IEC TR 62874

Edition 1.0 2015-05

TECHNICAL REPORT

Guidance on the interpretation of carbon dioxide and 2-furfuraldehyde as markers of paper thermal degradation in insulating mineral oil

IEC TR 62874:2015-05(en)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

IEC Catalogue - webstore.iec.ch/catalogue
The stand-alone application for consulting the entire bibliographical information on IEC International Standards, Technical Specifications, Technical Reports and other documents. Available for PC, Mac OS, Android Tablets and iPad.

IEC publications search - www.iec.ch/searchpub
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and also once a month by email.

Electropedia - www.electropedia.org
The world's leading online dictionary of electronic and electrical terms containing more than 30 000 terms and definitions in English and French, with equivalent terms in 15 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary
More than 60 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.

IEC TR 62874

Edition 1.0 2015-05

TECHNICAL REPORT

Guidance on the interpretation of carbon dioxide and 2-furfuraldehyde as markers of paper thermal degradation in insulating mineral oil

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.040.10

ISBN 978-2-8322-2661-2

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

GUIDANCE ON THE INTERPRETATION OF CARBON DIOXIDE AND 2-FURFURALDEHYDE AS MARKERS OF PAPER THERMAL DEGRADATION IN INSULATING MINERAL OIL

FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a Technical Report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC TR 62874, which is a Technical Report, has been prepared by IEC technical committee 10: Fluids for electrotechnical applications.

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

Enquiry draft	Report on voting
10/903/DTR	10/917A/RVC

Full information on the voting for the approval of this Technical Report 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.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website 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.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

The cellulosic solid insulation of transformers and other electrical apparatus is subject to thermal degradation during their operational lifetime. This results in a progressive loss of paper's mechanical properties, such as tensile strength, which are related to the duration of the technical life of the equipment [3,4] [1].

During its thermal degradation process (also called "ageing" in this Technical Report), cellulose forms several by-products, some of which may be detected by means of insulating oil's chemical analysis [1,2]. The concentration and rate of increase of those by-products can be used as a tool to estimate the progress of paper thermal degradation in transformers and other electrical apparata in service.

For this reason, IEC technical committee 10 has prepared this Technical Report for the monitoring of insulating oil parameters related to cellulose ageing and the interpretation of results, as a guidance to the thermal degradation evaluation of insulating paper.

This Technical Report is based on the evaluation of cellulose ageing by-products content in insulating oil, and their rate of formation during the life of the oil-immersed electrical equipment. Statistical reference values reported in Annex A of this Technical Report are based on data collected by TC10. The final report of CIGRE WG D1.01.TF13 [7] was taken as a source of information concerning mechanisms and parameters influencing the formation of furanic compounds.

NOTE Methods for the estimation of actual degree of polymerization (DP) values of paper, which are widely available in literature, were not applied within this Technical Report. This is due to the fact that a number of different models have been developed and reported, and they often lead to different results. Moreover, the applicability of those models has not been sufficiently proven by comparison with field experience to be included into an IEC standard.

Health and safety

This Technical Report does not purport to address all the safety problems associated with its use. It is the responsibility of the user of the Technical Report to establish appropriate health and safety practices and determine the applicability of regulatory limitations prior to use.

The mineral oils which are the subject of this Technical Report should be handled with due regard to personal safety and hygiene. Direct contact with eyes may cause slight irritation. In the case of eye contact, irrigation with copious quantities of clean running water should be carried out and medical advice sought.

Some of the tests specified in this Technical Report involve the use of processes that could lead to a hazardous situation. Attention is drawn to the relevant standard for guidance.

Environment

This Technical Report involves mineral oils, chemicals and used sample containers. The disposal of these items should be carried out in accordance with current national legislation with regard to the impact on the environment. Every precaution should be taken to prevent the release into the environment of mineral oil.

1 Figures in square brackets refer to the Bibliography

GUIDANCE ON THE INTERPRETATION OF CARBON DIOXIDE AND 2-FURFURALDEHYDE AS MARKERS OF PAPER THERMAL DEGRADATION IN INSULATING MINERAL OIL

1 Scope

IEC TR 62874, which is a Technical Report provides guidance for the estimation of consumed thermal life of transformers' cellulosic insulators, through the analysis of some compound dissolved in the insulating mineral oil. A comparison between analytical results of 2-furfural (2-FAL) and carbon oxides and their correspondent typical values estimated for different families of equipment gives information on the estimated thermal degradation of papers.

The ageing rate of insulating papers can be evaluated, in short time ranges (e.g. 1 year), by regularly monitoring 2-FAL and carbon oxides content in the oil and by comparing them to typical rates of increase.

A statistical approach for the estimation of paper thermal degradation, and the evaluation of ageing rate is given.

Typical values for concentrations and rates of increase of the parameters related to paper ageing were extrapolated from a statistical database collected, and are reported in Annex A. They may be used as a rough guide, but they should not be considered as threshold values.

This Technical Report is only applicable to transformers and reactors filled with insulating mineral oils and insulated with Kraft paper. The approaches and procedures specified should be taken as a practical guidance to investigate the thermal degradation of cellulosic insulation, and not as an algorithm to calculate the actual degree of polymerization (DP) of papers.

The paper thermal life evaluation protocol described in this Technical Report applies to mineral oil impregnated transformers and reactors, insulated with Kraft paper. Any equipment filled with insulating liquids other than mineral oil (i.e. esters, silicones) or insulated with solid materials other than Kraft paper (i.e. TUP – thermally upgraded Kraft paper, synthetic polymers) is outside of the scope of this Technical Report.

This Technical Report is applicable to equipment that has been submitted to a regular monitoring practice during the service, and for which maintenance and fault history is known.

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.

None.

3 Significance

3.1 General

This Technical Report describes a statistical approach to paper thermal life evaluation. This means that all typical values are obtained from populations of transformers belonging to the same family for technical characteristics and application (see Annex A).

The approach used to collect statistical data, described in 6.1, can be applied by utilities or owners having a large population of units, to calculate individual reference values related to a specific family of transformers or reactors. This is very important because different population of transformers (i.e. operating in different climates or under different operational conditions) may have different typical values.

NOTE For an extensive survey on furanic compounds as markers for diagnosis of paper insulation degradation, see CIGRE Brochure 494/2012 [7].

3.2 Thermal and mechanical degradation of paper

3.2.1 General

There are main factors: design and materials, contaminants in the insulation system and operational conditions, that will determine the ageing of a transformer [1,2]. For the solid insulation – paper and pressboard – it means a combination of mechanical and dielectric performance, which are interlinked and synergetic. For a transformer, in the context of thermal ageing, it is the mechanical strength of the paper that matters. The ageing of paper results in a decreased mechanical strength and is assumed to reduce the ability of the transformer to withstand short circuit stress. This, however, has not been statistically demonstrated, yet.

Tensile strength, elongation and folding strength all decay with time, and more quickly at higher temperatures.

The mechanical performance of cellulosic insulation is given in terms of tensile index or degree of polymerization (DP), which are strongly influenced by ageing. The DP value is an average value of chain lengths of the cellulose molecules given as a number of glucose rings in a cellulose chain. It is measured through measurement of the viscosity of a paper solution, according to IEC 60450 [8].

It is more convenient to perform DP than tensile index, because of the limited amount of paper accessible for tests; therefore it is widely used for the evaluation of the cellulosic ageing status.

There are three main processes of degradation:

– hydrolysis;
– oxidation;
– pyrolysis.

3.2.2 Impact of temperature

Temperature affects the rate of degradation. This fact is reflected in IEC 60076-7 [3] and IEEE Std C57.91 [4] transformer loading guides.

IEC 60076-7 [3] suggests in accordance with Montsinger that the life of a transformer can be described according to Equation (1):

$$\textit{Life duration} = e^{-p\times\theta} \qquad (1)$$

where:

p is a constant (a value of 6 is suggested in the range 80 °C to 140 °C)

θ is the temperature in degrees Celsius.

This is a simplified version of Arrhenius law used in IEEE Std C57.91 [4].

Since a precise end-of-line criterion for a transformer is not really available, IEEE and IEC standards use an approach where ageing rate is considered. This is the inverse of lifetime – in Montsinger form:

$$\textit{Rate of ageing} = \textit{constant} \times e^{p \times \theta} \tag{2}$$

The constant in Equation (2) is dependent on many parameters, e.g. original quality of cellulosic products as well as environmental parameters (moisture content and oxygen in the system). A graphical representation of these influences is shown in Figure 1.

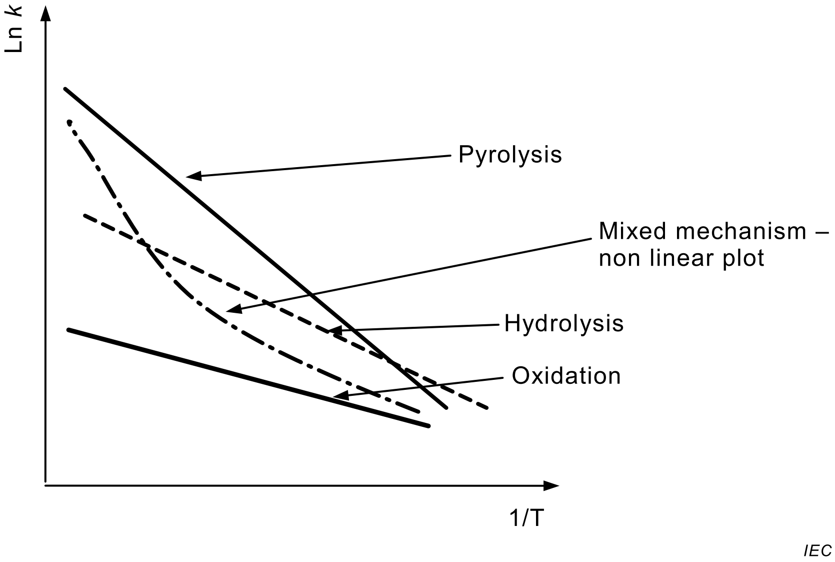

Figure 1 – Schematic diagram showing rate of ageing *k*, depending on different ageing mechanisms

3.2.3 Impact of humidity and oxygen

Humidity and oxygen ingress (oxidation) have an important impact on the ageing of Kraft paper. This means not only that the mechanical strength of paper rapidly decreases under ingress of moisture and air, but practically causes an increasing contamination of the combined liquid-solid insulation under these conditions. It is a consequence of the degradation products formed from oil and paper leading to a further degradation.

During the ageing of the combined cellulosic and oil insulation many by-products are formed – carbon oxides, water, acids, sludge and furanic compounds. Many of these degradation products, e.g. furanic compounds, are soluble in oil and stable enough to be used as diagnostic markers. Furanics are formed by dehydration reactions following hydrolysis of the cellulose and hemicellulose as well as by oxidative pyrolysis of cellulose. Their analytical determination is well known and reliable (see IEC 61198 [12]).

In a transformer all these processes – hydrolysis, oxidation and pyrolysis – act simultaneously, resulting in a non-linear mechanism (see Figure 1). Which process will dominate depends on the temperature and the operational parameters. In fact the application of one activation energy, although often practiced, is very difficult because of the complexity of the degradation processes.

3.3 Symptoms of paper ageing in insulating oil

3.3.1 General

The ageing of paper can be detected by direct investigation on the paper or by the measurement of by-products dissolved in the oil.

Cellulose degradation mainly affects the mechanical properties (tensile strength, elongation, burst strength, double fold strength, etc.) of paper (see Figure 2), but a direct measure of those parameters requires the sampling of a large amount of paper, which is normally impossible during the operational lifetime of a transformer. However, the relationship between the mechanical indexes and the degree of polymerization (DP) is well known. Degradation of paper does not significantly affect its resistance to the compression forces mostly and continuously applied to transformer windings through clamping.

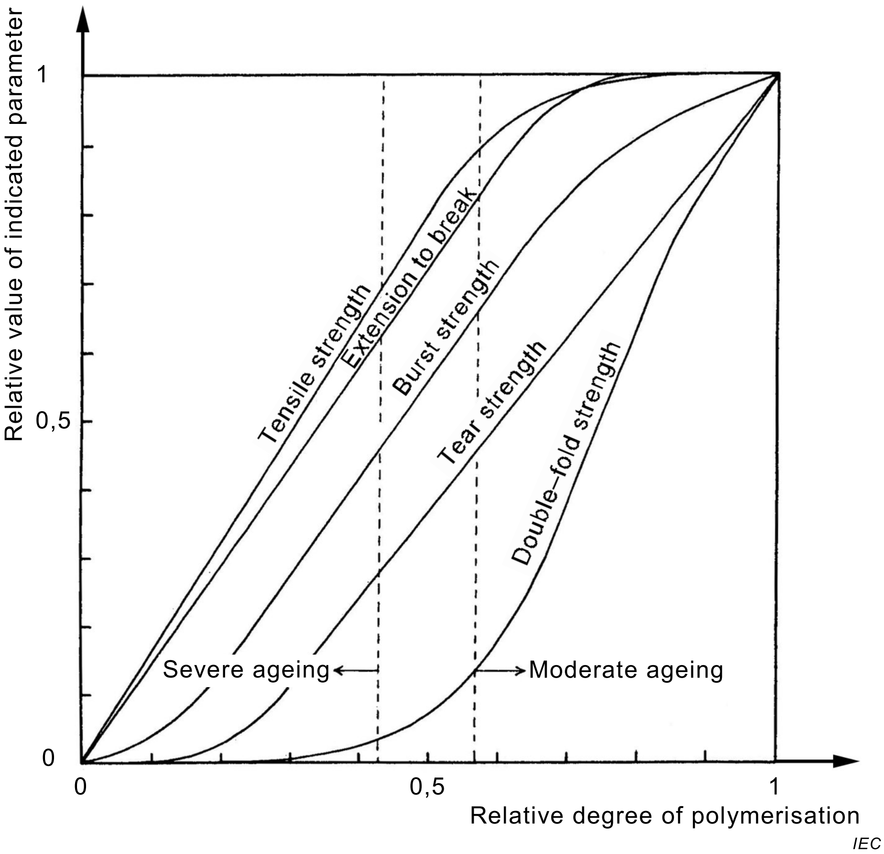

Figure 2 – Relationship between mechanical properties of insulating paper and paper degree of polymerization (DP) [5].

The DP value is the average number of glycoside rings in the cellulose polymer; in the native cellulose DP may be as high as or more than 10 000 units but after the purification process and other treatments the DP value of the electrical Kraft paper decreases to around 1 000 units (typical value: 1 200).

DP is measured in accordance with IEC 60450 [8], through measurement of the specific viscosity of a very small amount of paper dissolved in cupri-ethylene-diamine (CuED). From this measurement the intrinsic viscosity of solution is deduced and from this, using the Martin's formula, the DP value is easily calculated.

By-products of aged paper may be classified as volatile, soluble and insoluble, and are dependent on the specific decomposition process: pyrolysis, hydrolysis or oxidation.

3.3.2 Volatile by-products

Carbon oxides (CO and CO_2) are the ultimate products of cellulose degradation and are measured with dissolved gas analysis (DGA) in accordance with IEC 60567 [9]. It must be taken into account that both CO and CO_2 can be generated from oil oxidation as well.

Water can reach several per cent of the paper weight. Most of the water formed is adsorbed and retained in the solid insulation of the transformer and only a little part is dissolved in oil. Of course another contribution to total water is the ingress of moisture from atmosphere.

The detection of water in oil is performed in accordance with IEC 60814 [10].

3.3.3 Soluble by-products

A large number of oil soluble compounds (acids, alcohols, etc.) are generated from paper degradation. The most commonly used compound for diagnosis is 2-furfural (2-FAL) and its related compounds:

– 5 hydroxymethyl 2-furfural (5-HMF)
– 2 furfurylalcohol (2-FOL)
– 2 acetylfuran (2-ACF)
– 5 methyl 2-furfural (5-MEF).

The detection of 2-FAL and related compounds in oil is performed in accordance with IEC 61198 [12].

In the same way as with water, a relevant amount of generated furanic compounds is retained in the bulk of the paper. The ratio between the concentration of furanic compounds in the paper and in the oil differs for each single compound, and is affected by temperature. Increased temperature forces the equilibrium of furanic compounds to a higher concentration in the oil. Decreased temperature forces the equilibrium of furanic compounds to a higher concentration in the paper, especially in the case of dry paper.

Paper humidity and type of paper also influence the oil-to-paper concentration ratio of furanic compounds. A wet paper tends to retain a larger amount of furanic compounds, thus reducing the oil-to-paper concentration ratio.

Furanic compounds are not highly stable, and may be degraded by oxidation, mostly in oils with high oxygen content. Decay in the concentration of 2-FAL was observed in transformers during their operation, due to its inherent instability.

Acid compounds may be formed either by cellulose and/or oil oxidation, and a high acidity often accompanies other symptoms of paper ageing.

3.3.4 Insoluble by-products

Severe paper ageing can finally lead to the fragmentation of polymeric cellulose, and small paper fibres can be detached from the paper mass.

The cellulose fibres can be detected as particles present in insulating oil, in accordance with IEC 60970 [11].

3.4 Operational parameters influencing paper thermal ageing

In addition to transformer hours of service as a key parameter in defining “real age” of paper insulation in normal working regimes, other operational parameters such as load, type of cooling and transformer sub-type have a major influence on paper thermal ageing. The nature of the oil may also be a fundamental parameter for the estimation of paper thermal ageing.

The high-load of a transformer, implying elevated operating temperatures, promotes the paper thermal degradation process, observed with some types of transformers that are often overloaded (shunt reactors, HVDC, generator step-up (GSU) in thermal power plants (TPP), high voltage inter-tie transmission transformers).

The type of cooling, in terms of cooling media (water or air) and type of flow applied (forced or natural convection), affects efficiency of heat removal, thus influencing the rate of paper thermal degradation. The most efficient cooling can be achieved by applying water as coolant in forced oil flow.

For example, it was observed in most cases that the degree of paper degradation with GSU transformers in hydro power plants (HPP) is lower than with thermal power plant GSU units, having a similar service duration. These findings are correlated to different types of cooling (OFWF versus ONAF and OFAF), hours of service and loading history of HPP and TPP units [6].

Among different transformer sub-types, air-breathing transformers are subjected to more intensive paper degradation than sealed ones, due to higher oxygen and moisture content. Elevated concentrations of oxygen and water accelerate the paper degradation process.

Since the paper degradation process is temperature driven, every environmental and operational condition that may affect the temperature can also modify the degradation rate of the solid insulation. An elevated environmental temperature or a high loading can thus increase the rate of paper degradation, resulting in a sudden increase of 2-FAL, CO_2, CO and other by-products.

3.5 Role of oil type and condition

Oil type may affect the ageing rate of paper. Inhibited oils show a lower tendency to form acidity, and the oxidation process is slackened; the effect of oxygen in the paper oxidation process is reduced.

Transformers impregnated with inhibited oil may show a lower content of 2-FAL if compared with units insulated with an uninhibited oil, even if showing the same degree of polymerization (DP) of the paper.

The effect of passivators (triazole derivates) in the ageing of celluloses is still not well defined. By definition, metal passivators may induce a lower rate of the oil degradation process by deactivating the copper catalyst in oxidation processes, therefore slowing down the paper degradation process, but influence of metal passivators on 2-FAL concentration in the oil may not be straightforward. Some laboratory studies have shown that papers impregnated with oils to which a passivator has been added, may have a lower tendency to form furanic compounds; this may lead to optimistic estimation of ageing in presence of triazolic passivators.

The ageing condition of the oil may also affect the partition of furanic compounds between solid and liquid insulation; acidic oils may result in an increased 2-FAL concentration in oil, due to its augmented capability to extract polar compounds from the paper.

3.6 Fault conditions that may affect thermal ageing

In transformers where the degradation mechanism may be either thermal or electrical, the rate of paper degradation may increase rapidly as a consequence of significant temperature rise. High energy thermal and electrical faults involving excessive currents circulating through the insulation and large current follow-through lead to extensive destruction and carbonization of paper.

In presence of local thermal degradation due to a fault, the estimation of the paper's consumed thermal life may become very difficult, since the extension of the paper volume involved is unknown, and temperature may have strong variations even over a short time. Investigations on the presence of thermal faults through DGA should always accompany thermal life evaluation, to avoid misleading conclusions.

High energy electrical faults (discharges of high energy) usually involve a very small volume of paper, so that the contribution to the detected concentration of furanic compounds is negligible. In case of discharges with paper involved, a sharp increase of carbon oxides is observed, rather than an noticeable increase of 2-FAL. The formation of cellulose by-product has not been found to be related to partial discharges.

3.7 Maintenance operations that may affect thermal ageing indicators

3.7.1 General

Maintenance operations on the oil may affect (partially or totally) parameters used as indicators of cellulose thermal ageing (see 3.3). Their effects should be taken into account during the estimation of the total 2-FAL concentration, and in evaluating the rate of increase of the thermal ageing indicators.

3.7.2 Effects of oil reconditioning

Oil reconditioning may reduce 2-FAL concentration in oil, depending on the duration/efficiency of the treatment.

Oil reconditioning normally does not significantly affect 2-FAL, gas and moisture concentration in cellulose. On-line degassing or long-term reconditioning may reduce moisture in paper.

The equilibrium of 2-FAL distribution between oil and paper is restored in a time depending on temperature, cooling and oil circulation.

Dissolved gases and water dissolved in oil are mostly removed by vacuum degassing.

In the 6 months following a reconditioning, the rates of increase of 2-FAL, dissolved gases and moisture should not be considered as an indicator of increased ageing rate, the equilibrium being forced thermodynamically through the increase of concentration in the oil.

3.7.3 Effects of oil reclamation

Reclaiming the oil has major effects on the concentration of 2-FAL. Furanic compounds are polar and they are almost completely removed by fuller’s earth and other adsorbing media.

After an oil reclamation the trend of furanic compounds should be carefully recorded (with frequent sampling) to monitor the increase of 2-FAL, taking into account new equilibrium conditions.

NOTE For effects of reclamation on dissolved gases and moisture see 3.7.2

3.7.4 Effects of oil change

Oil change has major effects on the concentration of 2-FAL, as well. All the by-products dissolved in the oil are removed. Nevertheless, after an oil change a new equilibrium between solid and liquid insulation is dependent on temperature, cooling and oil circulation.

After an oil replacement the trend of furanic compounds should be carefully recorded (with frequent sampling) to monitor the increase of 2-FAL, taking into account new equilibrium conditions.

NOTE For effects of oil change on dissolved gases and moisture see 3.7.2

4 Monitoring protocol

4.1 General

A regular monitoring of parameters related to thermal ageing of cellulose is strictly required for the estimation of paper ageing condition and its rate of thermal degradation. No evaluation should be done and no action should be taken on the basis of a single determination.

Evaluation based on a few samples close to the end of the operational lifetime will not lead to reliable conclusions; the approach for the estimation of paper thermal degradation reported in this Technical Report cannot be applied if a regular monitoring was not performed during the life of the equipment.

4.2 Parameters

4.2.1 Basic monitoring

Parameters for a basic monitoring are (see 3.3):

– furanic compounds;

– DGA (dissolved gas analysis).

NOTE The use of DGA as a monitoring tool is solely addressed to the scope of this Technical Report, i.e. the estimation of paper ageing condition. For the application of DGA as a tool to intercept or reveal faulty conditions of transformers, refer to IEC 60599 [14].

4.2.2 Complementary monitoring

Parameters for complementary monitoring are (see 3.3):

– water content in oil;

– acidity;

– inhibitor content (for inhibited oils only, refer to IEC 60666 [13] for the detection method);

– passivator content (for passivated oils only, refer to IEC 60666 for the detection method);

– particle counting.

4.3 Recommended testing frequencies

The following sampling and testing frequencies are recommended for paper thermal degradation monitoring, depending on the age of the equipment and the results of previous estimations of paper thermal degradation.

In case of indications of typical or low paper thermal degradation:

– basic monitoring every 1 to 2 years.

In case of indications of high paper thermal degradation or high rates of paper thermal degradation, or in case of suspect of abnormal paper ageing due to high loading, defective or insufficient cooling or severe environmental conditions:

– basic and complementary monitoring at least twice per year.

In case of evidence of severe thermal degradation, or if DGA shows presence of thermal faults (T1-T2):

– refer to IEC 60599 for DGA interpretation and sampling frequency.

5 Typical values of paper ageing symptoms

5.1 General

Typical values are calculated for 2-FAL and carbon dioxide, for different families of equipment listed in 5.1. The sample population is divided in age ranges as follows:

- units with service age lower or equal to 1 year;
- units with service age higher than 1 year and lower or equal to 10 years;
- units with service age higher than 10 years and lower or equal to 30 years;
- units with service age higher than 30 years.

For each age range two reference values are calculated:

- the lower value corresponds to the value where 90 % of the population falls (90^{th} percentile)
- the higher value corresponds to the value where 98 % of the population falls (98^{th} percentile)

While calculating typical values for a family of equipment, it is highly recommended to follow the above listed criteria, taking into account also the following recommendations:

- discard values measured just following an oil reconditioning, reclaiming or replacement;
- discard values measured on units having been out of service for a long period;
- consider only values measured with units at constant power load (equilibrium conditions);
- the reliability of laboratories performing the analysis is of outmost importance.

While calculating typical rate of increase (RoI) values for a family of equipment, it is highly recommended to follow the above listed criteria:

- consider only values sampled with a reasonable time gap (> 6 months), to reduce the effects of test reproducibility;
- RoI should be preferably measured on a set of 3 to 4 values obtained with regular sampling, eventually using the moving average to reduce the effects of statistical fluctuations.

5.2 Families of equipment

For a better estimation of paper thermal degradation, equipment is classified in families, having different typical values of the parameters related to thermal degradation of paper. Families of equipment are:

- reactors
- power transformers
    - GSU (generation step-up units)
    - network transmission
    - large distribution (> 2 MVA)
- rectifiers
    - HVDC
    - LVDC
- furnace transformers
- industrial/distribution (< 2 MVA)

Moreover, when a sufficient amount of data is available, each family is divided in sub-families on the basis of design parameters (conservator breathing mode) and type of oil (inhibited or uninhibited).

6 Estimation of paper thermal degradation and ageing rate

6.1 General approach

NOTE The procedure for estimation of paper thermal degradation described in this Technical Report is based on the statistical evaluation of a population of transformers.

The approach to the estimation of paper thermal degradation proposed here is addressed to supply general information on the thermal degradation conditions and (if possible) on the rate of degradation.

Paper thermal degradation may be evaluated by means of comparing the value of parameters related to thermal degradation to the typical values obtained by the population of equipment.

Transformers and reactors having undergone major repair, oil change and/or reclamation, or having shown symptoms of thermal faults should be evaluated very carefully, for the reasons described in 3.6.

A unique set of threshold values for furanic compounds or carbon oxides cannot be established, due to the large variation of typical values resulting from different databases. Nevertheless, a statistical evaluation may be done on a selected population; thus, on the basis of typical values calculated as described in 5:

– LOW thermal degradation is associated with values lower than the 90^{th} percentile of the appropriate family of transformer, for the corresponding service age;
– TYPICAL thermal degradation is associated with values between 90^{th} and 98^{th} percentile of the appropriate family of transformer, for the corresponding service age;
– HIGH thermal degradation is associated with values higher than the 98^{th} percentile of the appropriate family of transformer, for the corresponding service age.

Units in LOW ageing condition can be assumed as having a paper thermal degradation lower than the one that should be expected on the base of the actual age of service.

Units in TYPICAL ageing condition can be assumed as having a paper thermal degradation close to the one that should be expected on the basis of the actual age of service.

Units in HIGH ageing condition can be assumed as having a paper thermal degradation higher than the one that should be expected on the basis of the actual age of service.

All reference values described in Annex A were obtained from a databank of units where 90% of the population has a service age of less than 35 years. Thus, all considerations relative to the ageing condition and the paper thermal degradation should refer to an average life of transformers of 30 to 40 years.

6.2 Practice

Follow the monitoring protocol described in Clause 4 regularly.

Examine the maintenance and fault history of the equipment, and give particular attention to events which may have influenced the content of cellulose degradation by-products (see 3.4 to 3.7) or to fault conditions which may jeopardize the evaluation of paper thermal ageing (see 3.6).

Verify to which of the families defined in 5.2 (or other families eventually identified) the unit belongs.

Establish actual values and rates of increase of 2-FAL and carbon dioxide in the unit, and refer to typical values in order to identify the condition of the unit in terms of ageing condition and/or ageing rate. Figure 3 reports a flow-chart of the whole practice procedure.

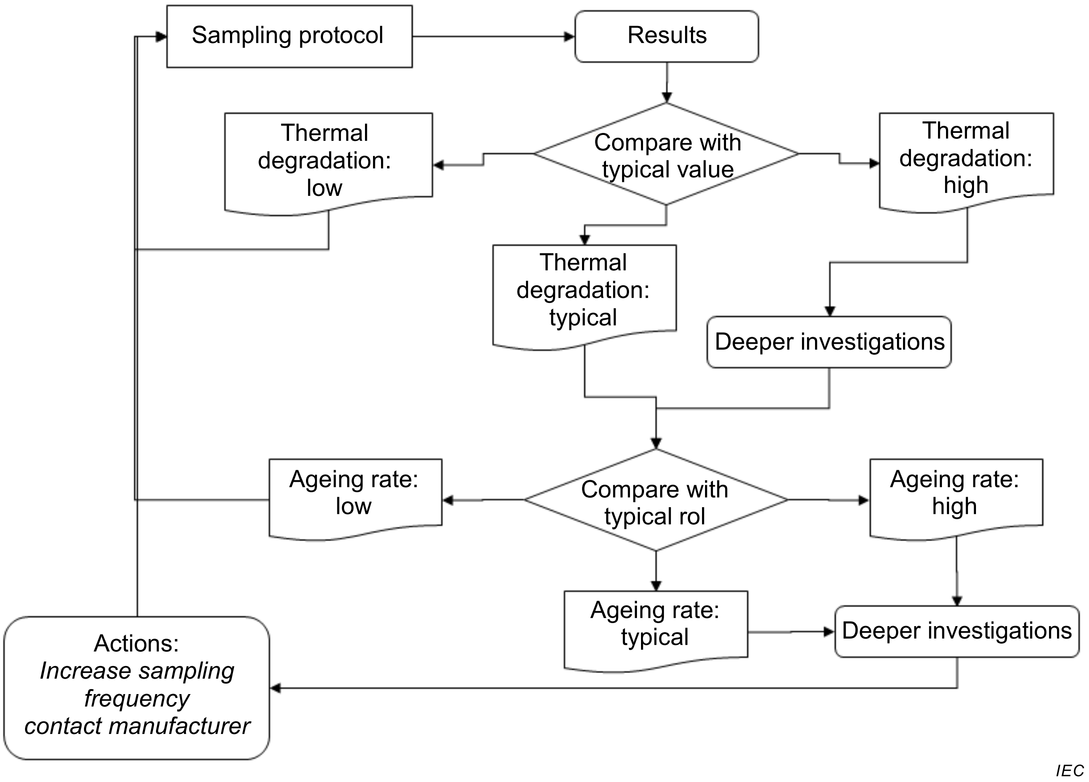

Figure 3 – Example of flow-chart for the estimation of paper degradation conditions

NOTE If 2-FAL evaluation and CO_2 evaluation produce different results, a conservative approach suggests considering the worst condition of the two obtained. In this case, a more frequent monitoring is recommended for a better assessment.

EXAMPLE One network transmission unit filled with uninhibited mineral oil, with 12 years of service, shows the following data:

– 2-FAL concentration = 2,5 mg/kg
– CO_2 concentration in oil = 6 500 µl/l

Tables A.1, A.2 and A.9 apply to this example. Search in the column [10 < Y ≤ 30] where the actual values fall in comparison with reference values.

2-FAL value indicates a TYPICAL ageing, CO_2 value indicates a LOW ageing. The unit should be considered in TYPICAL ageing condition, with a recommendation to continue a regular monitoring to confirm this evaluation.

7 Actions

A transformer or reactor found in HIGH ageing conditions or with a HIGH ageing rate may require an action to rectify the critical factor.

It is recommended to keep the unit under regular and strict monitoring to confirm the presence of abnormal paper thermal degradation.

In case of abnormal paper thermal degradation, refer to the manufacturer before taking any decision.

Annex A
(informative)

Typical values tables

A.1 General warning

Data reported in Annex A shall not be considered as thresholds or limits.

They are given as examples of typical values for some families of equipment, and are not exhaustive or comprehensive of all transformer types. Users having a sufficient number of units to calculate specific typical values and rates of increase are encouraged to build their own tables of values and to refer to them for evaluation.

A.2 2-FAL typical values

A.2.1 General

Typical values of 2-FAL concentration (Conc., expressed in mg/kg) and rate of increase (RoI, expressed in mg/kg/y) are listed in the following tables. Each table refers to the family of equipment and oil type described in the related note.

NOTE Values reported as N.A. (not available) were not calculated, because the number of cases in the population was too exiguous.

A.2.2 Family: GSU (generation step-up units)

NOTE In A.2.2, no distinction is made between units with open conservator and units with sealed conservator.

A.2.2.1 Sub-family: GSU impregnated with uninhibited oil

Table A.1 – 2-FAL typical values for GSU transformers, filled with uninhibited mineral oil (based on a population of 1 860 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	< 0,05	< 0,01	0,3	0,04	2,0	0,30	3,0	N.A.
98°	< 0,05	< 0,01	1,0	0,10	4,0	0,70	6,0	N.A.

A.2.2.2 Sub-family: GSU impregnated with inhibited oil

Table A.2 – 2-FAL typical values for GSU transformers, filled with inhibited mineral oil (based on a population of 176 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	N.A.	N.A.	0,1	N.A.	0,80	0,25	N.A.	N.A.
98°	N.A.	N.A.	0,15	N.A.	1,5	0,60	N.A.	N.A.

A.2.3 Family: network transmission units

Table A.3 – 2-FAL typical values for network transmission transformers, filled with uninhibited mineral oil (based on a population of 2 845 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	0,1	0,01	0,3	0,06	1,6	0,25	2,0	0,3
98°	0,2	0,02	1,1	0,6	3,5	0,80	4,5	1,1

A.2.4 Family: large distribution units

A.2.4.1 Sub-family: large distribution units with open conservator

Table A.4 – 2-FAL typical values for large distribution transformers, with open breathing conservator, filled with uninhibited mineral oil (based on a population of 7 107 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	< 0,05	< 0,01	0,7	0,20	1,5	0,30	N.A.	N.A.
98°	0,2	0,03	3,0	0,50	4,5	0,80	N.A.	N.A.

A.2.4.2 Sub-family: large distribution units with sealed conservator

Table A.5 – 2-FAL typical values for large distribution transformers, with sealed conservator, filled with uninhibited mineral oil (based on a population of 288 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	< 0,05	N.A.	0,15	0,02	1,6	0,40	N.A.	N.A.
98°	0,15	N.A.	0,85	0,04	5,0	0,70	N.A.	N.A.

A.2.5 Family: industrial distribution units

Table A.6 – 2-FAL typical values for industrial distribution transformers, filled with uninhibited mineral oil (based on a population of 3 885 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	0,60	0,02	0,70	0,10	1,3	0,30	N.A.	N.A.
98°	1,5	0,20	2,7	0,70	4,5	1,1	N.A.	N.A.

A.2.6 Family: LVDC units

Table A.7 – 2-FAL typical values for LVDC transformers, filled with uninhibited mineral oil (based on a population of 360 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	N.A.	N.A.	0,80	0,30	1,0	0,30	N.A.	N.A.
98°	N.A.	N.A.	1,4	0,80	3,0	0,80	N.A.	N.A.

A.3 Carbon dioxide typical values

A.3.1 General

Typical values of carbon dioxide concentration (Conc., expressed in µl/l) and rate of increase (RoI, expressed in µl/l/y) are listed in the following tables. Each table refers to the family of equipment and oil type described in the related note.

NOTE 1 Values reported as N.A. (not available) were not calculated, because the number of cases in the population was too exiguous.

Due to lack of data no division of data is described according to type of preservation system (open-breathing vs. sealed/nitrogen blanketed) that may affect CO_2 concentration. It is highly recommended to make such division for individual data bank analysis.

NOTE 2 Typical values and typical rates of increase for carbon oxides that are reported in IEC 60599 differ from the ones listed in the following tables. This is due to the different approach used in this Technical Report, where typical values are calculated for specific age intervals, and are aimed solely at the estimation of paper thermal degradation. For the application of DGA as a tool to intercept or reveal faulty conditions of transformers, refer to IEC 60599.

A.3.2 Family: GSU (generation step-up units)

Table A.8 – CO_2 typical values for GSU and excitation transformers, filled with uninhibited mineral oil (based on a population of 1 098 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	2 000	N.A.	5 000	1 500	6 000	1 500	8 000	N.A.
98°	2 500	N.A.	7 000	3 000	11 000	3 000	15 000	N.A.

A.3.3 Family: network transmission units

Table A.9 – CO_2 typical values for network transmission transformers, filled with uninhibited mineral oil (based on a population of 435 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	3 000	N.A.	5 000	N.A.	8 000	N.A.	8 000	N.A.
98°	5 000	N.A.	8 000	N.A.	11 000	N.A.	13 000	N.A.

A.3.4 Family: large distribution units

Table A.10 – CO_2 typical values for large distribution transformers, filled with uninhibited mineral oil (based on a population of 7 291 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	2 000	N.A.	4 000	N.A.	5 000	N.A.	6 000	N.A.
98°	3 500	N.A.	8 000	N.A.	9 000	N.A.	12 000	N.A.

A.3.5 Family: industrial distribution units

Table A.11 – CO_2 typical values for industrial distribution transformers, filled with uninhibited mineral oil (based on a population of 4 556 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	1 500	N.A.	3 500	N.A.	4 500	N.A.	5 000	N.A.
98°	3 500	N.A.	5 500	N.A.	7 000	N.A.	9 000	N.A.

A.3.6 Family: LVDC units

Table A.12 – CO_2 typical values for LVDC transformers, filled with uninhibited mineral oil (based on a population of 273 units)

Age →	< 1 Y		1 – 10 Y		10 – 30 Y		> 30 Y	
Percentile ↓	Conc.	RoI	Conc.	RoI	Conc.	RoI	Conc.	RoI
90°	N.A.	N.A.	3 000	N.A.	4 500	N.A.	N.A.	N.A.
98°	N.A.	N.A.	4 500	N.A.	7 500	N.A.	N.A.	N.A.

Bibliography

[1] CIGRE WG D1.01.10, Brochure 323/2007, Ageing of cellulose in mineral-oil insulated transformers

[2] L. Lundgaard, W. Hansen, D. Linhjell & T. Painter, (2002), "*Ageing of Oil Impregnated paper in power transformers*", IEEE Trans Pow. Del., Vol 19, No.1, 2004, pp 230-238.

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

[4] IEEE Std C57.91-1995 IEEE Guide for loading Mineral-oil-immersed Transformers

[5] Lawson, M.A. Simmons, P.S. Gale. "Thermal ageing of cellulose paper insulation". IEEE Transactions on Electrical Insulation, Vol EI-12, No. 1, Feb. 1977, pp. 61-66

[6] J.Lukic, A.Bojkovic, V.Rajakovic, K.Drakic, D.Jovanovic, D.Teslic. "Monitoring Insulating Paper Degradation With High Performance Liquid Chromatography Determination of Furan Compounds", Regional Conference and Exhibition on Electricity Distribution, CIRED, Herceg Novi, Montenegro, October 2004, R-3.1, p. 72.

[7] CIGRE WG D1.01.TF13, Brochure 494/2012, Furanic Compounds for Diagnosis

[8] IEC 60450, *Measurement of the average viscometric degree of polymerization of new and aged electrical papers*

[9] IEC 60567, *Oil-filled electrical equipment – Sampling of gases and analysis of free and dissolved gases – Guidance*

[10] IEC 60814, *Insulating liquids – Oil-impregnated paper and pressboard – Determination of water by automatic coulometric Karl Fischer titration*

[11] IEC 60970, *Insulating liquids – Methods for counting and sizing particles*

[12] IEC 61198, *Mineral insulating oils – Methods for the determination of 2-furfural and related compounds*

[13] IEC 60666, *Detection and determination of specified additives in mineral insulating oils*

[14] IEC 60599, *Mineral oil-impregnated electrical equipment in service – Guide to the interpretation of dissolved and free gases analysis*

____

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch