to motors, pumps, lighting, battery chargers, and other components. When the load to which power is being provided is vital to the safe shutdown of the generating unit or serves some other vital function, the dry-type transformers may be qualified as Class 1E (or nuclear safety-related), with special requirements in addition to those specified for normal duty transformers. The purpose of the qualification requirements for Class 1E transformers is to verify that the particular design of the transformer will withstand even the most extreme environmental and operational conditions conceivable while operating in its particular environmental conditions.

Depending upon the application and operating environment, Class 1E transformers could be subject to the following qualification standards:

- IEEE Standard 344
- IEEE Standard 323
- IEEE Standard 638

All class 1E transformers must be seismically qualified in accordance with IEEE 344, Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Generation Stations. Qualification may be by actual test or by analysis based on testing of similar transformers. Actual testing is typically done on a shaker table, designed to vibrate the transformer in simulation of an earthquake. The requirement for seismic qualification must be specified to the prospective manufacturers because special design characteristics might be necessary. For example, the designer might find it necessary to provide special support of the active part for lateral restraint. Caution: if the seismic design includes directly securing the transformer to the enclosure (without noise isolation), enclosure vibration and excessive noise can result as unintended consequences.

In addition to seismic qualification, transformers qualified as Class 1E may be subject to more general qualifying requirements of IEEE 638, Standard for Qualification of Class 1E Transformers for Nuclear Power Generating Stations, which is intended for transformers serving in mild environments.

Transformers qualified as Class 1E may be subject to more general qualifying requirements of IEEE 323, Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations, especially if the transformer serves in a harsh environment.

As part of the qualification of the transformer, short-circuit qualification may be included. Qualification will be either by in-depth analysis of the design by the manufacturer, by comparison to a similar transformer that has been tested, or by actual test of the purchased transformer. Short-circuit qualification by actual testing will require a special test facility that has a strong enough power source to provide the short circuit current that is required.



Key Technical Point
Short-circuit qualification testing will require a special test facility with a strong enough power source to provide the short circuit current.

Some other service conditions are important to consider for proper operation and service life of the transformer, depending upon the relevant operating environment.

2.4.1 Power Quality

With growing use of solid-state equipment, such as uninterruptable power supplies (UPSs), computers, high-energy discharge lights, electronic ballasts, and variable frequency drives, power quality has become an increasing concern for components in the auxiliary systems of generating stations. Such loads will result in an increase in the nonlinear nature of the currents and generate harmonic currents that cause transformers and system neutrals to overheat and destroy themselves. The nonlinear harmonic current and these harmonics might be sufficient to cause overheating and high noise levels in the transformer. Excessive harmonic content of load circuits will result in high levels of stray losses in the transformer and can cause overheating. As covered previously, high temperatures in the winding are directly related to the expected life of the transformer. If the dry-type transformer is excessively noisy or is running hotter than expected based on total loading, power quality should be investigated as a possible cause.



Key Technical Point
If the transformer is excessively noisy or is running hotter than expected, power quality should be investigated as a possible cause.

When a nonlinear load is supplied from a transformer, it is sometimes necessary to derate the transformer capacity to avoid overheating and subsequent insulation failure. The K-Factor is used by transformer manufacturers and their customers to adjust the load rating as a function of the harmonic currents caused by the load(s). K-Factor is a weighting of the harmonic load currents according to their effects on transformer heating, as derived from American National Standards Institute (ANSI)/IEEE C57.110. A K-Factor of 1.0 indicates a linear load (no harmonics). The higher the K-Factor, the greater the harmonic heating effects. For more information on this topic, see Appendix D.

When buying a new transformer, if the transformer is to supply loads that are made up substantially of these types of equipment, it can be prudent to have a study performed to predict harmonic content and include this special loading information in the transformer purchase order or specification.

2.4.2 Radiation

If the transformer is to operate in an area subject to high levels of radiation, it would be prudent to have a study of components done to ensure that short-term or long-term performance will not be affected.

2.4.3 Seismic

If the transformer is to be designated *nuclear safety-related*, seismic qualification level must be determined for the service location. Qualifying the transformer for safe/reliable service under this condition might require special design. For example, special supports can be added to the standard design to ensure that the transformer's active part does not tip over or shift and that the enclosure does not distort to a point of transformer dysfunction. Also, hold-down bolts that are typically removed after the transformer is in its operating position might be required to stay in place. See IEEE 344 for more details of seismic qualification requirements.

2.4.4 Temperature



Key Technical Point
A key to long operating life of a transformer is to avoid high temperatures, particularly in areas adjacent to insulating materials.

A key to expecting a long operating life of a transformer is to avoid high temperatures, particularly in the areas adjacent to insulating materials. As has been covered previously, a major contributor to aging in insulation is temperature over time.

When purchasing a new dry-type transformer, additional assurance of conservative operating temperature can be gained by procuring a temperature rise that is lower than the highest allowable for the insulation thermal rating. For example, one could purchase an 80°C rise transformer with a 220°C insulation system. All of the previous recommendations still apply for maintaining the cooling system in optimum condition, but, in addition to the expectation of a reasonable life expectancy, the opportunity to qualify for a life extension and/or to load somewhat beyond nameplate is gained.

2.4.5 Airborne Contaminants—Choosing a Transformer

In choosing a transformer for a particular application, a primary consideration should be the environment in which the transformer will be expected to operate (see Section 3 for more on transformer selection).

2.5 Coatings and Sealants

The varnishes and epoxies used in the process of forming the coils (windings) of dry-type transformers serve to seal the winding conductors against moisture and other contaminants that would potentially allow dielectric breakdown and failure of the transformer.

The purpose of processing coils of dry-type transformers after they are completed is to provide for long-lasting service with high resistance to moisture getting into paper, tolerance for particle buildup, and ease of cleaning. For many years, the standard process was a varnish dip or vacuum impregnation of resin. In more recent times, several alternative methods have evolved for improved performance of the intended purpose.

2.5.1 Conventional Vacuum-Pressure Impregnation

The simplest and most common of the processes is to first dry the coils in an oven to remove all moisture. Then, the coils are vacuum-impregnated with a resin and brought back to atmospheric pressure before removing. The resin is then baked to cure it into its hardened, permanent state. The result is a conventional dry-type transformer with high tolerance for moisture and airborne contaminants that might otherwise cause dielectric breakdown and equipment failure.

Vacuum-pressure impregnation (VPI) transformer coils are shown in Figure 2-12.

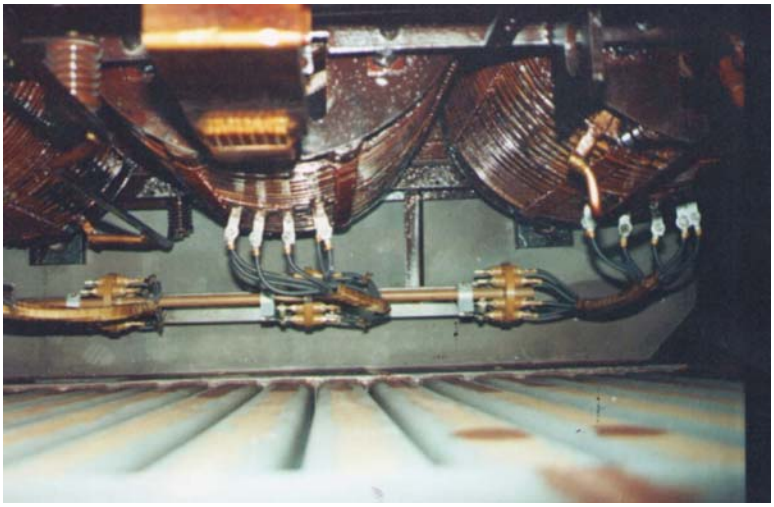


Figure 2-12
Example of a VPI transformer—inside a sealed-tank enclosure

2.5.2 Vacuum-Pressure Encapsulated/Resin-Encapsulated

Another process available also involves vacuum/pressure, but the medium applied is silicone resin. The result is a coil that is encapsulated in a silicone resin that remains pliable in service. At a glance, these two processes can appear the same. However, unlike the vacuum impregnated process, the encapsulation process results in the winding being sealed within the processed materials but not necessarily impregnated by it. In some cases, the process of dipping in the medium (for example, silicone) and curing is repeated to provide a second dip in order to get a thicker coating. Figure 2-13 shows a resin-encapsulated transformer winding.



Figure 2-13
A resin-encapsulated transformer winding

The vacuum-pressure encapsulated (VPE) process provides a positive seal around the coils to prohibit entry of contaminants and moisture and is considered superior to VPI for withstanding harsh environments.

2.5.3 Solid Cast

For maximum isolation of the turns of the winding from the surrounding environment, coils are cast into an epoxy cylinder, wherein a vacuum has drawn epoxy into all voids and has filled the mold, leaving an epoxy cylinder that contains the winding within. Unlike the previously described processes, the cast coil is not a thin coating but rather is a solid block, permitting no moisture or other foreign materials to penetrate any part of the winding. Because the resulting cylinder has substantial thickness and because epoxy is brittle without some type of strengthener, there are basically two methods of providing strength: packing out with fiber glass or use of a homogenously filled resin. For cylinders that include fiberglass, the volume of the mold is essentially packed out with glass fiber so that no significant areas of the mold will be without fiberglass when the epoxy cures. By contrast, for the filled-epoxy coil, silica or another granular material is mixed with the epoxy as it enters the mold so that the entire casting is strengthened by the fill eliminating the concern for pockets of pure resin.

The process of casting involves installing a mold around the completed winding, pulling a vacuum, and introducing the liquid epoxy under tightly controlled temperature and pressures to impregnate the winding. The rate at which the epoxy is drawn into the mold and the temperature controls are critical to allow curing to take place from the inside out, so as to prevent stresses being set up that will result in cracking. The final product is a coil that is embedded in a solid (cylindrical) block of reinforced epoxy and impenetrable by airborne contaminants. Cooling ducts for this coil are provided by steel bars that are included in the mold and removed as part of the disassembly of the mold.

Additional advantages of the cast coil design over other dry-type designs include inherent short-circuit withstand and increased dielectric ratings. (Cast coils can be provided with the same BILs as for equivalent liquid-filled transformers.)

Figure 2-14 provides an example of a solid cast dry-type transformer

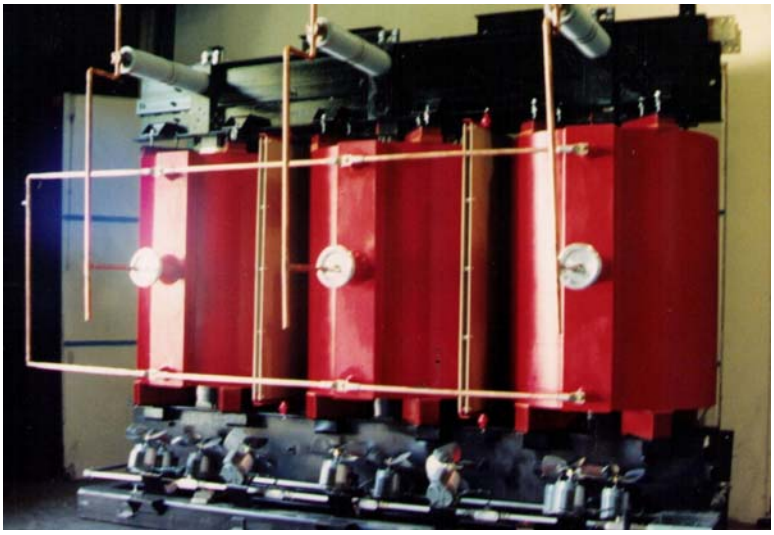


Figure 2-14
An example of a solid cast dry-type transformer (filled resin)

2.5.4 Processes Applicable to Sheet Windings in Cast Coil Transformers

Because of the typically lower-voltage ratings of secondaries of dry-type transformers, they are often provided as sheet-wound coils (because of design/manufacturing advantages for high currents/low voltages). The physical distinctive of a copper or aluminum sheet winding provides different challenges for providing resin or epoxy sealing. Often, because of lower concerns for contamination or moisture entry for the low-voltage winding, there is no special treatment for this winding, although it might get dipped along with the high voltage. When specified to be fully cast, the transformer can be provided with a sheet low-voltage winding that is encased in a molded cast—the same as the high voltage. Otherwise, the low voltage of a cast coil transformer may not be cast at all. For some designs, the sheet low-voltage winding is wound onto a cylinder of

hardboard and wrapped, when completed, in another cylinder of hardboard. Then, the ends (top and bottom when uprighted) are filled with poured epoxy to seal the winding for protection from airborne contaminants. This is another form of encapsulation.

2.6 Cooling Classes

All transformers are sources of waste heat resulting from the losses generated in the core and coils, especially when loaded. Therefore, it is important that the heat be sufficiently dissipated to avoid creating hot spots in excess of the insulation's thermal rating. Dry-type transformers always include cooling ducts to allow the cooling medium (air, nitrogen, or Freon) to flow (primarily by natural convection) through the windings. Some transformers are provided fans under the coils to assist in air movement up and through the windings. Some transformers include ventilation grills/louvers to allow exchange of air in the enclosure with outside ambient. The various options relating to cooling designs are summarized in Table 2-5, and each class is discussed afterward.

Table 2-5
Transformer cooling classes [2]

Description	Class	International Electrotechnical Commission Equivalent
Ventilated self-cooled	AA	AN
Ventilated forced-air-cooled	AFA	AF
Ventilated self-cooled/forced-air-cooled	AA/FA	AN/AF
Nonventilated self-cooled	ANV	____
Sealed self-cooled	GA	____

Note: in the IEC symbols, *N* indicates natural.

2.6.1 Self-Cooled

Class AA is the designation for identifying that the transformer is self-cooled. That is to say that there is no forced (fan) cooling included. Air within the coil ducts is heated and rises and escapes the coil, drawing cooler air into the bottom of the coil. Likewise, the heated air rises in the enclosure and escapes the ventilating grill near the top of the enclosure, causing cooler outside air to be drawn into the lower grills.

2.6.2 Forced-Cooled

Class AFA transformers are dependent on forced cooling (fans) for heat removal, and fans must run continuously while the transformer is loaded. Enclosure openings can include filters with a dependence upon fans to force air through the filters (therefore, no self-cooled rating is included).

2.6.3 Double-Rated

Class AA/FA for transformers designates that the transformer has a self-cooled rating (kVA) but has a higher rating (kVA) when fans are operating. The boost in kVA rating can be by 25%–50%, depending on the base kVA rating of the transformer. Table 2-6 shows standard forced-cooled ratings.

Table 2-6
Dry-type transformer self-cooled and forced-air-cooled ratings [3]

Self-Cooled (AN) Ratings (kVA)	Forced-Air-Cooled (AN/AF) Ratings (kVA)
750	1,000
1,000	1,333
1,500	2,000
2,000	2,667
2,500	3,333
3,750	5,000
5,000	6,667
7,500	10,000

Note: fan cooling increases the kVA rating by 33%. If a critical load is being supplied by the transformer, the load should be within the transformers self-cooled (AN) rating, because a cooling fan could fail.

2.6.4 Nonventilated

Class ANV transformers are so designated to indicate that they are air-cooled but without designed provisions for air exchange with the surrounding environment. For nonventilated enclosures, the heated air from the winding and core rises to the top of the enclosure and is cooled as it comes into contact with the enclosure, which absorbs heat from the air and radiates it to the outside environment. As the air is cooled, it drops to the bottom of the enclosure and is drawn into the coil once again.

2.6.5 Sealed-Tank

Class GA transformers are provided with sealed tanks that are designed to withstand a range of pressures for operation within the temperature range of the transformers' operation. Whereas all previous transformers covered use air as the cooling medium, the sealed tank, by virtue of its being sealed from the surrounding atmosphere, allows for using other gases. The two gases commonly used are nitrogen and Freon. Freon has better dielectric properties than nitrogen (resulting in higher BILs available) and also better heat transfer characteristics (allowing smaller tanks) but has fallen into disfavor because of greenhouse gas concerns from leakage to the atmosphere. Freon gases that are in use are of various formulations, some of which are of greater concern than others for their relative effects on the environment.

2.6.6 SF6 GA Transformers

These transformers are not known to be installed in the United States but are mentioned herein because they exist and might be available. Although SF6 has excellent dielectric properties, its heat transfer properties are not good. For SF6 to cool the transformer, the gas must be pumped in a cycle through a cooling loop, much like pumping oil for cooling a liquid-filled transformer.

2.7 Reactor Design and Construction

Dry-type reactors have some physical characteristics similar to dry-type transformers, such as a coil that creates of a flux field generated by current passing through the coil; however, a reactor has no secondary coil or terminals. An iron core-type reactor has a core similar to that of a transformer, except that the core has an air gap that is installed to restrain flux in the magnetic circuit. This reactor is constructed much like a transformer, in that coils are wrapped around the limb of a core (usually in a layer configuration) and the magnetic circuit is closed by a top and bottom yoke. The winding conductors are wrapped with paper or coated with epoxy, enamel, and so forth and should be maintained in the same manner as a typical dry-type transformer of similar physical size. An iron-core reactor is (if appropriate) enclosed in a sheet-metal housing that is grounded during operation. Figure 2-15 shows a sketch of an iron core, and Figure 2-16 is a photograph of an iron-core reactor.

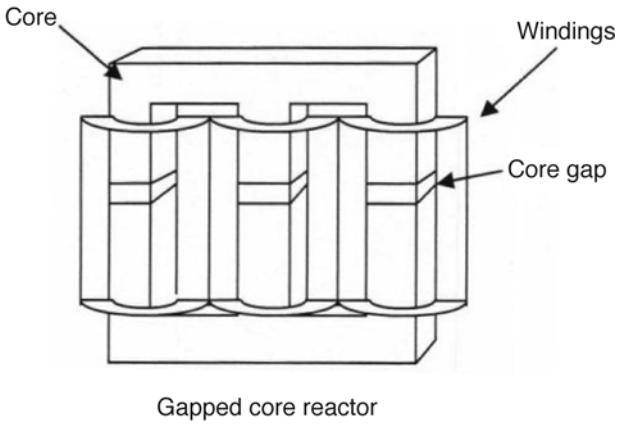


Figure 2-15
Sketch of an iron-core reactor



Figure 2-16
Example of a dry-type gapped core reactor
Used with permission from ABB, Publication LV016

On the other hand, an air-core reactor has no core but is rather a simple coil; it is constructed on a support frame, and the coil and frame are mounted on insulators to allow for high flux around the bottom and top of the coil and to provide clearance for the entire coil to be energized. Figures 2-17 and 2-18 show air-core reactors.

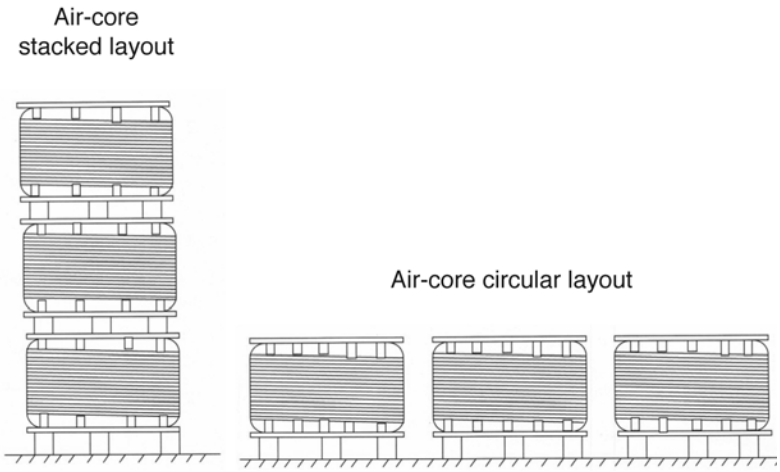


Figure 2-17
Sketch of air-core reactors

The air-core reactor often does not have a metal enclosure, because of the high magnetic field surrounding it. This field presents challenges for its installed location—especially when installed indoors. Some of these challenges are covered in Section 3.



Figure 2-18
Example of an air-core reactor (outdoors)
Used with permission from ABB

Components that make up a dry iron-core reactor are similar to those listed for a dry-type transformer of similar size and voltage rating.

The reactor ratings include the following:

- Continuous voltage
- Fault current rating (10-second rating and 1-minute rating)
- Continuous current rating
- BIL
- Frequency (60 Hz for United States)

Section 3: Application of Dry-Type Transformers and Reactors

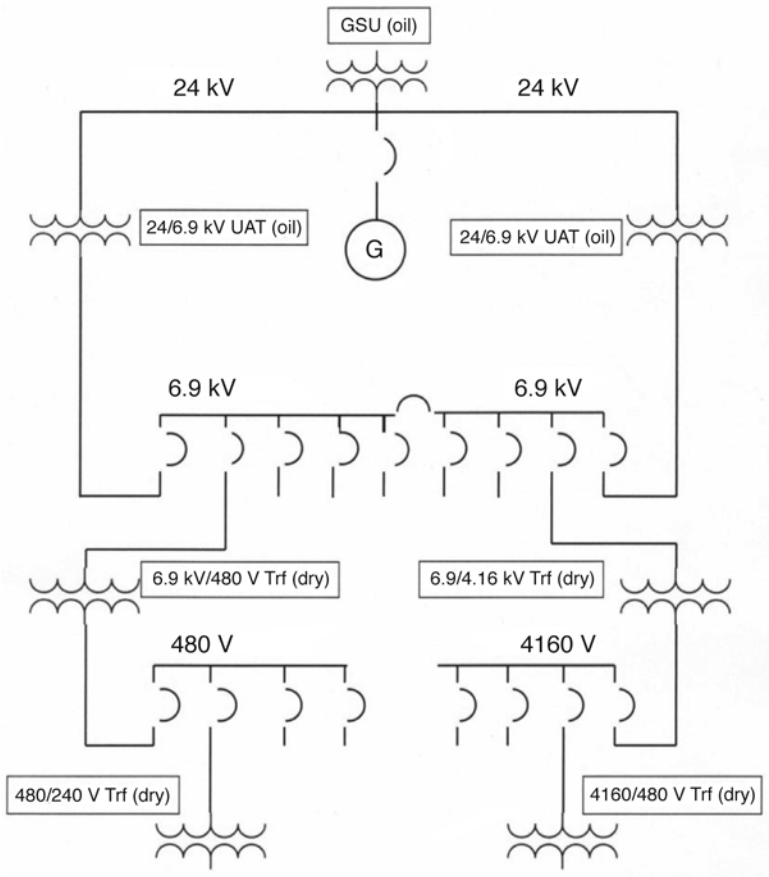
Dry-type transformers in nuclear power plants are typically used for load center (often called *unit secondary load centers*) applications. A conventional load center often includes an assembly of low-voltage metal-enclosed switchgear fed by a dry-type transformer. The typical size of transformers used in these applications can range from 500 to 3000 kVA.

Where consequences of fire and/or spill represent acceptable risk, liquid-filled transformers are the economical choice. Also, for high-voltage or large-capacity transformers, there is no other choice than liquid-filled. However, where voltages and capacities are within the range of availability of dry-type transformers, the additional cost should be weighed against the value of providing power without risk of spill or fire.

For virtually any application of less than 20 MVA and less than 25kV, there is a dry-type transformer and an enclosure that is suitable. Dry-type transformers are aboard ships, on wind generators, in high-rise buildings, in backyards, and in power-generating plants. They are used to provide power to single-load large motors and are close-coupled to switchgear to provide power for distribution to many small loads.

3.1 Location in the Power System

Dry-type transformers have many uses at a nuclear plant. Figure 3-1 illustrates typical locations of dry-type transformers in a nuclear plant.



UAT = unit auxiliary transformer
Trf = transformer
GSU = generator step-up unit

Figure 3-1
One-line diagram showing typical locations of dry-type transformers

The dry-type transformers illustrated in Figure 3-1 are typically used in what are known as *secondary unit substations*, which are typically indoor applications. Most industrial and commercial customers prefer dry-type distribution transformers for indoor applications because they present fewer fire risks. They are also suitable for installation near load centers, thereby reducing cabling costs and improving voltage regulation.

3.2 Special Applications

The nuclear safety-related category applies to systems, structures, components, procedures, and controls (of a facility or process) that must be ensured to remain functional during and following design-basis events. The functionality of the equipment ensures that key regulatory criteria, such as levels of radioactivity released, are met. Examples of safety-related functions include shutting down a nuclear reactor and maintaining it in a safe-shutdown condition.

The terms *nuclear safety-related* and *Class 1E* are synonymous as they relate to electrical equipment.

Unusual operating conditions are conditions outside of the normal operating conditions to which equipment might be exposed with expectation of continued operation for some given amount time (for example, excessive loading).

3.2.1 Nuclear Safety-Related

Dry-type transformers have many applications in a nuclear generating station for providing power to load centers and to larger individual loads (motors, adjustable speed drives, and so forth), including special applications of dry-type transformers as power feeds to safety buses. For example, the dry-type transformer can serve to step down voltage from a diesel-generator or other on-site emergency shutdown source of power. Also, dry-type transformers can serve to step down voltage from the secondaries of unit auxiliary transformers or station auxiliary transformers to provide a normal source to these same loads. To determine whether a particular transformer in a distribution system must be considered nuclear safety-related, an analysis must be conducted to evaluate whether the component is essential to safe shutdown. Because of their critical role in providing power for safety systems, the transformers that are considered essential to safe shutdown must comply with Nuclear 1E Qualification requirements for environmental conditions according to IEEE Standard 323 (also see IEEE Standard 638) and seismic qualification according to IEEE Standard 344.

Compliance with these standards means that not only must the transformers be designed and manufactured to be capable of normal service, but they must be qualified for reliable service under specified operating and environmental conditions for the duration of the defined qualified life of the transformers. See IEEE Standard 323 for detailed requirements for qualifying the transformer. The purpose of the qualification program is to verify that the transformer will not only perform its function when installed but will continue to perform reliably before, during, and after a design basis event. A design basis event is postulated for a particular installation and can include such events as a loss-of-coolant accident and a seismic event.

3.2.2 Unusual Operating Conditions

Operation at high altitudes. Unless specified differently, the designer of a transformer will assume installation at an altitude less than 1000 m above mean sea level. If the installation is higher than that, a special design could be required to compensate for lower dielectric strength and reduced cooling effectiveness of the air. See IEEE Standard C57.12.01 for more information and correction factors that are applicable.

Special loading. Extreme transient load demands, such as high in-rush currents for large motors, can represent unusual mechanical stresses on the winding conductors and spacer blocks of the transformer and can necessitate special design to adequately restrain the mechanical forces. When such special loading is anticipated, the transformer specification should include a description of the loading characteristics so that an adequate design can be quoted.

Excitation limits. When a transformer is overexcited, magnetic saturation of the core can cause high stray losses and subsequent overheating of the core, as well as high noise levels. Care must be taken in specifying and applying the transformer that impressed voltages do not exceed standard limits. See IEEE Standard C57.12.01 for more detail.

Nonsinusoidal loading. If power quality issues are expected, because of the nature of the loading, quality factors should be studied prior to purchase of the transformer to determine whether a special design is justified. A means of communicating harmonic levels is to assign a K-Factor [4]. Transformers can be designed to provide power to circuits with high K-Factors without overheating.

See Appendix D for additional discussion on harmonics and K-Factor ratings of transformers.

Seismic environment. If the transformer is to be applied in an area subject to significant seismic activity, the specification should include parameters to which the transformer is to be designed/constructed. Sometimes, even a minor alteration of the standard design can mean the difference between failure and successful withstand of the event.

3.3 Non-Safety-Related Applications

Power transformers are expected to perform their intended function for a reasonable lifetime even if not serving in Class 1E applications. All of the same issues can apply, but non-safety-related applications do not include the stringent qualification requirements of Class 1E. It would be prudent to examine the application carefully before specifying or ordering any transformer and to choose the type of active part and the type of enclosure to fit the application. If there are water or steam pipes in the room, one might choose to add deflectors to avoid spraying (or dripping) onto the transformer or to provide the transformer with rain shields or an outdoor enclosure. If the environment in which the transformer is to operate will be hotter than the standard 30°C average/40°C maximum, either room cooling should be added or the transformer should be derated accordingly (or specified for a lower winding rise) to compensate.

3.4 Spill Containment and Fire Protection

Avoidance of vaults, spill containment pits, firewalls, fire suppression systems, and/or requirements to maintain distance from buildings and other equipment can mean significant cost savings. Because all materials that make up dry-type transformers are resistant to fire initiation and propagation, none of the requirements for spill or fire applies. Dry-type transformers are typically the least costly choice when compared with a liquid-filled transformer that requires spill containment and/or fire protection—and when total installed cost is considered.

3.5 Transformer Protection

Because power transformers provide a vital function in a distribution system and their failure represents substantial cost in down time, lost revenue (sometimes), and replacement cost, it would be prudent to provide a level of protection for them, as practical based upon the value of the transformer and the implications of a failure. The most basic form of protection of a dry-type transformer is provided by an upstream circuit breaker, designed to trip on overcurrent. A medium or large transformer will be served by a dedicated breaker, whereas small power transformers can be combined with other transformers or other types of loads on a single shared breaker, in which case fuses should be installed on primary of these transformers. An electrical fault on the transformer circuit will be expected to trip the breaker, isolate the fault, and prevent or minimize damage to the transformer(s).

A grounding resister can be installed between the neutral of a wye-connected winding and ground to limit phase-to-ground fault current allowed through the winding.

Surge arresters or surge suppressors can be installed on the primary circuit of the transformer to limit voltage transients from breaker operations or from a lightning surge on the line. Lightning arresters are normally recommended for dry-type transformers installed outdoors. The typical BIL for a dry-type transformer is lower than for liquid-filled transformers, and arresters should be rated accordingly.

For dry ventilated transformers, the only local indication of abnormal condition will typically be winding temperature. An alarm can be provided to indicate when temperatures reach a preset limit.

Some sealed-tank transformers are provided with winding temperature indicators and some only with a gas temperature indicator. It can be prudent to install remote alarm capability for overheating if it is not already provided.

Key Technical Point
Loss of pressure in a Freon-filled transformer can be a trigger for implementation of EPA restrictions on operations.

For a sealed-tank design (unless there is a leak), gas pressure generally follows temperature, and a pressure gage is provided. Normal operating range for some sealed-tank transformers is -2 to 4 psig (0.875 to 1.29 bar). However, most sealed-tank designs are pressurized to maintain a positive pressure even for an unloaded condition (for example, 0.5 to 6 psig (1.05 to 1.43 bar)). Although a high pressure can be an indication of extreme temperature in the transformer (the temperature gage should be checked for accuracy), a lower than expected pressure can be an indication of a leak. Loss of pressure in a Freon-filled transformer can result in an overheating condition and also can be a trigger for implementation of EPA restrictions on operation.

An alarm can be provided for loss of power to fans.

When transformers installations involve exposure to lightning or other surges (for example, high voltage connected to an exposed outdoor bus), BIL levels should be specified accordingly and installation of lightning/surge arresters should be considered. See IEEE Standard C62.2 for information with regard to application of arresters. It has recently become a recommendation to apply lightning/surge arresters to dry-type transformers used indoors.

Key Technical Point
It has recently become a recommendation to apply lightning/surge arresters to dry-type transformers used indoors.

Fault protection typically consists of overcurrent protection by breaker settings. See Figure 3-2 for a schematic of typical dry-type transformer protection.

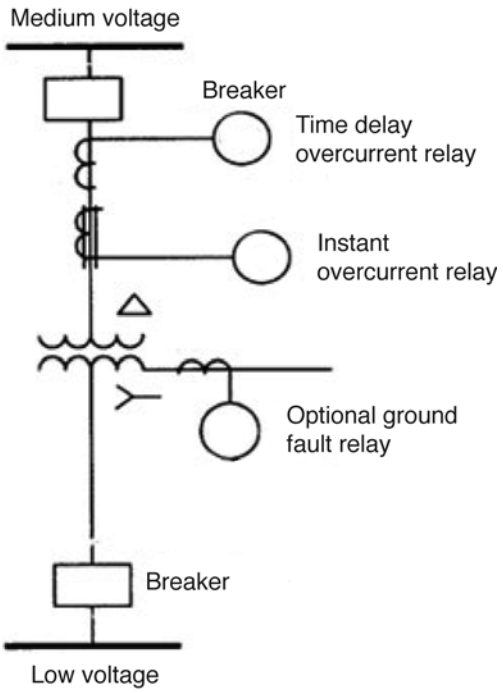


Figure 3-2
A typical dry-type transformer protection schematic

3.6 Installation Environment

When locating transformers, areas exposed to high moisture levels, water or chemical spray or vapors, or high levels of dust should be avoided. When possible, areas of high traffic including transport of trash, debris, or other contamination hazard should be avoided. Where there is potential for water (or other chemical) spray or leaks, suitable outdoor enclosures should be considered to compensate. When moist conditions are expected, not only should the enclosure type be carefully chosen but provisions for compensating for expected condensation, such as thermostatically controlled heaters, should be included.

It should be noted that the active parts of sealed-tank dry-type transformers are impervious to environmental hazards, because the active part of the transformer is hermetically sealed from the surrounding environment. However, care must be taken in cold environments when the gas in the sealed tank condenses at low temperatures (when the transformer is deenergized for substantial periods during cold weather). One possible solution is to include heaters inside to preclude the low temperatures.

When the installation is to be outdoors, the design should include provisions for shielding not only the active part but also the ancillary components (instruments, panels, and control cabinets) from rain, snow, sleet, and airborne contaminants. Also, the roof design should avoid standing water, especially in the vicinity of roof-mounted bushings.

3.7 Space and Access



Key Human Performance Point
When choosing a location for a transformer, allow enough space around the enclosure for personnel access and safe working conditions.

When choosing a location for the transformer, care must be taken to allow enough space around the enclosure for personnel access, panel removals or door opening, safe working conditions, and adequate air for ventilating the transformer. Recommendations for particular transformers can be found in the manufacturer's instruction books/leaflets.

Whether locating indoors or outdoors, care must be taken to allow a pathway for removal and for bringing in a replacement. A periodic review of access issues might be prudent, because cable tray and pipes can be added at any time that would interfere with removal or replacement of the transformer.

When the transformer is to be installed inside a room, certain precautions are recommended. Sufficient air conditioning or ventilation must be provided to the room to maintain air temperature at the inlets to the transformer at or below standard assumptions of ambient temperature (40C is the peak temperature, whereas the maximum daily [24 hours] average is 30C). For more details and guidance with regard to this issue, see IEEE Standard C57.94.

3.8 Transformer Loading

Transformers are designed for continuous loading at their nameplate kVA rating(s), when operating under certain environmental and loading conditions. To expect a normal life of operation, any exception to the assumed conditions must be evaluated. For example, the loading is expected to be at the design frequency, with limited harmonics. The power factor is assumed to be 0.8–1.0. The ambient is assumed to be 40°C or below, and the average for any 24-hour period is assumed to be 30°C or below. The transformer can be loaded beyond nameplate kVA without voiding the expected life under certain conditions, which are provided in IEEE Standard C57.96.

3.9 Sound

The audible noise generated by dry-type transformers is produced primarily by the vibrations in the core at a frequency twice that of the applied voltage. If the noise level of the transformer is higher than expected, the cause could be overexcitation, excessive harmonics, a failing fan motor, or a failure to loosen tie-down bolts upon installation. Also, for transformers that are seismically qualified, the core might not be designed for isolation from the frame and enclosure, and core noise might be transmitted to the sheet metal enclosure by direct bolting/welding.



Key Technical Point
If the noise level of the transformer is higher than expected, the cause could be overexcitation, excessive harmonics, a failing fan motor, or a failure to loosen tie-down bolts upon installation.

3.10 Enclosures

Whereas dry-type transformers are best adapted to indoor applications, the inclusion of National Electrical Manufacturers Association (NEMA) 3R enclosures will provide adequate protection from the elements. There are special precautions, however, for outdoor applications of ventilated enclosures. They are as follows:

- If the transformer is to be deenergized for extended periods of time, the lack of a heat source within the enclosure can allow condensation. Thermostatically controlled heaters should be included to preclude condensation. This caution applies to all dry-type transformers but especially to outdoor installations.
- Rain shields, if provided separately, are to be installed so that precipitation shall not be allowed to enter the enclosure.
- Roof-mounted bushings should be elevated to prevent water from standing against or entering the gasket area of the mounting. Roofs should be designed to shed water.
- The transformer should be mounted off the ground (on railroad ties or concrete base) to prevent contact with standing water.

For indoor applications where there are no significant risks of water spray or unusual airborne contamination, a NEMA 1 enclosure may be an acceptable choice.



Key Human Performance Point
Ventilation grills should be specified as appropriate for the installed environment.

Ventilation grills should be specified as appropriate for the installed environment. For example, if the transformer is to be installed in a high-traffic area, a requirement for single-V or double-V grills, to prohibit accidental entry by wires, rebar, or other such thin material, might be appropriate.

Dry-type ventilated or nonventilated enclosures can be designed for cable terminations within the transformer compartment, wherein high-voltage and low-voltage cables are brought right into the enclosure for termination, or they may include separate compartments for these connections. Air-to-air bushings or slotted insulation barriers can be supplied to penetrate the enclosure for an external high-voltage or low-voltage connection. Provisions for close-coupling to a low-voltage switchgear or a nonsegregated phase bus can be provided, as well as flexible bus connections.

Of course, sealed-tank design is a special case, and the typical transformer includes a high-voltage terminal compartment with bushings for penetrating the tank and either a low-voltage terminal compartment or provisions (including bushings and flange) for close-coupling to a low-voltage switchgear or a nonsegregated phase bus.

If there are ancillary components required for connection to the high voltage (of the sealed-tank transformer), they are usually installed in the high-voltage terminal compartment. Such devices as surge arresters, capacitors, or disconnect switches will be incorporated into this compartment. If such components are to be required for connection to the low voltage, they can be installed in the low-voltage terminal compartment. If the design includes close-coupling the transformer to the switchgear, provisions must be made in the switchgear compartment for the components.

3.11 Transformer Selection, Sizing, and Loading

3.11.1 Transformer Cooling

Dry-type transformer cooling classes are listed in Table 2-5.

Ambient temperature conditions should be determined before ordering a transformer, to determine whether it is higher than the ambient assumed for transformer design. If the ambient is more than 30°C average for a 24-hour period or peaks at more than 40°C, the kVA rating of the specified transformer can be increased or a lower winding rise can be specified. If the ambient conforms to (or is lower than) the standard, the transformer might be expected to be loaded to nameplate capacity without overheating. If ambient is lower or higher than the standard assumed, the dry-type transformer can be operated above or below its nameplate capacity, as suggested in Table 3-1.

Table 3-1
Self-cooled continuous loading on basis of average ambient temperature [5]

Type of Unit	Maximum Rated Hottest-Spot Temperature (°C)	Hottest-Spot Temperature in a 30°C Ambient (°C)	Percent of Rated kVA/°C Increase for Average Ambient Less Than 30°C or Decrease for Average Ambient Greater Than 30°C
Ventilated self-cooled	150	140	(0.57)
	180	170	(0.43)
	220	210	(0.35)
Sealed self-cooled	150	140	(0.65)
	180	170	(0.49)
	220	210	(0.40)

To determine temperatures for an existing indoor service location, a temperature recorder can be placed in the area. Temperatures for an outdoor location can be obtained from the National Oceanic and Atmospheric Administration. Unless it is known that the transformer loading will peak in winter, the temperatures of interest should be on/near the hottest day of summer.

See Table 3-2 for per unit loading capability as a function of ambient temperature.

Table 3-2
Continuous per unit loading capability as a function of ambient temperature [5]

Cooling Mode	Maximum Ambient Temperature (°C)	Insulation Temperature Class (°C)		
		130	150	180
AA	10	1.20	1.16	1.12
	20	1.13	1.11	1.08
	30	1.07	1.06	1.04
	40	1.00	1.00	1.00
FA	10	1.15	1.13	1.10
	20	1.11	1.09	1.07
	30	1.05	1.04	1.03
	40	1.00	1.00	1.00

3.11.2 Transformer Sizing

The appropriate capacity for a new transformer is the sum of the following considerations:

- Total loading to be connected to the transformer initially
- Future loading to be connected to the transformer (if known)
- Allowance for starting currents for all connected motors that can be started simultaneously

Allowance for future load growth (typically assumed to be about 20% of initial loading). A special case for sizing of transformers is when two transformers are serving a double-ended switchgear lineup, with a tie breaker that, when closed, will allow powering the entire lineup from one (or the other) of the two transformers. In this case, each transformer is typically sized to provide power to the entire lineup.

Also a special case to be considered is whether the loading is likely to be at a very low power factor. If this is the case, either the power factor should be improved or the transformer load capacity should be adjusted for operation on a derated basis.

Because dry-type transformers (especially open-wound dry-ventilated or nonventilated transformers) are dependent upon air for dielectric strength and cooling, it should be noted that the characteristics of air vary depending upon elevation above sea level because of the changes in air density. For installations more than 1000 m (3300 ft) above sea level, transformers are designed with larger air spacing and use correction factors, such as those in Table 3-3, to obtain adequate air dielectric strength.

Table 3-3
Dielectric strength correction factors for altitudes greater than 1000 m (3300 ft) [2]

Altitude		Altitude Correction Factor for Dielectric Strength
(m)	(ft)	
1,000	3,300	1.00
1,200	4,000	0.98
1,500	5,000	0.95
1,800	6,000	0.92
2,100	7,000	0.89
2,400	8,000	0.86
2,700	9,000	0.83

Table 3-3 (continued)
Dielectric strength correction factors for altitudes greater than 1000 m (3300 ft) [2]

Altitude		Altitude Correction Factor for Dielectric Strength
(m)	(ft)	
3,000	10,000	0.80
3,600	12,000	0.75
4,200	14,000	0.70
4,500	15,000	0.67

3.11.3 Specification

Among the characteristics that should be included in the purchase order or specification for a dry-type transformer are the following:

- Rating in kVA, including multiple ratings if forced cooling is to be provided
- Process type (VPI, VPE, or cast coil)
- Frequency
- Single- or three-phase
- Primary and secondary voltage ratings
- BIL for primary and secondary, including any neutrals
- Deenergized voltage taps (as needed, but most typical is ±2, 2.5% of nominal value)
- Winding configurations (for example, delta or wye) and phase displacements
- Whether neutral is solidly grounded or grounded through an impedance device
- Impedance with impedance base kVA (typically the lowest kVA rating of the transformer)
- K-Factor (where applicable)
- Temperature rise
- Designed for indoor or outdoor service
- Type of enclosure (ventilated, nonventilated, or sealed)
- Any special requirements for ventilating grills (for dry-ventilated transformers)
- Special requirements (bushings, flanges, jacking/lifting points, and so forth)
- Special requirement for direct replacement needs (for example: dimensional, terminal locations, weight, and base design)

- Accessories (arresters, capacitors, temperature indicator, and so forth)
- Nuclear safety-related (if applicable)
- Seismic or other special duty (if applicable)

3.12 Reactor Applications

Reactors are used in power circuits for a variety of reasons, such as current limiting, harmonic filtering, volt-ampere-reactive compensation, neutral grounding, switching transients, circuit detuning, load balancing, and other power conditioning.

Most applications associated with reactors are on the transmission system, and, therefore, most power plant personnel will not typically be involved with their application or maintenance. There are only limited usages where plant personnel will encounter discrete reactors.

Shunt reactor sizing is based upon transmission system design and transmitted power operation. Loading is controlled by the voltage applied to the terminals.

Reactors, both oil-cooled and dry-coil, can be designed and used for a number of purposes in switchyards or local to plant or loads, including the following:

- Buffer reactors to mitigate transients for electric arc furnaces by operating the furnace at low electrode current and long arc length (sometimes called *electric arc furnace reactors*).
- Capacitor (or damping) reactors installed in series with a shunt-connected capacitor bank.
- Power flow control reactors installed in series on transmission lines.
- Filter reactors applied in conjunction with capacitor banks to form series-tuned harmonic filter circuits or can be used in conjunction with capacitor banks and resistors to form broadband harmonic filter circuits.
- Shunt reactors connected phase to ground, phase to neutral, or between phases in a power system to compensate for capacitive current.
- A bus reactor is a current-limiting device for connection between two different buses or two sections of the same bus for the purpose of limiting and localizing the disturbance because of a fault in either bus.
- For power factor correction, the reactor connected as a load (from line to ground).
- Line traps connected in series on the power circuit to allow power frequencies to flow, while restricting certain carrier frequencies.

- For limiting short circuit currents, the reactor is connected in series, allowing normal load currents to flow, while blocking current surges.
- As neutral grounding devices, reactors connected between the neutral of a transformer (or generator) and ground. (By limiting neutral current flowing to ground, single phase-to-ground fault current is limited, while allowing enough current to flow to activate a relay or trip a breaker.)

3.12.1 Application Issues

Steel core. For dry steel-core reactors, the issues/concerns for the environment and operating conditions are similar to those of dry-type transformers, and enclosure options are similar. The area for installing the reactor should be clean and dry and not subject to water or chemical spray or leakage. The area should not be subject to caustic vapors or flooding. If the core-type reactor is to be located outdoors, suitable outdoor enclosures shall be furnished to avoid rain, snow, sleet, and so forth. For outdoor installations, it is presumed that an enclosure will be provided because the steel in the core is susceptible to rust when prolonged moisture is present.

Air core. For dry air-core reactors, similar concerns for a clean, dry environment are valid, but, because a core is not included, the reactor can be designed for outdoor exposure without an enclosure and without special concerns for weather. However, any unusual conditions that can restrict cooling or degrade dielectric clearances should be noted when specifying this device.

Stray flux concerns. Also, a special concern for choosing or preparing a location for installing an air-core reactor, whether indoors or outdoors, is the potential effect of this device on surrounding components/materials. Because this type of reactor has no core, the magnetic flux generated by the coil is unrestrained and will extend far beyond the boundaries of the reactor. All conducting materials—steel, aluminum, copper, and so forth—in proximity to the reactor have the potential to heat up in response to currents induced in them. If the reactor is furnished in an enclosure, it can be expected that the manufacturer will design adequate shielding to prevent enclosure heating, and this shielding will alleviate much of the concern for the surrounding environment. To avoid problems with the installation, the purchaser must work closely with the provider to ensure that connecting terminals and conductor routings are appropriately designed, that any conducting materials in the area are not a problem, and that steel columns or rebar in walls will not heat up. For outdoor installations, the same issues are of concern, and distance to steel beams, columns, and so forth must be considered. The design of the installation must be coordinated closely with the manufacturer.

The air-core reactors can require relatively large space because the magnetic field spreads freely in the surroundings and can cause excessive heating in iron reinforcements in concrete walls, floors and ceilings, wire fences, and other metal items.

The distance should be sufficiently large to keep the magnetic field below 80 A/m at the floor and at the ceiling. At adjacent walls, the magnetic field should not exceed 30 A/m^2.

For an installation of an air-core reactor without an enclosure or shield, one manufacturer cautions as follows:

> The supplier should inform the purchaser regarding necessary distances from the reactor, at which the magnetic field values have declined to those mentioned above.
>
> Considerable forces due to the field can draw loose iron items in the vicinity into the reactor and cause damage. So it is recommended to keep the surroundings clean.
>
> Possible disturbing influence of the magnetic field on the functioning of other electro technical product in the vicinity must be considered.
>
> Humans should not regularly stay for long time periods near the strong magnetic field from such reactors when current is flowing through the windings.
>
> Persons wearing pacemaker should stay far away from such reactors. [6]

Section 4: Aging, Degradation, and Failures

It is generally believed that failure occurs when a transformer can no longer withstand the stresses imposed upon it during operation.

Degradation that occurs over time can be considered aging. However, accelerated degradation in a short time can also lead to a failure. This general statement can be made of most structures, systems, and components, and transformers are not an exception. Understanding how transformers degrade over time and the factors that contribute to degradation and to the rate of degradation is essential to understanding aging.

The main factors that contribute to dry-type transformer aging are temperature, moisture, and time. Other factors that contribute to degradation include extreme operational conditions (such as overloads), adverse conditions within its surroundings (such as a high temperature and humidity index), through faults, and electrical surges.

Transformers are designed to operate within certain voltages, loadings, and temperature levels. If these parameters are maintained in specified limits, a transformer will operate well beyond its intended design life. Transformer design life is based on load for a time at temperature.

Life extensions at nuclear stations have resulted in consideration for using dry-type transformers and reactors far beyond their original design life. Therefore, it is important to gain an understanding of the factors that determine end of life for a transformer. It is recommended that condition assessments for the purpose of life extension of dry-type transformers and reactors include reviews of maintenance practices and past/current operating conditions in order to provide an expectation of continued operating life.

There are two times in the life of a transformer when risk of failure is greatest (that is, the odds of a failure are greatest): at the beginning of its service life (infant mortality) and when it has been in service for many years (aging).

4.1 Infant Mortality

Shipping and handling is quite important and can contribute to premature failure of a transformer. Whether by ship, rail, or truck, shipments can be hazardous to the life of a transformer. As a transformer is jostled back and forth and bumped up and down, the structural integrity of the active part is challenged. If not adequately blocked/braced, parts will move out of their intended positions relative to each other. A most common displacement is spacer sticks falling out of axial cooling ducts, leaving the coils unsupported and more susceptible to a through fault. Coil blocking, top and bottom, is also vulnerable.

Why is risk high for a new transformer? The answer lies in the events leading up to the initial energization. Consider the following facts at this point:

- The transformer has been tested in the factory but has never seen full load and full voltage at the same time.
- The transformer might have been fully assembled at the factory but has been (partially) disassembled for shipment and reassembled in the field.
- The transformer has just experienced the hazards of shipping/handling.
- Although factory testing cannot fully verify the transformer's ability to perform its function successfully over time, field testing is even more limited. The true test comes when the transformer is subjected to full voltage and full load current continuously.

If a transformer has been properly specified for its service parameters and is properly designed and manufactured to those parameters, if it is not abused in shipping/handling, and if it is properly assembled and tested, it should not fail early in its service life.

4.2 Aging

4.2.1 General Discussion

Because aging is degradation over time, why do some transformers seem to operate well beyond their design life while others develop problems and have to be taken out of service early?

Over its operating life, a transformer can suffer the impact of thermal, mechanical, electrical, and electromagnetic stresses. How a transformer responds to these stresses during normal and unusual operating conditions will influence how (and when) it degrades and eventually fails.

Of course, some transformers might be manufactured with inherent weaknesses, but early and periodic inspections provide the opportunity to identify the weaknesses and allow the owner to determine whether appropriate actions are in order.

Most of the components that make up a transformer have extremely long lives, when operated within the normal limits of operating temperature and loading. Under normal limits of moisture concentrations and temperatures, steel, copper (or aluminum), and many other components have basically unlimited life expectancies. The primary component that determines the life of a transformer is the winding insulation materials. The life of the insulation is a function of temperature and time, as well as typical moisture levels during its service life. Because insulation temperature is a result of ambient temperature and winding temperature rise and because winding rise is a result of loading, the correlation between ambient temperature and loading can be used to determine (or to control) the expected life of the transformer. For example, in cooler climates, a transformer can be loaded somewhat beyond nameplate while maintaining a standard life expectancy. On the other hand, by restricting load or by specifying a lower temperature rise than the maximum allowable for the insulation rating, a longer life expectancy can be applied for a standard ambient (especially relevant for achieving a desired qualified life for nuclear application).

4.2.2 Aging as Related to Operation Beyond Hottest Spot Temperature Rating

The following discussion and charts were taken from IEEE C57.96-1999 [5]:

The rate of thermal aging of insulation is presumed to be consistent with the Arrhenius theory, in which it can be said that the logarithm of insulation life is a function of the reciprocal of absolute temperature, in accordance with the following relationships:

$$\log_{10} \text{life}\ (t) = (B_{10}/T) + A_{10}$$

or

$$\log_{e} \text{life}\ (t) = (B_{e}/T) + A_{e}$$

where

t is the time in hours

T is the absolute temperature, in Kelvin, at the hottest spot (that is, $\Theta_{HS} + 273$)

Θ_{HS} is the temperature, in °C, at the hottest spot

A_{10}, B_{10} are constants to the base 10 for the appropriate life expectancy curve of each insulation system, as shown in Figure 4-1

A_e,B_e are constants to the Naperian base for the appropriate life expectancy curve of each insulation system, as shown in Figure 4-2.

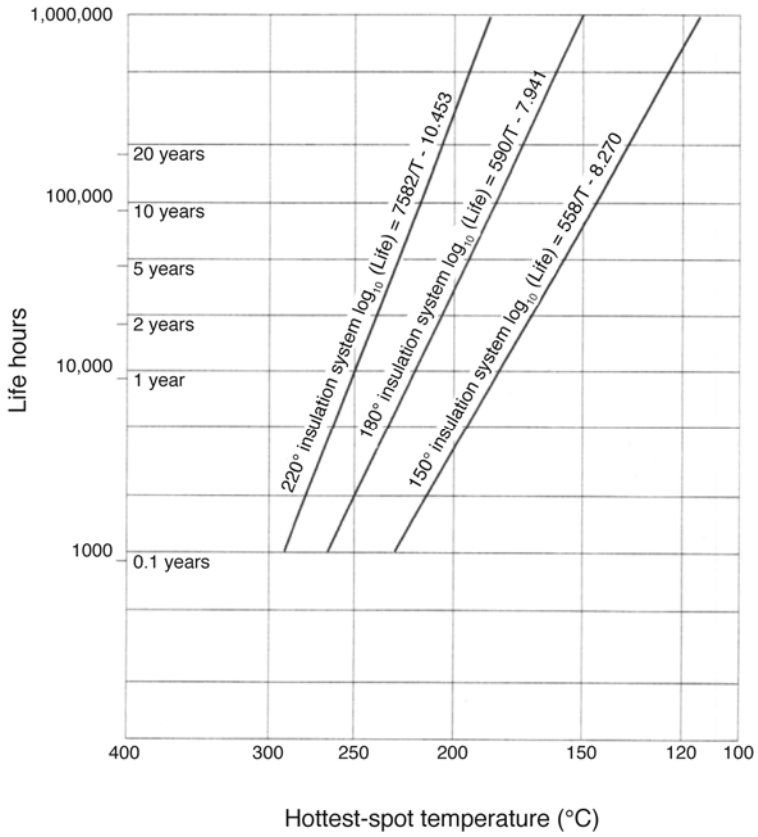


Figure 4-1
Life expectancy curve—base 10

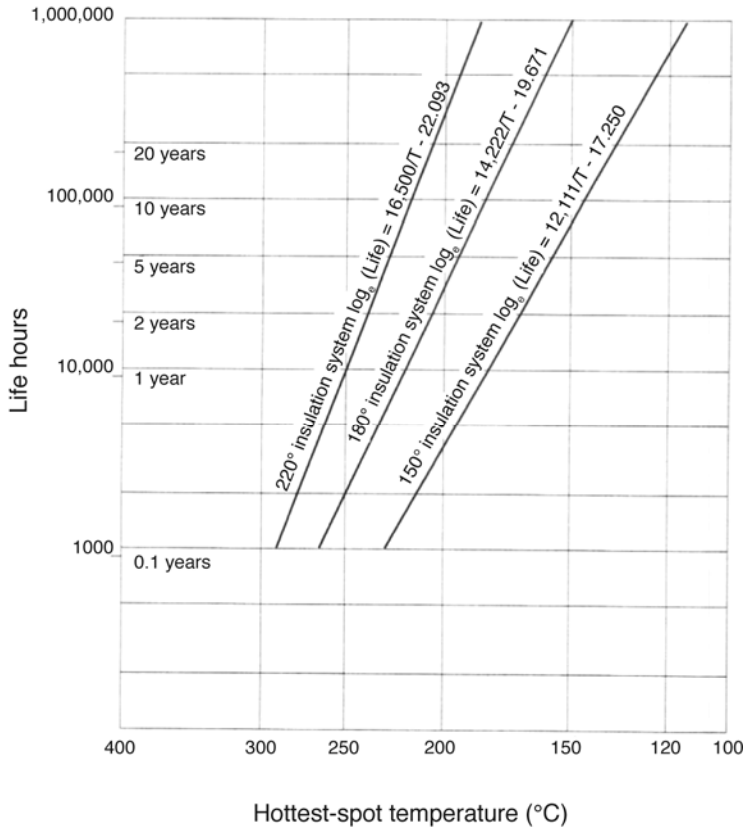


Figure 4-2
Life expectancy curve—base e

4.3 Various Operational Stressors

Degradation of a transformer begins as soon as it is placed in service. The results of that degradation will be evident over time by the following:

- Reduced dielectric strength
- Reduced mechanical strength
- Reduced thermal capability
- Reduced electromagnetic capability

Failure occurs when the level of either of these properties is reduced so that a transformer can no longer perform.

4.3.1 Dielectric Stress

Dielectric stress will result when the transformer sees an increase in voltage beyond its design capability. This overvoltage can be of short duration, such as from switching surges, or sudden load reduction on the circuit that the transformer shares with other loads. The overvoltage can be of long duration because of a discrepancy between transformer rating and applied voltage (such as a wrong choice of tap connection). In any case, the overvoltage condition can exceed the voltage withstand capability of the transformer insulation and cause an internal dielectric breakdown (or fault), or it can begin a process of carbon tracking on insulating surfaces that can ultimately fail the transformer by causing a fault.

Aging on the insulation materials is directly related to factors such as the time the transformer has been in service, the temperatures to which the insulation has been exposed, and the moisture levels of the insulation during the service time. The effect of moisture is to accelerate the rate of aging, for a given average temperature. If a transformer is known to be exposed to high humidity, accidental water spray, or windblown rain, corrective actions should be considered if a reasonable service life is to be expected.

Because of overvoltages, deficiencies in insulation materials, designs, or degradation, the insulation can be stressed (weakened) and voltage breakdown can begin. The breakdown can develop quickly, leading to an electrical fault and failure of the transformer, or it can slowly develop by electrical discharges (called *partial discharges* [pd]) that degrade the insulating properties of the material by the development of carbon tracking. If the conditions creating this stress continue, the tracking will eventually evolve into a fault.

Moisture can contribute to reduced dielectric strength in the insulation and lead to surface creepage discharge along pressboard barriers and eventually a flashover.

Aged or stressed insulation can degrade and develop shorts between coil turns in a winding. The type of degradation can lead to overheating in a winding, affect output voltage level, and grow into a major dielectric breakdown (internal fault).

4.3.2 Structural Stress

Structural damage can result while shipping or handling a transformer, causing a shift in conductors relative to each other. Such physical deformation can result in excessive dielectric stress, or cooling ducts can be deformed, causing heat buildup.

Also, a common source of structural damage to transformer windings is a result of the forces that are developed when fault current is passing through the windings. Most of the forces resulting from a through fault are of two types—axial and radial. Axial forces are in parallel with the core leg/limb and cause

vertical movement of one or both windings (relative to each other). These forces are sometimes referred to as *telescoping* forces. They are the reason that coils that are made up of wire-wound primaries and secondaries must be tightly clamped from top to bottom.

Radial forces are in a direction perpendicular to the core leg/limb and are basically repelling forces between the two windings. Forces on the outer (usually higher-voltage) winding are causing the conductors to be in tension, and the forces on the inner (usually lower-voltage) winding are causing the conductors to tend to buckle (because of buckling forces).

Continuous vibration from core noise during transformer operation can also be a problem for the structural integrity of the transformer. If isolating pads under the active part are omitted or if hold-down bolts are not loosened or removed (according to instructions from the supplier) before the transformer is first energized, the 120-hz noise from the core can get into the enclosure and not only generate acoustic noise but also vibrate panel bolts until they fail.

4.3.3 Thermal Stress

Overloading/undercooling. Thermal excursions can result from overloading of the transformer or from undercooling. The overload can be of short duration and very high current (such as during sustained through fault), or it can be of long duration of a nominal overcurrent. Undercooling can be a result of dust/debris blocking coil cooling ducts, fan failure, or blockage of ventilating grill areas (such as from failing to change out filters). In any case, the temperature increase in the winding(s) will result in thermal degradation and premature aging of the insulation materials and shorten the viable life of the transformer. The mode of failure will ultimately be a dielectric breakdown (fault) within the winding(s).



Key Technical Point
Ventilated and non-ventilated dry-type transformers that are periodically deenergized or that are subjected to extreme load cycling should be equipped with thermostatically controlled heaters.

Thermal cycling. Although loading is not expected to be constant for transformer operation, extreme load cycling that is repeated often can be detrimental, especially if the loads are motors and starting currents are substantial. Also, heating up and cooling down can result in moisture accumulation in ventilated and nonventilated enclosures. Transformers subject to such loading excursions should be equipped with thermostatically controlled heaters.

Overvoltage. Continuous (or long periods of) overvoltage can cause excess heating in the core with eventual damage to not only the core itself but also to the adjacent windings of the transformer. Also, circulating currents in the core because of multiple grounds can cause similar results at nominal voltage. In either case, a result is excessive heating in the winding insulation, which can cause premature aging and/or early failure.

Overtemperature and aging. Aging on the insulation materials is directly related to factors such as the time that the transformer has been in service, the temperatures to which the insulation has been exposed, and the moisture levels of the insulation during the service time. The effect of moisture is to accelerate the rate of aging, for a given average temperature. If a transformer is known to be exposed to high humidity, accidental water spray, or windblown rain, corrective actions are to be considered if a reasonable life in service is to be expected.

Detrimental environment. Some dry-type transformers are installed in areas that include dust and other airborne particles and gas vapors. If a transformer must be installed in such an environment, care should be taken to mitigate the consequences by selection of transformer type and/or altering the immediate environment by modification of building or room structure. Because air is a primary dielectric medium for ventilated and nonventilated transformers, airborne contaminants can have a cumulative effect on the transformer's thermal and dielectric performance. Therefore, a significant maintenance task involves periodic inspections and cleaning the transformer as needed.

4.3.4 Electromagnetic Stress

Transformers should be expected to survive a through-fault experience, although they are not typically certified with the ability to survive a particular fault level and duration unless they are specified to do so, with a requirement for the manufacturer to qualify them. However, even for a transformer that is specified to withstand one through fault, it is not necessarily able to withstand repeats of the fault. The fact is that faults are very stressful on the structural integrity of a transformer and the accumulated damage can result in eventual failure. The predominant characteristic of a through-fault failure can be structural, thermal, or dielectric breakdown, but typically all three failure modes are evident.

There are certain special designs for applications where fault duty is repeated (such as for traction loading or furnace application). These transformers are very special and must be specified for their specific service requirements.

4.4 Summary of Industry Experience

This section evaluates industry data on dry-type transformers and reactors. Industry reports along with Institute of Nuclear Power Operations (INPO) and NRC documents have been reviewed. The equipment failure history and the stressors that prevent dry-type transformers and reactors from performing their functions were evaluated. The failures, their causes, and recommendations to prevent their reoccurrence are covered.

4.4.1 INPO Database (Licensee Event Report, Equipment Performance Information Exchange, and Operating Experience Database)

The following is a summary and discussion of the failures documented in the INPO Equipment Performance Information Exchange database.

4.4.1.1 Station 1, Failure 1 and Failure 2

At Station 1, Failure 1 occurred in May 2007 and Failure 2 occurred in September 2003 on two different manufacturers' 4160/480-V three-phase transformers.

Both transformers failed in a very similar fashion. The high-voltage busbars had indications of phase-to-phase arcing and phase-to-ground short. Phase-to-ground indications were found at the end of the transformer assembly. Disassembly of the high-voltage winding and examination of the winding revealed the likely start of the failure. The high-voltage winding consists of several hundred turns of paper-insulated aluminum conductors in four layers of winding. These transformers were forced-air-rated, so the four high-voltage winding layers were arranged with spacers between them to facilitate cooling air flow through the winding. The four winding layers were connected in series with what is commonly called a transition connection. This transition area was the location of highest voltage stress as the voltage potential can be greater than 2 kV. The paper-insulated winding turns were designed to insulate less than 100 V. The failure occurred in the transition area between the second and third coil layers. This was an age-related failure that might have been worsened by the design of the transformer high-voltage windings. Both transformers were manufactured in 1971. According to one of the manufacturers, the transformers should last 20 years, and manufacturers do not recommend operating them beyond 25 years. Both transformers were replaced. The station initiated a program to replace the older dry-type transformers in conjunction with planned bus outages.

4.4.1.2 Station 2

A 30-kVA control power transformer failed because of overloading. Preliminarily, the failure was attributed to a design deficiency. The transformer was undersized for its loads, and the circuit configuration caused transient overvoltage conditions. The corrective action being considered included reviewing the loads and addressing the condition, as needed. Because 30 kVA dry-type transformers are considered highly reliable, no preventive maintenance was being contemplated.

4.4.1.3 Station 3

Failure of a 4160/230-V transformer occurred in May 2004 because of a high-voltage winding insulation breakdown. This resulted in a turn-to-turn failure in the second-phase winding. This turn-to-turn failure led to the second-phase arcing to Phases 1 and 3 and the transformer tripping off-line. This insulation breakdown was a result of a manufacturing defect during the initial fabrication of the transformer and was considered to be isolated and random. The transformer was replaced, and the preventive maintenance program was under review with the goal to provide insight into indications of localized heating.

4.4.1.4 Station 4

Failure of a 6.9/4.16-kV transformer occurred in September 2007 while operating unloaded. The control room received a transformer trouble alarm, and a local check of the transformer revealed that the hottest spot temperature indication gauge was pegged high. Thermography readings were taken of the transformer enclosure, and the highest reading was 93°C. The readings were compared with thermography readings on a similar type of transformer that was running loaded, and the average thermography enclosure reading was found to be 28°C. The cause of the transformer overheating was high core losses resulting from multiple core grounds creating circulating currents. This failure appears to be a result of marginal transformer design. A contributing factor could be an accumulation of dirt and moisture on the core and concrete dust on the winding. Rust was noted between the core laminations, and this could have led to breakdown of the lamination insulation.

4.4.1.5 Station 5

A 1500/2000-kVA, AA/FA, 13,200-V delta to 480-V wye transformer failed high-voltage leads, and the transformer experienced a phase-to-phase failure in April 2004. The two failed leads were in contact with each other, and, over time, corona caused the insulation to degrade to the point where a phase-to-phase failure occurred. The damaged leads were reworked, and, in July 2004, the transformer was energized for an unloaded soak. Five hours into the soak, the transformer failed. It is believed that the high-voltage lead fault that occurred in April 2004 could have affected the high-voltage windings, resulting in the fault that occurred in July 2004. Following the failure in April 2004, Doble[3] testing identified that winding power factors for all phases had significantly increased, and the recommendation was made to retest the transformer before placing it in service. Work processes did not capture this recommendation. An evaluation team is working to address the type and extent of testing of 13.8-kV–480-V transformers following an electrical transient.

[3] *Doble* is a registered trademark of Doble Engineering Company.

4.4.1.6 Station 6

A gas-cooled 1000-kVA, 4160/480-V transformer failed in July 2002. A visual inspection of the transformer indicated degradation of all three coil windings. The faulted transformer was removed and replaced. An investigation of the transformer revealed inadequate varnish near the top of the high-voltage windings. The plant has revised a preventive maintenance program to inspect and, if necessary, VPI treat dry-type transformers that have inadequate varnish on the coils.

4.4.1.7 Station 7

A gas-cooled transformer failed in March 2005. Post-failure testing of the transformer revealed excessive winding insulation degradation and low (high-voltage) winding resistance to ground. This was a sealed transformer, so there were no unusual odors associated with an electrical fault, and a visual inspection of the transformer could not immediately be made. The transformer had been tested earlier in March 2005, prior to the failure. Doble test results indicated unusually high excitation readings. The testing company and station electrical technical support attributed the test results to core magnetization and recommended placing the transformer in service.

4.4.2 NRC 1E Notices, Bulletins, and Circulars

4.4.2.1 1E Information Notice 83-37, "Transformer Failure Resulting from Degraded Connection Cables," failure due to in-rush current

The NRC 1E Information Notice 83-37 involves Brunswick U-1 4160/480-V transformer feeding bus E-6.

The normal feed to bus E-6 was deenergized as a result of inadvertent tripping of one of the station auxiliary transformers during performance testing. This resulted in the emergency diesel generators starting and loading as designed. When bus E-6 was energized, its main feed transformer overheated and tripped off. Inspection revealed that the transformer was damaged beyond repair because of arcing at the C-phase winding tap lug. The winding tap connections are made with stranded aluminum cable. Investigation revealed that the set screw that attaches the barrel of the lug to the stranded cable had been overtightened, causing some of the wire strands to break. When the transformer was energized, the in-rush current caused localized overheating at the lug connection and the resulting failure. Inspection of the remaining 4160/480-V safety-related transformers revealed that eight of 48 cable-to-lug connections had minor signs of degradation. All defective safety-related cables were replaced, and all lug connectors were removed, cleaned, and reinstalled.

4.4.1.2 NRC Information Notice 92-63, "Cracked Insulators in ASL Dry Type Transformers"

The NRC 1E Information Notice 92-63 involves cracks in Westinghouse ASL Dry-Type Transformers at Washington Nuclear Project (WPN), Unit 3, where cracks were discovered on the ceramic insulators that support the high-voltage coils in certain class 1E and non-Class 1E 4-kV/480-V 1000-kVA and 1500-kVA dry-type transformers. Diablo Canyon Nuclear Power Plant, Unit 2, found a hairline crack on a support insulator in a 4-kV/480-V 1000-kVA dry-type transformer. The insulators are in the transformer to support the high-voltage windings. They were arranged around the top and bottom periphery of each high-voltage coil and were held in place by pressure rings, one at each end. Jack bolts apply a compressive force to the pressure rings and are designed to maintain the spatial relationship of the coils during normal operation, a system fault, or a seismic event. Some of the insulators at WPN were installed off-center and not perpendicular to the pressure ring. Westinghouse sent a customer notification letter to all power plants that could have ASL dry-type transformers informing them of this issue.

4.5 Failure Review

The survey in Section 4.4.1 has covered the types of failures of dry-type transformers. The two Station 1 failures were because of manufacturing/design defects. The failure in Station 2 was attributed to being undersized for its loads, and the circuit configuration caused transient overvoltage conditions.

Station 3 and Station 4 failures were because of design defects.

The Station 5 failure could possibly have been prevented by implementing a maintenance program that includes a thorough off-line inspection of all internal and external electrical leads and connections. InterNational Electrical Testing Association–Measuring and Testing Specification (NETA-MTS) and Facilities Instructions Standards and Testing (FIST) 3-30 recommend thorough visual inspection of insulation, bolted connections, and wiring. Performing a thorough visual inspection would have revealed the phase leads in contact with each other. The phase leads could have been rerouted and this failure avoided.

The Station 6 failure could possibly have been prevented by implementing a maintenance program that included a thorough off-line inspection of evidence of deterioration of varnish or resin. ANSI/IEEE Standard C57.94 recommends performing a careful inspection of the insulation varnish or resin. It is estimated that cleaning and recoating the transformer with varnish or resin will extend the life of the transformer by 7 to 10 years.

The cause of the Station 7 failure is unknown.

The Brunswick U-1 identified in Information Exchange Notice (IEN) 83-37 failure was the result of a manufacturing defect. The failure could possibly have been prevented by implementing a maintenance program that included a

thorough off-line inspection of all electrical leads and connections and an on-line thermography scan of all accessible electrical connections. NETA-MTS and FIST 3-30 recommend thorough visual inspection of insulation, bolted connections, and wiring.

The WPN and Diablo Canyon cracked insulators identified in IEN 92-63 were discovered by visual inspection. NETA-MTS and FIST 3-30 recommend thorough visual inspection of insulation, bolted connections, and wiring.

4.6 Stressors, Aging Mechanisms, and Potential Failure Modes

The effects of the preceding elements/stressors are considered to be significant for the overall operating condition of the transformer and/or reactor and their components. Table 4-1 summarizes the stressors acting upon dry-type transformers and reactors and indicates the aging mechanisms, types of degradation, and failure modes that can result from exposure to these stresses.

Table 4-1
Stressors, aging mechanisms, and potential failure modes

Stressor	Cause	Aging Mechanism	Age-Related Degradation	Potential Failure Mode	Comments
Temperature	Ohmic heating, winding, and core losses	Thermal deterioration, cracking	Loss of dielectric strength of organic winding and electrical connection insulation	Dielectric breakdown, flashover	Generally a slow process. Detected by overheating during inspection—for example, thermography.
	Loss/reduction in cooling	Thermal deterioration	Loss of mechanical and electrical properties of solid insulation	Dielectric breakdown; flashover	Generally a slow process. Detected by overheating during inspection—for example, thermography, various Doble tests.
Environmental factors	Moisture and humidity	Decomposition of insulation	Loss of dielectric strength	Insulation breakdown; flashover	Typical for outdoor installations without proper enclosure and indoor high-humidity areas.
Voltage	Contaminants; moisture	Accumulation of contaminants on bushing weather shield	Loss of surface insulating properties; surface tracking	External flashover of bushing between phase and ground	Accelerated in high dust, salt, and moisture environments. Detected by visual observation or bushing tests.
	Low dielectric strength, contaminants	Ionization and corona breakdown	Degradation of insulating materials	Dielectric breakdown; flashover	Detected by periodic inspection.

Table 4-1 (continued)
Stressors, aging mechanisms, and potential failure modes

Stressor	Cause	Aging Mechanism	Age-Related Degradation	Potential Failure Mode	Comments
Current	External fault or surge conditions	Electro-magnetic forces on conductors/ core	Movement or dislocation of windings and/or core	Loss of spacing of windings; turn-to-turn shorts	Not significant at normal current levels. Detected by acoustics or relay activation.
Vibration	Loose internal components	Cyclic wear/fatigue	Wear and possible cracking of components; loss of tolerances, misalignment	Binding; component deformation or breakage	Detected by vibration or acoustics.

4.7 Degradation Effect on Components

The chief components of importance to a transformer are the core and windings, otherwise known as the *active part*.

4.7.1 Core

Cores consist of many thin strips (laminations) of grain-oriented magnetic steel, stacked to form each limb and each yoke. Each lamination is thin and is coated with insulation on each surface to restrain eddy currents between the laminations and thereby reduce core heating and losses when the transformer is energized. Anything that can damage the core insulation, such as vibration, moisture, overexcitation, or heating, can cause the core to degrade.

Multiple core grounds cause high circulating currents and degrade transformer core and iron-core reactor magnetic core. The core problems could be core bolt shorting; shorts between core laminations; core overexcitation; burned, damaged, or displaced core insulation; and/or loose laminations.

The cores can be tested by an insulation resistance test of the core-to-ground (core insulation megger), to verify the integrity of the insulation system. In core-form transformers, megger testing is used to check the core-to-ground insulation level by disconnecting the ground wire/strap for testing and measuring the resistance between that strap and the grounded frame or tank. Low resistance readings are indicative of foreign material between the core and the enclosure or other problems with the core insulation system and should be corrected prior to placing a transformer in service.

Integrity of core mounting prevents loosening or dislocation of the core because of vibration or forces caused by electrical load transients, such as faults. Core loosening is not a commonly expected condition; however, tolerances can be checked to detect any movement of the core or windings.

4.7.2 Windings

Winding insulation can degrade as a result of vibration over a long period of time. Another cause of degradation is insulation aging from overheating, which can be because of overloading or stray flux heating. During fault interruptions and/or switching operations or other abnormal operations, insulation can be subjected to severe mechanical and electrical stresses that occur initially during the initial peak voltage and then by oscillatory voltages that can last several cycles. Even though stresses can be caused during switching operations, they are much higher during short circuits. Severe damage to winding insulation can be identified by visual inspection or insulation resistance, insulation power factor, or turns ratio testing.

Windings can be tested for insulation resistance, winding ratio, and insulation power factor, as follows:

- An insulation resistance test is performed on each winding with the other winding grounded and isolated from one winding to another. This test indicates the condition of the winding insulation, as well as the presence of any moisture.
- The winding ratio test is used to verify the transformation ratio of the primary to secondary windings and can reveal shorted turns.
- Power factor testing detects insulation degradation. Significant increase in the power factor can be an indication of substantial insulation degradation or the presence of moisture or other contamination. Warning: some users have stopped doing power factor testing on dry-type transformers, because of unreliability of results caused by (presumably) varying humidity in the transformer area.



Key Technical Point
Warning: Some users have stopped doing power factor testing on dry-type transformers, because of unreliability of results caused by (presumably) varying humidity in the transformer area.

4.8 Failure Mechanisms

Transformer and reactor failures can be attributed to dielectric breakdown, short circuit, deterioration of insulation properties, insulator, arrester, and bushing failure mechanisms.

4.8.1 Short-Circuit Failure

Some of the problems leading to failures when a transformer experiences a through-fault are as follows:

- Loose windings caused by repetitive through faults, degraded (mechanically weakened) insulation as a result of overloads, or an overheated transformer (high ambient air temperature, cooling equipment failure, or ventilation issues because of dust and dirt)
- Inadequate strength in the windings, including a variety of problems depending on the type of winding used (Such problem areas can develop from pd activity within the winding, weakened mechanical bonds in the insulation system allowing relative motion between winding conductors, and weakened winding strength.)
- Inadequate structural support of windings and leads for withstanding the short-circuit forces

It should be noted that the actual failure might be thermal, dielectric, or structural in nature, originating from damage caused during a short circuit, such as shearing of paper or shorting of turns, burning of insulation, or displacement of winding turns. The actual transformer failure can occur quite some time following the short circuit, when the initial damage caused by the short develops into a more critical winding deficiency.

4.8.2 Thermal Aging

If the transformer or reactor temperature does not exceed the rating of the insulation, dry-type transformers and reactors can be expected to have a trouble-free long life. Failure can result from thermal aging if the transformer is overloaded to the extent that hot spot temperatures above the rating of the insulation exist, especially for long periods of time. Damage to the insulation can also result from operation for long periods of time without adequate ventilation and/or cooling, operation at higher than expected ambient temperatures, or excessive repeat subjections within a short duration to short-circuit overload (locked rotor (motor)) conditions.

4.9 Summary

In general, dry-type transformers and reactors can be expected to have long trouble-free lives. If conditions and elements such as design deficiencies, transients, adverse environmental conditions, vibrations, electrical cycling, contaminants, or lack of ventilation/cooling exist, the transformers can deteriorate. If the degradation of the transformer is allowed to continue without proper inspection and preventive maintenance, the transformer will fail. Inspection and surveillance, along with preventive and corrective maintenance, must be instituted to maintain reliable equipment and long service life.

Section 5: Maintenance

Inspection and surveillance along with preventive and corrective maintenance provide an effective maintenance program to maintain reliable transformers and reactors.

Given the materials of construction, such as steel, copper (aluminum), and resins, there is very limited maintenance required for these pieces of equipment; however, this is not to say that this equipment does not require any maintenance, especially if it is expected to meet or exceed intended design life.

5.1 Overview



Key Technical Point
Rule: insulation life is halved for every 10°C that the insulation is operated above its temperature rating. Conversely, life is doubled for every 10°C that the transformer is operated below its temperature rating.

ANSI/EEE C57.96-1989 indicates a 20-year life expectancy for the insulation system in a transformer if the insulation system is not subjected to any unusual service conditions. On the other hand, some manufacturers indicate that dry-type transformers and reactors, when properly installed and maintained, can be expected to operate for about 30 years and their life varies widely based on the insulation system, ambient temperature, loading, and hot spot temperature rise. The transformer and reactor thermal life is directly related to the thermal degradation of the insulation system. A general rule is that the insulation life is halved for every 10°C (18°F) the insulation is operated above its temperature rating. Alternatively, the insulation life will approximately double for every 10°C (18°F) the insulation is operated below its temperature rating.

5.2 Cooling System

A maintenance program can help prolong the life of a transformer and reactor by keeping the cooling system, fans, louvers, and cooling passages (as applicable) free of obstructions and maintaining operation within design limits. The various transformer standards have been reviewed to identify recommended maintenance. There are several ways that this important operating characteristic can be managed. One is by efficient heat removal. Cooling ducts are designed into the windings of all types of power transformers. These ducts must be kept free of debris or accumulated dust for them to provide their designed function of heat removal. If fans are provided, they must be kept operational with appropriate temperature settings for turning them on. For enclosures with ventilating openings or louvers, these areas must also be kept free of debris or accumulated dust. If air filters are provided, a maintenance program should be set up to ensure that the filters are changed out on a routine schedule.

5.3 Power Factor Versus Insulation Resistance

Key Technical Point
Many users prefer the more stable results of insulation resistance as an indication of insulation integrity/condition.

Power factor testing is listed among optional tests in several locations within this section, and guidance is available from the instrument manufacturers for proper application. However, it should be noted that many users have experienced less-than-satisfactory results from the application of this test to dry-type transformers, as a result of the influence of humidity on the results. Many users prefer the more stable results of an insulation resistance test as an indication of insulation integrity/condition.

5.4 Applicable Industry Standards

Transformer standards have been reviewed to identify recommended maintenance recommendations. The following is a summary of these recommendations.

5.4.1 Recommended Practice for Electrical Equipment Maintenance [7]

National Fire Protection Association (NFPA) 70B provides maintenance recommendations based on the type of transformer, whether it is sealed or ventilated. Maintenance recommendations for both sealed and ventilated type transformers include reading and recording current and voltage levels at peak loading. If the transformer nameplate rating is exceeded, steps should be taken to reduce the load and/or adjust the voltage to the proper range. Temperature readings should be taken on a regular basis. If the temperature gauge is equipped with a maximum temperature indicator, its reading should be recorded, along with the existing transformer temperature and the maximum temperature indicator reset. Excessive temperature can be an indication of overloading or inadequate cooling. An external inspection of the transformer should be made periodically to ensure that the ventilating louvers are not clogged with dirt and that the case ground is adequate.

For sealed dry-type transformers, which are usually equipped with a pressure gauge, additional maintenance recommendation is to record and trend tank pressure. A continuous low- or zero-pressure reading can be an indication of a leaking tank. High pressure is an indication of overload or internal winding or core heating problems.

Key Human Performance Point
If an internal inspection of a sealed-tank enclosure is to be performed, the tank must be purged with dry air prior to entering.

5.4.2 Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type General-Purpose Distribution and Power Transformers [8]

ANSI/IEEE C57.94 recommends deenergizing the transformer, applying grounds to the transformer terminals for personnel safety, and inspecting the transformer at regular periodic intervals. If an internal inspection of a sealed-tank transformer is to be done, the gas in the tank must be purged with dry air (-50°F [-45°C] dew point or lower) prior to entering. The windings should be inspected for dirt, especially on insulating surfaces and in ventilation passages, where it

might restrict air flow. Inspection should include observing for evidence of rusting, corrosion, degraded (hot) electrical connections, or deterioration of insulation varnish or resin. The windings should be cleaned with a vacuum cleaner, and the cooling passages and windings should be blown with compressed dry air or nitrogen at a pressure not to exceed 25 psig (1.72 bar). (**Caution**: some vendors do not recommend blowing compressed air onto windings because of the risk of driving harmful material into the winding ducts). The lead supports, tap changer, and terminal boards should be brushed or wiped down with a lint-free cloth.

5.4.3 Maintenance Testing Specifications for Electric Power Distribution Equipment and Systems [9]

NETA-MTS provides guidance for inspection and electrical testing of dry-type transformers. It recommends performing a visual inspection looking for physical damage, such as cracked insulators, loose bolted connections, defective wiring, and general condition. Auxiliary devices such as cooling fans and temperature indicators should be verified for proper functioning. If applicable, equipment and core grounding should be verified. Transformers should be thoroughly cleaned prior to testing unless as-found and as-left tests are being done. Insulation-resistance, winding-to-winding, and winding-to-ground tests should be performed with results recorded at 30 seconds, 1 minute, and 10 minutes. Table 5-1 can be used for guidance with test voltage and acceptable results.

Table 5-1
Transformer insulation resistance test voltage

Transformer Coil Rating Type	Minimum DC Test Voltage	Recommended Minimum Insulation Resistance in Megohms
0–600 V	1,000 V	500
601–5,000 V	2,500 V	5,000
5,001–15,000 V	5,000 V	25,000

This report does not provide any maintenance recommendations for reactors.

5.4.4 Transformer Maintenance (U.S. Department of Interior, Bureau of Reclamation) [10]

FIST 3-30 provides guidance for types of maintenance and maintenance intervals for dry-type transformers in Table 5-2.

Table 5-2
Dry-type transformer maintenance summary (Bureau of Reclamation)

When new, after energizing and allowing temperature and loading to stabilize	• Do an infrared scan, and compare with temperature gage, if any. • If transformer is gas filled (nitrogen, N_2), check pressure gage against data sheets; never allow gas pressure to fall below 1 psi (0.06 bar). • Check loading, and compare with nameplate rating. • Functionally test fans and controls for proper operation. • Functionally test temperature alarms and annunciator points. • Check area around transformer, and clear of debris and parts storage. • Check transformer room for proper ventilation.
After one week of operation at normal loading	• Perform infrared scan, and compare with temperature gage, if any. • Check temperature gage, if any, and compare with nameplate rating. • Check loading and compare with nameplate rating.
Annually (Note: the time between these periodic inspections can be increased if the first internal inspection of windings and connections are found clean and in good condition and if loading is at or below nameplate rating.)	• Perform an infrared scan before deenergizing. • Deenergize and remove panels for internal inspection. • Use vacuum to remove as much dirt as possible. • After vacuuming, use low-pressure dry air (20–25 psi [1.38–1.72 bar]) to blow off remaining dirt. **Caution:** make sure that air is dry. • Check for discolored copper and discolored insulation. • Check for corroded and loose connections. • Check for carbon tracking on insulation and insulators. • Check for cracked, chipped, and loose insulators. • If windings are found dirty, add filter material to air intake ports. • Check fan blades for cleanliness; remove dirt and dust. • Check fans, controls, alarms, and annunciator points. • Check pressure gage on N_2-filled transformers; compare with weekly data sheets; never allow pressure to fall below 1 psi (0.06 bar). • Repair all problems found in preceding inspections.

5.4.5 Dry-Type Transformers for General Applications [11]

Although dry-type transformers are described as virtually maintenance free, the importance of periodic inspections and cleaning is cited, for the purpose of increasing life expectancy.

Some maintenance activities, such as the following, are only safe/practical while the transformer is deenergized:

- Tap changing
- Internal inspection and cleaning
- Locating causes of faulty performance
- Replacing parts
- Internal painting

Warning: corrective maintenance should only be performed by a person who is familiar with the construction and operation of the apparatus and the hazards involved.

The following steps, provided for performing corrective maintenance for a dry-type transformer, are reproduced verbatim as follows:



Key Human Performance Point
Be sure that the transformer is disconnected from all electric power sources before servicing.

- Be sure that the transformer is disconnected from all electric power sources before servicing (live parts whose potential exceeds 30 volts to ground are considered to present a shock hazard).
- After power has been disconnected from the transformer, attach ground leads or their equivalent to the input and output termination of the transformer. Such grounding may be unnecessary in the case of low-voltage transformers that can be visibly isolated from energized conductors by other disconnecting means.
- Inspect insulators, terminals, and terminal boards for discharge (tracking), breaks, cracks, or burns. Clean the insulators where abnormal conditions, such as salt deposits, dust or acid fumes prevail. This is necessary to avoid flashover as a result of the accumulation of foreign substance on their surface.
- Inspect terminals for alignment, tightness, pressure, burns, or corrosion. Replace pitted or badly burned terminals. If pitting or burning is of a minor nature and any plating is not damaged, smooth down the surface with clean fine sandpaper (not emery) or follow manufacturer's recommendations.
- Inspect for moisture conditions which may cause corrosion or harmful lowering of insulation levels.
- Inspect air ducts for the accumulation of dust and foreign substances; if necessary, blow out the accumulation.
- See that bolts, nuts, washers, pins, terminal connectors, including ground connection, are in place and in good condition.



Key Human Performance Point
Attach grounding leads to the input and output terminations of the transformer.

- Periodically inspect ground connections and ground contact surfaces for looseness of connections, erosion, corrosion and/or other conditions deleterious to a good low-impedance and current-carrying connection.
- Check insulated joints for localized heating and the condition of the insulation around the joints. When localized joint heating is present, the joint should be reconstituted and reinsulated. Any noted insulation deterioration should be cause for re-insulating the joint.

This standard does not provide maintenance recommendations for reactors.

5.5 Insurance Recommendations

American Nuclear Insurers recommends that switchyard dry-type transformers should be internally inspected for cleanliness and subjected to an insulation resistance/power factor test. There are no specific maintenance recommendations for in-plant dry-type transformers and reactors.

5.6 Summary of Maintenance Recommendations

5.6.1 Routine Maintenance

5.6.1.1 Off-Line Inspection and Testing

Off-line inspection and testing should be performed at regular intervals. If the transformer is operating in normal service conditions as defined by ANSI/IEEE C57.12.01 with regard to ambient temperature range, altitude and supply voltage proper, a two-year off-line inspection interval is recommended. For unusual service conditions, such as atmospheric contamination, more frequent inspection intervals are recommended. Off-line testing can be classified as either routine maintenance or extraordinary maintenance. Transformer manufacturers recommend that routine maintenance be performed every one to two years.

Routine maintenance consists of the following steps:

1. Deenergize and ground the transformer prior to performing testing.
2. Remove all panels to access the transformer internals.
3. Thoroughly vacuum all dust and dirt from all surfaces. Cloths moistened with isopropyl alcohol can be used to wipe down the coils.
4. If there is evidence of moisture, the transformer should be dried out with heated air. The air temperature should not exceed 105°C. For outdoor installations, inspect for moisture/water entry, and correct as needed.
5. Blow out the high-voltage and low-voltage windings and all cooling and ventilation passages with dry air or nitrogen (**Caution**: some manufacturers do not recommend blowing air within the windings). Do not use air pressure greater than 25 psi (1.73 bar).

6. Verify the tightness of all bolted connections, such as high-voltage and low-voltage, tap changer, yolk and spacer bolts, and core ground, if applicable.
7. Inspect for tightness and alignment of coil blocking. Report any loose or displaced blocking.
8. Perform winding insulation resistance test in accordance with ANSI/IEEE Standard C57.94.

5.6.1.2 On-Line Monitoring



Key Technical Point
Installation of thermography windows in strategic locations on the enclosure will allow online thermal scans of critical internal components.

On-line monitoring of dry-type transformers consists of infrared thermography, overcurrent relays, winding temperature indicators, and hot spot detectors to detect winding temperature. These methods can be used to trend the accumulation of dirt and debris in cooling passages, resulting in rising winding temperature. Although it is generally recommended to not remove paneling while the transformer is energized, infrared thermography trending can be used to detect heating caused by blockage of transformer filters or ventilating grills. Thermography scans can be performed at three- to six-month intervals, and, as data are gathered and trended, the scanning interval can be adjusted based on experience. Installation of thermography windows in strategic locations on the enclosure will allow on-line thermal scans of critical internal components (core, buswork, and terminals). Winding temperature relays and hot spot detectors continuously monitor the condition of the transformer and are used to switch cooling fans on and to initiate alarms. Internal inspection (and cleaning as needed) of the ventilated transformers can be performed at every outage.

Sound level can be trended also, because this can be an indication of loose core clamps, defective vibration isolators (if equipped), or high input voltage. Normal sound level ranges according to NEMA are tabulated in Table 5-3.

Table 5-3
Audible sound levels for dry-type transformers 15,000-V nominal system voltage and below [12]

AUDIBLE SOUND LEVELS FOR DRY-TYPE TRANSFORMERS 15000-VOLT NOMINAL SYSTEM VOLTAGE AND BELOW

Equivalent Two-Winding kVA	Average Sound Level, Decibels		Equivalent Two-winding kVA	Average Sound Level, Decibels
	Self-cooled Ventilated*	Self-cooled Sealed*		Ventilated Forced Air Cooled **,†
0–50	50	50	...	...
51–150	55	55	...	...
151–300	58	57	3–300	67
301–500	60	59	301–500	67
501–700	62	61	501–833	67
701–1000	64	63	834–1167	67
1001–1500	65	64	1168–1667	68
1501–2000	66	65	1668–2000	69
2001–3000	68	66	2001–3333	71
3001–4000	70	68	3334–5000	73
4001–5000	71	69	5001–6667	74
5001–6000	72	70	6668–8333	75
6001–7500	73	71	8334–10000	76

* Class AA rating
**Does not apply to sealed-type transformers
†Class FA and AFA ratings

5.6.2 Special (Nonroutine) Maintenance

If the failure rates are high for specific types or classes of dry-type transformers or if adverse inspection results are found on a specific transformer, the time intervals between inspections should be reduced.

Extraordinary maintenance is performed in the event that the transformer has experienced stress, such as an internal or external fault, overload, or overvoltage; has been subjected to an excessive number of short circuits; or has been out of service for an extended period of time. The following are suggested actions for extraordinary maintenance:

- Deenergize (or verify that the transformer is deenergized), and connect personnel safety grounds to the transformer high-voltage and low-voltage terminals.
- Remove all panels, and thoroughly inspect the transformer core and coil assembly and any insulators for cracks or other visible damage according to NETA-MTS.
- Verify the tightness of all bolted connections, such as high-voltage and low-voltage connections, tap changer connections, yolk and spacer bolts, and core ground, if applicable.
- Inspect for tightness and alignment of clamping blocks and displacement of cooling duct sticks/spacers, and report any anomalies.
- Observe for distorted (buckled, deformed) windings.
- Observe for indications of overheating or arcing damage, such as smoke traces, carbon, or deposits of molten copper or aluminum.
- Check for deteriorated or defective vibration isolators.
- Perform winding insulation resistance test in accordance with ANSI/IEEE Standard C57.94.
- Perform high-potential test according to IEEE Standard C57.12.91.
- Perform turns ratio test, checking ratio with taps at each position according to NETA-MTS.
- Perform core insulation resistance test in accordance with the manufacturer's recommendations.
- Verify that all protective relays and alarm devices operate as designed.
- Note: if any signs indicative of failure or damage are discovered, report such findings immediately. **Do not clean or remove evidence of failure/damage until authorized**.

A summary of the recommended transformer maintenance tasks and intervals is given in Table 5-4. Because the environmental condition, loading, cycling, and insulation rating vary widely from installation to installation, the intervals can be increased or decreased based on experience.

Table 5-4
Summary of transformer maintenance recommendations

Task Category	Task (Preventive Maintenance/Predictive Maintenance) Description	Frequency
Startup and at normal loading	▪ Check loading, and compare with nameplate rating. ▪ Functionally test fans and controls for proper operation. ▪ Functionally test temperature alarms and annunciator points. ▪ Check area around transformer clear of debris and parts storage. ▪ Check transformer room for proper ventilation and cooling.	When new and after loading and loading stabilizes
Operator rounds	▪ Check pressure for gas-filled transformers (must be greater than 1 psig [1.08 bar]). ▪ Check to ensure that vents are clear. ▪ Check temperature gage, and identify any adverse trends or high temperature indications. ▪ Check for any abnormal sound and vibration.	Weekly
Periodic scans and trending	▪ Thermography: perform an infrared scan while energized and with stabilized loading. Note: this scan will be limited to enclosure unless thermography windows are installed. ▪ Acoustic: perform acoustic measurement testing and trend. ▪ Vibration: if design is susceptible to vibration, perform vibration testing to detect any abnormal vibration and trend.	3–6 months

Table 5-4 (continued)
Summary of transformer maintenance recommendations

Task Category	Task (Preventive Maintenance/Predictive Maintenance) Description	Frequency
Cleaning and inspection	▪ Perform internal inspection. Deenergize, ground, and remove panels, as necessary. ▪ Verify proper core grounding. ▪ Vacuum to remove dirt and dust. Blow off remaining dirt after vacuuming. Use low-pressure dry air (20–25 psi [1.38–1.72bar]). Cloths moistened with isopropyl alcohol can be used to wipe down the coils. ▪ Check for discolored copper, discolored insulation, corroded and loose connections, and carbon tracking on insulation and insulators. ▪ Check for loose or displaced blocking and cooling duct spacers and for distorted windings or bus. ▪ Check for cracked, chipped, and loose insulators. ▪ Replace filters if equipped to air intake ports. ▪ Check fan blades for cleanliness; remove dirt and dust. Cloths moistened with isopropyl alcohol can be used to wipe down blades and other surfaces. ▪ Check fans, controls, alarms and annunciator points, and pressure gage temperature gage for proper operation. ▪ Check and tighten all bolted connections, including mounting bolts. ▪ Check for deteriorated or defective vibration isolators. ▪ Repair all problems found in preceding inspections. **Core and coil repairs should be performed under the guidance of qualified field service personnel of the original equipment manufacturer-approved transformer repair vendor.** ▪ Verify proper secondary voltage phase-to-phase and phase-to-ground after energization and prior to loading.	Plant outage (1.5–2 years); increase intervals based on experience
Calibration	Check and calibrate temperature gage and pressure gage (on-gas filled transformers).	According to plant calibration program

Table 5-4 (continued)
Summary of transformer maintenance recommendations

Task Category	Task (Preventive Maintenance/Predictive Maintenance) Description	Frequency
Testing	▪ Perform insulation resistance testing—winding-to-winding and windings-to-ground according to ANSI/IEEE 57.94. ▪ Perform single-phase excitation current tests on each phase according to ANSI/IEEE C57.94 and ANSI/IEEE C57.12.91. ▪ Perform insulation system power factor test according to the manufacturer's recommendation. ▪ Perform a turns ratio test between windings on the as-found tap setting. ▪ Test arresters (if applicable).	Perform based on findings, experience, and criticality (safety-related or reliability-related)

A summary of the recommended maintenance tasks and intervals for current limiting and neutral grounding reactors is given in Table 5-5. Note that the dry-type reactors are expected to be trouble-free and maintenance recommendations could not be found in any of the standards. Because the environmental condition, loading, cycling, and insulation rating vary widely from installation to installation, the intervals can be increased or decreased based on experience.

Table 5-5
Summary of reactor maintenance recommendations

Task Category	Task (Preventive Maintenance/Predictive Maintenance) Description	Frequency
Startup and at normal loading	▪ Check loading, and compare with nameplate rating. ▪ Check area around reactor clear of debris and parts storage. ▪ Check room for proper ventilation and cooling ▪ Check nearby steel structures, fencing, conduit, or other equipment for indications of high temperatures.	When new and after loading and loading stabilizes
Operator rounds	▪ Check to ensure that vents are clear. ▪ Check for any abnormal sound and vibration.	Weekly
Periodic scans and trending	▪ Thermography: perform an infrared scan while energized and with stabilized load. Scan nearby steel structures, fencing, and other equipment for localized elevated temperatures. ▪ Acoustic: perform acoustic measurement testing and trend.	3–6 months
Cleaning and inspection	▪ Perform internal inspection. Deenergize, ground, and remove panels, as necessary. ▪ Vacuum to remove dirt and dust. Blow off remaining dirt after vacuuming. Use low-pressure dry air (20–25 psi). Cloths moistened with isopropyl alcohol can be used to wipe down the coils. ▪ Check for discolored copper, discolored insulation, corroded and loose connections, and carbon tracking on insulation and insulators. ▪ Check for cracked, chipped, and loose insulators. ▪ Perform insulation resistance testing. ▪ Check and tighten all bolted connections, including mounting bolts. ▪ Repair all problems found in preceding inspections. Coil repairs should be performed under the guidance of qualified field service personnel of the original equipment manufacturer or an approved repair vendor.	Plant outage (1.5–2 years); increase intervals based on experience

5.7 Troubleshooting

Effectiveness of maintenance inspections in assessing the condition of dry-type transformers is related to the inspector's ability to understand/identify anomalies. Table 5-6 contains problems, their typical indicators, and suggested remedies to consider. This chart, of course, is not exhaustive but is intended for use as a tool to better assess the condition being analyzed.

Table 5-6
Troubleshooting guide

Indication	Possible Cause	Suggested Remedy
Hot transformer	High ambient temperature	▪ Improve ventilation. ▪ Provide additional cooling.
	Overload	▪ Reduce load. ▪ Improve power factor. ▪ Check for circulating currents for paralleled transformers—different ratios or impedances. ▪ Check for open phase in delta bank.
	High voltage	Change circuit voltage and taps.
	Insufficient cooling	▪ Remove dirt, duct, and so forth from surfaces. ▪ If equipped, check fans, pumps, valves, and so forth for proper operation.
	Winding failure—incipient fault	▪ Check winding. ▪ Remove any foreign object or damaged material. ▪ Repair or replace insulation and insulation materials.
	Short-circuited core	▪ Test for exciting current and no-load loss; if high: ▪ Inspect core, remove, and repair ▪ Check core bolts and clamps, and tighten. ▪ If possible, check insulation between laminations.
	High harmonic loads	Measure neutral current—replace with K-rated transformer.

Table 5-6 (continued)
Troubleshooting guide

Indication	Possible Cause	Suggested Remedy
Noisy transformer	Overload	▪ Reduce load. ▪ Improve power factor. ▪ Check for circulating currents for paralleled transformers—different ratios or impedances. ▪ Check for open phase in delta bank.
	Metal part ungrounded, loose connection	▪ Check clamps, cores, and parts normally grounded for loose or broken connections, missing bolts or nuts, and so forth. ▪ Tighten loose clamps, bolts, and nuts. ▪ Replace missing ones.
	External parts and accessories in resonant vibration	▪ Tighten clamps, cores, and parts. ▪ Install shims, if needed.
	Incipient fault—core or winding	▪ Check winding. ▪ Remove any foreign object or damaged material. ▪ Repair or replace insulation and insulation materials.
No voltage—unsteady voltage	Winding failure—lightning; overload; short circuit from foreign object or low strength dielectric	▪ Check winding. ▪ Remove any foreign object or damaged material. ▪ Repair or replace insulation and insulation materials.
Rust and paint deterioration	Weather, pollution, and corrosive or salt atmosphere; overloads	▪ Remove rust and deteriorated paint. ▪ Clean surfaces. ▪ Prime and repaint with proper paints and sufficient coatings.
	Excessive heating discoloration	Check sizing, input voltage, or loading amps.

Table 5-6 (continued)
Troubleshooting guide

Indication	Possible Cause	Suggested Remedy
Hot neutral line	Overload	▪ For a too small neutral conductor, replace. ▪ For severe unbalance between phases, rebalance and equalize loads.
	One leg of wye bank open	▪ Check associated fuse. If blown, remove cause and replace. ▪ Check for open circuit in winding of transformer in bank. ▪ Measure odd harmonic amps with root-mean-square meter.
Voltage unbalanced	Open neutral unbalanced loads	▪ Severe unbalance between phases: rebalance and equalize loads. ▪ Check fuses. If blown, remove cause and replace. ▪ Check for open circuit in winding of transformer.
Voltages high and unbalanced	Open neutral on wye bank ground in winding of one transformer in wye	▪ Check neutral connections and load balance. ▪ Check values of voltages between phases and phase-to-ground voltages. Vector should indicate source of trouble.
No voltage—one phase of delta connected bank	Grounds on two legs of delta (delta collapse—loads single phasing)	Remove grounds from at least one leg of delta source.
Overloads on two delta bank	Open in third transformer of bank; operating in open delta	▪ Check fuses on supply to their bank. ▪ Check winding of transformers in third transformer for continuity.
Low voltage on two phases of delta	Open in one phase of delta supply; two transformers now connected across one phase	▪ Check fuse on supply. ▪ Check supply circuit back to source for open circuit.

Section 6: Installation and Replacement

There are various reasons for buying a new transformer for an operating nuclear station. Plant upgrades with new auxiliary systems to power could require addition of transformers for new applications. The necessity of installing a new motor of a different voltage than has existed at the particular station will necessitate transforming power to the needed voltage. There are other scenarios by which a power station would think of purchasing new transformers, but perhaps the reason with the greatest and most far-reaching consequences relates to the time in service of the operating transformers. Many of the nuclear stations in the 1960s were granted a 40-year operating license; however, many stations have sought or will seek license renewal. Although many transformers function well past 40 years, others have deteriorated in one way or the other to a point at which a reliability study will indicate a need for replacement. With this background in mind, this section addresses pertinent issues relating to the decision to replace and the process of getting a suitable replacement into service.

6.1 Considerations for Retirement

Occasionally, a transformer will fail without warning, and the engineer will be assured by the knowledge that a spare is in stock—or it will be necessary to scramble to find a replacement suitable for the installation. However, most dry-type transformer failures occur as a result of conditions that have deteriorated over time, and reasonable monitoring of the transformer, along with periodic inspections/tests should help to provide adequate warning that the transformer is in trouble.

When a weakness is discovered in one transformer, other (similar design/application) transformers should be checked to see whether they have the same problem. The first order of business should be to determine the root cause of the deteriorating condition and whether anything can reasonably be done to halt the deterioration. If it is concluded that the transformers must be replaced, there are several factors that are important to consider in the development of a specification for the replacement(s).

6.1.1 Service Issues

Key Technical Point
If the total harmonic distortion exceeds 0.05 per unit, as described in IEEE Standard C57.12.01, the procurement specification should include a K-Factor rating.

Is the root cause of the condition related to loading of the transformer(s)? If the loads have excessive harmonics and those harmonics are not reasonably correctable, the new transformers should be specified for an appropriate K-Factor. If the harmonic content of the load is more than 0.05 per unit, as described in IEEE Standard C57.12.01, the procurement specification should include a K-Factor in accordance with C57.110 and UL 1561.

If power factor of the load circuit is lower than 0.8 and the power factor cannot reasonably be improved, the new transformer might need to be specified for operation on a derated basis.

If the condition includes evidence of thermal breakdown of insulation materials, overloading or undercooling should be considered as a possible root cause. Consideration should be given to specifying a lower winding temperature rise, while maintaining full thermal rating for the insulation. If cooling ducts are clogged or covered by dust/debris and eliminating the source is not an option, a different type of enclosure or transformer might be more appropriate to the environment. Options for improvement include the following:

- Filters
- Nonventilating enclosure
- Cast coil
- Sealed-tank design

If the cause is related to insulation deterioration and moisture entry, other options for enclosure or transformer type should be considered.

If the cause is a result of dielectric breakdown with no apparent insulation problems, the circuit might need to be evaluated for possible lightning or switching surges and arresters might need to be included on the new transformer.

6.1.2 Other Replacement Issues

If the transformer being replaced is designated as a nuclear safety-related transformer, the procurement specification shall confirm that service appropriately, along with special requirements for compliance with IEEE Standard 323, IEEE Standard 344, and other standards as appropriate. If it is not to be nuclear-safety-related, the specification should clearly state that fact, because its destination is a nuclear station.

Appropriate parameters to which the replacement is expected to be designed for minimizing of field modifications should be included in the specification. It might be appropriate to invite the bidders or the supplier to the site to take measurements and to scope out the job for themselves. Any particular space restrictions should be noted in the specification so as to minimize installation difficulties.

Any special moving/handling requirements should be included in the specification, such as intention to dismantle the transformer (and to what extent).

It should be noted that the replacement represents an opportunity to upgrade the transformer on any points of weakness or to take advantage of technological advances since the original installation. The following are examples of options for upgrade:

- Digital monitoring of winding temperature
- Monitoring of core temperature
- Infrared windows provided at key locations around the enclosure
- Fan sensors for monitoring fan operation

6.2 Factory Inspections

Depending upon the relative importance of a purchased transformer's service and the complexity of the design, the engineer might consider whether to have an inspection of one or more of the transformers performed in the factory during the manufacturing process. An inspection at the beginning of the winding and core-cutting process will provide an opportunity to inspect/approve methods/procedures being applied to construct each winding.

A typical point of such inspection is after completion of the active part and prior to installation in its enclosure. The following are some of the items that might be included in the inspection list:

- Stick, spacer alignments
- Coil clamping system integrity
- Cooling ducts clear of debris
- Core stacking
- Condition of lead/bus terminations
- Clearances for dielectric
- Adequacy of bus/lead support
- Condition of observable insulation materials
- Single point of core ground
- Tap lead terminations
- Mounting integrity of current transformers, arresters, and so forth
- Compare enclosure with outline drawing
- Check dimensions for direct replacement of in-service transformer
- Jacking, lifting, and pulling provisions in accordance with outline
- DETC (applicable for sealed tank)

6.3 Factory Testing

Factory testing is important as validation of the design and manufacturing integrity of the transformer and to confirm parameters that are necessary to meet the requirements of the installation. The engineer should be familiar with each test requirement, in order to determine what tests are important and be able to read/review test results. The value of having an advocate at the factory to observe/approve testing should be considered. The following is a list of some tests that are typically performed on a dry-type transformer:

- **Quality control pd on coils**. In the construction of cast coils, it is imperative to not leave any voids or cracks in the epoxy cast when curing is complete. Each coil is tested (typically on a test core prior to installing onto the assembled core) to ensure its void/crack-free condition.
- **Winding resistance**. Winding resistance is measured to confirm the design, to check for proper connections/terminations, and to calculate I^2R losses.
- **Core insulation resistance**. When the core is insulated with a single point of ground, this ground is lifted and resistance of the insulation is measured (typically with megohm or gigaohm results). This test confirms the quality of insulation and absence of unintentional grounds. Unintentional grounds can result in circulating ground currents and overheating of parts.
- **Turns ratio**. Winding turn-turn ratio is a measurement of voltage in versus voltage out, as an indication of the relative number of turns in high- and low-voltage windings. This measurement can also reveal shorted turns and open circuits. Ratio is checked for each tap position.
- **Polarity and phase relation test**. Polarity and phase relation tests are performed to confirm that the interconnections of windings are proper for meeting the requirements of the specification and of the installation.
- **No-load losses and excitation current**. No-load losses are the sum of losses associated with an energized (but not loaded) transformer. Some of those losses are core losses, I^2R losses resulting from excitation currents, and I^2R losses resulting from circulating currents between parallel windings. It should be noted that no-load losses relate directly to (the square of) excitation current.

  Excitation current (in terms of factory tests) is the current required to maintain rated voltage under an open circuit condition. An anomaly in this measurement can be an indication of a problem either in a winding or in the core.
- **Load loss and impedance voltage**. Load losses in a transformer are the sum of the losses resulting from applying rated current through a winding, with the other winding(s) shorted. The primary contributor to these losses is I^2R of windings, but also contributing are I^2R losses in leads and bus bar and also stray losses throughout the transformer.

  Impedance is measured and reported in percent of rated voltage that is required to drive rated current through the short-circuited transformer and is sometime referenced as percentage impedance voltage.



Key Technical Point
Anamolies in excitation current readings may indicate a problem either in the core and/or a winding.

It should be noted that load loss and impedance voltage is not a routine test for dry-type transformers rated ≤500kVA. It is only required by standard (unless specified otherwise) to be done on one of a particular design. For transformers ≥501kVA, it is a routine test.

- **Impulse tests**. Impulse tests are performed on transformers to ensure that the finished transformer will survive, without damage, a voltage surge. A standard wave shape for impulse test is 1.2/50μs—that is, the voltage will rise to its peak within 1.2μs and will decay to 50% of its peak at approximately 50μs. Peak of the wave is BIL voltage (or a percentage of it for reduced waves). The front and tail of the applied wave are dependent upon the electrical characteristics of the windings. Therefore tolerances are allowed by standard (see IEEE Standard C57.91 for tolerances and allowances).

  Impulse tests (when required) are to be reported on a form, illustrated in IEEE Standard C57.98.

- **Induced-voltage test**. The induced-voltage test serves the purpose of demonstrating the transformer's ability to withstand a temporary overvoltage condition without exceeding limits of the pd and without generating sufficient pd to alter the transformer in such a way as to continue the pd after voltage is reduced to rated operating level. Because the voltage for the test exceeds the transformer ratings, the frequency of the test must be sufficiently high as to avoid excessive flux heating of the core. Partial discharge (picocoulombs) is monitored during the test. Although pd has become the standard parameter measured/monitored for the induced test, some owners continue to require parallel monitoring of radio interference voltage (microvolts) during the induced period (radio interference voltage was the standard until recent years). For pass-fail criteria and further details regarding this test, see IEEE Standard C57.12.91.

- **Applied-voltage (high-potential) test (factory witness)**. The purpose of the applied-voltage test is to demonstrate that all parts of the windings are sufficiently insulated from ground. All terminals are shorted to each other, and grounds are lifted for any grounded windings. The voltage to be applied to the transformer is based on the lowest BIL of any part of any connected winding. For example, if the BIL of the neutral of a wye-connected winding is lower than the BIL of the line end of the same winding, the voltage to be applied to both is based on the lower BIL.

- **Insulation-power-factor test**. For the insulation power-factor test, the result is derived by dividing real power (dissipation power) in kilowatts to apparent power (kVA) when the transformer is tested in accordance with conditions set forth by IEEE Standard C57.12.91. Its purpose is to verify the dielectric integrity of the insulation system as a whole. Some have found that test results vary broadly, based on the condition of the air space (especially moisture content). For this reason, insulation resistance is the preferred method of confirming insulation integrity (see "Insulation-resistance test"). It should be noted that neither insulation power factor nor insulation resistance is a routine test for dry-type transformers and must be specified for the manufacturer to conduct them.

- **Insulation-resistance test**. The purpose of this test is to verify the condition of the insulation system in total. The parameter that will affect the results most strongly is moisture. As with core insulation, the winding insulation resistance should measure in megohms. If the manufacturer does not provide guidelines you can find minimum values in IEEE C57.94.
- **Audible sound levels**. Unless specified by the owner, sound level tests are only conducted to confirm a particular design and are not conducted for every dry-type transformer. See the charts in IEEE Standard C57.12.01 for standard sound limits for your transformer.

6.4 Receiving and Handling

For any dry-type transformer or reactor, there are precautions that will reduce the risk of damage during receiving, moving assembly, and testing. The manufacturer-provided instruction book should be read carefully before receiving the transformer. The installation can be complex or simple, but in either case the manufacturer's instructions should be followed not only to maintain warranty but also for the safety of the transformer and the personnel installing it. Generally speaking, the larger the equipment, the more complicated a proper installation will be. The following are issues for medium power dry-type transformers.

6.4.1 Receiving Inspection

Prior to unloading the transformer, it should be inspected for evidence of external damage or of movement during transit. If evidence of movement during shipping (for example, displacement of load, loose tie-downs, or broken footings), an internal inspection should be conducted to carefully examine the active part (core/coil assembly) for damage/displacement. If observations are that the transformer is potentially damaged, a hidden damage claim should be filed with the shipper in the event that damage is later revealed.

Prior to unloading a sealed-tank transformer, pressure readings should be verified to coincide with measured ambient temperature in accordance with manufacturer-provided charts. Lower-than-expected pressure can be a sign of a leak to be located and repaired. This correlation should be repeated prior to energizing the transformer on its pad.

An internal inspection of a sealed-tank transformer should be performed only if there are specific reasons to suspect internal damage. Gas should be removed prior to cutting the top from the transformer. Freon gas should be captured in accordance with EPA requirements. The vendor is to be notified in advance of an internal inspection at any time during the warranty period.

If the transformer is to be stored prior to installation, appropriate protection from physical damage should be provided, as well as protection from rain, snow, or sleet.

Before lifting, rolling, or skidding the transformer, the outline drawing should be reviewed to determine the appropriate points on the enclosure for jacking or pulling (it might not be as obvious as it seems). Lifting can be by crane lift, jacking, or forklift. If lift is by crane/hoist, care must be taken to follow the manufacturer's cautions/restrictions on the angle of pull to avoid damage to lift points or to the sheet metal enclosure. Lateral movement can be (if allowed by the manufacturer) by forklift, rolling (on pipes or heavy-duty roller cars), skidding (on greased rail/plates), or the use of air pallets.

During movement of the transformer, care must be taken to not allow the tilt of the transformer to exceed the limits set forth by the manufacturer in the instruction manual.

For ventilated and nonventilated enclosures, a spreader bar is often required to prevent damage to the cabinet during lifting. The dimensional requirements of this bar and maximum angles of lift are likely on the outline drawing. If not, refer to general instructions in the instruction book.

If the instructions are to remove hatches from the cover and lift directly from the active part, it is very important that the covers be replaced when the move is completed, because omitting these hatches will leave the transformer vulnerable to airborne debris that will be detrimental to safe operation. The top of the cabinet is often not observable from the floor level, and omitted hatches can go unnoticed for a long time.

If it is necessary to remove the enclosure to get the transformer to its service location, extreme care must be taken during disassembly, movement, and reassembly to not allow any damage to components on the active part. Consult the manufacturer for special instructions.

When the transformer move is completed and it is properly positioned on its pad, follow the manufacturer's instructions to loosen (or remove) hold-down bolts that secure the active part to the enclosure's base. This is important to allow the rubber noise isolation pads to function properly in isolating core noise from the enclosure.

Prior to energization and before placing the transformer into service, fans and other auxiliary devices should be checked for proper operation. Also check proper and secure connections of ratio taps, high- and low-voltage bus, and instruments.

For outdoor installations, any separately shipped hoods or rain shields must be installed before the transformer is subjected to rain, snow, or sleet.

6.4.2 Receiving Tests

Upon receipt of a transformer in a ventilated or nonventilated enclosure, sufficient panels should be removed for a thorough internal inspection for any signs of damage or displacements. If any such anomalies are discovered, a damage claim should be filed immediately with the shipper.

Upon receipt of a sealed-tank transformer, pressure should be checked against a manufacturer-supplied pressure/temperature chart. If pressure is lower than expected, a leak could have developed during shipment.

Core ground should be lifted and core insulation resistance measured against the manufacturer's recommendation as to minimum acceptable levels (in megohms or gigohms).

Perform power factor or insulation resistance test. If the test fails, consider moisture as the problem and dry out the unit and retest. If test-after-drying fails, contact the manufacturer.

Perform an applied potential (high-potential) test for successful withstand.

Perform a turn-to-turn ratio test for each tap position.

6.5 Storage of Spare Transformers and Reactors

Upon successful completion of all receiving tests (unless it is to go directly into service), the transformer or reactor is to be moved into a warehouse for storage until time of installation. If storage is to be out-of-doors, the transformer should be installed on timber or stands to avoid exposure to standing water and covered with a tarp or heavy-gauge plastic. Thermostatically controlled heaters should be installed inside the transformer's enclosure to avoid condensation.

For storage in a warehouse, the transformer or reactor should be covered by a tarp or heavy-gauge plastic to protect from dust/debris. If the warehouse is subject to damp conditions, thermostatically controlled heaters should be installed in the transformer to preclude condensation.

If the chosen location for storage is close to an aisle or passageway with heavy traffic, additional protection of the transformer can be justified, such as crating/framing or guard rails.

6.6 Final Inspection Prior to Energizing

When the transformer has been moved from storage into place and completely assembled, it should be inspected prior to applying tests. The following are suggestions of what to look for:

- Any equipment or tools left inside the enclosure or on the active part
- Routing, support, and condition of all bus and cables
- Loosened (or removed) hold-down bolts at the bottom of the active part (if applicable)
- Alignment/positioning of any observable sticks, blocks, or spacer materials that are part of the coil design
- Overall positioning of coils (for circular wound, coils should be concentric with each other and with core limb)

- Knicks, cuts, and scrapes of varnish or other sealant of winding
- Any loose blocking material or jacks (if provided)
- Any debris (especially metallic) on/near coils
- Heavy dust
- All bolts, nuts, and washers installed and tight (leads, bus, and taps)
- Cable routing and support between the winding hottest-spot sensor (resistance temperature device or thermistor in winding) and the panel-mounted instrument
- Alignment of fans (if applicable)
- Air filters in place on grills (if applicable)
- Core ground lead/strip tight in core yoke and insulated cable routing to frame/case ground

6.7 Startup Testing

When the transformer has been assembled in place and thoroughly inspected for proper/complete installation and for damage, initial testing should be performed to validate the transformer's suitability for service and to establish baseline data for future comparison. The following tests are recommended as a minimum:

- **Core-ground resistance test (megger)**. This presumes that the core has an accessible single-point ground.
- **Insulation resistance test**. This test is preferred for dry-type transformers over power factor tests because of the significant influence of the condition of the air on power factor results.
- Turn-to-turn ratio measurement—at all tap positions
- Winding resistance for future reference
- Polarity, phase relation
- **High-potential (applied) test**. The purpose of this test is to ensure that the transformer is able to hold voltage. If the transformer is observed to be wet or if it has been exposed to wet conditions, it should be dried out thoroughly prior to application of the high-potential test (or prior to placing in service if the high-potential test is not to be performed).

If arresters are installed as part of the transformer installation, they should be tested prior to energization of the transformer.

Section 7: References

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3. Requirements for Ventilated Dry-Type Power Transformers, 501 kVA and Larger, Three-Phase, with High-Voltage 601 to 34 500 Volts, Low-Voltage 208Y/120 to 4160 Volts. IEEE C57.12.51-2008. IEEE, Piscataway, NJ: 2008.
4. IEEE Recommended Practice for Powering and Grounding Electronic Equipment. IEEE Standard 1100-2005. IEEE, Piscataway, NJ: 2005.
5. Guide for Loading Dry-Type Distribution and Power Transformers. IEEE C57.96-1999. IEEE, Piscataway, NJ: 1999.
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7. Recommended Practice for Electrical Equipment Maintenance. NFPA 70B-2010. National Fire Protection Association. Quincy, MA: 2010
8. Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type General Purpose Distribution and Power Transformers. IEEE C57.94-1982. IEEE, Piscataway, NJ: 1982.
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12. Transformers, Regulators, and Reactors. NEMA TR1-1980. National Electrical Manufacturers Association, Rosslyn, VA: 1980.
13. Standard Terminology for Power Reactors and Distribution Transformers. IEEE C57.12.80-2002. IEEE, Piscataway, NJ: 2002.

Appendix A: IEEE Standards

A.1 Standards Applicable to Dry-Type Transformers

- ANSI/IEEE C57.12.9, Test Code for Dry-Type Distribution and Power Transformers.
- American Society of Mechanical Engineers NQA-1-2000, Quality Assurance Program Requirements for Nuclear Facility Applications.
- IEEE 32-1972, IEEE Standard Requirements, Terminology and Test Procedures for Neutral Grounding Devices.
- IEEE 57-94, IEEE Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type General Purpose Distribution and Power Transformers.
- IEEE 57-96, Guide for Loading Dry-Type Distribution and Power Transformers.
- IEEE 308-1991, Standard Criteria for Class 1E Power Systems for Nuclear Power Generating Stations, as tailored in Appendix A.
- IEEE 323-2003, IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations.
- IEEE 344-1992, Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations, as tailored in Appendix B.
- IEEE 383-2003, Standard for Qualifying Class 1E Electric Cables and Field Splices for Nuclear Power Generating Stations.
- IEEE 384-1992, IEEE Standard Criteria for Independence of Class 1E Equipment and Circuits, as tailored in Appendix C.
- IEEE 638-1992 (Reaffirmed 2006), IEEE Standard for Qualification of Class 1E Transformers for Nuclear Power Generating Stations.
- IEEE 741-1997, Standard Criteria for the Protection of Class 1E Power Systems and Equipment in Nuclear Power Generating Stations, as tailored in Appendix D.
- IEEE C57.124-1991, IEEE Recommended Practice for the Detection of Partial Discharge and Measurement of Apparent Charge in Dry-Type Transformers.

- IEEE 638, IEEE Standard for Qualification of Class 1E Transformers for Nuclear Power Generating Stations.
- IEEE C37.101-2006, IEEE Guide for Generator Ground Protection.
- IEEE C37.121-1989, American National Standard for Switchgear—Unit Substations—Requirements.
- IEEE C57.12.01-2005, General Requirements for Dry-Type Distribution and Power Transformers, Including Those with Solid-Cast and/or Resin Encapsulated Windings.
- IEEE C57.12.55-1987, Transformers Used in Unit Installations, Including Unit Substations —Conformance Standard.
- IEEE C57.12.51-2008, Standard for Ventilated Dry-Type Power Transformers, 501 kVA and Larger, Three-Phase, with High-Voltage 601 V to 34,500 V; Low-Voltage 208Y/120 V to 4160 V-General Requirements.
- IEEE C57.12.55-1987, Transformers Used in Unit Installations, Including Unit Substations—Conformance Standard.
- IEEE C57.12.70-2000, Standard Terminal Markings and Connections for Distribution and Power Transformers.
- IEEE C57.12.91-2001, Standard Test Code for Dry-Type Distribution and Power Transformers.
- IEEE C57.16-1996 (Reaffirmed 2000), Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Reactor.
- IEEE C62.92.2-1989, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems NECA 409 -2002, Recommended Practice for Installing and Maintaining Dry-Type Transformers.
- NEMA 20, Dry Type Transformers for General Applications.

A.2 EPRI Report

Power Transformer Maintenance and Application Guide. EPRI, Palo Alto, CA: 2002. 1002913.

A.3 NRC Documents (NUREGs, IE Notices, Bulletins, and Circulars)

- 1E Information Notice 83-37, "Transformer Failure Resulting from Degraded Connection Cables," failure due to in-rush current.

  When a 4160/480-V transformer at Brunswick Unit 1 D tripped off when the bus was energized. The transformer was damaged beyond repair because of arcing at the CØ winding tap lug. The winding tap connections are made with stranded aluminum cable. The set screw that attaches the barrel of the lug to the stranded aluminum cable had been over tightened, causing some of the wire strands to break. When the transformer was energized, the in-rush current caused localized overheating at the lug connection, resulting in failure.

- NRC Information Notice 92-63, "Cracked Insulators in ASL Dry Type Transformers."

  Cracks were identified in the ceramic insulators on Westinghouse ASL 4-kV/480-V dry-type transformers that support the high-voltage coils. The insulators support the high-voltage windings. Some of the insulators were installed off-center resulting in cracks.

A.4 Other Document

"In the Berkshires, Part 1, William Stanley Started Something." *I EEE Power and Energy Magazin*e. Vol. 10, No. 4 (July/August 2012).

Appendix B: Glossary of Terms and Acronyms

B.1 Glossary of Terms [13]

The following is a glossary of terms used in the report:

AA. The cooling class for a dry-type self-cooled transformer or reactor that is cooled by the natural circulation of air.

AA/FA. the cooling class for a dry-type transformer that has a self-cooled rating with cooling obtained by natural circulation of air and a forced-air-cooled rating with cooling obtained by the forced circulation of air.

accessories. Devices that perform a secondary or minor duty as an adjunct or refinement to the primary or major duty of a unit of equipment.

AFA. The cooling class for a dry-type forced-air-cooled transformer that derives its cooling by the forced circulation of air.

ANV. The cooling class for a dry-type nonventilated self-cooled transformer, which is constructed as to provide no intentional circulation of external air through the transformer and which operates at zero gauge pressure.

basic lightning impulse insulation level. A specific insulation level expressed in kilovolts of the crest value of a standard lightning impulse.

bus reactor. A current-limiting reactor for connection between two buses or two sections of the same bus for the purpose of limiting and localizing the disturbance resulting from a fault in either bus.

cast coil transformer. A dry-type transformer in which the coils of at least one winding are cast into a thermosetting resin that solidifies to become a solid, rigid, insulating system protecting the coils from contact with water, some contaminants, and damage resulting from casual physical contact.

coil (of a transformer). The assemblage of windings that encircle a ferromagnetic core limb for the purpose of producing or linking magnetic flux.

continuous rating. The maximum constant load that can be carried continuously without exceeding established temperature-rise limitations under prescribed conditions.

core form transformer. A transformer in which those parts of the circuit surrounded by the windings have the form of legs with two common yokes.

drip-proof enclosure: An enclosure so constructed that falling drops of liquid or solid particles striking the enclosure at any angle within a specified variation from the vertical shall not interfere with the successful operation of the enclosed equipment.

dry-type transformer. A transformer in which the core and coils are in a gaseous or dry compound insulating medium.

GA. The cooling class for a sealed dry-type self-cooled transformer with a hermetically sealed tank.

gas-filled transformer. A sealed transformer, except that the windings are immersed in a dry gas that is other than air or nitrogen.

general-purpose transformers. Step-up or step-down transformers or autotransformers generally used in secondary distribution circuits of 600 V or less in connection with power and lighting service.

hottest spot temperature. The hottest temperature of the current carrying components of a transformer in contact with insulation or insulating fluid.

hottest spot temperature rise. The arithmetic difference between the hottest spot temperature and the ambient temperature.

impulse test. An insulation test in which the voltage applied is an impulse voltage of specified wave shape.

indoor transformer. A transformer that, because if its construction, must be protected from the weather.

neutral grounding reactor. A current-limiting inductive reactor for connection in the neutral of a device for the purpose of limiting and neutralizing disturbances resulting from ground faults.

nonventilated dry-type transformer. A dry-type transformer that is so constructed as to provide no intentional circulation of external air through the transformer and operating at zero gauge pressure.

outdoor transformer. A transformer of weather-resistant construction suitable for service without additional protection from the weather.

primary winding. The winding on the energy input side.

rated kVA of a transformer. The output that can be delivered for the time specified at rated secondary voltage and rated frequency without exceeding the specified temperature-rise limitations under prescribed conditions.

reactor. An electromagnetic device, the primary purpose of which is to introduce inductive reactance into a circuit.

secondary winding. The winding on the energy output side.

shell-form transformer. A transformer in which the laminations constituting the iron core surround the windings and usually enclose the greater part of them.

turns ratio of a transformer. The ratio of the number of turns in a higher voltage winding to the number of turns in a lower voltage winding.

ventilated dry-type transformer. A dry-type transformer that is so constructed that the ambient air can circulate through its enclosure to cool the transformer core and windings.

winding (of a transformer). The assembly of turns forming an electric circuit associated with one of the voltages assigned to the transformer or reactor.

winding hottest spot temperature. The highest temperature inside the transformer winding. It is greater than the measured average temperature (using the resistance change method) of the coil conductors.

yoke. An element of the ferromagnetic material, not surrounded by windings, used to connect that ferromagnetic limbs that the windings encircle.

B.2 Other Definitions

axial spacers. Sticks, rods, or corrugated materials installed between windings and between layers of a winding that serve to hold space between the layers for cooling and/or dielectric purposes.

butt-lap. A core joint design consisting of a block (book) of laminations that overlap another book to form an electromagnetic transition between a limb and a yoke.

clamping jacks. Adjustable jacks that serve the purpose of maintaining compression on the coils.

core loss. The amount of energy dissipated in the form of heat within the cores of electrical equipment when those cores are subjected to alternating magnetizing force.

electric center. The geometric location of the center active turn in a winding.

grain oriented. A characteristic of magnetic core steel that includes a high percentage of dipoles aligning in the general direction of the length of the steel. The dipole alignment enhances the ability of the steel to conduct magnetic flux in the direction of the alignment.

mitered joint. A core joint design consisting of edges cut on a bias (see also *butt-lap* and *step-lap*).

radial spacers. Spacer blocks between disks or helical turns that serve the purpose of holding space between them for cooling and/or dielectric purposes.

step-lap. A core joint design consisting of a block (book) of laminations of varying lengths, matching a similar joint design on the adjoining piece, to form an electromagnetic transition between a limb and a yoke.

yoke clamps. Steel braces mounted onto either side of a yoke and bolted together in such a way as to maintain compression on the yoke.

B.3 Acronyms

ANSI	American National Standards Institute
EPRI	Electric Power Research Institute
BIL	basic impulse level
DETC	de-energized tap changer
EPA	Environmental Protection Agency
FIST	Facilities Instructions Standards and Testing
GSU	generator step-up unit
IEN	Information Exchange Notice
IEEE	Institute of Electric and Electronic Engineers
INPO	Institute of Nuclear Power Operations
MTS	Measuring and Testing Specification
NEMA	National Electrical Manufacturers Association
NETA	InterNational Electrical Testing Association
NFPA	National Fire Protection Association
NRC	Nuclear Regulatory Commission

NUREG	Nuclear Regulatory Commission regulation
UPS	uninterruptable power supply
VPI	vacuum-pressure impregnation
VPE	vacuum-pressure encapsulated
WPN	Washington Nuclear Project

Appendix C: Summary of Key Points



Key O&M Cost Point
Emphasizes information that will result in reduced purchase, operating, or maintenance costs.

Page	Key Point
1-4	When spill and fire protection considerations are included, dry-type transformers are typically less costly to install and to maintain.
2-11	Ventilated dry-type transformers are typically smaller and less costly than nonventilated dry-type transformers.
2-18	The choice of rectangular winding for the high-voltage coil and sheet winding for the low-voltage coil will be the least costly option.
2-18	To purchase the least costly transformer, specify a 150°C rise for a 220°C insulation system.



Key Technical Point
Targets information that will lead to improved equipment reliability.

Page	Key Point
1-4	Locating dry-type transformers close to loads represents lower line losses and less line voltage drop with which to contend.
2-18	Conductors must be braced and insulated to maintain dielectric integrity while withstanding a short circuit.
2-18	To extend the thermal life of a transformer with a 220°C insulation system, allow only an 80°C or 110°C rise transformer.
2-22	Short-circuit qualification testing will require a special test facility with a strong enough power source to provide the short circuit current.
2-22	If the transformer is excessively noisy or is running hotter than expected, power quality should be investigated as a possible cause.
2-23	A key to long operating life of a transformer is to avoid high temperatures, particularly in areas adjacent to insulating materials.
3-5	Loss of pressure in a Freon-filled transformer can be a trigger for implementation of EPA restrictions on operations.
4-7	Ventilated and nonventilated dry-type transformers that are periodically deenergized or that are subjected to extreme load cycling should be equipped with thermostatically controlled heaters.
5-19	Rule: insulation life is halved for every 10°C that the insulation is operated above its temperature rating. Conversely, life is doubled for every 10°C that the transformer is operated below its temperature rating.
5-25	Installation of thermography windows in strategic locations on the enclosure will allow online thermal scans of critical internal components.
6-38	If the total harmonic distortion exceeds 0.05 per unit, as described in IEEE Standard C57.12.01, the procurement specification should include a K-Factor rating.



Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or ease completion of the task.

Page	Key Point
3-6	When choosing a location for a transformer, allow enough space around the enclosure for personnel access and safe working conditions.
3-7	Ventilation grills should be specified as appropriate for the installed environment.
5-20	If an internal inspection of a sealed-tank enclosure is to be performed, the tank must be purged with dry air prior to entering.
5-23	Be sure that the transformer is disconnected from all electric power sources before servicing.
5-23	Attach grounding leads to the input and output terminations of the transformer.

Appendix D: Harmonics and K-Factor Transformers

Non-safety-related dry-type transformers are not subjected to qualified life requirements. In general duty applications, transformers can be subjected to nonlinear harmonic currents. These currents can be caused by equipment such as UPSs, adjustable frequency drives, computers, copiers, high intensity discharge lights, and electronic ballasts. If the transformer rating is 50 MVA or less and these currents have a harmonic factor exceeding 0.05 per unit as defined in ANSI/IEEE C57.12.80-1978, they can contribute to transformer winding losses, which can be the limiting factor affecting the transformer's capacity. The eddy-current losses in transformer windings are proportional to the per-unit current squared times the per unit frequency squared. Other stray losses are proportional to the current raised to a value slightly less than two. To conservatively estimate the stray losses and eddy-current losses, the total current is used. The results are summed up and tabulated for each harmonic. ANSI/IEEE C57.110-1986 provides guidance to calculate the transformer derating based on the harmonic content of the transformer load current. According to IEEE 1100-2005, the K-Factor is calculated from the following equation.

$$K = \frac{\sum_{h=1}^{h_{max}} (f_h^2 \cdot h^2)}{\sum_{h=1}^{h_{max}} (f_h^2)}$$

where f_h is the frequency, in hertz, of harmonic h.

The following is an example of the calculation for a nonlinear load's K-Factor [4].

Harmonic number h	Nonlinear load current I_h(%)	I_h^2	$I_h = \sqrt{I_h^2/\Sigma I_h^2}$	I_h^2	$I_h^2 h^2$
1	100	1.000	0.909	0.827	0.827
3	33	0.109	0.300	0.090	0.811
5	20	0.040	0.182	0.033	0.827
7	14	0.020	0.127	0.016	0.794
9	11	0.012	0.100	0.010	0.811
11	9	0.008	0.082	0.007	0.811
13	8	0.006	0.073	0.005	0.895
15	7	0.005	0.064	0.004	0.912
Total		1.20		0.992	6.688
				K-factor = 6.688	

Table D-1 shows typical load K-Factors.

Table D-1
Typical load K-Factors [4]

Load	K-Factor
Electric discharge lighting	K-4
UPS with optional input filtering	K-4
Welders	K-4
Induction heating equipment	K-4
Programmable logic controllers and solid-state controls (other than variable speed drives	K-4
Telecommunications equipment (for example, private branch exchange)	K-13
UPS without input filtering	K-13
Multiwire receptacle circuits in general care areas of health care facilities, classrooms of schools, and so forth	K-13
Multiwire receptacle circuits supplying inspection or testing equipment on an assembly or production line	K-13
Mainframe computer loads	K-20
Solid-state motor drives (variable speed drives)	K-20
Multiwire receptacle circuits in critical care areas and operating/recovery rooms of hospitals	K-20

Manufacturers have developed transformers capable of supplying high harmonic nonlinear loads that can remain within specified temperature limits. These transformers are given K-Factor ratings, which range from 4 to 50. The higher K-Factor rating indicates an ability to handle progressively more harmonic current. A transformer with a K-Factor rating of 13 is sufficient to handle nonlinear electronic loads. Some of the design features of K-Factor rated transformers are as follows:

- The neutral bus rating is increased to 200% of secondary full-load ampere rating to be able to handle increased third harmonic and phase imbalance currents.
- The winding conductors are sized and configured to reduce heating resulting from harmonic load currents. The windings might consist of conductors made up of many small strands. This reduces the skin effect of the higher frequencies and also accommodates the third harmonic circulating current.
- Distorted voltage waveforms can cause core iron saturation. The transformer core is specially designed to keep the core flux density below saturation.

In addition, efforts are being made to reduce the voltage harmonics that occur in power transformers. Transformers made to carry K-Factor ratings and have reduced voltage harmonics are built to the following specifications:

- Eddy current losses are held to a minimum.
- The core is designed for low flux density.
- Neutral conductors have increased capacity.
- An electrostatic shield is placed between the primary and the secondary windings.
- Effort is made to significantly reduce the harmonic voltage distortion between the primary input and the secondary output voltages.

Conventional transformers, because they are already installed, are often used to supply nonsinusoidal load currents with a total harmonic distortion exceeding 0.05 per unit, as described in IEEE Standard C57.12.01. This results in additional losses, so a common practice is to derate the transformer to keep it operating within its designed temperature range. It is preferable to use a K-Factor transformer over an oversized conventional transformer for the following reasons:

- The oversized transformer can have higher fault current capability, which would necessitate secondary protective devices with higher interrupting rating.
- The oversized transformer can have higher in-rush current, which would necessitate an increase in the size of the primary protective devices to prevent nuisance tripping on energization.

- The oversized transformer can require larger primary conductors.
- K-Factor transformers have a 200% rated neutral bus to accommodate large neutral current from single-phase nonlinear loads.

Non-safety-related transformers are expected to have high availability and reliability and to meet the service life requirements under the specified service conditions as Class 1E transformers. Guidance for meeting availability goals can be obtained from IEEE Standard 493.

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