



IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Distribution, Power, and Regulating Transformers

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std 1276™-2020
(Revision of IEEE Std 1276-1997)



STANDARDS

IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Distribution, Power, and Regulating Transformers

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Transformers Committee
of the
IEEE Power and Energy Society

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Abstract: Technical information is provided in this guide related to liquid-immersed power, distribution, and regulating transformers that are designed to operate at temperatures that exceed the normal thermal limits of IEEE Std C57.12.00™, under continuous load, in the designed average ambient and at rated conditions. Guidelines for applying high-temperature solid and liquid materials as insulation systems; guidelines for loading high-temperature liquid-immersed power, distribution, and regulating transformers; and guidelines on test procedures for qualifying new high-temperature solid and liquid insulating materials are included.

Keywords: high-temperature insulation, hybrid insulation system, IEEE 1276™, liquid-immersed, power transformer, distribution transformer, regulating transformer, loading guide, mixed hybrid, full hybrid

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Introduction

This introduction is not part of IEEE Std 1276-2020, IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Distribution, Power, and Regulating Transformers.

Liquid-immersed transformers utilizing high-temperature insulation systems are being used increasingly by the industry. Standards including IEEE Std C57.154™ and IEEE Std C57.100™ have been developed to provide methods to evaluate new high-temperature insulation systems as well as to specify requirements for the design, testing, and application of transformers built with these high-temperature insulation systems.¹ This guide is intended to give the user some background information on the application and use of high-temperature insulation in power, distribution, and regulating transformers.

This revision of IEEE Std 1276 expands the scope of high-temperature insulation systems beyond those described in the 1997 version. The 1997 scope was limited to high-temperature insulation systems based on high-temperature solid materials in mineral oil power transformers. The revised scope includes a wider range of liquid insulation system options using high-temperature insulating liquids as well as to cover distribution and regulating transformer applications. Additionally, with the development of IEEE Std C57.154™-2012 [B27], this IEEE guide provides a place for additional guide-like information that was not suitable for a standard.² Some clauses from IEEE Std C57.154-2012 have been copied into this version of IEEE Std 1276 to provide a connection between the two documents. With this revision, an expanded discussion related to guidance for loading of transformers with high-temperature insulation systems is provided.

Additionally, as part of the revision of this document, some items from the 1997 version that have been placed in IEEE Std C57.154 that are more of a standardized nature have been removed. Examples of this include the temperature limits for different insulation systems, as well as nameplate and testing information. These have been expanded in IEEE Std C57.154 in part because the scope of transformers covered has been increased beyond power transformers and the insulating liquids covered are beyond just mineral oil.

To complete this document, there is a discussion on how to evaluate high-temperature insulation systems using the test methodology outlined in IEEE Std C57.100. [Annex A](#) provides guidance on how to conduct such testing, providing more detail than that provided within IEEE Std C57.100. This detail was needed to clarify how to conduct such testing to develop new life curves using higher temperature materials, as well as to provide more specific information developed as a result of the publication of IEEE Std C57.100™-2011 [B24], which makes implementation of this standard easier to understand. This detail is well suited to this document as it is an IEEE guide. [Annex B](#) provides examples of insulation system testing for two high-temperature insulation systems. Finally, [Annex C](#) discusses gas analysis for high-temperature insulation systems.

¹Information on references can be found in [Clause 2](#).

²The numbers in brackets correspond to those of the bibliography in [Annex D](#).

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IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Distribution, Power, and Regulating Transformers

1. Overview

The intent of this guide is to provide information on the application and use of high-temperature insulation in liquid-immersed distribution, power, and regulating transformers. It addresses only those areas where the application and use differ from the existing standards for these types of transformers.

1.1 Scope

This guide applies to liquid-immersed distribution, power, and regulating transformers that are designed to operate at temperatures that exceed the normal thermal limits of IEEE Std C57.12.00 under continuous load, in the designed average ambient, and at rated conditions.

~~This guide provides technical information related to liquid-immersed power transformers insulated with high-temperature materials.~~

- ~~— Guidelines are provided for applying existing qualified high-temperature materials to insulation systems suitable for high-temperature liquid-immersed power transformers.~~
- ~~— Recommendations are made regarding the loading of high-temperature liquid-immersed power transformers.~~
- ~~— Technical information is provided for insulation system temperature ratings and test procedures for qualifying new high-temperature materials as they become available.~~

~~No specific guidance is provided on insulating fluids other than mineral oil. This subject is to be covered in a future revision of this guide once more field experience is available using fluids other than mineral oil in combination with high-temperature solid materials.~~

1.2 Purpose

The purpose of this guide is to provide an informative technical background for the design, testing, and application of high-temperature transformers covered within the scope of IEEE Std C57.154.

~~This guide is intended as a first step in the direction of standardizing the application of high-temperature insulation systems in transformers using insulation materials such as aramid papers, aramid transformerboards, high-temperature enamels, and hybrid systems that include both high-temperature materials and cellulose materials. It provides technical information for the transformer designer as well as for the transformer user.~~

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (shall equals is required to).^{3,4}

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

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

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

³The use of the word *must* is deprecated and shall not be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁴The use of *will* is deprecated and shall not be used when stating mandatory requirements, *will* is only used in statements of fact.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ASTM D92, Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester.⁵

ASTM D93, Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester.

ASTM D1305, Standard Specification for Electrical Insulating Paper and Paperboard — Sulfate (Kraft) Layer Type.

ASTM D3455, Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin.

ASTM D3487, Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus. ASTM D4063, Standard Specification for Pressboard for Electrical Insulating Purposes.

ASTM D4652, Standard Specification for Silicone Fluid Used for Electrical Insulation.

ASTM D6871, Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus.

ASTM D5213, Standard Specification for Polymeric Resin Film for Electrical Insulation and Dielectric Applications.

~~This guide should be used in conjunction with the following publications. When the following publications are superseded by an approved revision, the latest revision shall apply.~~

⁵ASTM publications are available from the American Society for Testing and Materials (<http://www.astm.org/>).

IEEE Std C57.12.00TM~~1993~~, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers,^{6,7}~~(ANSI)~~.¹

[IEEE Std C57.12.10TM, IEEE Standard Requirements for Liquid-Immersed Power Transformers. IEEE Std C57.12.80TM, IEEE Standard Terminology for Power and Distribution Transformers.](#)

IEEE Std C57.12.90TM~~1993~~, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating ~~Transformers, and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers~~~~(ANSI)~~.

[IEEE Std C57.15TM-2009, IEEE Standard Requirements, Terminology, and Test Code for Step-Voltage Regulators.](#)

[IEEE Std C57.19.00TM, IEEE Standard General Requirements and Test Procedure for Outdoor Power Apparatus Bushings.](#)

[IEEE Std C57.19.03TM, IEEE Standard Requirements, Terminology, and Test Code for Bushings for DC Applications.](#)

IEEE Std C57.91TM~~1995~~, IEEE Guide for Loading Mineral-Oil-Immersed Transformers~~(ANSI)~~.

IEEE Std C57.100TM~~1986 (Reaff 1992)~~, IEEE Standard Test ~~Procedure~~ ~~Procedures~~ for Thermal Evaluation of ~~Liquid Oil~~ Immersed Distribution ~~and Power~~ Transformers~~(ANSI)~~.

[IEEE Std C57.106TM, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment.](#)

[IEEE Std C57.111TM, IEEE Guide for Acceptance of Silicone Insulating Fluid and Its Maintenance in Transformers.](#)

⁶IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>), 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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[IEEE Std C57.121™, IEEE Guide for Acceptance and Maintenance of Less Flammable Hydrocarbon Fluid in Transformers.](#)

[IEEE Std C57.131™, IEEE Standard Requirements for Tap Changers.](#)

[IEEE Std C57.147™, IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.](#)

[IEEE Std C57.154™, IEEE Standard for the Design, Testing and Application of Liquid-Immersed Distribution, Power and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures.](#)

[IEEE Std C57.157™, IEEE Guide for Conducting Functional Life Tests on Switch Contacts Used in Insulating Liquid-Immersed Transformers. NEMA MW 1000, Magnet Wire.](#)⁸

[UL 746B, Standard for Safety, Polymeric Materials—Long Term Property Evaluations.](#)⁹

~~[IEEE Std C57.104-1991, IEEE Guide for the Interpretation of Gases Generated in Oil Immersed Transformers \(ANSI\).](#)~~

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

[3.1 Definitions](#)

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

⁸NEMA publications are available from the National Electrical Manufacturers Association (<http://www.nema.org/>).

⁹UL publications are available from Underwriters Laboratories (<http://www.ul.com/>).

¹⁰[IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.](#)

This clause defines terms as they are used in this guide. The term “transformer” refers to liquid-immersed power transformers, unless an [alternative](#) ~~alternate~~ meaning is specified.

~~**3.1 aramid:** A manufactured material in which the base polymer is a long-chain synthetic polyamide with at least 85% of the amide linkages attached directly to two aromatic rings. Paper and transformerboard are made from this material and have been shown to be suitable for use in high-temperature and hybrid high-temperature insulation systems.~~

average winding temperature: The average temperature of ~~a~~ [the](#) winding as determined from the ohmic resistance measured across the terminals of the winding, in accordance with the cooling curve procedure specified in IEEE Std C57.12.90TM. [\(IEEE Std C57.12.80TM\)](#) ~~-1993.~~

average winding temperature rise ~~($\Delta\theta_w$)~~: The arithmetic difference between the average winding temperature [of a winding](#) and the [ambient](#) ~~average~~ temperature. [\(IEEE Std C57.12.80TM\)](#) ~~of the air surrounding the transformer.~~

NOTE—Also, “rise,” unless otherwise stated, will refer to the average winding temperature rise.

cellulose: ~~The term “cellulose,”~~ Unless otherwise stated, [this term](#) refers to unbleached kraft insulation material from which paper and transformerboard are made, that is suitable for use in [conventional and hybrid](#) ~~65°C average winding temperature rise~~ insulation systems.

conventional: [A description applied to temperature-rise limits, insulation materials, or insulation systems operating at temperatures within the normal thermal limits of IEEE Std C57.12.00TM.](#)

full hybrid insulation winding: [A winding composed of conventional solid insulation with high-temperature solid insulation used in areas in contact with the winding conductor to allow higher than conventional average winding and hottest spot temperature rises.](#)

high temperature: [A description applied to temperature-rise limits, insulation materials, or insulation systems operating at higher temperatures than conventional.](#)

high-temperature insulation system: High-temperature insulation used throughout the transformer, except for some minor insulation components in lower temperature areas, together with high-temperature insulating liquid operating at higher than conventional top liquid, average winding, and hottest spot temperature rises.

high-temperature insulation winding: A winding composed of high-temperature insulation used throughout the winding to allow higher than conventional average winding and hottest spot temperature rises.

hybrid insulation system: High-temperature solid insulation operating above conventional temperatures, combined with conventional solid insulation and an insulating liquid operating at conventional temperatures.

insulation system: Materials or combination of materials, which by experience or accepted tests, have been shown to give the required life at a continuous temperature. (Derived from IEEE Std C57.12.80™)

NOTE—For the purpose of this standard, this required life is defined by IEEE Std C57.12.00 and the thermal classes are listed in IEEE Std C57.154.

mixed hybrid insulation winding: A winding composed of conventional solid insulation with high-temperature solid insulation used only selectively to allow higher than conventional hottest spot temperatures, while operating at conventional average winding temperature rises.

~~**3.5 high temperature:** Used to describe materials, insulation systems, and transformers that are designed to operate at a maximum hottest spot temperature above 120 °C.~~

~~**3.6 high-temperature insulation system:** An insulation system composed of all high-temperature solid insulation materials, with or without high-temperature fluids.~~

~~**3.7 hottest-spot differential temperature:** The temperature difference between the hottest spot of the conductors in contact with insulation and the average winding temperature.~~

~~3.8 hybrid high-temperature insulation system: An insulation system usually composed of hightemperature solid insulation material adjacent to winding conductors and cellulose materials in the areas where the maximum temperature at rated load does not exceed 120 °C. This system typically uses conventional mineral oil as the insulating liquid.~~

~~3.9 insulation system: A system composed of solid insulating materials and insulating fluid. Synonym: system.~~

~~3.10 maximum hottest conductor temperature: Used in discussions involving the life testing of materials, in lieu of the phrase winding hottest spot temperature (θ_h).~~

mobile transformer: Transformers that are usually mounted on trailers for easy transport to temporarily replace stationary transformers taken out of service because of failure or maintenance. These transformers are also used for applications requiring increased power for temporary or seasonally increased loads.

normal insulation life: The time span during which the process of material decomposition reaches a benchmark as described in [Annex I 5.3](#), Table [I.2](#), of IEEE Std C57.91TM-2011 ~~1995~~.

NOTE—See IEEE Std C57.91-2011 [B22].

reference temperature: The reference temperature shall be defined as 20 °C plus the rated average winding rise. For multiple winding transformers that have more than one base rated average winding rise, the highest average winding rise shall be used to determine the reference temperature. (IEEE Std C57.12.80TM)

thermally upgraded kraft (TUK): Cellulose-based paper that has been chemically modified to reduce the rate at which the paper decomposes. Aging effects are reduced either by partial elimination of water forming agents (as in cyanoethylation) or by inhibiting the formation of water through the use of stabilizing agents (as in amine addition, dicyandiamide). (Derived from IEEE Std C57.12.80TM)

top liquid temperature: The temperature of the top layer of the insulating liquid in a transformer, representative of the temperature of the top liquid in the cooling flow stream. Generally measured 50 mm below the surface of the liquid. (Derived from IEEE Std C57.12.80™)

~~3.13 system: See: insulation system.~~

~~3.14 transformerboard: Pressboard specifically manufactured for use as transformer dielectric insulation.~~

4. High-temperature operation

~~4. Merits of operating at high temperatures~~

For given quantities of active materials (core steel and conductor), the capacity ~~throughput~~ of the transformer can be increased if the allowable ~~average winding~~ temperature rises (top liquid/winding average/winding hottest spot) ~~are~~ ~~rise is~~ increased beyond the limits of IEEE Std C57.12.00 ~~65°C rise insulation system limit.~~

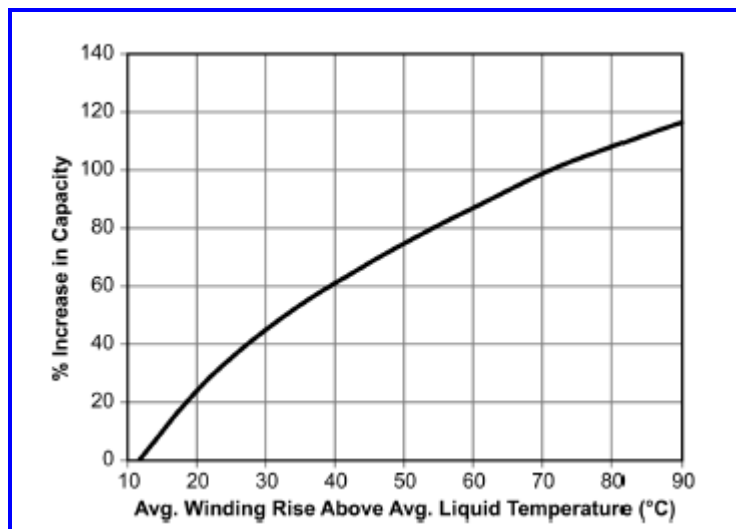
Transformer properties, such as ratings, overload capability, weight, dimensions, aging, cooling equipment, losses, and cost, could be affected by using high-temperature insulation systems.

The degree of freedom for specifying and designing transformers increases by using higher temperature limits. With the growing availability of both high-temperature solid and liquid insulation materials, this degree of freedom continues to expand.

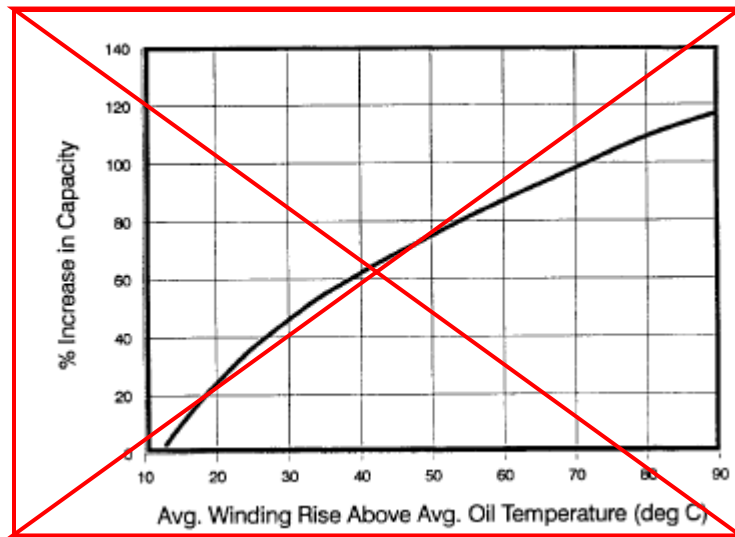
~~NOTE For a transformer, percent reactance increases proportionally with the rated power throughput (MVA). Load losses increase in proportion to the MVA ratio squared, with an additional increase due to increased conductor resistance at the elevated temperature.~~

As examples, ~~Figure~~ ~~Figures~~ 1 and ~~Figure~~ 2 illustrate the ~~results merits~~ of increasing the average winding temperature rise over average ~~liquid oil~~ temperature ~~-($\Delta\theta_{w/o}$)~~ for ~~a hypothetical two~~ ~~particular~~ transformer design ~~family families~~. Figure 1 expresses the relationship between transformer capacity increase and ~~the average winding temperature rise over average liquid temperature, whereas $\Delta\theta_{w/o}$ while~~ Figure 2 shows the relationship between reduced core and coil weight and ~~this same parameter~~. These results will be different for each transformer design family; however, the intention is to illustrate the concept of possible increase of the transformer capacity and reduction of dimensions and weights when high-temperature operation is considered ~~$\Delta\theta_{w/o}$~~ .

Most modern transformers operate with a ~~relatively~~ low ~~average winding temperature rise over average liquid temperature~~. For example, an increase in this parameter ~~$\Delta\theta_{w/o}$~~ ~~Therefore, a small~~ ~~increase in $\Delta\theta_{w/o}$~~ can yield ~~an a significant~~ increase in the transformer rating for a given weight, or a decrease in transformer weight for a given rating.



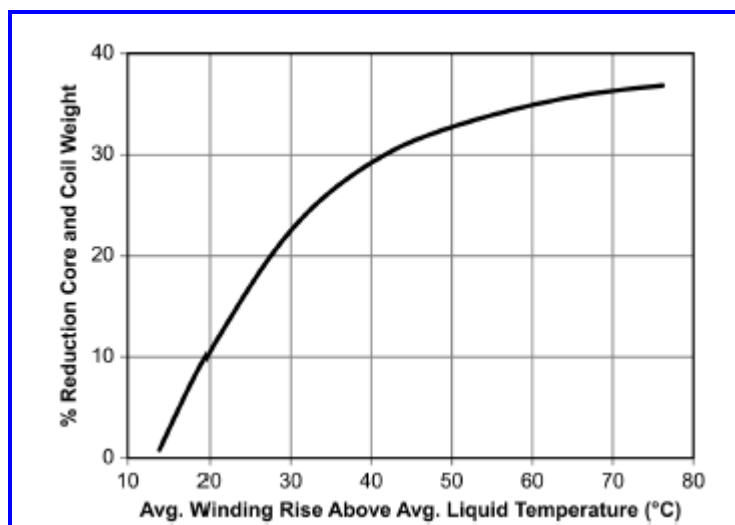
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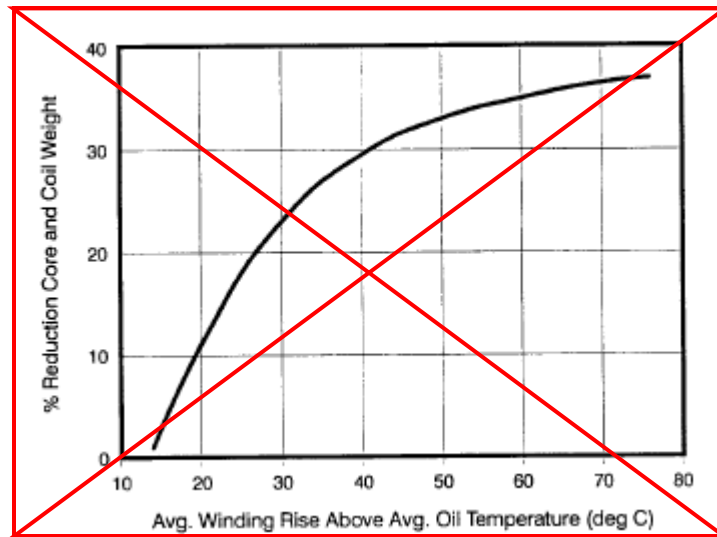
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Figure 1—Relationship between transformer capacity increase and average winding temperature rise over average liquid temperature

~~$\Delta\theta_{w/o}$~~



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Figure 2—Relationship between reduced core and coil weight and average winding temperature rise over average liquid temperature

~~$\Delta\theta_{w/o}$~~

NOTE—The curves presented in Figure 1 and Figure 2 will depend on various technical parameters, like rating, cooling type, and so on. These figures are general in nature and only intended to show the principle.

5. Insulation materials

5.1 General

Common insulation materials are listed in Table 1, Table 2, and Table 3 along with typical parameters and characteristics that are useful for proper evaluation. However, the appearance of these materials does not imply that any specific combination is suitable for use in high-temperature, liquid-immersed transformer applications.

It is important to note that design parameters specific to the material selected can be obtained from the manufacturer of the product. The insulation materials are separated into three tables, one each for solids, wire enamels, and liquids.

Each material should be evaluated for compatibility with other materials in the insulation system and not only for thermal capability. Experience has shown that the thermal life characteristics of composite insulation systems cannot be reliably inferred solely from information concerning individual component materials.

It should also not be assumed that the insulation system thermal class would necessarily default to the lowest temperature class of the insulation system's individual components. Insulating materials having different temperature classes can be combined to form an insulation system having a temperature class that is higher or lower than that of any of the individual components. However, the individual component thermal class could provide guidance in the selection and positioning of the various materials within the insulation design.

5.2 Solid insulation

Solid insulation is available in the form of paper, film, sheet, and board as well as in various shapes for mechanical applications used within the dielectric structure. Table 1 lists many readily available high- temperature materials compared with typical parameters to cellulose based papers and boards. Note that this typical performance information is based on components tested individually as isolated samples in air. Dielectric and thermal performance as an insulation system when immersed in the selected insulating liquid may be substantially different from the component values and the values associated with impregnation in a specific liquid. Note also that the typical thermal test in air is referenced to 60 000 h compared with the life expectancy for liquid-immersed transformers of 180 000 h. Consequently, the in-air thermal classes shown in Table 1 are not directly acceptable for liquid-immersed applications.

Table 1—Typical properties of solid insulation materials in air

Material			ASTM standard reference	Relative permittivity at 25°C	Dissipation factor (%)		Moisture absorption (%)	Density (g/cm ³)
					At 25 °C	At 100 °C		
Cellulose based		n/a	D1305	3.3–4.1	0.4	1.0	7.0	0.97–1.2
Cellulose based		n/a	D4063	2.9–4.6	0.4	1.0	7.0	0.8–1.35
Polyester glass ^b		130–210		4.8	1.3–7.0	n/a	0.2–1.1	1.8–2.0
Polyester glass ^b		130–210		n/a	n/a	n/a	0.16–0.28	1.8–2.0
Polyphenylene sulfide (PPS)		160–200		3.0	0.06	0.12	0.05	1.35
Aramid		200–220		1.6–3.2	0.5	0.5	5.0	0.66–1.10
Aramid		220		1.7–3.5	0.5	0.5	5.0	0.52–1.15
Polyimide		200–260	D5213	3.4	0.2	0.2	1.0–1.8	1.33–1.42
NOTE 1—All data have been taken from measurements in air.								
NOTE 2—Relative permittivity and dissipation factor data are referenced to 50/60 Hz.								
NOTE 3—Moisture data are based on conditions of 50% relative humidity at a temperature of 23 °C.								

(New)

^aThermal class in air according to UL 746B.

^bTypically only used in lower voltage applications due to possible air entrapment during the manufacturing process.

Thermal classes are often assigned based on service experience or functional tests of the solid insulation immersed in the applicable liquid. IEEE Std C57.100 provides the method used for functional life testing to determine such thermal classes when service experience is not available. Service experience has shown that cellulose paper when used with mineral oil can be classified as a 105 class material, and thermally upgraded cellulose paper and cellulosic board are both classified as 120 class materials in most liquids.

NOTE—Such experiences also include low-voltage windings with no paper wrapping when the conductors are in direct contact with the board.

All data provided in Table 1 is a reference of values and should not be used without confirmation from the manufacturer and under agreement with the customer. Due to the large variety of solid and liquid combinations that could be used in liquid-immersed insulation systems, and the effects of these combinations for the indicated properties, the manufacturer of the insulation materials should be contacted to provide detailed information for further combinations.

5.3 Wire enamel insulation

The list in Table 2 shows a range of available insulating enamels used to coat both round and rectangular copper and aluminum winding wires. Additional information may be found in the specific applicable sections of NEMA MW 1000. Note that the appearance of a coating in this list does not imply compatibility with any of the many available insulating liquids when used in high-temperature applications.

Also note that the typical test in air is referenced to 20 000 h compared with a life expectancy for liquid-immersed transformers of 180 000 h. Procedures for verifying compatibility with mineral oil are defined in ASTM D3455, which uses low-temperature testing based on historical uses. This technique may not be directly comparable with results at elevated temperatures in a wide range of insulating liquids, such as are listed in Table 3.

Table 2—Typical enamels for wire insulation

Chemical name	Thermal class	NEMA designation	Common acronym	Common name
Polyvinyl acetal	105	MW15 MW 18 MW19	PVF PVA	Polyvinyl formal
Aromatic polyamideimide	200	MW81	ATW	Polyamideimide
Aromatic polyimide	220	MW16 MW20	PIW	Polyimide
Epoxy	155	n/a	Epoxy	Epoxy
Polyarylethersulfone	155	n/a	PPSU PAES	Polyphenylsulfone
Polyarylsulfone	180	n/a	PAS	Polyarylsulfone
Polyaryletheretherketone	220	n/a	PEEK	Polyarylether- etherketone
NOTE 1—Thermal class in air according to NEMA MW 1000, Part 2, Clause 3.58.1.				
NOTE 2—Although polyvinyl acetal enamel insulation is classified as a 105 thermal class when tested in air, it has in practice been applied in insulation systems of a 120 thermal class along with thermally upgraded paper insulation in most liquids based on the proven service experience for more than 50 years.				

(New)

5.4 Insulating liquids

Table 3 shows typical performance characteristics of insulating liquids that are used in liquid-immersed transformers. Mineral oil complying with ASTM D3487 is the most common insulating liquid used in transformers and is generally the performance reference to which all other liquids are compared. This liquid is also the reference for comparing high-temperature performance.

According to the rules for classifying liquids, a fire point greater than 300 °C, as determined according to ASTM D92, classifies the liquid as a less-flammable liquid. However, neither the flash point nor the fire point is sufficient to define high-temperature capability. The thermal capability of different types of insulating liquids can differ based on their specific chemical reaction characteristics versus temperature. It is important to obtain the short-term and long-term temperature limits recommended by the respective manufacturer. The liquid manufacturer can be contacted to determine whether a specific product is suitable for use at higher temperatures than conventional mineral oil.

The thermal classes listed in Table 3 are provided only as a starting point for further investigation since there is no generally accepted procedure for establishing a thermal class for insulating liquids. These temperatures are estimated or generally accepted by the industry.

6. Transformer accessories

6.1 General

General requirements for standard accessories should be in accordance with IEEE Std C57.12.00 and specific product standards, such as IEEE Std C57.12.10. The liquid temperature will likely be the key factor in determining the need for special thermal requirements for most accessories. All accessories need to be demonstrated as being compatible with the specific insulating liquid if an alternative to mineral oil is specified. Typically, this compatibility information may be available from the supplier of the insulating liquid and/or from the specific accessory supplier.

Table 3—Typical properties of insulating liquids

Generic name	Reference standard	Estimated thermal class ^a	Flash point ^c (°C)	Fire point ^c (°C)	Water content ^d (mg/kg)	Density at 25°C (g/cm ³)	Relative permittivity ^e at 25°C	Dissipation factor ^f at 25°C (%)	Kinematic viscosity (mm ² /sec)		Thermal conductivity at 25°C (W/mK)	Specific heat at 25°C (J/kg·°C)
									At 40°C	At 100°C		
Mineral oil	ASTM D3487 IEEE Std C57.106	105	145	160	25	0.88	2.2	0.05	9.2	2.3	0.12	2100
Natural ester	ASTM D6871 IEEE Std C57.147	120-130 ^b	330	360	50	0.91	3.2	0.08	33	9.0	0.17	2000
Synthetic hydrocarbon		120-130	275	316	50	0.97	3.2	0.02	28	5.8	0.16	2100
Synthetic PAO hydrocarbon		120-130	230	250	15	0.83	2.1	0.01		4.1	0.14	2100
High-molecular-weight hydrocarbon	IEEE Std C57.121	140-155	264	304	15	0.83	2.1	0.01	—	8.6	0.13	2300
Dimethyl silicone	ASTM D4652 IEEE Std C57.111	140-155 ^b	310	360	50	0.87	2.2	0.01	—	11.8	0.14	2100
						0.96	2.7	0.01	40	14.3	0.15	1500

NOTE—The values in this table are provided only as a general guide for comparison of the different liquids. For specific physical properties and acceptance limits, refer to the standard(s) noted for each liquid. Physical properties and acceptance limits for liquids with no reference standard should be verified with the liquid manufacturer.

(New)

a The thermal classes shown are estimated or generally accepted by the industry since there is no accepted procedure for establishing a thermal class for insulating liquids.

b Due to the oxidation stability properties of these insulating liquids, the estimated temperature limits apply to sealed type transformers or transformer with nitrogen preservation systems that effectively prevents the ingress of air.

c Cleveland open cup test per ASTM D92. The flash point may also be determined according to the Pensky-Martins closed cup test per ASTM D93, which generally gives lower values than those shown. ASTM D6871 defines the minimum flash point and fire point temperatures as 275 °C and 300 °C, respectively.

d Technically, absolute water content is not a performance characteristic since it is not inherent in the liquid, but rather it is reflective of the processing, storage, and handling conditions.

It is included here for comparative reference purposes.

e Relative permittivity and dissipation factor data are referenced to 50/60 Hz.

For high-temperature application, it is recommended to have the accessories qualified to operate at the top liquid temperature of the transformer.

NOTE—Hybrid transformers are designed to operate at a 65 °C top liquid temperature rise, which allows the use of standard accessories.

6.2 Leads and cables

The thermal class of insulation used on interconnection and accessory leads and cables is not necessarily based on the transformer insulation system designation. However, the temperature limits for the leads and cables should be defined using a method such as the thermal class of the insulation systems outlined in Table 3 and Table 4 of IEEE Std C57.154-2012 [B27]. This thermal class may be dependent on the type of insulating liquid.

Material selection for lead and interconnection cables is independent of the insulation system selected for the transformer windings. However, high-temperature insulation is recommended for lead cables in high- temperature insulation systems; otherwise the leads may need to be oversized to allow for the use of lower temperature materials.

In full hybrid windings, high-temperature insulation is typically used at least in lead exit areas, where cables connect with windings operating at temperatures higher than conventional. Frequently, these cables are connected directly to hot-spot areas of the windings, or hot spots can be created in connection points. The selection of insulation material for the remaining length of the cable would be based on its designed temperature gradient and may include conventional insulation materials. Heat sinks or larger contact points may be used to control hot spots at the connection points.

Similar to mixed hybrid insulation windings, the use of high-temperature insulation materials can be selective and limited to specific areas only. Even if the entire winding is conventional, the lead exits or entire lead cables can still be designed to operate at temperatures higher than conventional. In such cases, the cable insulation would then be selected appropriate to the designed temperatures.

6.3 Bushings

General requirements and test procedures for outdoor power apparatus bushings intended for use in liquid- immersed transformers and reactors are established in accordance with IEEE Std C57.19.00. General requirements and test procedures for dc apparatus bushings intended for use in liquid-immersed converter transformers and smoothing reactors would be in accordance with IEEE Std C57.19.03.

The bushings defined in these standards are often liquid-filled condenser type that are designed specifically for top liquid temperatures operating above a 65 °C temperature rise or standard bushings may be de-rated for the specific temperature of the application. The maximum current of the bushing may need to be reduced for the cases where the top liquid temperature rise exceeds 65 °C. RIP (resin impregnated paper) and RIS (resin impregnated synthetic) bushings are also becoming common for both conventional and high-temperature applications.

NOTE—IEEE Std C57.19.100-2012 [B21] provides an example of de-rating calculations for top liquid temperature rises between 55 °C and 65 °C, and the same method could be used for higher temperature rise applications such as might be seen with high-temperature insulation systems.

6.4 Gasket materials

High-temperature bushing gaskets made of fluorocarbon, fluorosilicone, or other suitably high-temperature materials can be used when the top liquid temperature rise exceeds 65 °C at rated transformer operating conditions. All accessories would need such high-temperature gasket materials when the temperature of the specific gasket location exceeds conventional temperatures. Suppliers of high-temperature insulating liquids may be able to provide recommendations for such gaskets known to be compatible with the use of such liquids at elevated temperatures.

6.5 Tap changers

The general requirements for de-energized (DETC) and load tap changers (LTC) are generally in accordance with IEEE Std C57.131 for transformers operating at high temperatures. However, special design considerations may be necessary when the temperature of the liquid surrounding the tap changer exceeds 105 °C. This temperature limit is based on normal rated load and a maximum ambient temperature of 40 °C. Relocating the switch to a cooler position in or on the transformer tank can be an option.

For a small increase in the insulating liquid temperature, de-rating a larger capacity switch may be acceptable. For high-temperature applications, a reduced switching capacity of the tap changer is not permissible to comply with the applicable IEEE loading guide and Table 5 and Table 6 of IEEE Std C57.154-2012 [B27]. Tests according to IEEE Std C57.131 should be performed to verify that the maximum admissible temperatures of the tap changer are not exceeded. In particular, the temperature rise of contacts that continuously carry the through-current may not exceed the admissible limits in steady state when carrying 1.2 times the maximum rated through-current. For reactance-type load tap changers, the design test would need to be performed in the bridging position, with the currents calculated according to IEEE Std C57.131. See IEEE Std C57.157 for more information on testing of tap-changer contact.

Tap changers immersed in the insulating liquid of the transformer, in-tank on-load tap changers (OLTCs), are resistor type tap changers. As such, this means that during tap changing operations, additional heat is generated by transition resistors. Current OLTCs are limited to operate at liquid temperatures up to 130 °C depending on the design and the manufacturer. Higher liquid temperatures require a special tap-changer design facilitating appropriate materials. To achieve a higher thermal class, all materials used in a tap changer must be approved for higher temperatures considering switching operations to allow for a load-switching operation also under overload conditions.

6.6 Liquid temperature indicator

A thermometer that measures top liquid temperature should be in accordance with the requirements of IEEE Std C57.12.10, except that the indicator may need to have a scale that ranges from zero as a minimum to a maximum of 10 °C above the maximum top liquid temperature, with long time emergency loading. Maximum temperatures are shown in Table 5 and Table 6 of IEEE Std C57.154-2012 [B27]. The alarm contacts may then need to be adjustable over a range of 40 °C as a minimum to a maximum temperature equal to the maximum gauge scale temperature.

6.7 Winding temperature indicator

Thermometers that simulate or measure the winding hottest spot temperature should be in accordance with the requirements of IEEE Std C57.12.10, except that the indicator may need to have a scale that ranges from zero as a minimum to a maximum of 40 °C above the maximum winding hottest spot temperature, with long time emergency loading. Maximum temperatures are shown in Table 5 and Table 6 of IEEE Std C57.154-2012 [B27]. The alarm contacts would need to be adjustable over a range of 40 °C as a minimum to a maximum temperature equal to the maximum winding hottest spot temperature, with long time emergency loading.

6.8 Bushing-type current transformer

Most conventional bushing-type current transformers (BCTs) manufactured and produced in accordance with IEEE standards use materials suitable for insulating liquids not exceeding a continuous temperature of 95 °C. Special design and material considerations are necessary when the temperature of the insulating liquid or BCT operating ambient exceeds 95 °C. When specifying a BCT for use in high-temperature, liquid-immersed transformer applications, the liquid type and maximum temperature or maximum insulation temperature class should be specified. The current ratio and rating factor (RF) may also need to be coordinated with the transformer loading requirements.

6.9 Liquid preservation system

General requirements for the liquid preservation systems should be in accordance with the requirements of IEEE Std C57.12.10. The interior of the transformer should be sealed from the atmosphere for top liquid temperatures ranging from -20 °C to a value that is the sum of the maximum top liquid temperature rise, the maximum rated ambient temperature, and an additional 20 °C. For insulation systems using high-temperature insulation materials, the maximum top liquid temperature rise is specified for different insulation systems in IEEE Std C57.154.

7. Insulation systems

7.1 Conventional insulation system temperature ratings

~~5. Insulation system temperature ratings, test procedures, and material aging qualification~~

~~5.1 Insulation system temperature ratings for 55 °C² and 65 °C rise systems~~

Traditionally, cellulose-based insulation systems have been thought of in terms of the temperature rise: first 55 °C rise and more recently 65 °C rise. In IEEE Std C57.154, the conventional insulation system is defined as a 120 thermal class with a 65 °C average winding rise, an 80 °C hottest spot rise, and a hottest spot temperature of 110 °C. According to IEEE Std C57.12.00, the liquid in a conventional insulation system has a minimum thermal class of 105. The rises ~~Cellulose-based insulation systems have been grouped into two temperature rise classes, 55 °C and 65 °C. They~~ denote the rated ~~highest-permitted~~ average winding rise over a standard average daily ambient temperature of 30 °C. The thermal class is assigned based on the maximum hottest spot temperature as demonstrated later in this clause. Although the bulk of the insulation between conductors will experience a degree of degradation related to the average winding temperature, the maximum degradation occurs in the insulation that is in contact with the conductors at the highest local, or “hottest spot,” temperature existing within the winding. This winding hottest spot temperature is calculated as the sum of the following:

~~²Discussions of 55 °C rise systems are included in this guide for historical reference only.~~

- The ambient temperature (θ_a) of 30 °C averaged over a 24 h period, with a maximum ambient of 40 °C during the period, according to IEEE Std C57. [12.00 91-1995](#)
- The average winding rise over the ambient temperature ($\Delta\theta_w$)
- The winding hottest-spot rise over the average winding temperature rise ($\Delta\theta_{h/w}$)

As an example, for thermally upgraded cellulose, the [rated](#) average winding rise over ambient temperature [is must not exceed](#) 65 °C, and the sum of the latter two components [equals](#) ($\Delta\theta_w + \Delta\theta_{h/w}$) [must not exceed](#) 80 °C, which [results in produces](#) a maximum hottest spot temperature of 120 °C ([40 65](#) °C + [65 40](#) °C + 15 °C = 120 °C).

Effectively, the highest daily average winding hottest spot temperature that can be withstood on a continuous basis without [higher than rated excessive](#) loss of life is 110 °C for the upgraded cellulose material ([30 65](#) °C + [65 30](#) °C + 15 °C = 110 °C).

In [practice reality](#), the highest winding hottest spot temperature is seldom sustained over an extended time period. It varies with the load, which is changing in accordance with daily, weekly, monthly, and seasonal cycles. The rate of loss of life is an exponential function of the time that the insulating materials are exposed to the winding hottest spot temperature. Consequently, the typical life of [many liquid-immersed transformers a power transformer](#) is [often estimated at](#) some 30 years [or more of service](#). This 30-year life represents [1.5 four to five](#) times the normal insulation life, under continuous full-load conditions, for a [120 thermal class 65°C rise](#) insulation system.

[7.2 Types of high-temperature insulation systems](#)

[Different alternatives for the application of high-temperature materials can be defined. When all insulation materials are classified as high-temperature materials, including the liquid insulation and all applied solid insulation materials, it is a high-temperature insulation system. If any portion of the solid insulation or the liquid insulation is of conventional thermal class, the insulation system is defined as either a mixed or a full hybrid.](#)

[The maximum allowed temperature rise limits are presented in IEEE Std C57.154. The set of temperature rise limits for a transformer is expected to comply with the maximum values presented, but they may be adjusted since, in many cases, the top liquid temperature is used as an indirect limitation for the hottest spot temperature rise. This is especially relevant for the high-temperature insulation systems since the usual top liquid temperature rise limit of a transformer should not be higher than the average winding temperature rise, indirectly limiting the hottest spot temperature rise, which may be challenging to measure accurately.](#)

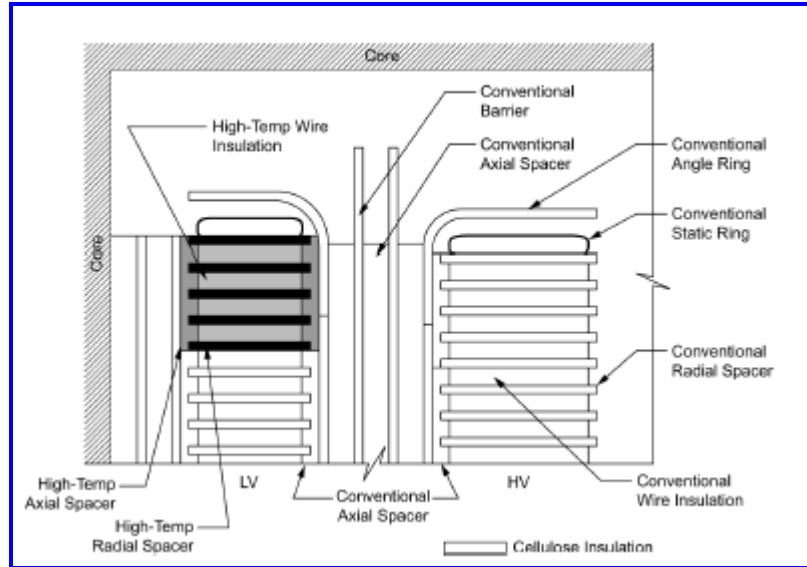
7.2.1 Hybrid insulation system

[Two hybrid insulation winding types share the use of conventional barrier insulation and the use of high- temperature insulation on the windings. These two winding types are mixed hybrid and full hybrid insulation systems. There is also a high-temperature insulation system. For more detail on each, see IEEE Std C57.154.](#)

7.2.1.1 Mixed hybrid insulation system

[The mixed hybrid insulation winding uses high-temperature insulation for certain components or parts of windings, such as the conductors in regions operating at temperatures above conventional limits.](#)

[However, the majority of the solid insulation would still be conventional. The average winding temperature is conventional, whereas a portion of the winding exceeds conventional hottest spot temperatures. See Figure 3 for an illustration of this type of winding.](#)



(New)

Figure 3— Illustration of a mixed hybrid insulation winding

NOTE—This winding type uses high-temperature insulation to protect only a portion of the winding from temperatures that exceed the conventional hottest spot temperature limit.

The key to this winding type is that the average winding temperature remains equal to or below conventional limits, and only a portion of the winding exceeds the conventional hottest spot temperature limit. Examples of winding zones with extra losses and higher heat development that could benefit from high-temperature insulation are as follows:

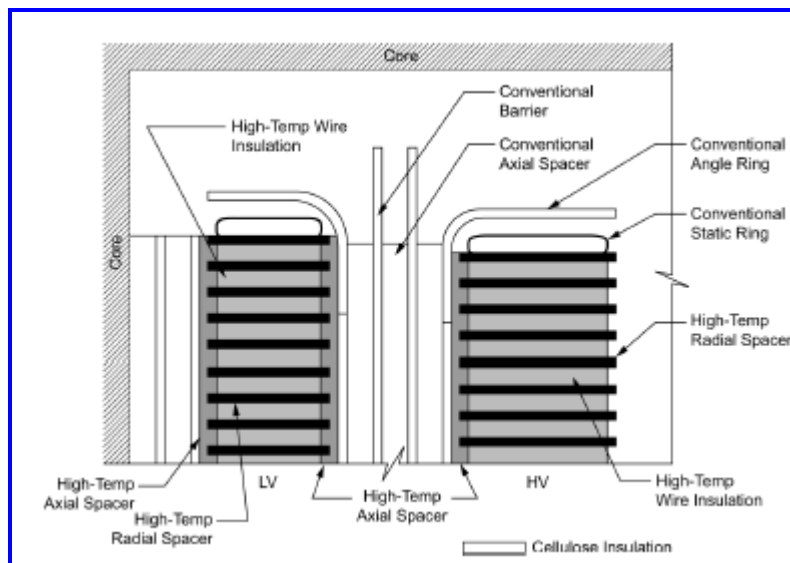
- Winding ends due to the radial component of the magnetic leakage field
- Zones of the windings where harmonic current heating might be concentrated, such as in rectifier, arc furnace, or converter transformers

Types of material in winding are high-temperature insulation applied to minor selected areas of the winding and used with the specific intent to protect strategic locations from excessive aging. Types of material in barriers are conventional materials. Temperature limits for average winding are equal to the conventional insulation system and for winding hottest spot are higher than the conventional insulation system.

7.2.1.2 Full hybrid insulation system

The full hybrid insulation winding uses high-temperature material throughout the winding, which operates above conventional temperatures. The conductor insulation and the radial and axial spacers separating the coil sections are composed of high-temperature materials. Other insulation components are also composed of high-temperature materials, where conventional temperatures are exceeded.

Conventional insulation would then typically be used in all other areas, such as barrier cylinders and angle rings that operate at conventional temperatures. See Figure 4 for an illustration of this type of winding.



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Figure 4—Illustration of a full hybrid insulation winding

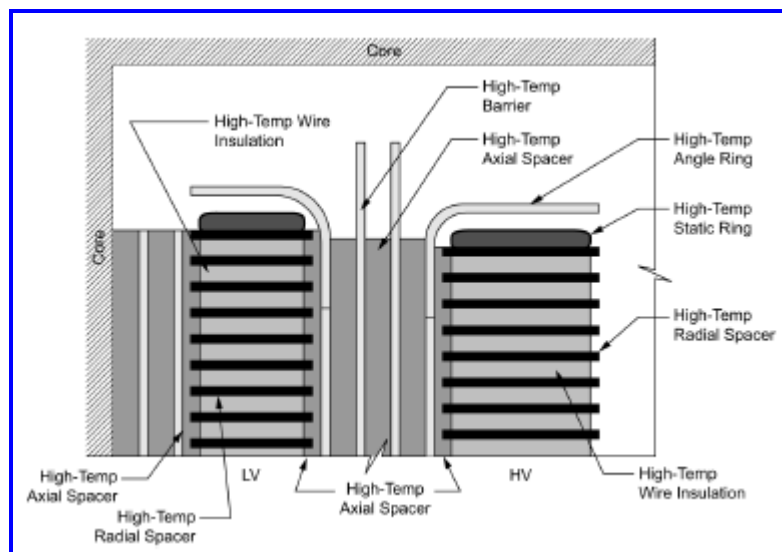
NOTE—The full hybrid insulation winding is similar to the high-temperature winding. The differences are the barriers and peripheral insulation made of conventional material.

The types of material used in the winding are high temperature for all insulation operating at temperatures higher than conventional. The types of material used in the barriers are conventional materials. Therefore, the temperature limits for the average winding are higher than for conventional windings, and for the winding, the hottest spot is also higher than conventional.

7.2.2 High-temperature insulation system

This winding style will use high-temperature insulation materials throughout the winding such as conductor insulation, radial and axial spacers separating the coil sections, barrier cylinders, and angle rings.

The types of material used in the winding are high temperature, and the types of material used in the barriers are also high temperature. Temperature limits for average winding and winding hottest spot are both higher than conventional. See Figure 5 for an illustration of this type of winding.

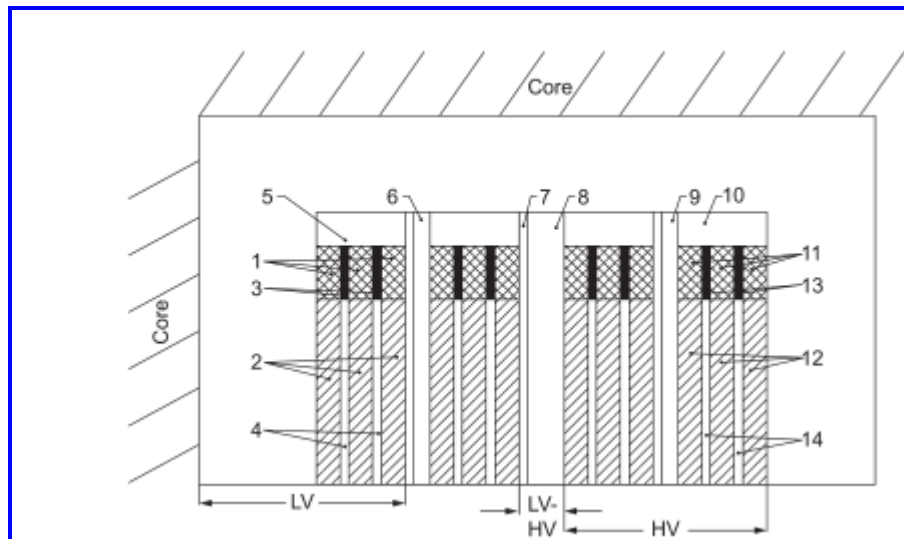


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Figure 5— Illustration of a high-temperature insulation winding

7.2.3 Insulation systems—distribution transformers

As with the insulation systems described in 7.2.1, which are commonly used for either power or mobile transformers, these concepts may also be applied to distribution transformers. Two hybrid insulation winding types share the use of conventional barrier insulation and the use of high-temperature insulation on the windings. These two winding types are mixed hybrid and full hybrid insulation systems. There is also a high- temperature insulation system. These possible insulation systems are shown in Figure 6, with the detail by insulation system type identified in Table 4.



(New)

Figure 6—Illustration of winding insulation of distribution transformers

(see Table 4)

Table 4—Distribution transformer winding/insulation system comparison

Transformer insulation region		Winding insulation system		
Position in Figure 6	Description	Mixed hybrid	Full hybrid	High temperature
1	LV conductor insulation—1/4 of winding height (top)	H	H	H
2	LV conductor insulation—rest of winding	C	H	H
3	LV layer insulation—1/4 of winding height (top)	H	H	H
4	LV layer insulation—rest of winding	C	H	H
5	LV end insulation	C	C	H
6	LV cooling duct spacing insulation	C	C	H
7	LV-HV paper or board insulation	H	H	H
8	LV-HV spacing insulation	C	C	H
9	HV cooling duct spacing insulation	C	C	H
10	HV end insulation	C	C	H
11	HV conductor insulation—1/4 of winding height (top)	H	H	H
12	HV conductor insulation—rest of winding	C	H	H
13	HV layer insulation—1/4 of winding height (top)	H	H	H
14	HV layer insulation—rest of winding	C	H	H

(New)