

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Power transformers –

Part 14: Liquid-immersed power transformers using high-temperature insulation materials

Transformateurs de puissance –

Partie 14: Transformateurs de puissance immergés dans du liquide utilisant des matériaux isolants haute température



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

**Part 14: Liquid-immersed power transformers
using high-temperature insulation materials**

FOREWORD

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International Standard IEC 60076-14 has been prepared by IEC technical committee 14: Power transformers.

This first edition of IEC 60076-14 is an International Standard which cancels and replaces the second edition of the Technical Specification IEC/TS 60076-14 published in 2009. It constitutes a technical revision.

This International Standard includes the following significant technical changes with respect to the Technical Specification:

- a) the hot-spot relationship to thermal class is now defined;
- b) a new 140 thermal class is defined;
- c) the number of insulation systems is reduced to only three: conventional, hybrid and high-temperature;

- d) homogeneous high-temperature insulation system has been changed to just high-temperature insulation system;
- e) winding definitions were introduced to define variations in the hybrid insulation system;
- f) the system example drawings have been revised for clarity;
- g) all suggested limits corresponding to Part 7 loading guide have been defined in a similar format;
- h) moisture equilibrium curves for high-temperature materials have been added to the moisture and bubble generation annex;
- i) an annex has been added to introduce the concept of thermal enhancement of cellulose by ester;
- j) some guide information, such as overload temperature limit suggestions was retained, but most of the other informative text was moved into informative annexes.

The text of this standard is based on the following documents:

FDIS	Report on voting
14/755/FDIS	14/759/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 60076 series can be found, under the general title *Power transformers*, on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

This part of IEC 60076 standardizes liquid-immersed transformers that use high-temperature insulation. As a system, the solid insulation may encompass a broad range of materials with varying degrees of thermal capability. The insulating and cooling liquids also vary substantially, ranging from mineral oil to a number of liquids that also have a range of thermal capability.

This international standard is not intended to stand alone, but rather builds on the information and guidelines documented in other parts of the IEC 60076 series. Accordingly, this document follows two guiding principles. The first principle is that liquid-immersed transformers are well known and are well defined in other parts of this series and therefore, the details of these transformers are not repeated in this international standard, except where reference has value, or where repetition is considered appropriate for purposes of emphasis or comparison.

The second principle is that the materials used in normal liquid-immersed transformers, typically kraft paper, pressboard, wood, mineral oil, paint and varnish, which operate within temperature limits given in IEC 60076-2, are well known and are considered normal or conventional. All other insulation materials, either solid or liquid that have a thermal capability higher than the materials used in this well-known system of insulation materials are considered high-temperature. Consequently, this standard or normal insulation system is defined as the “conventional” insulation system for comparison purposes and these normal thermal limits are presented for reference to illustrate the differences between other higher-temperature systems.

This international standard addresses loading, overloading, testing and accessories in the same manner. Only selected information for the “conventional” transformers is included for comparison purposes or for emphasis. All other references are directed to the appropriate IEC document.

POWER TRANSFORMERS –

Part 14: Liquid-immersed power transformers using high-temperature insulation materials

1 Scope

This part of IEC 60076 applies to liquid-immersed power transformers employing either high-temperature insulation or combinations of high-temperature and conventional insulation, operating at temperatures above conventional limits.

It is applicable to:

- power transformers in accordance with IEC 60076-1;
- convertor transformers according to IEC 61378 series;
- transformers for wind turbine applications in accordance with IEC 60076-16;
- arc furnace transformers;
- reactors in accordance with IEC 60076-6.

This part of IEC 60076 may be applicable as a reference for the use of high-temperature insulation materials in other types of transformers and reactors.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60076-1, *Power transformers – Part 1: General*

IEC 60076-2, *Power transformers – Part 2: Temperature rise*

IEC 60076-5, *Power transformers – Part 5: Ability to withstand short-circuit*

IEC 60076-7, *Power transformers – Part 7: Loading guide for oil-immersed power transformers*

IEC 60076-16, *Power transformers – Part 16: Transformers for wind turbine applications*

IEC 60085, *Electrical insulation – Thermal evaluation and designation*

IEC 60137, *Insulated bushings for alternating voltages above 1 000 V*

IEC 60214-1, *Tap-changers – Part 1: Performance requirements and test methods*

IEC 60296, *Fluids for electrotechnical applications – Unused mineral insulating oils for transformers and switchgear*

IEC 60836, *Specifications for unused silicone insulating liquids for electrotechnical purposes*

IEC 61099, *Specifications for unused synthetic organic esters for electrical purposes*

IEC 61378-1, *Convertor transformers – Part 1: Transformers for industrial applications*

IEC 61378-2, *Convertor transformers – Part 2: Transformers for HVDC applications*

3 Terms and definitions

For the purposes of this document, the following terms and definitions, as well as those given in IEC 60076-1 and IEC 60076-2 apply.

3.1

insulation system

system composed of solid insulating materials and an insulating liquid

3.2

temperature index

TI

numerical value of the temperature in degrees Celsius derived from the thermal endurance relationship at a time of 20 000 h (or other specified time)

[SOURCE: IEC 60050-212:2010, 212-12-11, modified – Notes 1 and 2 have been deleted]

3.3

thermal class

designation of Electrical Insulation Materials (EIM) or Electrical Insulation Systems (EIS) equal to the numerical value of the maximum used temperature in degrees Celsius for which the EIM/EIS is appropriate

Note 1 to entry: See IEC 60085.

3.4

conventional

modifier applied to temperature-rise limits, insulation materials or insulation systems operating at temperature limits defined by IEC 60076-2

3.5

kraft paper

paper made almost entirely from pulp of high mechanical strength, manufactured from soft-wood by the sulphate process

[SOURCE: IEC 60050-212:2010, 212-16-03]

3.6

thermally upgraded paper

TUP

cellulose-based paper which has been chemically modified to reduce the rate at which the paper decomposes

Note 1 to entry: See IEC 60076-2 for the complete definition.

Note 2 to entry: This note applies to the French language only.

3.7

high-temperature

temperature rise limits and/or insulation materials applied in systems consisting of solid materials and/or liquid, capable of operating at higher temperatures than conventional

3.8

conventional insulation system

insulation system consisting of solid insulation materials used throughout the transformer and insulating liquid operating at temperatures within the normal thermal limits specified in IEC 60076-2

3.9

high-temperature insulation system

insulation system consisting of high-temperature insulation used throughout the transformer, except for some insulation components in lower temperature areas, together with high-temperature insulating liquid, capable of operating at higher than conventional top liquid, average winding and hot-spot temperature rises

3.10

high-temperature insulation winding

winding with high-temperature insulation used throughout, to allow higher than conventional average winding and hot-spot temperature rises

3.11

hybrid insulation system

insulation system consisting of high-temperature solid insulation capable of operating above conventional temperatures, combined with conventional solid insulation and an insulating liquid, operating at conventional temperatures

3.12

full hybrid insulation winding

winding with high-temperature solid insulation used for all parts in thermal contact with the conductor, combined with conventional solid insulation to allow higher than conventional average winding and hot-spot temperature rises

3.13

semi-hybrid insulation winding

winding with high-temperature solid insulation used only for the conductor insulation to allow higher than conventional average winding and hot-spot temperature rises

3.14

mixed hybrid insulation winding

winding with high-temperature solid insulation used only selectively, combined with conventional solid insulation to allow higher than conventional hot-spot temperature rises, while operating at conventional average winding temperature rises

3.15

normal cyclic loading

loading and ambient temperature cycle which, from the point of view of relative thermal ageing rate (according to the mathematical model), is equivalent to the rated load at yearly average ambient temperature.

Note 1 to entry: Higher ambient temperature or a higher-than-rated load current may be applied during part of the cycle. This is achieved by taking advantage of low ambient temperatures or low load currents during the rest of the load cycle.

Note 2 to entry: For planning purposes, this principle can be extended to provide for long periods of time whereby cycles with relative thermal ageing rates greater than unity are compensated for by cycles with thermal ageing rates less than unity.

[SOURCE: IEC 60076-7:2005, 3.5]

3.16**long-time emergency loading**

loading resulting from the prolonged outage of some system elements that will not be reconnected before the transformer reaches a new and higher steady-state temperature

[SOURCE: IEC 60076-7:2005, 3.6]

3.17**short-time emergency loading**

unusually heavy loading of a transient nature (less than 30 min) due to the occurrence of one or more unlikely events which seriously disturb normal system loading

[SOURCE: IEC 60076-7:2005, 3.7]

3.18**rated average winding temperature rise**

contractually agreed upon average winding temperature rise as defined on the nameplate in contrast to calculated or actual tested value

3.19**reference temperature**

rated average winding temperature rise +20 °C, or rated average winding temperature rise + yearly external cooling medium average temperature, whichever is higher

Note 1 to entry: When there is more than one power rating specified, the highest rating shall be used to determine the reference temperature.

Note 2 to entry: For transformers that have more than one rated average winding temperature rise, assigned for different windings at the same power rating, the highest average winding rise shall be used to determine the reference temperature for this power rating. In this case the losses in service will be lower than calculated.

Note 3 to entry: See IEC 60076-1 for complete details on reference temperature.

Note 4 to entry: The term “rated average temperature rise” is meant to be the same as guaranteed temperature rise.

4 Insulation systems

4.1 General

An insulation system used in liquid-immersed transformers contains one or more solid materials for insulating the conductive parts and a liquid, for insulation and heat transfer. This insulation shall withstand the electrical, mechanical, and thermal stresses for the expected life of the device. The thermal class ratings for solid insulation and wire enamels determined by test procedures performed in air are not acceptable for use in transformers conforming to this standard.

The solid insulation used in transformers covered by this standard shall have thermal performance and temperature ratings evaluated in combination with the intended liquid. The procedure for evaluating a combined solid and liquid insulation is described in IEC/TS 62332-1, which results in a thermal index, from which the thermal class is determined. By agreement between manufacturer and purchaser, service experience or other suitable test procedures are acceptable to verify thermal class. See Table 1 for a list of preferred insulation system thermal classes and the associated hot-spot temperature. Refer to IEC 60085 for more information on thermal evaluation procedures.

Table 1 – Preferred insulation system thermal classes

Thermal class	Hot-spot temperature °C
105	98
120	110
130	120
140	130
155	145
180	170
200	190
220	210

Since ageing and lifetime of the insulation system so strongly depend on the temperature, combinations of insulating materials with different thermal capabilities are used within a unit in order to optimise the thermal and economical design of the transformer. In order to simplify and standardize, three distinct insulation systems are defined, based on the degree of high-temperature insulation content. The conventional insulation system is the basis for reference and contains no high-temperature insulation. This system is used as a reference only in this document.

Although a winding with radial spacers, typical for a core-type power transformer is used to illustrate the various insulation systems, the application is not limited to this type of transformer. Each of the insulation systems described is an illustration of the definition and the description is applicable to any other type of transformer with different types of windings, such as layer-type and shell-type pancake windings.

4.2 Winding insulation types

4.2.1 General

The transformer winding insulation is a component of the insulation system. Subclauses 4.2.3 to 4.2.4 illustrate different low voltage (LV) and high voltage (HV) winding types with examples based on power transformers, which have a high degree of winding separation. Table 2 summarizes and compares the different variations.

The barrier insulation between the individual windings shall be treated as a separate entity when properly designed cooling channels separate the material from the winding itself. In this case, the liquid circulation provides sufficient cooling to avoid exceeding the thermal capability of the barrier insulation. If the barrier insulation touches the winding then it shall be considered part of that winding. This is especially important for layer type windings when the layer insulation touches the winding conductor. In this application, the layer insulation shall be treated in the same manner as the winding conductor insulation.

Sufficient testing shall be performed to verify the thermal profile. This shall be accomplished by actual thermal measurement of critical locations taken during prototype and unit testing. Once thermally mapped, materials shall be selected appropriate to the temperature requirements of the specific location. Supporting test data sufficient to validate the manufacturer's thermal model shall be available upon request as part of the type testing.

NOTE The different insulation systems can be explained by considering the transformer as an assembly of individual isolated windings, separated by insulation barriers and cooling channels. A series of winding types could then be used to illustrate how parts of different insulation systems can be combined in a single transformer. In some cases it might not be necessary to use high-temperature insulation in the same way for all windings.

4.2.2 Summary of winding/system insulation types

Table 2 summarizes the key attributes that identify the different winding types. These same attributes also define the corresponding insulation systems.

Table 2 – Winding/system insulation comparison

		Conventional insulation system	Hybrid insulation systems			High-temperature insulation system ^b
			Semi-hybrid winding	Mixed hybrid winding	Full hybrid winding	
Type of insulating component ^a Conventional (C) or high-temperature (H)	Liquid	C or H	C or H	C or H	C or H	H
	Conductor insulation	C	H	C and H combination	H	H
	Spacers/strips	C	C	C and H combination	H	H
	Barrier solid	C	C	C	C	H
Insulating component application temperature Conventional (C) or high-temperature (H)	Top liquid rise	C	C	C	C	H
	Average winding rise	C	H	C	H	H
	Hot-spot winding rise	C	H	H	H	H
a Only basic transformer parts are shown and the temperature of other parts will depend on the results of the thermal mapping. b Since thermal gradients exist in all transformers, some conventional insulation is acceptable in locations where conventional temperatures are maintained.						

4.2.3 Hybrid winding types

4.2.3.1 General

Three hybrid winding types share the use of conventional barrier insulation and the use of high-temperature insulation on the windings.

4.2.3.2 Semi-hybrid insulation winding

The semi-hybrid insulation winding shall use high-temperature insulation only on the winding conductor. For layer windings, the layer insulation shall also be high-temperature. Conventional cellulose-based insulation may be used in all other areas. See Figure 1 for an illustration of this winding style.

Type of material in winding

High-temperature for conductor insulation only

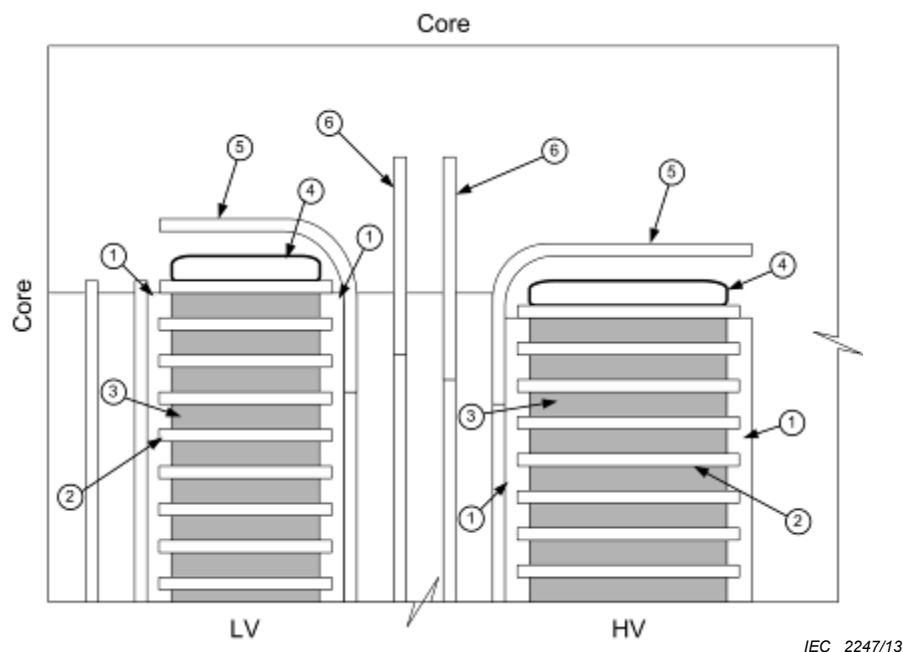
Type of material in barriers

Conventional

Winding temperature rise limits

Average winding: Higher than conventional

Winding hot-spot: Higher than conventional



IEC 2247/13

Key

LV low voltage
HV high voltage

- | | |
|--|-----------------------------|
| 1 conventional axial spacers against the winding | 4 conventional static rings |
| 2 conventional radial spacers | 5 conventional angle rings |
| 3 high-temperature conductor insulation | 6 conventional barriers |

Figure 1 – Example of semi-hybrid insulation windings

4.2.3.3 Mixed hybrid insulation winding

The mixed hybrid winding shall use high-temperature insulation for certain components or parts of windings, such as the conductors in regions operating at hot-spot temperatures above conventional limits. However, the majority of the solid insulation may be conventional. The average winding temperature is conventional while a portion of the winding exceeds conventional hot-spot temperatures. See Figure 2 for an illustration of this type of winding.

NOTE This winding type uses high-temperature insulation only for the purpose of protecting a portion of the winding from temperatures that exceed the conventional hot-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 hot-spot temperature limit. Examples of winding zones with extra losses and higher heat development that could benefit from high-temperature insulation are winding ends due to the radial component of the magnetic leakage field and zones of convertor transformer windings, where harmonic currents are concentrated.

Type of material in winding

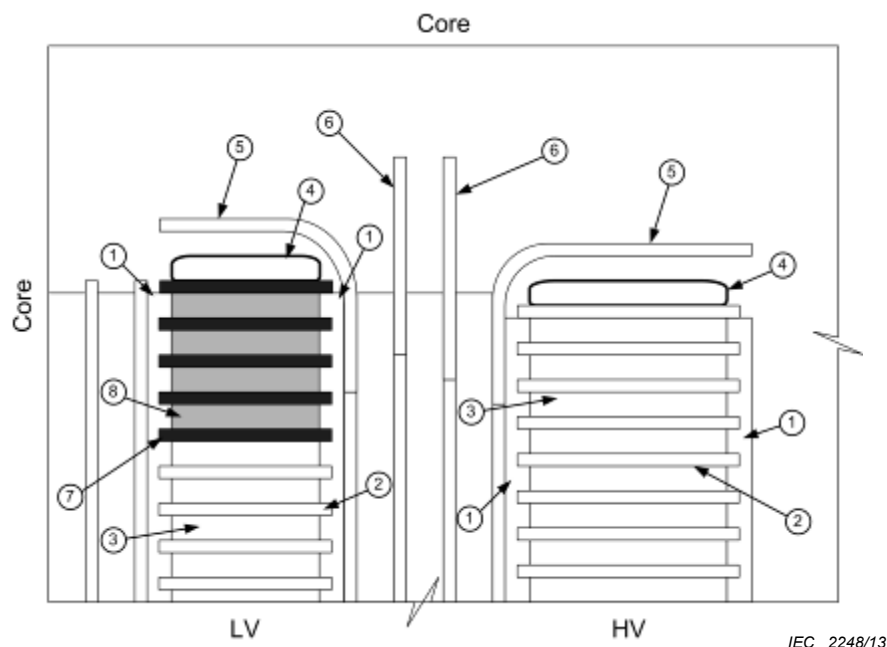
High-temperature applied to minor selected areas of the winding and used with the specific intent to protect strategic locations from excessive ageing

Type of material in barriers

Conventional

Winding temperature rise limits

Average winding: Conventional
Winding hot-spot: Higher than conventional



Key

LV low voltage

HV high voltage

- | | |
|--|--|
| 1 conventional axial spacers against the winding | 5 conventional angle rings |
| 2 conventional radial spacers | 6 conventional barriers |
| 3 conventional conductor insulation | 7 high-temperature radial spacers |
| 4 conventional static rings | 8 high-temperature conductor insulation in the hottest areas |

Figure 2 – Example of a mixed hybrid insulation winding

4.2.3.4 Full hybrid insulation winding

The full hybrid insulation winding shall use high-temperature material throughout the winding, which operates above conventional temperatures. The conductor insulation and the radial and axial spacers separating the coil disks shall be composed of high-temperature materials. Other insulation components shall also be composed of high-temperature materials, where conventional temperatures are exceeded. Conventional cellulose-based insulation may be used in all other areas, such as barrier cylinders and angle rings that operate at conventional temperatures. See Figure 3 for an example of this winding style.

Type of material in winding

High-temperature for all insulation operating at temperatures higher than conventional

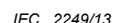
Type of material in barriers

Conventional

Winding temperature rise limits

Average winding: Higher than conventional

Winding hot-spot: Higher than conventional



HV high voltage

- | | | | |
|---|--|---|---------------------------|
| 1 | high-temperature axial spacers against the winding | 4 | conventional static rings |
| 2 | high-temperature radial spacers | 5 | conventional angle rings |
| 3 | high-temperature conductor insulation | 6 | conventional barriers |

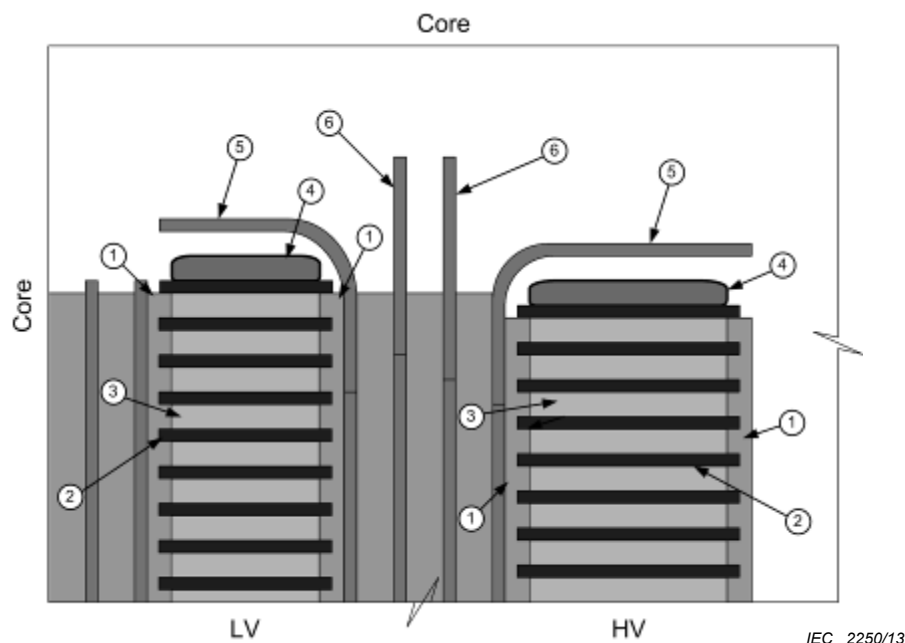
Figure 3 – Example of full hybrid insulation windings

The high-temperature insulation winding shall use high-temperature insulation material throughout the winding. The high-temperature insulation may include different temperature classes, all above conventional. See Figure 4 for an example of this winding style.

High-temperature

High-temperature

Winding hot-spot: Higher than conventional

**Key**

LV low voltage
HV high voltage

- | | |
|--|---------------------------------|
| 1 high-temperature axial spacers against the winding | 4 high-temperature static rings |
| 2 high-temperature radial spacers | 5 high-temperature angle rings |
| 3 high-temperature conductor insulation | 6 high-temperature barriers |

Figure 4 – Example of high-temperature insulation system

5 Temperature rise limits

5.1 General

Maximum temperature rise limits for continuous operation for various combinations of solid and liquid insulating materials are presented in Tables 3 and 4. Rated temperature-rise values that are selected lower than the maximum shown shall be selected on 5 K increments. An accurate thermal model verified by adequate test data shall be required to determine the actual maximum values of any specific transformer design.

The many different dielectric liquids available offer a range of thermal capabilities. However, for simplification this standard recognizes only three liquid categories represented by mineral oil, ester and silicone liquids, each characterized by different top liquid temperature rises. This standard does not make a distinction between ester liquids based on the source of the product. Consequently, both synthetic and natural ester are considered thermally equivalent. Note that other liquids are not intended to be excluded and limits appropriate to specific thermal capability shall be applied according to the thermal capability of the liquid.

NOTE 1 Some of the limiting factors to be considered in determining the permissible maximum temperatures are:

- freely breathing units that introduce moisture and free oxygen into the transformer tank, which are major contributors to insulation ageing. This ageing is accelerated as the temperature increases;
- ageing of materials such as cellulose-based insulation, which introduces moisture inside the transformer tank;
- velocity of the liquid in the cooling ducts, since long exposure of the liquid to high temperature will accelerate degradation;
- accelerated ageing of the liquid and insulating materials due to catalytic action caused by the presence of bare copper and silver surfaces which generate by-products, such as particles and copper derivatives dissolved in insulating liquids;

- gas bubbles caused by overheated trapped moisture between the winding conductors and the conductor insulation.

NOTE 2 See Annex B for more general information on bubbling and an equation for calculating the approximate temperature where bubble generation occurs. While this information is based on cellulose-based insulation and mineral oil, the concepts are essentially the same for high-temperature materials. However, studies indicate that high-temperature insulation materials tend to have lower moisture content than cellulose-based insulation and consequently tend to initiate bubbling at higher temperatures (for additional information see p.5 of IEEE 1276-1997).

NOTE 3 Although design references in this standard refer mainly to core-type transformer design, the design principles and guidelines are applicable to shell-type technology. The typical layout of windings in shell-type transformers is different than shown in the examples, but it will have no influence on the recommended temperature limits for both solid insulation materials and liquids.

**Table 3 – Maximum continuous temperature rise limits
for transformers with hybrid insulation systems**

	Conventional insulation system ^a	Hybrid insulation systems				
		Semi-hybrid insulation winding	Mixed hybrid insulation winding	Full hybrid insulation winding ^b		
Minimum required solid high-temperature insulation thermal class	105	120	130	130	140	155
Top liquid temperature rise (K)	60	60	60	60	60	60
Average winding temperature rise (K)	65/70	75	65	85	95	105
Hot-spot temperature rise for solid insulation (K)	78	90	100	100	110	125
NOTE 1 Liquid operates at conventional temperatures.						
NOTE 2 The temperature rise limits for hybrid insulation systems do not depend on cooling mode.						
NOTE 3 The temperature rise limits shown are based on normal cooling medium temperatures according to IEC 60076-1. For alternate ambient temperature conditions, see IEC 60076-2.						
a Conventional insulation system included only for reference purposes.						
b Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank.						

**Table 4 – Maximum continuous temperature rise limits
for transformers with high-temperature insulation systems**

	Ester liquid				Silicone liquid			
Minimum required high-temperature solid insulation thermal class	130	140	155	180	130	140	155	180
Top liquid temperature rise (K)	90	90	90	90	115	115	115	115
Average winding temperature rise (K)	85	95	105	125	85	95	105	125
Hot-spot temperature rise (K)	100	110	125	150	100	110	125	150
NOTE 1 Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank. NOTE 2 The temperature rise limits shown are based on normal cooling medium temperatures according to IEC 60076-1. For alternate ambient temperature conditions, see IEC 60076-2. NOTE 3 The high-temperature insulation frequently includes different temperature classes, all above conventional. NOTE 4 For cellulose/ester insulation systems, see 5.3.								

5.2 Thermally upgraded paper (TUP)

Cellulose paper treated by a chemical process, known as thermally upgraded paper is accepted as capable of operating as a 120 class material in mineral oil in some countries. If it is agreed between the manufacturer and the purchaser that thermally upgraded paper (TUP) is a 120 class material, then it shall be considered a high-temperature insulation and may be used for semi-hybrid applications with temperature limits defined in Table 3.

5.3 Cellulose used in ester liquid

Based on ageing tests, both kraft paper and thermally upgraded paper have been shown to exhibit improved life characteristics when combined with ester liquid. Annex C presents a technical argument in support of these claims, summarizing many years of investigation. If it is agreed between the manufacturer and the purchaser that cellulose paper has a higher temperature capability, then it shall be considered a high-temperature insulation suitable for use in high-temperature insulation systems. The specific thermal class shall be determined by agreement between the manufacturer and the purchaser.

6 Components and materials

6.1 General

All components and materials used in the construction of the transformer shall comply with the requirements of the relevant IEC standards where they exist, unless otherwise agreed or specified. In particular, bushings shall comply with IEC 60137 and tap-changers shall comply with IEC 60214-1. Insulating liquid shall comply with IEC 60296 for mineral oil, IEC 61099 for synthetic ester liquid, IEC 60836 for silicone liquid, or as agreed for other liquids. All components and materials shall be suitable for the expected operating temperature and shall be compatible with the specific liquid.

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 shall be defined by the thermal class of the insulation used according to Tables 3 and 4 and is usually dependant on the temperature of the liquid.

Material selection for lead and interconnection cables is independent of the insulation system selected for the transformer windings. However, high temperature insulation shall be used for lead cables in high temperature insulation systems, as defined for the wire insulation in 3.9 and 4.2.4.

In semi-hybrid and full hybrid windings, high temperature insulation shall be 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 are created in connection points. The selection of insulation material for the remaining length of the cable shall be based on its designed temperature gradient and may include conventional insulation materials.

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 shall be selected appropriate to the designed temperatures.

7 Special design considerations

7.1 Short-circuit considerations

The mechanical construction of the winding and support structure shall be designed to take into consideration the possible increased expansion or contraction of the transformer windings, due to the larger temperature range. In addition, the processing of the windings shall be such that the tightness of the construction will be maintained in service.

The transformer shall be designed to withstand short-circuit events as defined in IEC 60076-5. The maximum value of the average temperature of each winding shall be calculated in accordance with that standard and shall meet the defined limits.

Where the design incorporates epoxy-bonded winding conductors, the maximum temperatures obtained under highest permissible operating conditions shall be taken into account, since the epoxy is mechanically weaker at higher temperatures. Specially formulated high-temperature epoxy shall be specified to prevent this softening effect, if required to maintain the short-circuit strength of the transformer.

7.2 Dielectric requirements

The dielectric properties of high-temperature insulation systems shall be fully analysed to prevent unacceptable degradation of the dielectric properties over the wider operating temperature range of the transformer.

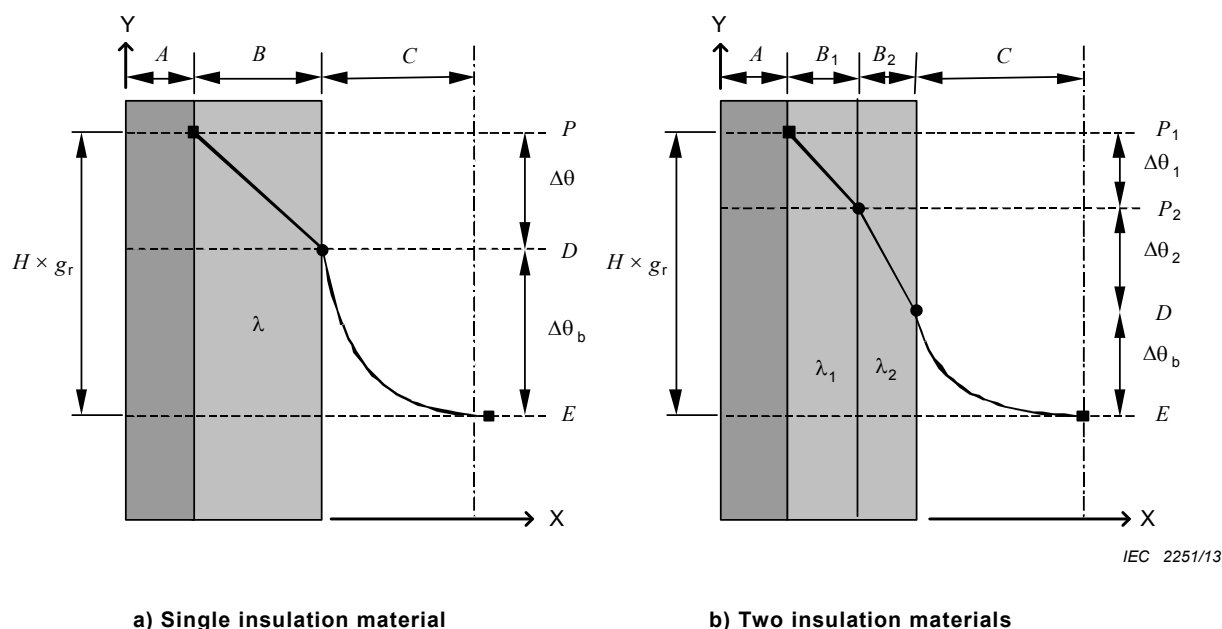
7.3 Temperature requirements

A thermal gradient is to be expected within a given transformer and insulation shall be selected with a thermal class appropriate to the specific location. As with any transformer, these are design specific and hence an adequate thermal model of the winding is required. The thermal model of the winding shall be verified by prototype, model and/or full size transformer testing, as deemed necessary to validate a design or family of designs. In the defined high-temperature insulation systems there will be several hot-spots (one for each type of insulation) and all need careful consideration. See Figure 5 and Figure 6 for additional information.

It is important to note that in many cases the liquid in the winding cooling duct can have a higher temperature than that of the liquid in the top of the tank. This shall be taken into consideration, since the temperature of the liquid adjacent to the winding contributes to the hot-spot temperature.

NOTE 1 The conductor to liquid temperature gradient of an insulated winding is generally the sum of the temperature gradient across the solid insulation and the temperature gradient across the boundary layer. In high-temperature insulation systems the temperature gradient across the boundary layer is usually greater than in conventional insulation systems.

NOTE 2 In Figure 5, the maximum winding surface temperature in point *D* is given by the sum of the liquid temperature in the cooling duct and the temperature rise across the boundary layer, which depends on the heat transfer coefficient at the winding surface and the heat flux density through the winding surface.



Key

X axis	distance from conductor
Y axis	temperature
<i>A</i>	thickness of the conductor
<i>B</i>	thickness of the solid insulation material
<i>B</i> ₁	thickness of the high-temperature insulation material
<i>B</i> ₂	thickness of the conventional insulation material
<i>C</i>	thickness of the boundary layer of the liquid
<i>D</i>	winding surface temperature
<i>E</i>	liquid temperature in the cooling duct
<i>g</i> _r	average winding to liquid temperature gradient at rated current
<i>H</i>	hot-spot factor
<i>P</i>	hot-spot temperature in contact with the solid insulation material
<i>P</i> ₁	hot-spot temperature in contact with the high-temperature insulation material
<i>P</i> ₂	hot-spot temperature in contact with the conventional insulation material
Δ <i>θ</i>	temperature gradient inside the solid insulation
Δ <i>θ</i> ₁	temperature gradient inside the high-temperature insulation
Δ <i>θ</i> ₂	temperature gradient inside the conventional insulation
Δ <i>θ</i> _b	temperature gradient inside the boundary layer of the liquid
λ	thermal conductivity of the solid insulation material
λ ₁	thermal conductivity of the high-temperature insulation material
λ ₂	thermal conductivity of the conventional insulation material

Figure 5 – Temperature gradient conductor to liquid

7.4 Overload

The general principles and equations of the loading guide for oil-immersed transformers as described in IEC 60076-7 apply, except for the overload limits, since temperatures and time constants will vary for different insulating systems. Maximum suggested overload temperatures are listed in Tables 5 and 6. Any other overload requirements shall be specified in the enquiry, or be agreed upon at the contract stage.

Table 5 – Suggested maximum overload temperature limits for transformers with hybrid insulation systems

	Conventional insulation system ^a	Hybrid insulation system				
		Semi-hybrid insulation winding	Mixed hybrid insulation winding	Full hybrid insulation winding ^b		
Minimum required solid high-temperature insulation thermal class	105	120	130	130	140	155
Top liquid temperature with normal cyclic loading (°C)	105	105	105	105	105	105
Top liquid temperature with long-time emergency loading (°C)	115	115	115	115	115	115
Top liquid temperature with short-time emergency loading (°C)	115	115	115	115	115	115
Insulation hot-spot temperature with normal cyclic loading (°C)	120	130	140	140	150	165
Insulation hot-spot temperature with long-time emergency loading (°C)	140	140	150	150	160	175
Insulation hot-spot temperature with short-time emergency loading (°C)	160	160	170	170	180	195
^a Conventional insulation system included only for reference purposes. Refer to IEC 60076-7 for additional information. ^b Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank.						

Table 6 – Suggested maximum overload temperature limits for transformers with high-temperature insulation systems

	Ester liquid				Silicone liquid			
Minimum required high-temperature solid insulation thermal class	130	140	155	180	130	140	155	180
Top liquid temperature with normal cyclic loading (°C)	130	130	130	130	155	155	155	155
Top liquid temperature with long-time emergency loading (°C)	140	140	140	140	165	165	165	165
Top liquid temperature with short-time emergency loading (°C)	140	140	140	140	165	165	165	165
Hot-spot temperature with normal cyclic loading (°C)	140	150	165	190	140	150	165	190
Hot-spot temperature with long-time emergency loading (°C)	150	160	175	200	150	160	175	200
Insulation hot-spot temperature with short-time emergency loading (°C)	170	180	195	220	170	180	195	220
NOTE Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank.								

8 Required information

8.1 Information to be provided by the purchaser

8.1.1 Ambient temperatures and loading cycle

The temperature of the cooling medium shall be in accordance with the normal service conditions of IEC 60076-1. The temperature limits noted in Tables 3 and 4 shall be modified according to IEC 60076-2 if the ambient temperatures differ from normal service conditions. Any particular loading cycle information shall be supplied by the purchaser.

8.1.2 Other unusual service conditions

For all other unusual service conditions IEC 60076-1 shall apply.

8.2 Information to be provided by the manufacturer

8.2.1 Thermal characteristics

Recognizing that the insulation systems defined in this standard are relatively unfamiliar throughout the industry and that they can vary widely due to application and manufacturer's practice, supplier information shall include the following information:

- type of insulation system, (hybrid or high-temperature) with a reference to the number of this publication;
- type of winding insulation for each winding (conventional, semi-hybrid, mixed hybrid, full hybrid or high-temperature);
- high-temperature solid insulation thermal class and generic name (if different materials are used in different windings, this shall be indicated by winding);
- calculated maximum hot-spot temperature for each winding;
- rated average winding temperature rise for each winding;
- time constant for each winding;
- type of liquid by generic and trade name;
- rated top liquid temperature-rise;
- type test data including temperature rise and when available, short circuit.

8.2.2 Guarantees

When specified, the load losses and the short-circuit impedance shall be guaranteed at the reference temperature. The load losses at the reference temperature shall also be used in a temperature-rise test. The same tolerances for guarantees apply, as recommended in IEC 60076-1.

The top liquid, average winding and hot-spot temperature rises shall not exceed the values given in Tables 3 and 4.

9 Rating plate and additional information

9.1 Rating plate

In addition to the requirements in IEC 60076-1, the rating plate shall include the following information:

- number of this IEC standard;
- type of liquid by trade name, standard and year of standard;
- rated top liquid temperature rise;

- rated average winding temperature rises for each winding, if they are not all the same.

The following items shall be identified on the rating plate by the Insulation System Code as described in Annex D:

- type of insulation system, (hybrid or high-temperature);
- winding insulation type and thermal class for each winding, if they are not all the same.

9.2 Transformer manual

The manual shall highlight that, due to the presence of insulating materials different from cellulose-based insulation and mineral insulating oil, different behaviour can be expected in respect to gas and moisture development. Consequently, this should be considered if onsite degassing and drying treatment is necessary.

10 Test requirements

10.1 Routine, type and special tests

All tests for power transformers and reactors shall be as prescribed in IEC 60076-1. All tests for converter transformers shall be performed according to IEC 61378-1 for industrial transformers and IEC 61378-2 for HVDC transformers. For wind turbine transformers, the test requirements in IEC 60076-16 shall apply.

10.2 Dissolved gas analysis

On category II and III transformers as defined in IEC 60076-5, it is desirable to collect DGA (dissolved gas analysis) data for future reference as a diagnostic tool, since the characteristics are likely to differ from conventional transformers. It is especially important therefore to establish a baseline for future reference.

10.3 OD cooled compact transformers

The time constant of OD cooled compact transformers with a high winding to liquid temperature rise is smaller than in conventionally insulated transformers. Particular care is required to shorten the time between switch off and measurement of the winding resistance.

The time from switch off to first recording should ideally be less than 1 min. If this short switch off time cannot be achieved, it is permitted to switch off the cooling fans and pumps at the same time as the shutdown in order to reduce the measuring uncertainty of the cooling curve.

10.4 Evaluation of temperature-rise tests for windings with multiple hot-spots

Mixing high-temperature and conventional insulations will generally lead to more than one hot-spot temperature in a winding. A simple example is the mixed hybrid insulation system, where the winding has a hot-spot temperature for the conventional insulation and one for the areas protected by the high-temperature insulation. This is illustrated by the following calculations and Figure 6.

Two different hot-spot temperatures shall be verified either by calculation or test: P_1 for the insulation system between B and C and P_2 for the insulation system between E and C . The temperatures in each part of the winding should be evaluated as described in IEC 60076-7. The hot-spot factors, H_1 and H_2 also shall be calculated by the manufacturer.

The temperature difference of the liquid in the tank between the top and the bottom is:

$$\Delta\theta_{\text{LW}} = \theta_o - \theta_b \quad (1)$$

where

$\Delta\theta_{\text{LW}}$ is the axial temperature rise of the liquid in the tank;

θ_o is the top liquid temperature in the tank;

θ_b is the bottom liquid temperature in the tank.

To estimate the liquid temperature in the cooling ducts at the boundary of two different winding parts, (point *C*, in Figure 6), the total temperature gradient is split into two parts:

$$\Delta\theta_{\text{LW1}} = \frac{l_1}{l_1 + l_2} \times \Delta\theta_{\text{LW}} \quad \text{for section 1} \quad (2)$$

where

$\Delta\theta_{\text{LW1}}$ is the axial temperature rise of the liquid in the upper part of the winding;

$\Delta\theta_{\text{LW}}$ is the axial temperature rise of the liquid in the tank;

l_1 is the length of the upper part of the winding using high-temperature insulation;

l_2 is the length of the lower part of the winding using conventional insulation.

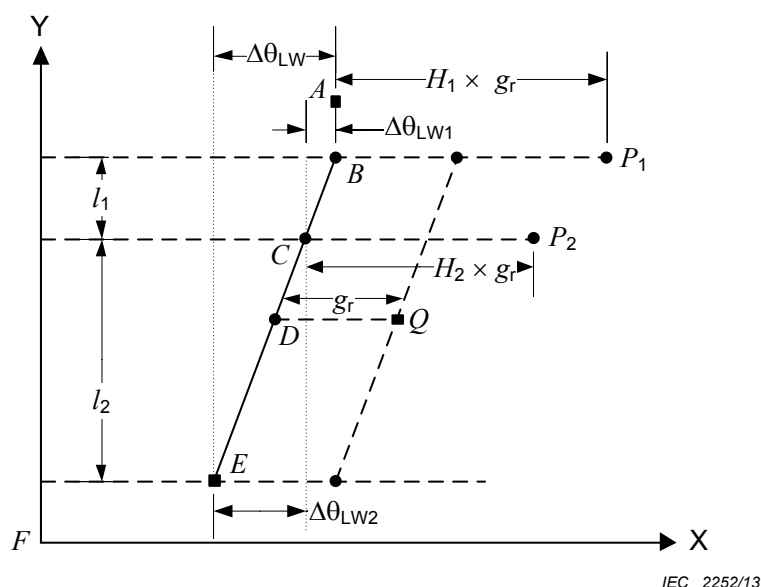
$$\Delta\theta_{\text{LW2}} = \Delta\theta_{\text{LW}} - \Delta\theta_{\text{LW1}} \quad \text{for section 2} \quad (3)$$

where

$\Delta\theta_{\text{LW2}}$ is the axial temperature rise of the liquid in the lower part of the winding;

$\Delta\theta_{\text{LW}}$ is the axial temperature rise of the liquid in the tank;

$\Delta\theta_{\text{LW1}}$ is the axial temperature rise of the liquid in the upper part of the winding.



Key

- X axis indicates temperature
- Y axis indicates the axial position along the transformer height
- A* average temperature of the tank outlet (top liquid temperature)
- B* liquid temperature in the tank at the top of the winding (assumed to be the same as *A*)
- C* liquid temperature in the winding at the boundary of two different insulation materials
- D* average liquid temperature in tank
- g_r average winding to liquid temperature gradient at rated current
- E* bottom liquid temperature entering the winding
- F* represents the bottom of the tank
- H_1 hot-spot factor associated with part of the winding using high-temperature insulation
- H_2 hot-spot factor associated with part of the winding using conventional insulation
- l_1 length of the upper part of the winding using high-temperature insulation
- l_2 length of the lower part of the winding using conventional insulation
- P_1 hot-spot temperature in contact with the high-temperature insulation material
- P_2 hot-spot temperature in contact with the conventional insulation material
- Q* average winding temperature determined by resistance measurement
- $\Delta\theta_{LW}$ temperature rise of the liquid in the tank
- $\Delta\theta_{LW1}$ axial temperature rise of the liquid in the upper part of the winding
- $\Delta\theta_{LW2}$ axial temperature rise of the liquid in the lower part of the winding
- measured point
- calculated point

Figure 6 – Modified temperature diagram for windings with mixed hybrid insulation system

10.5 Dielectric type tests

The insulating system shall be dielectrically suitable for operation at elevated temperatures, when required.

11 Supervision, diagnostics, and maintenance

11.1 General

Supervision and diagnostics of transformers are part of the strategic approach for risk analysis and asset management, which should result in an appropriate maintenance programme and reliable service life. In high-temperature transformers, it is highly desirable to monitor the performance of the insulation system, since significant historical data is not yet available.

NOTE A good general diagnostic approach can be found in IEEE 62.

11.2 Transformers filled with mineral insulating oil

Because of the temperature limitation of the mineral insulating oil in insulation systems containing cellulose-based insulation, the amount of solid high-temperature insulating material will generally be small relative to the total amount of insulation material. Hence, it is likely that the composition of gases, due to heating, inception of partial discharges and electrical arcing will be close to that of conventional transformers, operating under the same conditions.

In transformers with hybrid insulation systems, the most probable source of gas generation is the mineral insulating oil. However, when overheating, thermal faults, partial discharges or electrical arcing arise, decomposition of high-temperature solid insulation is possible with the potential for generating gases and other by-products (moisture, particles, furans, metals).

It is desirable to periodically take oil samples for analysis. IEC 60422 provides guidance for the supervision and maintenance of mineral insulating oils.

11.3 Transformers filled with high-temperature insulating liquids

When overheating, thermal faults, partial discharges or electrical arcing arise in transformers with high-temperature insulation systems, decomposition of the liquid and/or solid insulation is possible with the potential for generating gases and other by-products (moisture, particles, furans, metals).

On category II and III transformers as defined in IEC 60076-5, it is desirable to collect DGA data for future reference as a diagnostic tool, since the characteristics are likely to differ from conventional transformers. IEC 60944 and IEC 61203 provide guidance for the supervision and maintenance of silicone transformer liquids and transformer esters in equipment respectively.

Annex A (informative)

Insulation materials

A.1 General

This Annex A lists several high-temperature Electrical Insulation Materials (EIM) for informational purposes only. The appearance of these materials does not imply that any specific combination is suitable for use in high-temperature liquid-immersed transformer applications, as an Electrical Insulation System (EIS).

Common solid insulation materials are listed in Table A.1 along with typical parameters and characteristics, which are useful for proper evaluation. It is important to note that design parameters specific to the material selected should be obtained from the manufacturer of the product. The insulation materials are separated into 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. It should also be noted that whilst the thermal capability of the individual materials may be satisfactory, the interaction of these individual elements in the system might render the system unacceptable.

A.2 Ageing and lifetime of insulation materials

Material ageing is the result of a process that splits the molecules of the insulation material and consequently changes some material properties. This is an endothermic process, which means that sufficient energy shall be supplied to enable the atoms to split the molecules. In transformers this energy is provided mainly by the transformer losses. The more energy supplied the faster the splitting rate. The energy takes the form of heat, which increases the temperature. The temperature is then a relevant indicator of the ageing rate and the lifetime. Other factors than the temperature, such as the presence of acids, oxygen and/or water may influence the lifetime. Assuming that these other factors are constant, the lifetime of insulation material normally follows the equation:

$$L = a \times e^{\frac{b}{T}} \quad (\text{A.1})$$

where

- L is the lifetime in h;
- a is a constant with the dimension hour;
- e is the base of the natural logarithm (2,718...);
- b is a constant with the dimension Kelvin;
- T is the temperature in Kelvin.

Equation (A.1) is derived from Arrhenius' equation. When taking the natural logarithm on both sides of Equation (A.1), the result is:

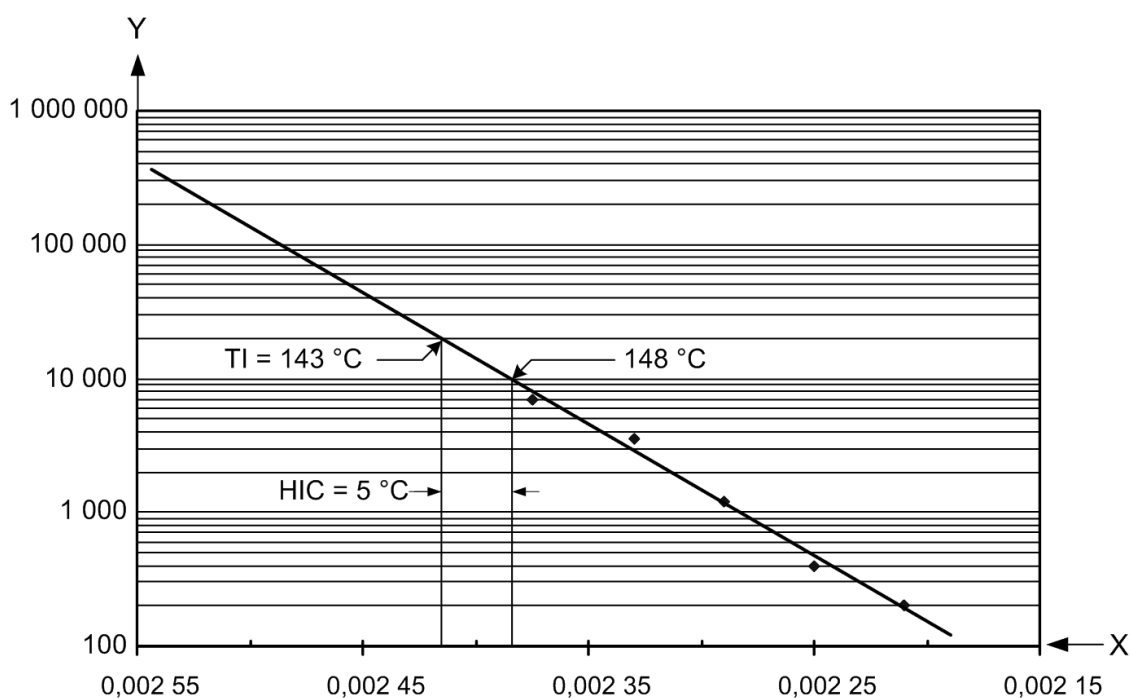
$$\ln(L) = \ln(a) + \frac{b}{T} \quad (\text{A.2})$$

Equation (A.2) is represented by a straight line (in semi logarithmic coordinates of L versus $1/T$), which is determined by means of a thermal endurance test described in IEC 60216-1.

The end-of-life criterion shall be defined prior to the thermal endurance test. It may be an absolute value or a percentage of the original value of a material property that is crucial for the insulating function of the material, and preferably a property that deteriorates faster than other vital properties of the material. For mineral oil-immersed transformers with cellulose-based insulation, the tensile strength of the paper that covers the winding conductors is often used as one of the parameters that determine the degree of ageing of the whole transformer. The degree of polymerization (DP) is also used as an ageing indicator, with a value of 200 generally considered to be end of life for cellulose-based insulation.

During the thermal endurance test, samples of the material are heated to several different temperatures and the time to end of life is noted. The time durations versus the reciprocal value of the absolute temperatures are plotted in a coordinate system, where the time axis has a logarithmic scale (see Figure A.1).

The dots in the diagram are the results from a thermal endurance test. The straight line is the regression line. As will be seen, the dots are situated closely to the regression line, which confirms that the lifetime versus temperature relationship for the tested material follows Arrhenius' equation.



IEC 2253/13

Key

X axis reciprocal value of the absolute temperature $1/T$ (1/K)

Y axis lifetime (h)

Equation $Y = 6 \times 10^{-23} \times e^{25\,390/T}$ $R_2 = 0,983\,5$

NOTE The X axis ($1/T$) is normally represented right-to-left, so that higher temperatures are at the right hand side of the graph.

Figure A.1 – Example of a thermal endurance graph

In this example, a vertical line is drawn at the point where the extended regression line crosses the 20 000 h ordinate, and this vertical line hits the abscissa axis at a point corresponding to a temperature of 143 °C. This means that the temperature index TI of this material is 143 °C.

Another vertical line is drawn from the point where the regression line crosses the 10 000 h ordinate, and this vertical line hits the abscissa axis at a point corresponding to 148 °C. The halving interval (HIC) is then the difference between 148 and 143, which equals 5 °C.

A lifetime of 20 000 h (somewhat more than 2 years) at the temperature index TI would normally be too short as an acceptable lifetime. To obtain an acceptable lifetime the thermal class assigned to the material shall be chosen lower than TI. How much lower depends on how long a lifetime the user of the material requires. The relation between lifetime and temperature can be read from the extended regression line in the diagram or calculated by means of the regression line equation.

If for example 20 years (175 200 h) lifetime is required, the extrapolated temperature from the regression line would be 128 °C. If 30 years (262 800 h) lifetime is required, the extrapolated temperature from the regression line would be 126 °C. As an alternative, the extrapolated result of the thermal endurance test may be selected longer than 20 000 h. In some countries, 65 000 and 180 000 h have been used for liquid-immersed insulation systems.

The thermal class is equal to the maximum service temperature that the user of the material finds appropriate, taking into account the required lifetime of the transformer where the material is going to be used. The loading pattern of the transformer and the real ambient temperatures at the site where the transformer will be situated should also be considered. The transformer may in many cases be loaded below its rated loading for long periods, which would reduce the ageing rate and extend the lifetime.

In some performed tests, the end of life has been defined to have occurred when 50 % of the initial tensile strength is consumed. However, this limit, or any other defined limit for end of life, should not be perceived too literally. A transformer may operate satisfactorily for many years after the end of life according to this definition is reached. The decomposition of the material happens gradually. There are no sharp limits. This defined end of life serves more as a warning that the ability of the transformer to withstand stresses under abnormal service conditions, like high short-circuit currents, is essentially lower compared to a new transformer. Also transport of the transformer from one site to another involves a higher risk.

NOTE Clause A.2 presents the classic theory of ageing for a simple material. More detailed analyses of the complex mechanisms of material ageing in a typical transformer can be found in the technical papers listed in the Bibliography.

A.3 Solid insulation

Solid insulation is available in the form of paper, film, sheet and board as well as various shapes for mechanical applications used within the dielectric structure. Table A.1 lists many readily available materials, along with typical parameters. Note that this typical performance information is based on components tested individually as isolated samples in air. Dielectric and thermal performance as a 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. Consequently, the in air thermal classes shown in Table A.1 are not directly acceptable for liquid-immersed applications.

Thermal classes shall be assigned based on service experience or functional tests of the solid immersed in the applicable liquid. For example, in Table A.1, although cellulose-board is classified as a 105 material when tested in air, it can in practice be applied as a thermally upgraded material in most liquids, including ester liquids. The justification for this is the good service experiences obtained with non-thermally upgraded cellulose-based board in transformers labelled “thermally upgraded” during the last 50 years.

It should also not be assumed that the system thermal class would necessarily default to the lowest temperature class of the system's individual components. On the contrary, the thermal capability will often favour the highest temperature component. However, the individual

component thermal class should provide guidance in the selection and positioning of the various materials within the insulation design.

Based on the interpretation of test data during the development of alternative liquids, it has been proposed that liquids with significantly higher water saturation levels at operating temperatures may allow higher operating temperature limits for the solid insulation because of their ability to remove the moisture from the solid.

Table A.1 – Typical properties of solid insulation materials

Material	Thermal class (IEC 60085) °C	IEC standard reference	Relative permittivity at 25 °C	Dissipation factor %		Moisture absorption %	Density g/cm ³	Form
				At 25 °C	At 100 °C			
Cellulose-based	105	60554-3	3,3 – 4,1	0,4	1,0	7,0	0,97 – 1,2	Paper
Cellulose-based thermally upgraded	120		3,3 – 4,1	0,4	1,0	7,0	0,97 – 1,2	Paper
Cellulose-based	105 ^b	60641-3	2,9 – 4,6	0,4	1,0	7,0	0,8 – 1,35	Board
Stratified resin bonded paper (Bakelite)	130		5,8	2,5		2,3	1,36	Board
Polyphenylene sulfide (PPS)	155		3,0	0,06	0,12	0,05	1,35	Film
Polyester glass ^a	130 – 200	60893-3	4,8	1,3 – 7,0	N/A	0,2 – 1,1	1,8 – 2,0	Sheet
Polyester glass ^a	130 – 220	61212-3	N/A	N/A	N/A	0,16 – 0,28	1,8 – 2,0	Shapes
Polyimide	220	60674-3	3,4	0,2	0,2	1,0 – 1,8	1,33 – 1,42	Film
Aramid	220	60819-3	1,6 – 3,2	0,5	0,5	5,0	0,30 – 1,10	Paper
Aramid	220	61629-1	1,7 – 3,5	0,5	0,5	5,0	0,52 – 1,15	Board

NOTE 1 All data has been taken from measurements in air.

NOTE 2 Relative permittivity and dissipation factor data are referenced to 50 Hz or 60 Hz.

NOTE 3 Moisture data is based on air having a relative humidity of 50 %.

^a Typically only used in lower voltage liquid-immersed applications due to possible air entrapment during the manufacturing process.

^b Although cellulose-board is here classified as a 105 material when tested in air, it has in practice been applied as a thermally upgraded material in most liquids, including ester liquids. The justification for this is the good service experiences obtained with non-thermally upgraded cellulose-based board in transformers labelled “thermally upgraded” during the last 50 years.

A.4 Wire enamel insulation

The list in Table A.2 shows two insulating enamels used to coat both round and rectangular copper and aluminium winding wires that may be suitable for use in liquids at high-temperature. Additional information may be found in the specific applicable sections of the IEC 60317 series. Note that the appearance of a coating in this list does not imply compatibility with any of the many available dielectric liquids and is provided for general information only. In fact, most enamel coatings are not suitable for use in liquids at elevated temperatures. Procedures for verifying compatibility with different liquids are defined in IEC 60851-4. However, these procedures should be modified for high-temperature application.

Table A.2 – Typical enamels for wire insulation

Chemical name	Thermal class	IEC 60317 applicable part	Common acronym	Common name
Aromatic polyamideimide	200	26	AIW	Polyamideimide
Aromatic polyimide	220	7, 30	PIW	Polyimide
NOTE Thermal class in air according to IEC 60317.				

A.5 Insulating liquids

Table A.3 shows typical performance characteristics of readily available dielectric liquids that are used in liquid-immersed transformers. Mineral insulating oil, complying with IEC 60296, is the most common 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.

IEC 61100 provides rules for classifying liquids according to fire point and calorific value. A fire point greater than 300 °C, as determined according to ISO 2592 classifies the liquid as Class K. However, neither the flash point nor the fire point defines high-temperature capability. Sludge development, affinity to moisture and rate of oxidation all affect the thermal capability of a liquid. The liquid manufacturer should be contacted to determine if a specific product is suitable for use at higher temperatures than conventional mineral insulating oil, since it may depend on certain additives that may not be present in all products in the same generic category.

The maximum operating temperatures listed in Table A.3 are provided only as a starting point for further investigation, since there is no generally accepted procedure for establishing a thermal index for insulating liquids. These temperatures are estimated or generally accepted by the industry, but should not be taken as recommendations of this standard.

Table A.3 – Typical performance characteristics of unused insulating liquids

Generic name	IEC standard reference	Thermal class ^a °C	Flash point ^c °C	Fire point ^c °C	Water content mg/ kg	Density at 25 °C g/cm ³	Relative permittivity ^d at 25 °C	Dissipation factor ^d 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 insulating oil	60296	105	145	160	25	0,88	2,2	0,05	9,2	2,3	0,12	2 100
Synthetic hydrocarbon	60867	~130	230	250	15	0,83	2,1	0,01		4,1	0,14	2 100
Synthetic ester	61099	~130	275	316	50	0,97	3,2	0,02	28	5,8	0,16	2 100
Dimethyl silicone	60836	~155 ^b	310	360	50	0,96	2,7	0,01	40	14,3	0,15	1 500
Although the following liquids are used in some transformer applications, they are not yet defined by IEC standards.												
Synthetic PAO hydrocarbon	N/A	~130	264	304	15	0,83	2,1	0,01	-	8,6	0,13	2 300
Natural ester	N/A	~130 ^b	330	360	50	0,91	3,2	0,20	33	9	0,17	2 000
High molecular weight hydrocarbon	N/A	~155	280	312	10	0,87	2,2	0,01	-	11,8	0,14	2 100

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 IEC standard noted for each liquid. Verify physical properties and acceptance limits for liquids with no IEC document with the liquid manufacturer.

^a Thermal class is equal to the maximum recommendable operating temperature, which is expected to give an acceptable lifetime of the liquid.

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

^c Cleveland open cup test per ISO 2592. In IEC documents, flash point is determined according to the Pensky-Martens closed cup test per ISO 2719, which generally gives lower values than those shown.

^d Relative permittivity and dissipation factor data are referenced to 50 Hz or 60 Hz.

Annex B (informative)

Rapid temperature increase and bubble generation

B.1 General

Although the bulk of historical investigations concern overload conditions for transformers with cellulose-based insulation immersed in mineral oil, the principles of bubble generation are similar for transformers designed to operate at elevated temperatures. Studies have indicated that the largest single determining factor, other than temperature, is the moisture content in the solid insulation. Investigations by Oommen (see Bibliography) form the basis for Annex B, and his theory was selected for the unique perspective of an empirical formula to describe the phenomenon.

Experts agree that a bubble is formed by the expansion of a surface cavity, which has initial gas/vapour content. When this is applied to a paper wrapped conductor, it is assumed that tiny cavities on the paper surface are initially filled with small amounts of water vapour and dissolved gases. Under conditions of rapid temperature increase, the conductor and paper overheat and the cavity expands, at first into which water vapour is injected. As the cavity grows, the bubble has higher and higher quantities of water vapour. The gas content can hardly change in such limited time. Bubble formation is then to be dictated by water vapour release rather than the gas content of the mineral oil.

B.2 Basic assumption

The fundamental equation governing bubble formation is:

$$P_{\text{int}} = P_{\text{ext}} + \frac{2 \times \sigma}{R} \quad (\text{B.1})$$

where

P_{int} is the internal pressure;

P_{ext} is the external pressure;

σ is the surface tension pressure;

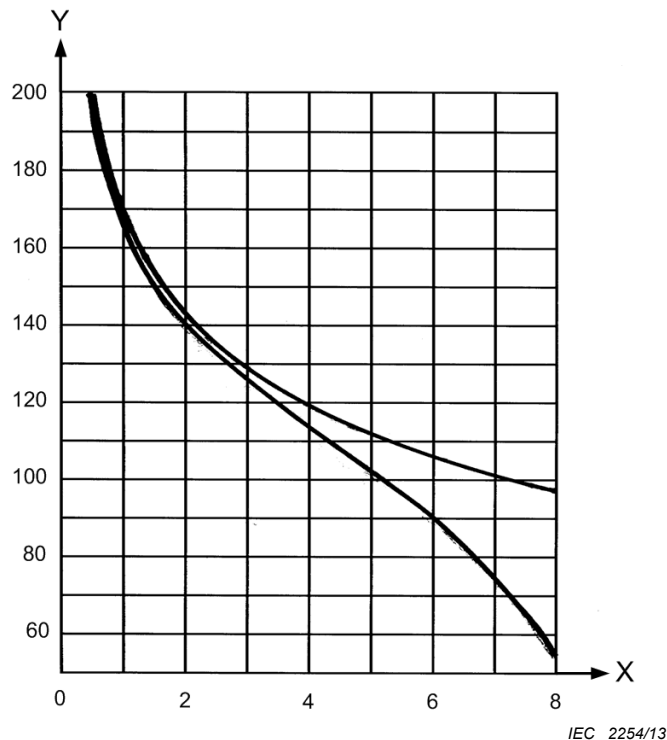
R is the radius of the bubble.

B.3 Experimental verification

Two coil models were used for experimental studies. One model had a fibre optic temperature sensor in place of a thermocouple sensor to sense hot-spot temperature and a separate winding was used to apply voltage for partial discharge (PD) detection of bubbles in addition to visual observation. Moisture content of the paper in the coil and gas content of the mineral oil were changed over a wide range. Moisture ranged from 0,5 % to 8,0 % (dry/oil free basis), and gas content, from fully degassed to fully nitrogen saturated. A rapid temperature rise simulated the conditions in a transformer winding under overload conditions. In addition to fully degassed and fully gas saturated systems, several tests were conducted with partly degassed mineral oil. In total, 22 coil model tests were conducted.

Figure B.1 shows the results of these tests in graphical form. The upper curve corresponds to degassed mineral oil, and the lower curve, to gas saturated mineral oil. Note that at low moisture values, the bubble evolution temperature is virtually the same for degassed and gas saturated systems. At 2 % moisture in paper, which corresponds to an aged transformer with

cellulose-based insulation, the estimated bubble evolution temperature is slightly above 140 °C. However, for a dry unit with a 0,5 % moisture level, the estimated bubble evolution temperature is above 200 °C.



Key

X axis	percent water in paper
Y axis	bubble evolution hot-spot temperature (°C)
Upper curve	gas-free systems
Lower curve	gas saturated systems

Figure B.1 – Bubble evolution temperature chart

B.4 Mathematical formulation of bubble generation

It was possible to fit the hot-spot temperature as a function of moisture and gas content and the total external pressure (atmospheric plus oil head). The empirical equation is given below:

$$\theta = \left[\frac{6\,996,7}{22,454 + 1,449\,5 \times \ln(W_{WP}) - (2,015 + \ln(P_{Pres}))} \right] - \left[\exp(0,473 \times W_{WP}) \times \left(\frac{V_g^{1,585}}{30} \right) \right] - 273 \quad (B.2)$$

where

- θ is the temperature for bubble evolution in °C;
- W_{WP} is the percent by weight of moisture in paper based on the dry, oil free weight of paper;
- P_{Pres} is the total pressure in kPa;
- V_g is the gas content of the liquid in percent (V/V).

The first part of the equation between the braces is for degassed mineral oil and was derived from the well-known Piper chart of vapour pressure vs. moisture relationship. The second term adjusts for the gas content of the mineral oil. The agreement between observed and computed temperatures was excellent, with not more than two degrees difference for tests with the single coil model, and not more than four degrees with the triple coil model (for