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REDLINE VERSION

Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MINERAL OIL-~~IMPREGNATED~~ FILLED ELECTRICAL EQUIPMENT IN SERVICE – GUIDANCE ON THE INTERPRETATION OF DISSOLVED AND FREE GASES ANALYSIS

FOREWORD

International Standard IEC 60599 has been prepared by IEC technical committee 10: Fluids for electrotechnical applications.

This third edition cancels and replaces the second edition published in 1999 and Amendment 1:2007. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) revision of 5.5, 6.1, 7, 8, 9, 10, A.2.6, A.3, A.7;

b) addition of new sub-clause 4.3;

c) expansion of the Bibliography;

d) revision of Figure 1;

e) addition of Figure B.4.

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

FDIS	Report on voting
10/967/FDIS	10/973/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.

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• withdrawn,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.

IMPORTANT – The "colour inside" logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this publication using a colour printer.

INTRODUCTION

Dissolved and free gas analysis (DGA) is one of the most widely used diagnostic tools for detecting and evaluating faults in electrical equipment filled with insulating liquid. However, interpretation of DGA results is often complex and should always be done with care, involving experienced insulation maintenance personnel.

This International Standard gives information for facilitating this interpretation. The first edition, published in 1978, has served the industry well, but had its limitations, such as the absence of a diagnosis in some cases, the absence of concentration levels and the fact that it was based mainly on experience gained from power transformers. The second edition attempted to address some of these shortcomings. Interpretation schemes were based on observations made after inspection of a large number of faulty oil-filled equipment in service and concentrations levels deduced from analyses collected worldwide.

MINERAL OIL-~~IMPREGNATED~~ FILLED ELECTRICAL EQUIPMENT IN SERVICE – GUIDANCE ON THE INTERPRETATION OF DISSOLVED AND FREE GASES ANALYSIS

1 Scope

This International Standard describes how the concentrations of dissolved gases or free gases may be interpreted to diagnose the condition of oil-filled electrical equipment in service and suggest future action.

This standard is applicable to electrical equipment filled with mineral insulating oil and insulated with cellulosic paper or pressboard-based solid insulation. Information about specific types of equipment such as transformers (power, instrument, industrial, railways, distribution), reactors, bushings, switchgear and oil-filled cables is given only as an indication in the application notes (see Annex A).

This standard may be applied, but only with caution, to other liquid-solid insulating systems.

In any case, the indications obtained should be viewed only as guidance and any resulting action should be undertaken only with proper engineering judgment.

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 60050-191:1990, *International Electrotechnical Vocabulary – Chapter 191: Dependability and quality of service* (available at http://www.electropedia.org)

IEC 60050-192:2015, *International Electrotechnical Vocabulary – Part 192: Dependability* (available at http://www.electropedia.org)

IEC 60050-212:2010, *International Electrotechnical Vocabulary – Part 212: Electrical insulating solids, liquids and gases* (available at http://www.electropedia.org)

IEC 60050-604:1987, *International Electrotechnical Vocabulary – Chapter 604: Generation, transmission and distribution of electricity – Operation* (available at http://www.electropedia.org)

IEC 60475, *Method of sampling insulating liquids*

IEC 60567:~~1992~~ 2011, ~~Guide for the sampling of gases and of~~ *Oil-filled electrical equipment* ~~and for the~~ *– Sampling of gases and analysis of free and dissolved gases – Guidance*

IEC 61198~~:1993~~, *Mineral insulating oils – Methods for the determination of 2-furfural and related compounds*

3   Terms, definitions and abbreviations

3.1   Terms and definitions

For the purposes of this document, the following terms and definitions, some of which are based on IEC 60050-191, IEC 60050-192, IEC 60050-212 and IEC 60050-604, apply.

3.1.1
fault
unplanned occurrence or defect in an item which may result in one or more failures of the item itself or of other associated equipment

NOTE – In electrical equipment, a fault may or may not result in damage to the insulation and failure of the equipment.

[SOURCE: IEC 60050-604:1987, 604-02-01]

3.1.2
non-damage fault
fault which does not involve repair or replacement action at the point of the fault

Note 1 to entry: Typical examples are self-extinguishing arcs in switching equipment or general overheating without paper carbonization or stray gassing of oil.

[SOURCE: IEC 60050-604:1987, 604-02-09]

3.1.3
damage fault
fault that involves repair or replacement action at the point of the fault

[SOURCE: IEC 60050-604:1987, 604-02-08]

3.1.4
incident
an event related to an internal fault which temporarily or permanently disturbs the normal operation of an equipment
event of external or internal origin, affecting equipment or the supply system and which disturbs its normal operation

Note 1 to entry: For the purposes of the present standard "incidents" are related to internal faults.

Note 2 to entry: For the purposes of the present standard typical examples of "incidents" are gas alarms, equipment tripping or equipment leakage.

[SOURCE: IEC 60050-604:1987, 604-02-03]

3.1.5
failure
the termination loss of ability of an item to perform a as required function

Note 1 to entry: In electrical equipment, failure will result from a damage fault or incident necessitating outage, repair or replacement of the equipment, such as internal breakdown, rupture of tank, fire or explosion.

[SOURCE: IEC 60050-192:2015, 192-03-01]

3.1.6
electrical fault
partial or disruptive discharge through the insulation

3.1.7
partial discharge
electric discharge that only partially bridges the insulation between conductors. ~~It may occur inside the insulation or adjacent to a conductor~~

Note 1 to entry: A partial discharge may occur inside the insulation or adjacent to a conductor.

~~NOTE 2 – X-wax is a solid material which is formed from mineral insulating oil as a result of electrical discharges and which consists of polymerized fragments of the molecules of the original liquid [IEV 212-07-24, modified]. Comparable products may be formed from other liquids under similar conditions.~~

Note 2 to entry: Scintillations of low energy on the surface of insulating materials are often described as partial discharges but should rather be considered as disruptive discharges of low energy, since they are the result of local dielectric breakdowns of high ionization density, or small arcs, according to the conventions of physics.

~~NOTE 3 – Sparking of low energy, for example because of metals or floating potentials, is sometimes described as partial discharge but should rather be considered as a discharge of low energy.~~

Note 3 to entry: For the purposes of this standard the following consideration may also be added:

–   Corona is a form of partial discharge that occurs in gaseous media around conductors that are remote from solid or liquid insulation. This term shall not be used as a general term for all forms of partial discharges

–   As a result of corona discharges, X-wax, a solid material consisting of polymerized fragments of the molecules of the original liquid, can be formed.

[SOURCE: IEC 60050-212:2010, 212-11-39]

3.1.8
discharge (disruptive)
passage of an arc following the breakdown ~~of the insulation~~

Note 1 to entry: The term "sparkover" (in French: "amorçage") is used when a disruptive discharge occurs in a gaseous or liquid dielectric.

The term "flashover" (in French: "contournement") is used when a disruptive discharge occurs over the surface of a solid dielectric surrounded by a gaseous or liquid medium.

The term "puncture" (in French: "perforation") is used when a disruptive discharge occurs through a solid dielectric.

Note 2 to entry: Discharges are often described as arcing, breakdown or short circuits. The following other specific terms are also used in some countries:

~~– sparkover (discharge through the oil);~~
~~– puncture (discharge through the solid insulation);~~
~~– flashover (discharge at the surface of the solid insulation);~~
– tracking (the progressive degradation of the surface of solid insulation by local discharges to form conducting or partially conducting paths);
– sparking discharges that, in the conventions of physics, are local dielectric breakdowns of high ionization density or small arcs.

~~NOTE 2 – Depending on the amount of energy contained in the discharge, it will be described as a discharge of low or high energy, based on the extent of damage observed on the equipment (see 5.2).~~

[SOURCE: IEC 60050-604:1987, 604-03-38]

3.1.9
thermal fault
excessive temperature rise in the insulation

Note 1 to entry: Typical causes are

–   insufficient cooling;

–   excessive currents circulating in adjacent metal parts (as a result of bad contacts, eddy currents, stray losses or leakage flux);

–   excessive currents circulating through the insulation (as a result of high dielectric losses), leading to a thermal runaway;

–   overheating of internal winding or bushing connection lead;

–   overloading.

3.1.10
typical values of gas concentrations
gas concentrations normally found in the equipment in service that have no symptoms of failure, and that are ~~overpassed~~ exceeded by only an arbitrary percentage of higher gas contents (for example 10 % (see 8.2.1))

Note 1 to entry: Typical values will differ in different types of equipment and in different networks, depending on operating practices (load levels, climate, etc.).

Note 2 to entry: Typical values, in many countries and by many users, are quoted as "normal values", but this term has not been used here to avoid possible misinterpretations.

3.2   Abbreviations

3.2.1   Chemical names and ~~symbols~~ formula

Name	~~Symbol~~ Formula
Nitrogen	N_2
Oxygen	O_2
Hydrogen	H_2
Carbon monoxide	CO
Carbon dioxide	CO_2
Methane	CH_4
Ethane	C_2H_6
Ethylene	C_2H_4
Acetylene	C_2H_2

NOTE   Acetylene and ethyne are both used for C_2H_2, ethylene and ethene are both used for C_2H_4

3.2.2   General abbreviations

D1   discharges of low energy

D2   discharges of high energy

DGA   dissolved gas analysis

CIGRE   ~~Conférence~~ Conseil International des Grands Réseaux Électriques

PD   corona partial discharges

S   analytical detection limit

T1   thermal fault, t <300 °C

T2   thermal fault, 300 °C <t< 700 °C

T3   thermal fault, t >700 °C

T   thermal fault

D   electrical fault

TP   thermal fault in paper

ppm   parts per million by volume of gas in oil, equivalent to μl(of gas)/l(of oil). See IEC 60567:2011, 8.7, note 1.

OLTC   on load tap changer

4 Mechanisms of gas formation

4.1 Decomposition of oil

Mineral insulating oils are made of a blend of different hydrocarbon molecules containing CH_3, CH_2 and CH chemical groups linked together by carbon-carbon molecular bonds. Scission of some of the C-H and C-C bonds may occur as a result of electrical and thermal faults, with the formation of small unstable fragments, in radical or ionic form, such as $H^\bullet$, $CH_3^\bullet$, $CH_2^\bullet$, $CH^\bullet$ or $C^\bullet$ (among many other more complex forms), which recombine rapidly, through complex reactions, into gas molecules such as hydrogen (H-H), methane (CH_3-H), ethane (CH_3-CH_3), ethylene ($CH_2 = CH_2$) or acetylene (CH $\equiv$ CH). C_3 and C_4 hydrocarbon gases, as well as solid particles of carbon and hydrocarbon polymers (X-wax), are other possible recombination products. The gases formed dissolve in oil, or accumulate as free gases if produced rapidly in large quantities, and may be analysed by DGA according to IEC 60567.

Low-energy faults, such as partial discharges of the cold plasma type (corona discharges), favour the scission of the weakest C-H bonds (338 kJ/mol) through ionization reactions and the accumulation of hydrogen as the main recombination gas. More and more energy and/or higher temperatures are needed for the scission of the C-C bonds and their recombination into gases with a C-C single bond (607 kJ/mol), C=C double bond (720 kJ/mol) or C≡C triple bond (960 kJ/mol), following processes bearing some similarities with those observed in the petroleum oil-cracking industry.

Ethylene is thus favoured over ethane and methane above temperatures of approximately 500 °C (although still present in lower quantities below). Acetylene requires temperatures of at least 800 °C to 1 200 °C, and a rapid quenching to lower temperatures, in order to accumulate as a stable recombination product. Acetylene is thus formed in significant quantities mainly in arcs, where the conductive ionized channel is at several thousands of degrees Celsius, and the interface with the surrounding liquid oil necessarily below 400 °C (above which oil vaporizes completely), with a layer of oil vapour/decomposition gases in between. Acetylene may still be formed at lower temperatures (<800 °C), but in very minor quantities. Carbon particles form at 500 °C to 800 °C and are indeed observed after arcing in oil or around very hot spots.

Oil may oxidize with the formation of small quantities of CO and CO_2, which can accumulate over long periods of time into more substantial amounts.

4.2 Decomposition of cellulosic insulation

The polymeric chains of solid cellulosic insulation (paper, pressboard, wood blocks) contain a large number of anhydroglucose rings, and weak C-O molecular bonds and glycosidic bonds which are thermally less stable than the hydrocarbon bonds in oil, and which decompose at lower temperatures. Significant rates of polymer chain scission occur at temperatures higher than 105 °C, with complete decomposition and carbonization above 300 °C (damage fault). Mostly Carbon monoxide and dioxide, as well as water, is formed, in much larger quantities than by oxidation of oil at the same temperature, together with minor amounts of hydrocarbon gases, furanic and other compounds. The latter Furanic compounds can be are analysed according to IEC 61198, and used to complement DGA interpretation and confirm whether or not cellulosic insulation is involved in a fault. CO and CO_2 formation increases not only with temperature but also with the oxygen content of oil and the moisture content of paper.

4.3 Stray gassing of oil

Stray gassing of oil has been defined by CIGRE [6][1] as the formation of gases in oil heated to moderate temperatures (<200 °C). H_2, CH_4 and C_2H_6 may be formed in all equipment at such

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[1] Numbers in square brackets refer to the Bibliography.

temperatures or as a result of oil oxidation, depending on oil chemical structure. Stray gassing is a non-damage fault. It can be evaluated using methods described in reference [6] and [12].

NOTE   Stray gassing of oil has been observed in some cases to be enhanced by the presence in oil of a metal passivator or other additives.

4.4   Other sources of gas

Gases may be generated in some cases not as a result of faults in the equipment, but through rusting or other chemical reactions involving steel, uncoated surfaces or protective paints.

Hydrogen may be produced by reaction of steel and galvanized steel with water, as long as oxygen is available from the oil nearby. Large quantities of hydrogen have thus been reported in some transformers that had never been energized. Hydrogen may also be formed by reaction of free water with special coatings on metal surfaces, or by catalytic reaction of some types of stainless steel with oil, in particular oil containing dissolved oxygen at elevated temperatures. Hydrogen, acetylene and other gases may also be formed in new stainless steel, absorbed during its manufacturing process, or produced by welding, and released slowly into the oil.

Hydrogen may also be formed by the decomposition of the thin oil film between overheated core laminates at temperatures of 140 °C and above (see [1]* of annex C).

Internal transformer paints, such as alkyd resins and modified polyurethanes containing fatty acids in their formulation, may also form gases.

Gases may also be produced, and oxygen consumed, by exposure of oil to sunlight or may be formed during repair of the equipment.

These occurrences, however, are very unusual, and can be detected by performing DGA analyses on new equipment which has never been energized, and by material compatibility tests. The presence of hydrogen with the total absence of other hydrocarbon gases, for example, may be an indication of such a problem.

NOTE   The case of gases formed at a previous fault and remnant in the transformer is dealt with in 5.4.

5   Identification of faults

5.1   General

Any gas formation in service, be it minimal, results from a stress of some kind, even if it is a very mild one, like normal temperature ageing. However, as long as gas formation concentration is below typical values and not significantly increasing, it should not be considered as an indication of a "fault", but rather as "the result of typical gas formation" (see Figure 1). Typical values are specific for each kind of equipment.

5.2   Dissolved gas compositions

Although the formation of some gases is favoured, depending on the temperature reached or the energy contained in a fault (see 4.1), in practice mixtures of gases are almost always obtained. One reason is thermodynamic: although not favoured, secondary gases are still formed, albeit in minor quantities. Existing thermodynamic models derived from the petroleum industry, however, cannot predict accurately the gas compositions formed, because they correspond to ideal gas/temperature equilibria that do not exist in actual faults. Large temperature gradients also occur in practice, for instance as a result of oil flow or vaporization

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* Figures in square brackets refer to the bibliography in annex C.

along a hot surface. This is particularly true in the case of arcs with power follow-through, which transfer a lot of heat to the oil vapour/decomposition gas layer between the arc and the oil, probably explaining the increasing formation of ethylene observed in addition to acetylene. In addition, existing thermodynamic models do not apply to paper that turns irreversibly to carbon above 300 °C.

5.3   Types of faults

Internal inspection of hundreds of faulty equipment has led to the following broad classes of visually detectable faults:

–   partial discharges (PD) of the cold plasma (corona) type, resulting in possible X-wax deposition on paper insulation, or of the sparking type, inducing pinhole, carbonized perforations (punctures) in paper, which, however, may not be easy to find;

–   discharges of low energy (D1), in oil or/and paper, evidenced by larger carbonized perforations through paper (punctures), carbonization of the paper surface (tracking) or carbon particles in oil (as in tap changer diverter operation); also, partial discharges of the sparking type, inducing pinhole, carbonized perforations (punctures) in paper, which, however, may not be easy to find;

–   discharges of high energy (D2), in oil or/and paper, with power follow-through, evidenced by extensive destruction and carbonization of paper, metal fusion at the discharge extremities, extensive carbonization in oil and, in some cases, tripping of the equipment, confirming the large current follow-through;

–   thermal faults, in oil or/and paper, below 300 °C if the paper has turned brownish (T1), and above 300 °C if it has carbonized (T2);

–   thermal faults of temperatures above 700 °C (T3) if there is strong evidence of carbonization of the oil, metal coloration (800 °C) or metal fusion (>1 000 °C).

Table 1 – Abbreviations

PD	Partial discharges
D1	Discharges of low energy
D2	Discharges of high energy
T1	Thermal fault, $t < 300$ °C
T2	Thermal fault, 300 °C $< t < 700$ °C
T3	Thermal fault, $t > 700$ °C

5.4   Basic gas ratios

Each of the six broad classes of faults leads to a characteristic pattern of hydrocarbon gas composition, which can be translated into a DGA interpretation table, such as the one recommended in Table 1 and based on the use of three basic gas ratios:

$$\frac{C_2H_2}{C_2H_4} \qquad\qquad \frac{CH_4}{H_2} \qquad\qquad \frac{C_2H_4}{C_2H_6}$$

Table 1 applies to all types of equipment, with a few differences in gas ratio limits depending on the specific type of equipment.

Table 1 – DGA interpretation table

Case	Characteristic fault	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$
PD	Partial discharges (see notes 3 and 4)	NS [a]	<0,1	<0,2
D1	Discharges of low energy	>1	0,1 – 0,5	>1
D2	Discharges of high energy	0,6 – 2,5	0,1 – 1	>2
T1	Thermal fault t <300 °C	NS [a]	>1 but NS [a]	<1
T2	Thermal fault 300 °C < t <700 °C	<0,1	>1	1 – 4
T3	Thermal fault t >700 °C	<0,2 [b]	>1	>4

NOTE 1 In some countries, the ratio C_2H_2/C_2H_6 is used, rather than the ratio CH_4/H_2. Also in some countries, slightly different ratio limits are used.

NOTE 2 – The above ratios are significant and should be calculated only if at least one of the gases is at a concentration and a rate of gas increase above typical values (see clause 9).

NOTE 2 Conditions for calculating gas ratios are indicated in 6.1 c).

NOTE 3 CH_4/H_2 <0,2 for partial discharges in instrument transformers. CH_4/H_2 <0,07 for partial discharges in bushings.

NOTE 4 Gas decomposition patterns similar to partial discharges have been reported as a result of the decomposition stray gassing of thin oil film between overheated core laminates at temperatures of 140 °C and above oil (see 4.3 and [1] of annex C).

[a] NS = Non-significant whatever the value.

[b] An increasing value of the amount of C_2H_2 may indicate that the hot spot temperature is higher than 1 000 °C.

Typical examples of faults in the various types of equipment (power transformers, instrument transformers, etc.), corresponding to the six cases of Table 1, may be found in Tables A.1, A.5, A.8 and A.12.

Some overlap between faults D1 and D2 is apparent in Table 1, meaning that a dual attribution of D1 or D2 must be given in some cases of DGA results. The distinction between D1 and D2 has been kept, however, as the amount of energy in the discharge may significantly increase the potential damage to the equipment and necessitate different preventive measures. Table 1 applies to transformers. For switching equipment see Clause A.7 and reference [8] in the bibliography.

NOTE Combinations of gas ratios that fall outside the range limits of Table 1 and do not correspond to a characteristic fault of this table may can be considered a mixture of faults, or new faults that combine with a high background gas level (see 6.1).

In such a case, Table 1 cannot provide a diagnosis, but the graphical representations given in Annex B may can be used to visualize which characteristic fault of Table 1 is closest to the case.

The less detailed scheme of Table 2 may can also be used in such a case in order to get at least a rough distinction between partial discharges (PD), discharges (D) and thermal fault (T), rather than no diagnosis at all.

Table 2 – Simplified scheme of interpretation

Case	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$
PD		<0,2	
D	>0,2		
T	<0,2		

5.5 CO_2/CO ratio

The formation of CO_2 and CO from oil-impregnated paper insulation increases rapidly with temperature. ~~Incremental (corrected)~~ High values of CO (e.g., 1 000 ppm) and CO_2/CO ratios less than 3 are generally considered as an indication of probable paper involvement in a fault, with ~~some degree of~~ possible carbonization, in the presence of other fault gases.

However, in some recent transformers of the closed-type or open (free breathing) transformers operating at constant load (i.e., with low breathing), CO can accumulate in the oil, leading to ratio $CO_2/CO < 3$, without any irregularities or faults if no other gases such as H_2 or hydrocarbons are formed [7].

High values of CO_2 (>10 000 ppm) and high CO_2/CO ratios (>10) can indicate mild (<160 °C) overheating of paper [6, 8] or oil oxidation, especially in open transformers. CO_2 can accumulate more rapidly than CO in open transformers operating at changing loads because of their different solubilities in oil. This, and the long term degradation with time of paper at low temperatures (<160 °C), can lead to higher CO_2/CO ratios in aged equipment.

In some cases, localized faults in paper do not produce significant amounts of CO and CO_2 and cannot be detected with these gases (the same for furanic compounds).

Involvement of faults in paper therefore shall not be based only on CO and CO_2, but shall be confirmed by the formation of other gases or other types of oil analysis.

In order to get reliable CO_2/CO ratios in the equipment, CO_2 and CO values should be corrected (incremented) first for possible CO_2 absorption from atmospheric air, and for the CO_2 and CO background values (see 6.1 and Clause 9), resulting from the ageing of cellulosic insulation, overheating of wooden blocks and the long term oxidation of oil (which will be strongly influenced by the availability of oxygen caused by specific equipment construction details and its way of operation).

Air-breathing equipment, for example saturated with approximately 9 % to 10 % of dissolved air, may contain up to 300 μl/l of CO_2 coming from the air. In sealed equipment, air is normally excluded but may enter through leaks, and CO_2 concentration will be in proportion of air present.

When excessive paper degradation is suspected ~~($CO_2/CO < 3$)~~, it is ~~advisable~~ recommended to ask for further analysis (e.g., of furanic compounds) or a measurement of the degree of polymerization of paper samples, when this is possible.

NOTE 1   In case of equipment containing negligible amounts of paper (e.g., most modern types of on load tap changers (OLTCs)) CO and CO_2 can increase with oil oxidation under thermal stress. CO_2/CO ratios can have values quite different from those in transformers.

NOTE 2   High levels of CO can also be formed in case of high energy discharges in oil only.

NOTE 3   In instrument transformers and some bushing types, low ratios <3 are observed without any paper degradation.

5.6 O_2/N_2 ratio

Dissolved O_2 and N_2 ~~may be~~ are found in oil as a result of contact with atmospheric air in the conservator of air-breathing equipment, or through leaks in sealed equipment. At equilibrium ~~taking into account~~ with air, the ~~relative solubilities~~ concentrations of O_2 and N_2 in oil are ~32 000 and ~64 000 ppm, respectively [8], and the O_2/N_2 ratio ~~in oil reflects air composition and~~ is ~0,5.

In service, this ratio may decrease as a result of oil oxidation and/or paper ageing, if O_2 is consumed more rapidly than it is replaced by diffusion. Factors such as the load and

preservation system used may also affect the ratio, but with the exception of closed systems, ratios less than 0,3 are generally considered to indicate excessive consumption of oxygen.

5.7 C_2H_2/H_2 ratio

In power transformers, on load tap changer (OLTC) operations produce gases corresponding to discharges of low energy (D1). If some oil or gas communication is possible between the OLTC compartment and the main tank, or between the respective conservators, these gases may contaminate the oil in the main tank and lead to wrong diagnoses. The pattern of gas decomposition in the OLTC, however, is quite specific and different from that of regular D1s in the main tank.

C_2H_2/H_2 ratios higher than 2 to 3 in the main tank are thus considered as an indication of OLTC contamination. This can be confirmed by comparing DGA results in the main tank, in the OLTC and in the conservators. The values of the gas ratio and of the acetylene concentration depend on the number of OLTC operations and on the way the contamination has occurred (through the oil or the gas).

NOTE If contamination by gases coming from the OLTC is suspected, interpretation of DGA results in the main tank should be made with caution by subtracting background contamination from the OLTC, or should be avoided as unreliable.

NOTE   Modern OLTCs are designed not to contaminate oil in the main tank.

5.8 C_3 hydrocarbons

The interpretation method of gas analysis indicated above takes into account only C_1 and C_2 hydrocarbons. Some practical interpretation methods also use the concentrations of C_3 hydrocarbons, and their authors believe that they are liable to bring complementary information that is useful to make the diagnosis more precise. Because the C_3 hydrocarbons are very soluble in oil, their concentrations are practically not affected by a possible diffusion into ambient air. Conversely, and because they are very soluble, they are difficult to extract from the oil and the result of the analysis may greatly depend on the extraction method used. Moreover, experience has shown that, in most cases, a satisfactory diagnosis can be made without taking into account these hydrocarbons and for the sake of simplification, they have been omitted from the interpretation method indicated above.

5.9   Evolution of faults

Faults often start as incipient faults of low energy, which may develop into more serious ones of higher energies, leading to possible gas alarms, breakdowns and failures.

When a fault is detected at an early stage of development, it may be quite informative to examine not only the increase in gas concentrations, but also the possible evolution with time toward a more dangerous high-energy fault of the final stage type resulting in failure.

For example, some current transformers have operated satisfactorily for long periods of time with very high levels of hydrogen produced by partial discharges. However, partial discharges may also cause the formation of X-wax. When the X-wax is present in sufficient quantity to increase the dissipation losses in the paper-oil insulation, a thermal fault may occur, eventually leading to catastrophic thermal runaway and breakdown.

In other occurrences, however, instant final breakdown may occur without warning.

5.10   Graphical representations

Graphical representations of gas ratios are convenient to follow this evolution of faults visually. Annex B gives examples of graphical representation of faults.

These representations are also useful in cases that do not receive a diagnosis using Table 1, because they fall outside the gas ratios limits. Using Figures B.1 or B.2, the zone or box that is closest to such an undiagnosed case can be easily visualized and attributed with caution to this case. Figure B.3 is particularly useful since it always provide a diagnosis in such cases.

6   Conditions for calculating ratios

6.1   Examination of DGA values

DGA sampling and analysis should be done in accordance with the recommendations of IEC 60567 and IEC 60475, respectively.

a) Values of 0 μl/l on a DGA report or below the analytical detection limits S shall be replaced by "below the S value for this gas" (see IEC 60567 for recommended S values).

b) If successive DGA analyses have been performed over a relatively short period of time (days or weeks), inconsistent variations (e.g. brutal large decreases of concentrations) may have to be eliminated as an indication of a sampling or analytical problem.

c) Gas ratios are significant and should be calculated only when at least one of the gases is at a concentration value is and a rate of gas increase above typical values and above typical rate of gas increase (see note 2 of table 2 and Clause 9). Nevertheless, it is recommended to also calculate them in cases where one or more gases show increasing or abnormal concentrations, even if they are lower than typical values. Avoid calculating ratios when gas concentrations are not high enough to be reasonably accurate according to IEC 60567.

d) If gas ratios are different from those for the previous analysis, a new fault may superimpose itself on an old one or normal ageing. In order to get only the gas ratios corresponding to the new fault, subtract the previous DGA values from the last ones and recalculate ratios. This is particularly true in the case of CO and CO_2 (see 5.4). Be sure to compare DGA values of samples taken at the same place and preferably in moving oil. Interpretation should also take into account treatments previously made on the equipment, such as repair, oil degassing or filtering, which may affect the level of gases in the oil.

NOTE   In the case of air-breathing power transformers, losses occur very slowly with time by diffusion through the conservator or as a result of oil expansion/temperature cycles, with the result that the measured gas levels may can be slightly less than the gas levels actually formed in the transformer. However, there is no agreement concerning the magnitude of this diffusion loss in service, some considering it as totally negligible, others as potentially significant, depending on the type of equipment used. In case of doubt, it may be expedient to measure the gas concentration in the conservator to get an idea of the volume ventilated. Significant diffusion losses may affect gas ratios, typical values of gas concentrations and of rates of gas increase. Typical values in open and closed transformers are relatively similar, suggesting that either gas loss in open transformers is lower than suspected, or that gas production is higher (because of higher oxygen availability) and compensated by higher gas loss. In any case, this has not been observed to significantly affect the identification of faults in open transformers.

6.2   Uncertainty on gas ratios

Because of the precision uncertainty on DGA values, there is also an uncertainty on gas ratios, which can be calculated using the precision uncertainty on DGA values described in IEC 60567.

Above 10 $\times$ S (S being the analytical detection limit), the uncertainty (precision and accuracy) is typically 5 $\pm$15 % on DGA values and up to 10 % this may also effect the uncertainty on gas ratios. Below 10 $\times$ S, the precision uncertainty on DGA values decreases increases rapidly, to typically 20 $\pm$30 % at 5 $\times$ S and up to 40 % on a gas ratio.

Caution should therefore be exercised when calculating gas ratios at low gas levels (lower than 10 $\times$ S), keeping in mind the possible variations resulting from the reduced precision higher uncertainty. This is particularly true for instrument transformers and bushings, where typical values of gas concentration may be below 10 $\times$ S.

7   Application to free gases in gas relays

During a fault, the production rate of gases of all types is closely linked to the rate of energy liberation. Thus, the low rate of energy liberation in partial discharges, or in a low-temperature ~~hot spot~~ thermal fault, will cause gases to evolve slowly and there is every probability that all the gas produced will dissolve in the oil. The higher rate of energy liberation of a high-temperature core fault, for example, can cause an evolution of gas rapid enough to result in gas bubbles. These will usually partially dissolve in the oil (and exchange with gases already dissolved) but some gas may well reach the gas collecting relay or gas cushion; this gas may approach equilibrium with the gases dissolved in the oil.

A very high rate of energy liberation associated with a power arcing fault causes a rapid and substantial evolution of gas (the resulting pressure surge normally operates the surge element of the gas collecting relay). The large gas bubbles rise quickly to the relay and exchange little gas with the oil so that the gas that collects in the relay is initially far from being in equilibrium with the gases dissolved in the oil. However, if this gas is left for a long time in the relay, some constituents will dissolve, modifying the composition of the gas collected. Acetylene, which is produced in significant quantities by an arcing fault, and which is very soluble, is a noteworthy example of a gas that may dissolve comparatively quickly to produce misleading results.

In principle, the analysis of free gases from a gas-collecting relay or from a gas cushion may be evaluated in the same way as the analysis of gases dissolved in the oil. However, where the surge element has operated and gas has accumulated in substantial quantities, there is a possibility of having a serious fault, and analyses of the gases should be undertaken to identify the fault. ~~Buchholz alarms due to air accumulation are also possible following a combination of warm days and sudden temperature drops at night.~~ If the rate of gas production is low, gases formed will usually dissolve entirely in oil. If it is high, or if the oil is over-saturated with gas, gas bubbles will rise rapidly in the oil and accumulate in the gas relay. The less soluble gases in bubbles (H_2, CO and CH_4) will not have time to dissolve in oil during their ascent and will be over-represented in the top oil of the tank and the gas relay, resulting in wrong fault identification.

After a Buchholz alarm, it is ~~therefore important~~ recommended to collect the gas at the relay as soon as possible ~~without burning it,~~ and sample the oil in the relay and in the top and bottom oil of the main tank. This will allow first to verify that the alarm is indeed due to a fault in the transformer and not to air accumulation following a combination of warm days and sudden temperature drops at night, or because of faults in oil pumps.

Where gas has accumulated slowly (e.g., as a result of coking of selector contacts or of core overheating), assessment of the gases dissolved in the oil is more informative than that of the free gases; this gas-in-oil analysis is also essential in order to determine the total rate of evolution of gases and thus check whether the fault is growing, which is the most important matter to investigate. When analysis of free gases is undertaken, it is necessary to convert the concentrations of the various gases in the free state into equivalent concentrations in the dissolved state, using Table 3, before applying the gas ratio method of Table 1, and to compare them to the dissolved gas concentrations in the oil of the relay and the main tank.

Applying the principles set out above, comparison of the actual concentrations in the oil with the equivalent concentrations in the free gas may give valuable information on how far gas bubbles may have risen through the oil and, hence, on the rate of gas evolution.

The calculation of dissolved gas concentrations equivalent to free gas concentrations is made by applying the Ostwald solubility coefficient for each gas separately. For a particular gas, the Ostwald solubility coefficient k is defined as follows:

$$k = \frac{\text{concentration of gas in liquid phase}}{\text{concentration of gas in gas phase}}$$

with concentrations in microlitres per litre.

~~The Ostwald coefficients for various gases in mineral insulating oils at 20 °C and 50 °C are given in table 4.~~

Table 3 contains the Ostwald solubility coefficients of various gases in mineral insulating oils as given in IEC 60567:2011, Table A.1.

Table 3 – Ostwald solubility coefficients for various gases in mineral insulating oils

Gas	k at ~~20~~ 25 °C	~~k at 50 °C~~
N_2	~~0,09~~ 0,091	~~0,09~~
O_2	~~0,17~~ 0,172	~~0,17~~
H_2	~~0,05~~ 0,056	~~0,05~~
CO	~~0,12~~ 0,132	~~0,12~~
CO_2	~~1,08~~ 1,09	~~1,00~~
CH_4	~~0,43~~ 0,429	~~0,40~~
C_2H_6	~~2,40~~ 2,82	~~1,80~~
C_2H_4	~~1,70~~ 1,84	~~1,40~~
C_2H_2	~~1,20~~ 1,24	~~0,9~~

~~NOTE~~ Data given in this table represent mean values obtained on some of the current types of transformer mineral insulating oils. Actual data may differ a little from these figures. Nevertheless, data given above may be used without influencing conclusions drawn from recalculated test results.

The Ostwald solubility coefficient is independent of the actual partial pressures of the gas concerned. The gas and liquid phases are assumed to be at the same temperature; this is rarely the case but the error introduced by any difference will not invalidate the conclusions reached.

If only free gas in the relay is analysed, gas content in oil of the relay at equilibrium may be calculated using the above equation and Ostwald solubility coefficients k for each gas given in Table 3.

When gas accumulates in the gas relay, collect and analyse as soon as possible the free gases in the relay, convert into gases in the relay oil, using k, then compare to gases in oil in the main tank. If results are comparable, this indicates equilibrium has been reached and gas has accumulated slowly. If they do not compare, this indicates that equilibrium has not been reached and gas has accumulated rapidly.

8   Gas concentration levels in service

8.1   Probability of failure in service

8.1.1   General

The probability or risk of having an incident or a failure in service is related to gas concentration levels and rates of gas formation [8].

Below certain concentration levels (quoted as typical values or normal values), the probability of having a failure is low (typically 10 % according to CIGRE [6] when using oil sampling). The equipment is considered healthy, although a failure cannot be totally ruled out, even at these

low levels, but it is improbable. A first rough screening between healthy and suspect analyses can therefore be obtained by calculating typical values for the equipment.

The probability of having a failure may increase significantly at values much above typical concentration levels. The situation is then considered critical, for even though a failure may never occur at these high levels, the risk of having one is high. For detecting such failures may be divided into two categories, see [9] in the bibliography.

– failures that develop within a very short time (which are therefore impossible to detect by oil sampling/laboratory analysis, but only by on-line detectors);

– failures developing over an extended time span. Only this second category may be detected by DGA laboratory analysis.

8.1.2 Calculation methods

Utilities with large DGA and equipment maintenance databases are able to calculate the probability of failure in service for a given type of equipment and at a given concentration level of a gas. This can be obtained by calculating the number of DGA analyses that have led to an actual failure or incident in service (gas alarm, failure, repair, outage, etc.), and comparing it to the total number of DGA analyses on this type of equipment and at this gas concentration level.

A large number of analyses is necessary to get reliable values of failure probability. Knowledge of these values, however, is useful when choosing the normality percentage most appropriate for a given network and type of equipment (see 8.2.3). Pre-failure values have thus been proposed by CIGRE [6, 8], above which the probability of failure increases very rapidly.

8.2 Typical concentration values

8.2.1 General

Typical concentration values are the acceptable gas quantities below which field experience shows no detectable or possible incipient fault, and that are overpassed exceeded by only an arbitrarily low percentage of higher gas contents, for example 10 %. Typical concentration values will be referred to in such an example as the 90 % typical values. This allows concentrating maintenance efforts on the 10 % of transformers most at risk.

However, typical concentration values are preferably to be considered as initial guidelines for decision making, when no other experience is available. They shall not be used to ascertain whether or not a fault exists within the equipment. They should be viewed as values above which the rate of gas formation may permit the detection of a probable fault.

Typical concentration values are affected by a number of factors, chiefly the operating time since commissioning, the type of equipment and the nature of the fault (electrical or thermal). For power transformers, the type of oil protection, load factor and operation mode are other influencing factors.

Typical concentration values may be calculated as follows and should preferably be obtained by the equipment users on the specific types of equipment.

8.2.2 Calculation methods

The simplest method of calculation consists in gathering all the DGA results concerning a specific type of equipment. For each characteristic gas considered, the cumulative number of DGA analyses where the gas concentration is below a given value is calculated, then plotted as a function of gas concentration. Using the plotted curve, the gas concentration corresponding to a given percentage of the total cumulative number of analyses (for instance 90 %) is the 90 % typical concentration value for that gas and type of equipment.

8.2.3 Choice of normality percentages

If the normality percentage chosen (e.g. 90 %, 95 % or other) is too low, suspicion will be placed on too many pieces of equipment, with a loss of credibility in the diagnosis and recommendations, and an increase in maintenance costs. If the normality percentage is chosen too high, failure may occur without advance warning, also involving considerable costs.

The choice of a normality percentage is often an educated guess, left to the experience of the user of similar equipment. A certain amount of leeway in the choice of a normality percentage is also provided by considering the probability of failure and the actual failure rate of the equipment in service. In the absence of such information or experience, users may choose conservative normality percentages such as 90 % as a rough screening value. Most organizations worldwide (IEC, IEEE) use a normality percentage of 90 % for typical values. However, other percentages can also be used.

If adequate databases are not available to calculate typical values, users may also adopt as a first step, values observed on other networks and indicated in the application notes. It is apparent from these values that, in general, typical values are lower in instrument transformers and bushings than in power transformers, especially those with a communicating OLTC.

8.2.4 Alarm concentration values

Alarm concentration values are those values of concentration above which the probability of an incident is sufficiently high to require urgent competent decisions and/or actions. Pre-failure concentration values have thus been proposed by CIGRE [8], and more recently as a function of type and location of faults [10].

Alarm concentration values should be set by users, manufacturers or independent experts, based on previous experience with equipment with similar characteristics (voltage, type, manufacturer, loading practices, age, etc.).

8.3 Rates of gas increase

If there is no increase in gas concentration over the last analysis, chances are that the fault has disappeared (or that a very small one is still there, in the case of air-breathing equipment, compensated by diffusion losses through the conservator (see 6.1).

What should be considered as a typical or alarm rate of gas increase depends very much on equipment type and age, type of identified faults, air-breathing and load patterns, and volume of the insulation involved. Ultimately the rate of increase should be decided by the user of the equipment, the manufacturer and/or other experts.

An increase in gas concentrations of more than 10 % per month above typical concentration values is generally considered a prerequisite for pronouncing the fault as active, provided it is clear that the precision on DGA values is better than 10 % after one month. Much higher rates of gas increase, such as 50 % per week, and/or evolving towards faults of higher energy (e.g. D2 or T3), are generally considered very serious, especially if they exceed alarm concentration values. In the case of power transformers, typical rates of gas production in millilitres per day are also reported (see table A.3). Special attention should be given to cases where there is an acceleration in the rate of gas increase.

NOTE – In the case of carbon oxides, rates of gas increase are dependent on the oil-to-paper ratio, which may be quite different depending on the equipment considered.

Typical rates of gas increase can be calculated as in the case of typical gas concentrations and are indicated in Table A.3. Pre-failure rates of increase have also been proposed by CIGRE [8].

On-line gas detectors monitors, including those already available for hydrogen, may be particularly well-suited for detecting non-typical rates of gas increase occurring within minutes,

hours or weeks, which is generally not possible with routine oil samplings done at monthly or yearly intervals [9]. However, when such increases are detected by a gas ~~detector~~ monitor, complete DGA analyses shall be made at the laboratory to confirm the ~~detector~~ monitor readings~~, evaluate the rates of increase of the various gases and identify the fault~~.

9 Recommended method of DGA interpretation (see Figure 1)

The procedure shall be as follows:

a) Reject or correct inconsistent DGA values (see 6.1). Calculate the rate of gas increase since the last analysis, taking into account the precision on DGA results.

   If all gases are below typical values of gas concentrations and rates of gas increase, report as "Normal DGA/healthy equipment".

   If at least one gas is above typical values of gas concentrations and rates of gas increase, calculate gas ratios and identify fault using Table 1 (see 5.4). Check for eventual erroneous diagnosis (see 4.3).

   If necessary subtract last values from present ones before calculating ratios, particularly in the case of CO, CO_2 (see 6.1).

   If DGA values are above typical values but below 10 × S (S = analytical detection limit), see 6.2.

b) Determine if gas concentrations and rates of gas increase are above alarm values. Verify if fault is evolving towards final stage (see 5.9). Determine if paper is involved (see 4.2 and 5.5).

c) Take proper action according to best engineering judgment and/or with the help of Figure 1.

   It is recommended to:

   1) increase sampling frequency (quarterly, monthly or other) when the gas concentrations and their rates of increase exceed typical values;

   2) consider performing complementary tests (acoustic, electrical, infrared) or reduce loading;

   3) consider removing the transformer from service for inspection or repair depending on results of complementary and other tests and on advice of transformer experts;

   4) consider immediate action when gas concentrations and rates of gas increase exceed alarm values.

10 Report of results

~~NOTE~~ The report should be adapted to the specific type of equipment considered.

The DGA interpretation report should include the following, when available:

a) ~~DGA~~ analysis report, including S values, method of ~~DGA~~ analysis (see IEC 60567:2011, Table A.1) and date of analysis.

   NOTE   Values of 0 ppm or µl/l on a DGA report or below the S values are replaced by "below the S value for this gas".

b) specific information on the equipment such as:

   1) date of commissioning, voltage, general type (e.g. power or instrument transformer), rated power;

   2) special features (e.g. sealed or air-breathing, type of OLTC (see A.2.1);

   3) oil volume;

   4) oil or gas sampling date;

   5) oil or gas sampling location;

c) special operations or incidents just before ~~and after~~ the oil or gas sampling, such as tripping, gas alarm, degassing, repair, outage;

d) previous DGA on the equipment;

e) indication of typical values for this specific equipment, if known;

f) indication of "Typical DGA/healthy equipment" or "Fault";

g) in case of "Fault", identification of the fault using Table 1 (see 5.4), with values of the calculated gas ratios indicated;

h) indication of paper involvement or not, with value of the CO_2/CO ratio or other methods (see 5.5);

i) recommended actions: (see 9.c)

   1) ~~new frequency of oil sampling,~~

   2) ~~furanic compound analysis if CO₂/CO ratio is lower than 3,~~

   3) ~~other tests.~~
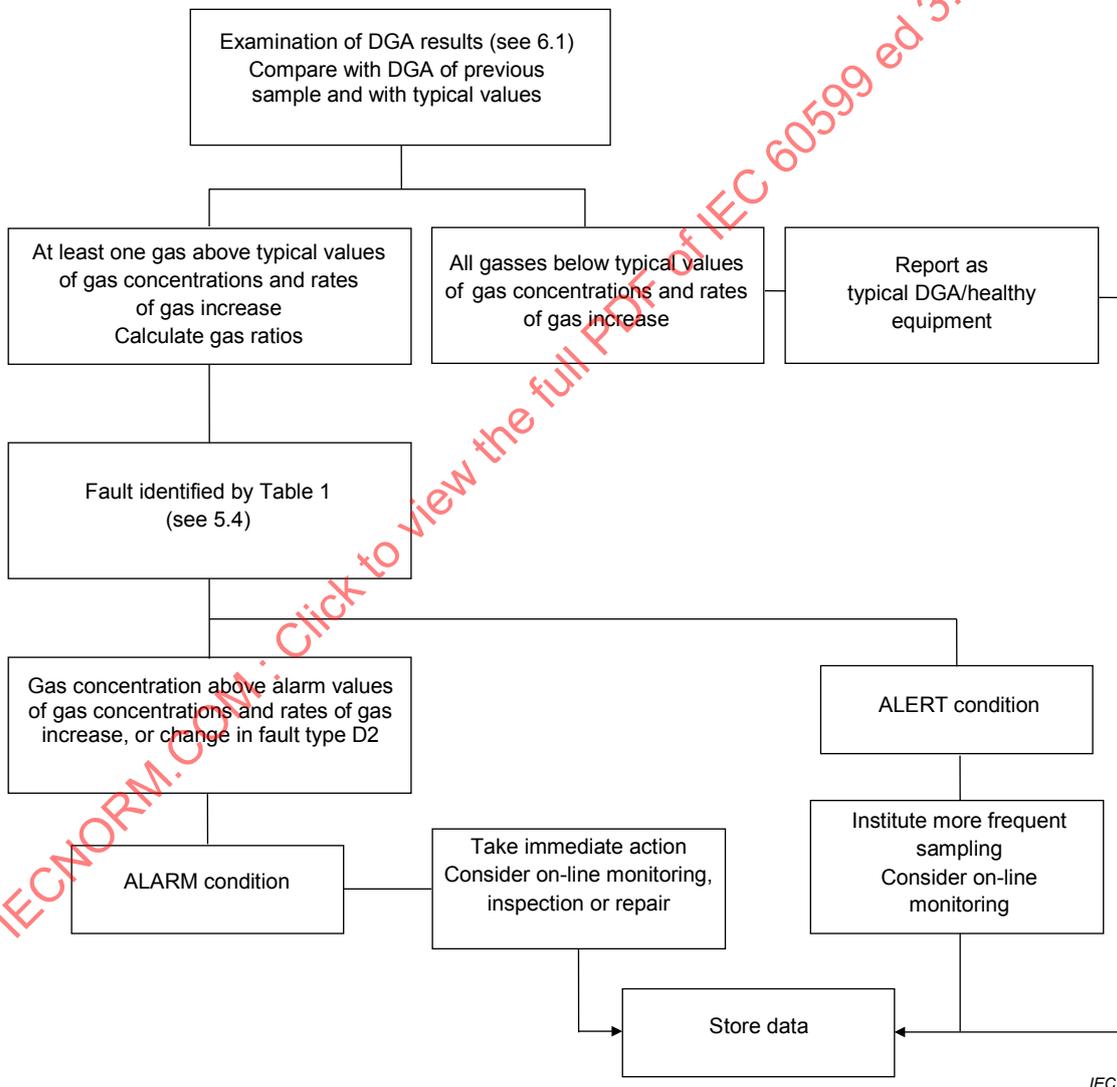
Figure 1 – Flow chart

~~NOTE – For power transformers, see also A.1.5.~~

Annex A
(informative)

Equipment application notes

A.1   General warning

WARNING: Typical concentration values given in these application notes are average values for various types of equipment. They only provide indications on the ranges of values usually observed in the equipment.

Individual users may get different typical values, depending on their specific equipment, manufacturing designs and load practices. They are urged to calculate their own values, following methods outlined in clause 8.

The values indicated in the present application notes should be consulted only in the absence of more precise in-house data from the user and should never be used in a contract without a special agreement between the parties. Thorough engineering judgment should be exercised in all cases.

The typical concentration values given in the tables are not limiting values. If the values are exceeded it is an indication that further routine DGA analyses should be undertaken with shorter intervals between samples to monitor any trends in the increase of gas produced and to provide further diagnostic information.

"Limit values" of gas concentrations and rates of gas increase in service are not the responsibility of TC10 but of IEC equipment committees.

"Typical values" in the following application notes **are not limit values**. They are given for information only, as a maintenance and predictive tool. In a given transformer population, they indicate for example that 90 % of DGA values in service are below the 90 % typical values and 10 % are above. When typical values are exceeded, the only action recommended in this standard is to increase the frequency of DGA analyses.

Typical values depend on several parameters (age, type and manufacturer of equipment, operating and loading practices, climate, etc.), and are not exactly the same for all electrical networks. Ranges of typical values are therefore indicated in the following application notes, covering the different individual values observed worldwide and surveyed by IEC and CIGRE.

Individual networks are strongly encouraged to calculate the typical values corresponding to their own specific transformer population, using DGA data meeting IEC 60567 specifications for accuracy and following methods indicated in Clause 8 and [6].

The ranges of typical values indicated in these application notes should be used only by default, when individual values are not available, and should not be used in a contract without a special agreement between the user and manufacturer of the equipment.

A.2   Power transformers

Values given in clause A.1 have been proposed by IEC technical committee 10. They will be reviewed by a Joint Working Group between IEC technical committees 10 and 14: Power transformers.

A.2.1   Specific sub-types

Specific sub-types of power transformers are as follows:

– air-breathing (open conservator type);

– sealed or nitrogen-blanketed;

– inter-tie transmission versus generation step-up;

– no OLTC communicating with main tank versus communicating OLTC;

– core-type or shell-type;

– reactors.

A.2.2 Typical faults

See Table A.1.

Table A.1 – Typical faults in power transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from incomplete impregnation, high-humidity in paper, oil super saturation or cavitation, and leading to X-wax formation
D1	Discharges of low energy	Sparking or arcing between bad connections of different or floating potential, from shielding rings, toroids, adjacent disks or conductors of winding, broken brazing or closed loops in the core
		Discharges between clamping parts, bushing and tank, high voltage and ground within windings, on tank walls
		Tracking in wooden blocks, glue of insulating beam, winding spacers. Breakdown of oil, selector breaking current
D2	Discharges of high energy	Flashover, tracking, or arcing of high local energy or with power follow-through
		Short circuits between low voltage and ground, connectors, windings, bushings and tank, copper bus and tank, windings and core, in oil duct, turret. Closed loops between two adjacent conductors around the main magnetic flux, insulated bolts of core, metal rings holding core legs
T1	Thermal fault $t < 300\,°C$	Overloading of the transformer in emergency situations
		Blocked item restricting oil flow in windings
		Stray flux in clamping beams of yokes
T2	Thermal fault $300\,°C < t < 700\,°C$	Defective contacts between bolted connections (particularly between aluminium busbar), gliding contacts, contacts within selector switch (pyrolitic carbon formation), connections from cable and draw-rod of bushings
		Circulating currents between yoke clamps and bolts, clamps and laminations, in ground wiring, defective welds or clamps in magnetic shields
		Abraded insulation between adjacent parallel conductors in windings
T3	Thermal fault $t > 700\,°C$	Large circulating currents in tank and core
		Minor circulation currents in tank walls created by a high uncompensated magnetic field
		Shorting links in core steel laminations

A.2.3 Identification of faults by DGA

Table 1 (see 5.4) applies directly to all transformer sub-types, except those equipped with a communicating OLTC. In the latter cases, if C_2H_2/H_2 is higher than 2 to 3, there ~~is~~ may be contamination from the OLTC into the main tank, in which case Table 1 does not apply or applies with care, after subtracting background contamination from the OLTC (see 5.7).

~~NOTE 1~~ Any gas formation below typical values of gas concentration and rates of gas increase should not be considered as an indication of "fault", but rather as "normal gas formation". Ratios are not significant in such a case (see Note 2 of Table 1).

NOTE 2 In the case of air-breathing power transformers, losses of gas occur very slowly with time by diffusion through the conservator or as a result of oil expansion cycles, with the result that the measured gas levels may be slightly less than the gas levels actually formed in the transformer. However, there is no agreement concerning the magnitude of this diffusion loss in service, some considering it as totally negligible, others as potentially significant, depending on the type of equipment considered. In case of doubt, to get an idea of the volume ventilated it may be expedient to measure the gas concentration in the conservator as well. Significant diffusion losses may affect gas ratios, typical values of gas concentrations and rates of gas increase (see 6.1).

A.2.4   Typical concentration values

Important note: Clause A.1: General warning, shall be consulted before using A.2.4.

Ranges of 90 % typical gas concentration values observed in power transformers, from more than 15 individual about 25 electrical networks worldwide and including more than 15 000 20 000 transformers, are given in Table A.2.

These levels are influenced mostly by equipment sub-type, fault type and age. Typical values, for example, are usually higher in sealed transformers than in air-breathing transformers of the same type. All types of influence factors and sub-types given in A.1.1 are included in table A.2.

The 90 % normality percentage is the most frequently used. However, this percentage depends on the characteristics of the transformer population.

The values given in table A.2 are for information only.

For hydrogen, for example, one network reported a typical value of 50 μl/l, another one 150 μl/l and the 23 others reported values between 50 μl/l and 150 μl/l. These ranges of values have been reported by CIGRE SC D1 and A2 (TF11) and approved by IEC TC 10 and TC 14.

Table A.2 – Ranges of 90 % typical gas concentration values observed in power transformers (all types), in μl/l

Values in microlitres per litre

Transformer sub-type	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
No OLTC	60-150	540-900	5 100-13 000	40-110	50-90	60-280	3-50
Communicating OLTC	75-150	400-850	5 300-12 000	35-130	50-70	110-250	80-270

NOTE 1 – The values listed in this table were obtained from individual networks. Values on other networks may differ.

NOTE 2 – "Communicating OLTC" means that some oil and/or gas communication is possible between the OLTC compartment and the main tank or between the respective conservators. These gases may contaminate the oil in the main tank and affect the normal values in these types of equipment. "No OLTC" refers to transformers not equipped with an OLTC, or equipped with an OLTC not communicating with or leaking to the main tank.

NOTE 3 – In some countries, typical values as low as 0,5 μl/l for C_2H_2 and 10 μl/l for C_2H_4 have been reported.

	C$_2$H$_2$	H$_2$	CH$_4$	C$_2$H$_4$	C$_2$H$_6$	CO	CO$_2$
All transformers		50 – 150	30 – 130	60 – 280	20 – 90	400 – 600	3 800 – 14 000
No OLTC	2 – 20						
Communicating OLTC	60 – 280						

"Communicating OLTC" in Tables A.2 and A.3 means that some oil and/or gas communication is possible between the OLTC compartment and the main tank or between the respective conservators. Gases produced in the OLTC compartment may contaminate the oil in the main tank and affect concentration values in these types of equipment. "No OLTC" refers to transformers not equipped with an OLTC, or equipped with a tap changer not communicating with or leaking to the main tank.

Typical values in Table A.2 apply to both breathing and sealed transformers, and correspond mostly to core-type transformers. Values in shell-type transformers are likely to be higher. In two countries, values for C$_2$H$_6$ are higher. In one country where transformers are operated below nominal load, values for CH$_4$ and CO and particularly for C$_2$H$_4$ are lower. In one country, values of 0,5 μl/l for C$_2$H$_2$ and 10 μl/l for C$_2$H$_4$ are reported. Values for H$_2$ may be higher in transformers where reactions between oil and transformer components (paints, metals) are occurring. Values in transformers frequently degassed, a practice used in a few countries, should not be compared with values of Table A.2.

A.2.5 Typical rates of gas increase

Rates of gas increase in millilitres per day, as compared to rates of gas concentration increase in percent per month (see 8.4), are believed to be more closely related to the size and severity of the fault, and not to be affected by the oil volume of the transformer.

However, these rates necessitate knowledge of the oil volume, which is not always possible.

What should be considered as typical rates of gas increase depends very much on equipment type and age, type of the identified faults, air-breathing and load patterns, and the volume of insulation involved. They should be ultimately decided by the user of the equipment, the manufacturer and/or other experts.

Experience has shown that the rates in table A.3 indicate a typical behaviour of air-breathing equipment.

The values given in table A.3 are for information only.

Table A.3 – Typical rates of gas increase for power transformers

Values in millilitres per day

Hydrogen	<5
Methane	<2
Ethane	<2
Ethylene	<2
Acetylene	<0,1
Carbon monoxide	<50
Carbon dioxide	<200
NOTE – The values listed in this table were obtained from individual networks. Values on other networks may differ. Values on other types of transformers, for instance sealed transformers, may also differ.	

~~Equation to calculate the rate of gas increase:~~

$$rate = \frac{(y_2 - y_1)\, m}{\rho\,(d_2 - d_1)} \; ml/day$$

~~where~~

~~y_1 is the reference analysis;~~

~~y_2 is the last analysis;~~

~~(y_2-y_1) is the increase, in microlitre per litre;~~

~~m is the mass of oil, in kilograms;~~

~~ρ is the mass density, in kilograms per cubic metre;~~

~~d_1 is the date for y_1;~~

~~d_2 is the date for y_2.~~

~~NOTE – Some users prefer typical rates of gas increase expressed in microlitres per litre per month or in per cent per month.~~

Important note: Clause A.1: General warning, shall be consulted before using A.2.5.

Ranges of 90 % typical rates of gas increase observed in power transformers, from four electrical networks and including more than 20 000 DGA analyses, are given in Table A.3. These ranges of values have been reported by CIGRE SC D1 and A2 (TF11) and approved by IEC/TC 10 and TC 14.

**Table A.3 – Ranges of 90 % typical rates of gas increase
observed in power transformers (all types), in μl/l/year**

	C_2H_2	H_2	CH_4	C_2H_4	C_2H_6	CO	CO_2
All transformers		35 – 132	10 – 120	32 – 146	5 – 90	260 – 1 060	1 700 -10 000
No OLTC	0 – 4						
Communicating OLTC	21 – 37						

Typical values in Table A.3 are valid for large power transformers with an oil volume >5 000 l. Values in small transformers (<5 000 l) are usually lower. Values in the early and late years of the equipment tend to be higher than the average values of Table A.3.

Values of Table A.3 may be converted into ml/day when the transformer oil volume is known. In some countries, it is preferred to express rates of gas increase in ml/day. Values in Table A.3 should not be used to calculate concentration values after several years and compare them to values in Table A.2, since values in these two tables are affected differently by the shape of their respective cumulative curves and gas losses.

When calculating typical rates of increase of individual networks, intervals should be chosen to provide an acceptable accuracy of results.

A.2.6   Specific information to be added to the DGA report (see Clause 10)

Specific information to be added to the DGA report is as follows:

– power rating;

– transformer sub-type: air-breathing or sealed;

– ~~top~~ oil temperature;

– type of cooling system: ONAN (oil natural air natural), OFAF (oil forced air forced), etc.;

– ~~hours of service;~~

- date of manufacturing;
- type of OLTC ~~(and whether it is~~ communicating with the main tank or not~~)~~;
- number of OLTC operations, if known;
- load since last DGA.

NOTE   OLTCs are often composed of a selector switch, located in the oil of the main tank, and of a diverter switch, located in a separate tank but on the same operating axle.

A.3   Industrial and special transformers

A.3.1   Specific sub-types

Specific sub-types of industrial and special transformers are as follows:

- furnace transformers;
- rectifier transformers;
- railway transformers;
- distribution transformers ~~(only industrial and service transformers,~~ below 10 MVA, not from utilities~~)~~;
- submersible distribution transformers;
- wind farm transformers.

A.3.2   Typical faults

See Table A.1.

A.3.3   Identification of faults by DGA.

See A.2.3.

A.3.4   Typical concentration values

See Table A.4.

The values given in table A.4 are for information only.

**Table A.4 – Examples of 90 % typical concentration
values observed on ~~a typical~~ individual network~~s (all types of transformers)~~**

Values in microlitres per litre

Transformer sub-type	H$_2$	CO	CO$_2$	CH$_4$	C$_2$H$_6$	C$_2$H$_4$	C$_2$H$_2$
Furnace [a]	200	800	6 000	150	150	200	[a]
Distribution	100	200	5 000	50	50	50	5
Submersible	86	628	6 295	21	4	6	<S [b]

NOTE   The values listed in this table were obtained from ~~one particular~~ two individual networks. Values on other networks may differ.

[a]   The data are influenced by the design and assembly of the on-load tap changer. For this reason, no statistically significant value can be proposed for acetylene.

[b]   < S means less than the detection limit.

A.4 Instrument transformers

A.4.1 Specific sub-types

CT: Current transformers (eyebolt or hairpin design)

VT: Voltage transformers

CTCV: Combined transformers (current-voltage)

CIVT: Cascade (inductive) voltage transformers

CVT: Capacitor voltage transformers

MVT: Magnetic voltage transformers (see [2]).

NOTE   Definitions of these specific sub-types can be found in [5].

A.4.2 Typical faults

See table A.5.

Failure rates have been reported as being about 1 % of the total population (see [2]), although much higher rates were observed on a limited number of sub-groups.

The most frequent final failures involve local or catastrophic dielectric breakdown of paper insulation, following lengthy partial discharge activity and/or thermal runaways.

Table A.5 – Typical faults in instrument transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from poor impregnation, humidity in paper, oil supersaturation, puckers or folds in paper, leading to X-wax deposition and increased dielectric losses
		Discharges related to switching operations from a nearby substation bus system (in the case of CTs) or to overvoltages at the edges of capacitor unit sections (case of CVTs)
D1	Discharges of low energy	Sparking around loose connections or floating metal strips
		Tracking in paper
		Arcing in static shielding connections
D2	Discharges of high energy	Local short circuits between capacitive stress grading foils, with high local current densities able to melt down foils
		General short circuits with power follow-through are often destructive, resulting in equipment breakage or explosion, and a DGA is not always possible after failure
T2	Thermal fault 300 °C < t < 700 °C	Circulating currents in paper insulation resulting from high dielectric losses, related to X-wax contamination, moisture or incorrect selection of insulating materials, and resulting in dielectric heating and thermal runaways
		Bad contacts in connections or welds
		Overheating due to the ferroresonant circuit in MVTs
T3	Thermal fault t > 700 °C	Circulating currents on steel lamination edges

A.4.3 Identification of faults by DGA

Table 1 (see 5.4) applies to all sub-types, with CH_4/H_2 lower than 0,2 instead of lower than 0,1 for partial discharges.

A.4.4   Typical concentration values

Ranges of 90 % typical values observed in instrument transformers are given in Table A.6. The 90 % normality percentage is the most frequently used. Factors of influence are equipment sub-type, fault type, and age.

The values given in Table A.6 are for information only.

Table A.6 – Ranges of 90 % typical concentration values observed in instrument transformers

Values in microlitres per litre

Transformer sub-type	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
CT	6 – 300	250 – 1 100	800 – 4 000	11 – 120	7 – 130	3 – 40	1 – 5
VT	70 – 1 000					20 – 30	4 – 16

NOTE 1   The values listed in this table were obtained from ~~one particular~~ several networks. Values on other networks ~~may~~ can differ.

NOTE 2   The value for H_2 in CTs is much lower for rubber ~~sealings~~ seals (±20 µl/l) than for metal ~~sealings~~ seals (±300 µl/l).

Table A.7 provides the maximum admissible values for sealed instrument transformers without any action to be taken on the transformer, which have been proposed by IEC TC 38:

Table A.7 – Maximum admissible values for sealed instrument transformers

Values in microlitres per litre

H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
300	300	900	30	50	10	2

A.5   Bushings

A.5.1   Specific sub-types

Specific sub-types of bushings are as follows:

– condenser type;
– non-condenser type.

A.5.2   Typical faults

See Table A.8.

In a number of instances, partial discharges result in increased dielectric losses, thermal runaway and final breakdown.

Most frequent final failures are related to the breakdown of core insulation between short-circuited layers (as a result of partial discharges or thermal runaway), flashovers along the internal surface of the porcelain (often resulting in explosions) and flashovers along the core surface.

Table A.8 – Typical faults in bushings

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from humidity in paper, poor impregnation, oil supersaturation or contamination, or X-wax deposition. Also in loose insulating paper displaced during transportation with puckers or folds in paper
D1	Discharges of low energy	Sparking around loose connections at capacitive tap Arcing in static shielding connections Tracking in paper
D2	Discharges of high energy	Localized short-circuits between capacitive stress grading foils, with high local current densities able to melt down foils (see definition of D2 in 5.3), but not leading to the explosion of the bushing
T2	Thermal fault 300 °C < t < 700 °C	Circulating currents in paper insulation resulting from high dielectric losses, related to contamination or improper selection of insulating materials, and resulting in thermal runaways Circulating currents in poor connections at bushing shield or high voltage lead, with the temperature transmitted inside the bushing through conduction by the conductor

A.5.3 Identification of faults by DGA

A simplified table of interpretation is proposed as shown in Table A.9.

Table A.9 – Simplified interpretation scheme for bushings

Fault	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$	$\dfrac{CO_2}{CO}$
PD		<0,07		
D	>1			
T			>1	
TP				<1, >20

NOTE – PD = partial discharges
    D = discharges
    T = thermal fault
    TP = thermal fault in paper

In cases where a single characteristic fault cannot be attributed using this simplified table, or when a more precise diagnosis is required, the general Table 1 should be used.

NOTE Some modern bushings contain mixtures of mineral oil and dodecylbenzene (DDB), in proportions not known. Gas compositions evolved from DDB are not the same as from mineral oil, and DDB absorbs more gas than mineral oil.

A.5.4 Typical concentration values

The following 95 % typical values are proposed.

The values given in Table A.10 are for information only.

Table A.10 – 95 % typical concentration values in bushings

Values in microlitres per litre

H$_2$	CO	CO$_2$	CH$_4$	C$_2$H$_6$	C$_2$H$_4$	C$_2$H$_2$
140	1 000	3 400	40	70	30	2

A.6 Oil-filled cables

A.6.1 Typical faults

Discharges and hot spots at cable terminations or junctions.

A.6.2 Identification of faults by DGA

Table 1 applies.

DGA is difficult to apply in cables due to the lack of representative oil samples (sampling sometimes possible only a long distance from the fault; lack of oil convection; gas trapped in paper insulation).

Also, modern cables often contain mixtures of mineral oil and dodecylbenzene (DDB), in proportions not known. Gas compositions evolved from DDB are not the same as from mineral oil, and DDB absorbs more gas than mineral oil under electric stress.

A.6.3 Typical concentration values

The values given in Table A.11 are for information only.

The data are coming from one particular network and only 95% values are available. The following 95 % typical concentration values have been observed on cables.

Table A.11 – Ranges of 95 % typical concentration values observed on cables

Values in microlitres per litre

H$_2$	CO	CO$_2$	CH$_4$	C$_2$H$_6$	C$_2$H$_4$	C$_2$H$_2$
150 – 500	40 – 100	220 – 500	5 – 30	10 – 25	3 – 20	2 – 10
NOTE These values are examples taken from one particular network. Values on other networks and with different types of cable designs may differ.						

A.7 Switching equipment

A.7.1 Specific sub-types

Specific sub-types of switching equipment are as follows:

– on-load tap-changers (OLTC) (vacuum and non-vacuum), including selector switches;

– switchgear.

A.7.2 Normal operation

The large majority of non-vacuum on-load tap-changers (OLTCs) of the reactive or resistive type produce gases of the arcing type D1 or D2 during their normal operation, because of the

arc-breaking-in-oil activity on the switching contacts. Change-over selector contacts or commutation contacts of vacuum type models can produce low amounts of D1 gases.

Some vacuum or non-vacuum resistive type models can produce T2 or T3 gas patterns, respectively under certain load conditions, not indicating any thermal irregularities.

A.7.3   Typical faults

See Table A.12.

Table A.12 – Typical faults in switching equipment

Type	Fault	Examples
D1	Discharges of low energy	Normal operation of OLTC, selectors Arcing on off-load selector switch ring, OLTC connections
D2	Discharges of high energy	Switch contacts do not reach their final position but stop halfway, due to a failure of the rotating mechanism, inducing a sparkover discharge Arcing on off-load selector switch ring, OLTC connections, of high energy or with power follow-through, with failure often transmitted to transformer windings
T2, T3	Thermal fault	Increased resistance between contacts of OLTC or change-over selector, as a result of pyrolitic carbon growth, selector deficiency or a very large number of operations Transition resistor temperatures >700°C due to faulty (prolonged) switching sequence

NOTE 1   In this table are given examples of faults detected by DGA of oil samples taken from the switching compartment.

NOTE 2   Switching equipment attached to transformers is complex and of various designs. The detailed description of these systems and the interpretation of DGA results ~~should~~ can be ~~made with the help of the switching~~ obtained from equipment manufacturer, particularly concerning the types of discharges ~~which can or cannot occur in this~~ and degree of heating that is normal for the specific equipment.

A.7.4   Identification of faults by DGA

~~Table 2 applies to all sub-types.~~

~~As the number of OLTC operations increases, a thermal effect has been observed to superimpose over the pure discharge effect of breaking current, possibly as a result of the increase in resistance of OLTC contacts contaminated by pyrolitic carbon.~~

Two methods are used for the identification of faults in OLTCs:

1) The C_2H_4/C_2H_2 ratio represents an individual fingerprint of the application. It is up to users to define ratio value ranges for normal operation, depending on the OLTC model and operation mode. Deviations of the found range indicate irregularities.

2) The Duval-triangle-2-method (see Annex B): for the large majority of OLTCs, normal operation will show coordinates in the "N" zone. Nevertheless, some applications will show coordinates in the X3, T2 or T3 zone for normal operation [11], as described in A.7.2. As long as coordinates don't move significantly, these fingerprints don't indicate a fault. With this, the triangle method can be used to track the evolution of gas formation graphically to detect excessive arcing or heating.

NOTE   All DGA interpretations for OLTC are strongly model type and operation dependent. In case of suspect DGA results, contact the manufacturer.

A.8   Equipment filled with non-mineral fluids

Gases formed in equipment filled with non-mineral fluids (natural esters, synthetic esters, silicones) are the same as with mineral oils, however, some adjustments to zone boundaries used for mineral oils are necessary to identify faults in non-mineral oils, as indicated in [8].
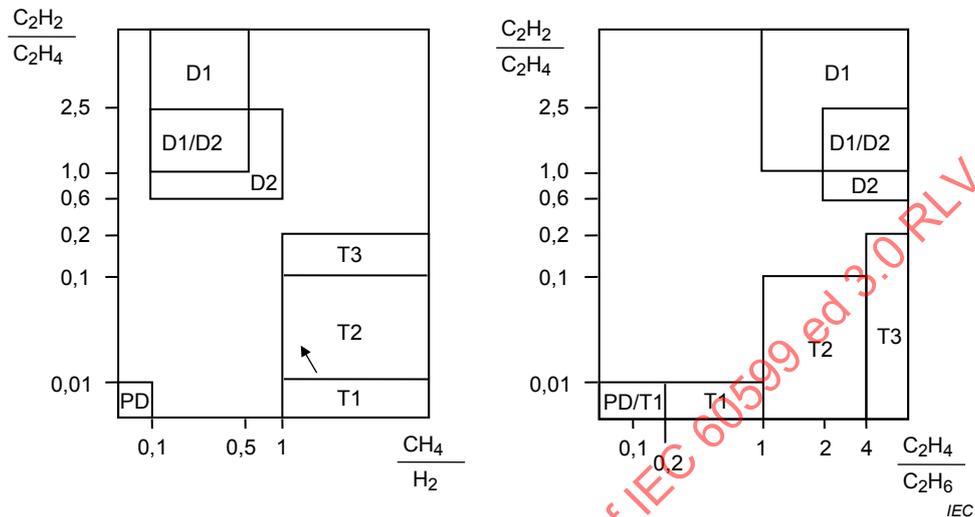
Examples of typical values observed with such fluids are also indicated in [8].

Annex B
(informative)

Graphical representations of gas ratios (see 5.10)

Graphical representations of gas ratios are given in Figures B.1, B.2, B.3 and B.4.

Key

PD   partial discharges

D1   discharges of low energy

D2   discharges of high energy

T1   thermal fault, $t < 300$ °C

T2   thermal fault, 300 °C $< t < 700$ °C

T3   thermal fault, $t > 700$ °C

NOTE 1   The arrow indicates increasing temperature.

NOTE 2   The axes are limited to values of 10 for clarification of presentation, but actually extend to unlimited values. The coordinates of each zone are the same as in Table 1 and Figure B.2.

Figure B.1 – Graphical representation 1 of gas ratios (see [3])

Key

PD   partial discharges

D1   discharges of low energy

D2   discharges of high energy

T1   thermal fault, t <300 °C

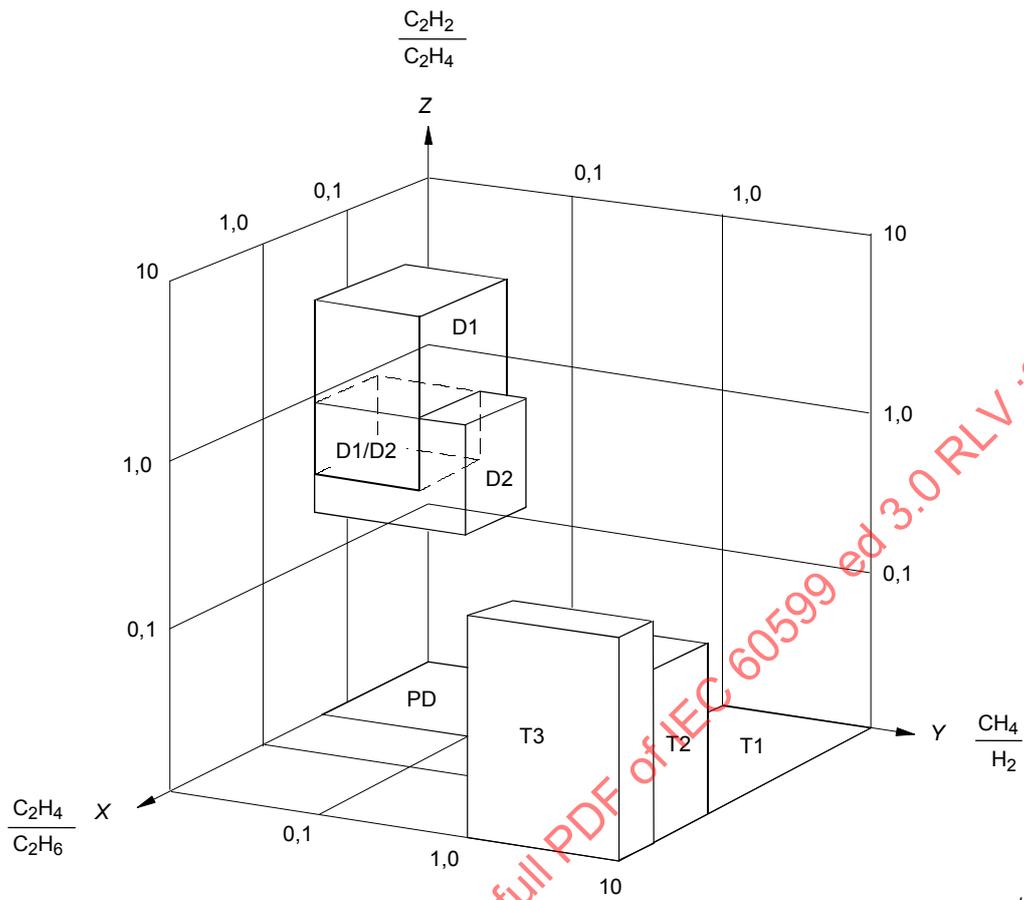T2   thermal fault, 300 °C < t <700 °C

T3   thermal fault, t >700 °C

NOTE 1   Each of the cases defined in Table 1 is represented by a volume or "box" on the 3-D graphic.

NOTE 2   The coordinates of each box are the same as in Figure B.1 and Table 1. It is more convenient to use this representation with the help of a computer software package.

Figure B.2 – Graphical representation 2 of gas ratios (see [4] of annex C)

where

$$\% \; C_2H_2 = \frac{100\,x}{x+y+z} \qquad \text{for } x = \left[C_2H_2 \right] \text{ in microlitres per litre}$$

$$\% \; C_2H_4 = \frac{100\,y}{x+y+z} \qquad \text{for } y = \left[C_2H_4 \right] \text{ in microlitres per litre}$$

$$\% \; CH_4 = \frac{100\,z}{x+y+z} \qquad \text{for } z = \left[CH_4 \right] \text{ in microlitres per litre}$$

Key
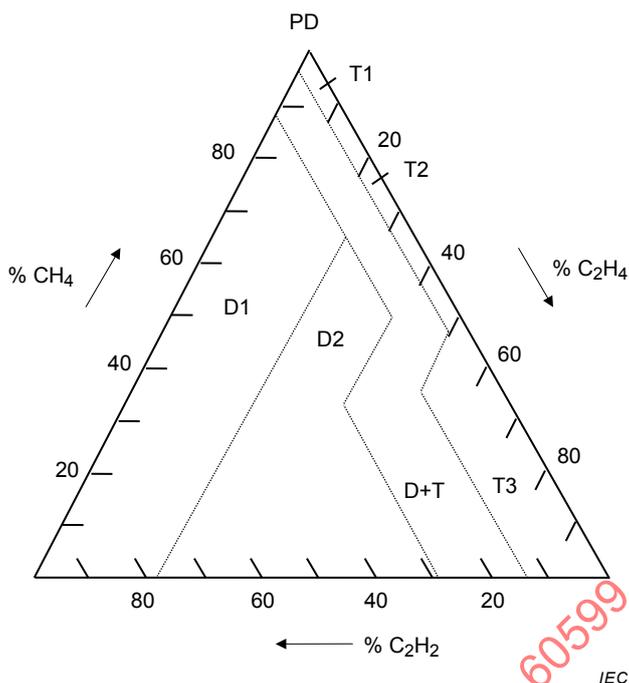
PD   partial discharges

D1   discharges of low energy

D2   discharges of high energy

T1   thermal fault, $t < 300$ °C

T2   thermal fault, 300 °C $< t < 700$ °C

T3   thermal fault, $t > 700$ °C

Limits of zones				
PD	98 % CH_4			
D1	23 % C_2H_4	13 % C_2H_2		
D2	23 % C_2H_4	13 % C_2H_2	~~38~~ 40 % C_2H_4	29 % C_2H_2
T1	4 % C_2H_2	~~10~~ 20 % C_2H_4		
T2	4 % C_2H_2	~~10~~ 20 % C_2H_4	50 % C_2H_4	
T3	15 % C_2H_2	50 % C_2H_4		

**Figure B.3 – Graphical representation 3 of gas ratios –
Duval's triangle 1 for transformers, bushings and cables (see [4])**

NOTE   See Figure B.3 for calculation of triangular coordinates.

Key

N   normal operation

T3   severe coking of contacts at $t > 700\ °C$

T2   severe coking of contacts at $t > 300\ °C$

X3   coking in progress or abnormal arcing D2

D1   abnormal arcing D1

X1   overheating at $t < 300\ °C$

	Limits of zones			
N	$19\ \%\ CH_4$	$23\ \%\ C_2H_4$	$2\ \%\ CH_4$	$6\ \%\ C_2H_4$
T3	$50\ \%\ C_2H_4$	$15\ \%\ C_2H_2$		
X3	$23\ \%\ C_2H_4$	$15\ \%\ C_2H_2$		
T2	$23\ \%\ C_2H_4$	$15\ \%\ C_2H_2$		
D1	$19\ \%\ CH_4$	$6\ \%\ C_2H_4$	$2\ \%\ CH_4$	$23\ \%\ C_2H_4$
X1	$19\ \%\ CH_4$	$23\ \%\ C_2H_4$		

**Figure B.4 – Graphical representation 4 of gas ratios –
Duval's triangle 2 for OLTCs (see A.7.2)**

NOTE   For some OLTCs mentioned in A.7.2 and A.7.3, normal gassing occurs either in zone N, T3, T2 or X3, depending on specific OLTCs models and operating conditions [11].

Bibliography

[1]   OOMMEN et al, *"New mechanisms of moderate hydrogen gas generation in oil-filled transformers", CIGRE,* Paris 1998, paper 12-206

[2]   EPRI Workshop, *Proceedings on Failed High Voltage Instrument Transformers, 1992*

[3]   DÖRNENBURG et al, *"Operational supervision by testing of insulating oil", Etz N° 98, 1977, pp 211-215*

[4]   ~~COUDERC et al., CEIDP San Francisco, 1996~~

[4]   DUVAL et al*, "Update on Hydro Quebec's experience in the interpretation of dissolved gas analysis in HV transformers",*CIGRE Symposium Berlin 1993*, Paper 110-14*

[5]   IEC 60050-321:1986, "*International Electrotechnical Vocabulary (IEV) – Chapter 321: Instrument transformers"*

[6]   CIGRE Technical Brochure 296, 2006, "*Recent developments on the interpretation of dissolved gas analysis in transformers"*

[7]   HOEHLEIN and FROTSCHER, *"Carbon oxides in the interpretation of dissolved gas analysis in transformers and tap changers", IEEE EI Mag., Dec. 2010*

[8]   CIGRE Technical Brochure 443: 2010, "*DGA in Non-Mineral Oils and Load Tap Changers and Improved DGA Diagnosis Criteria"*

[9]   CIGRE *Technical Brochure 409:* 2010*,* "*Report on Gas Monitors for Oil-Filled Electrical Equipment"*

[10]   CIGRE WG D1.47, Report to be published in 2015

[11]   DUVAL, *EuroTechCon Conference, Glasgow, "Application of Duval Triangles 2 to DGA analysis in load tapchangers", Nov. 2012*

[12]   ASTM Method D7150, "*Standard Test Method for the Determination of Gases Characteristic of Insulating Liquids under Thermal Stress", 2013*

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IEC 60599

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis

Matériels électriques remplis d'huile minérale en service – Lignes directrices pour l'interprétation de l'analyse des gaz dissous et des gaz libres

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MINERAL OIL-FILLED ELECTRICAL EQUIPMENT IN SERVICE – GUIDANCE ON THE INTERPRETATION OF DISSOLVED AND FREE GASES ANALYSIS

FOREWORD

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International Standard IEC 60599 has been prepared by IEC technical committee 10: Fluids for electrotechnical applications.

This third edition cancels and replaces the second edition published in 1999 and Amendment 1:2007. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) revision of 5.5, 6.1, 7, 8, 9, 10, A.2.6, A.3, A.7;

b) addition of new sub-clause 4.3;

c) expansion of the Bibliography;

d) revision of Figure 1;

e) addition of Figure B.4.

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

FDIS	Report on voting
10/967/FDIS	10/973/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.

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.

INTRODUCTION

Dissolved and free gas analysis (DGA) is one of the most widely used diagnostic tools for detecting and evaluating faults in electrical equipment filled with insulating liquid. However, interpretation of DGA results is often complex and should always be done with care, involving experienced insulation maintenance personnel.

This International Standard gives information for facilitating this interpretation. The first edition, published in 1978, has served the industry well, but had its limitations, such as the absence of a diagnosis in some cases, the absence of concentration levels and the fact that it was based mainly on experience gained from power transformers. The second edition attempted to address some of these shortcomings. Interpretation schemes were based on observations made after inspection of a large number of faulty oil-filled equipment in service and concentrations levels deduced from analyses collected worldwide.

MINERAL OIL-FILLED ELECTRICAL EQUIPMENT IN SERVICE – GUIDANCE ON THE INTERPRETATION OF DISSOLVED AND FREE GASES ANALYSIS

1 Scope

This International Standard describes how the concentrations of dissolved gases or free gases may be interpreted to diagnose the condition of oil-filled electrical equipment in service and suggest future action.

This standard is applicable to electrical equipment filled with mineral insulating oil and insulated with cellulosic paper or pressboard-based solid insulation. Information about specific types of equipment such as transformers (power, instrument, industrial, railways, distribution), reactors, bushings, switchgear and oil-filled cables is given only as an indication in the application notes (see Annex A).

This standard may be applied, but only with caution, to other liquid-solid insulating systems.

In any case, the indications obtained should be viewed only as guidance and any resulting action should be undertaken only with proper engineering judgment.

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 60050-191:1990, *International Electrotechnical Vocabulary – Chapter 191: Dependability and quality of service* (available at http://www.electropedia.org)

IEC 60050-192:2015, *International Electrotechnical Vocabulary – Part 192: Dependability* (available at http://www.electropedia.org)

IEC 60050-212:2010, *International Electrotechnical Vocabulary – Part 212: Electrical insulating solids, liquids and gases* (available at http://www.electropedia.org)

IEC 60050-604:1987, *International Electrotechnical Vocabulary – Chapter 604: Generation, transmission and distribution of electricity – Operation* (available at http://www.electropedia.org)

IEC 60475, *Method of sampling insulating liquids*

IEC 60567:2011, *Oil-filled electrical equipment – Sampling of gases and analysis of free and dissolved gases – Guidance*

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

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions, some of which are based on IEC 60050-191, IEC 60050-192, IEC 60050-212 and IEC 60050-604, apply.

3.1.1
fault
unplanned occurrence or defect in an item which may result in one or more failures of the item itself or of other associated equipment

[SOURCE: IEC 60050-604:1987, 604-02-01]

3.1.2
non-damage fault
fault which does not involve repair or replacement action at the point of the fault

Note 1 to entry: Typical examples are self-extinguishing arcs in switching equipment or general overheating without paper carbonization or stray gassing of oil.

[SOURCE: IEC 60050-604:1987, 604-02-09]

3.1.3
damage fault
fault that involves repair or replacement action at the point of the fault

[SOURCE: IEC 60050-604:1987, 604-02-08]

3.1.4
incident
event of external or internal origin, affecting equipment or the supply system and which disturbs its normal operation

Note 1 to entry: For the purposes of the present standard "incidents" are related to internal faults.

Note 2 to entry: For the purposes of the present standard typical examples of "incidents" are gas alarms, equipment tripping or equipment leakage.

[SOURCE: IEC 60050-604:1987, 604-02-03]

3.1.5
failure
loss of ability to perform as required

Note 1 to entry: In electrical equipment, failure will result from a damage fault or incident necessitating outage, repair or replacement of the equipment, such as internal breakdown, rupture of tank, fire or explosion.

[SOURCE: IEC 60050-192:2015, 192-03-01]

3.1.6
electrical fault
partial or disruptive discharge through the insulation

3.1.7
partial discharge
electric discharge that only partially bridges the insulation between conductors

Note 1 to entry: A partial discharge may occur inside the insulation or adjacent to a conductor.

Note 2 to entry: Scintillations of low energy on the surface of insulating materials are often described as partial discharges but should rather be considered as disruptive discharges of low energy, since they are the result of local dielectric breakdowns of high ionization density, or small arcs, according to the conventions of physics.

Note 3 to entry: For the purposes of this standard the following consideration may also be added:

– Corona is a form of partial discharge that occurs in gaseous media around conductors that are remote from solid or liquid insulation. This term shall not be used as a general term for all forms of partial discharges

– As a result of corona discharges, X-wax, a solid material consisting of polymerized fragments of the molecules of the original liquid, can be formed.

[SOURCE: IEC 60050-212:2010, 212-11-39]

3.1.8
discharge (disruptive)
passage of an arc following the breakdown

Note 1 to entry: The term "sparkover" (in French: "amorçage") is used when a disruptive discharge occurs in a gaseous or liquid dielectric.

The term "flashover" (in French: "contournement") is used when a disruptive discharge occurs over the surface of a solid dielectric surrounded by a gaseous or liquid medium.

The term "puncture" (in French: "perforation") is used when a disruptive discharge occurs through a solid dielectric.

Note 2 to entry: Discharges are often described as arcing, breakdown or short circuits. The following other specific terms are also used in some countries:

– tracking (the progressive degradation of the surface of solid insulation by local discharges to form conducting or partially conducting paths);

– sparking discharges that, in the conventions of physics, are local dielectric breakdowns of high ionization density or small arcs.

[SOURCE: IEC 60050-604:1987, 604-03-38]

3.1.9
thermal fault
excessive temperature rise in the insulation

Note 1 to entry: Typical causes are

– insufficient cooling;

– excessive currents circulating in adjacent metal parts (as a result of bad contacts, eddy currents, stray losses or leakage flux);

– excessive currents circulating through the insulation (as a result of high dielectric losses), leading to a thermal runaway;

– overheating of internal winding or bushing connection lead;

– overloading.

3.1.10
typical values of gas concentrations
gas concentrations normally found in the equipment in service that have no symptoms of failure, and that are exceeded by only an arbitrary percentage of higher gas contents (for example 10 % (see 8.2.1))

Note 1 to entry: Typical values will differ in different types of equipment and in different networks, depending on operating practices (load levels, climate, etc.).

Note 2 to entry: Typical values, in many countries and by many users, are quoted as "normal values", but this term has not been used here to avoid possible misinterpretations.

3.2 Abbreviations

3.2.1 Chemical names and formulae

Name	Formula
Nitrogen	N_2
Oxygen	O_2
Hydrogen	H_2
Carbon monoxide	CO
Carbon dioxide	CO_2
Methane	CH_4
Ethane	C_2H_6
Ethylene	C_2H_4
Acetylene	C_2H_2

NOTE   Acetylene and ethyne are both used for C_2H_2; ethylene and ethene are both used for C_2H_4

3.2.2 General abbreviations

D1   discharges of low energy

D2   discharges of high energy

DGA: dissolved gas analysis

CIGRE   Conseil International des Grands Réseaux Électriques

PD   corona partial discharges

S   analytical detection limit

T1   thermal fault, $t < 300\ °C$

T2   thermal fault, $300\ °C < t < 700\ °C$

T3   thermal fault, $t > 700\ °C$

T   thermal fault

D   electrical fault

TP   thermal fault in paper

ppm   parts per million by volume of gas in oil, equivalent to μl(of gas)/l(of oil). See IEC 60567:2011, 8.7, note 1.

OLTC   on load tap changer

4   Mechanisms of gas formation

4.1   Decomposition of oil

Mineral insulating oils are made of a blend of different hydrocarbon molecules containing CH_3, CH_2 and CH chemical groups linked together by carbon-carbon molecular bonds. Scission of some of the C-H and C-C bonds may occur as a result of electrical and thermal faults, with the formation of small unstable fragments, in radical or ionic form, such as $H^\bullet$, $CH_3^\bullet$, $CH_2^\bullet$, $CH^\bullet$ or $C^\bullet$ (among many other more complex forms), which recombine rapidly, through complex reactions, into gas molecules such as hydrogen (H-H), methane (CH_3-H), ethane (CH_3-CH_3), ethylene ($CH_2 = CH_2$) or acetylene ($CH \equiv CH$). C_3 and C_4 hydrocarbon gases, as well as solid particles of carbon and hydrocarbon polymers (X-wax), are other possible recombination products. The gases formed dissolve in oil, or accumulate as free gases if produced rapidly in large quantities, and may be analysed by DGA according to IEC 60567.

Low-energy faults, such as partial discharges of the cold plasma type (corona discharges), favour the scission of the weakest C-H bonds (338 kJ/mol) through ionization reactions and the accumulation of hydrogen as the main recombination gas. More and more energy and/or higher temperatures are needed for the scission of the C-C bonds and their recombination into gases with a C-C single bond (607 kJ/mol), C=C double bond (720 kJ/mol) or C≡C triple bond (960 kJ/mol), following processes bearing some similarities with those observed in the petroleum oil-cracking industry.

Ethylene is thus favoured over ethane and methane above temperatures of approximately 500 °C (although still present in lower quantities below). Acetylene requires temperatures of at least 800 °C to 1 200 °C, and a rapid quenching to lower temperatures, in order to accumulate as a stable recombination product. Acetylene is thus formed in significant quantities mainly in arcs, where the conductive ionized channel is at several thousands of degrees Celsius, and the interface with the surrounding liquid oil necessarily below 400 °C (above which oil vaporizes completely), with a layer of oil vapour/decomposition gases in between. Acetylene may still be formed at lower temperatures (<800 °C), but in very minor quantities. Carbon particles form at 500 °C to 800 °C and are indeed observed after arcing in oil or around very hot spots.

Oil may oxidize with the formation of small quantities of CO and CO_2, which can accumulate over long periods of time into more substantial amounts.

4.2 Decomposition of cellulosic insulation

The polymeric chains of solid cellulosic insulation (paper, pressboard, wood blocks) contain a large number of anhydroglucose rings, and weak C-O molecular bonds and glycosidic bonds which are thermally less stable than the hydrocarbon bonds in oil, and which decompose at lower temperatures. Significant rates of polymer chain scission occur at temperatures higher than 105 °C, with complete decomposition and carbonization above 300 °C (damage fault). Carbon monoxide and dioxide, as well as water, is formed, together with minor amounts of hydrocarbon gases, furanic and other compounds. Furanic compounds are analysed according to IEC 61198, and used to complement DGA interpretation and confirm whether or not cellulosic insulation is involved in a fault. CO and CO_2 formation increases not only with temperature but also with the oxygen content of oil and the moisture content of paper.

4.3 Stray gassing of oil

Stray gassing of oil has been defined by CIGRE [6][1] as the formation of gases in oil heated to moderate temperatures (<200 °C). H_2, CH_4 and C_2H_6 may be formed in all equipment at such temperatures or as a result of oil oxidation, depending on oil chemical structure. Stray gassing is a non-damage fault. It can be evaluated using methods described in reference [6] and [12].

NOTE   Stray gassing of oil has been observed in some cases to be enhanced by the presence in oil of a metal passivator or other additives.

4.4 Other sources of gas

Gases may be generated in some cases not as a result of faults in the equipment, but through rusting or other chemical reactions involving steel, uncoated surfaces or protective paints.

Hydrogen may be produced by reaction of steel and galvanized steel with water, as long as oxygen is available from the oil nearby. Large quantities of hydrogen have thus been reported in some transformers that had never been energized. Hydrogen may also be formed by reaction of free water with special coatings on metal surfaces, or by catalytic reaction of some types of stainless steel with oil, in particular oil containing dissolved oxygen at elevated temperatures. Hydrogen, acetylene and other gases may also be formed in new stainless steel, absorbed during its manufacturing process, or produced by welding, and released

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1   Numbers in square brackets refer to the Bibliography.

slowly into the oil. Internal transformer paints, such as alkyd resins and modified polyurethanes containing fatty acids in their formulation, may also form gases.

Gases may also be produced, and oxygen consumed, by exposure of oil to sunlight.

These occurrences, however, are very unusual, and can be detected by performing DGA analyses on new equipment which has never been energized, and by material compatibility tests. The presence of hydrogen with the total absence of other hydrocarbon gases, for example, may be an indication of such a problem.

NOTE   The case of gases formed at a previous fault and remnant in the transformer is dealt with in 5.4.

5   Identification of faults

5.1   General

Any gas formation in service, be it minimal, results from a stress of some kind, even if it is a very mild one, like normal temperature ageing. However, as long as gas concentration is below typical values and not significantly increasing, it should not be considered as an indication of a "fault", but rather as the result of typical gas formation (see Figure 1). Typical values are specific for each kind of equipment.

5.2   Dissolved gas compositions

Although the formation of some gases is favoured, depending on the temperature reached or the energy contained in a fault (see 4.1), in practice mixtures of gases are almost always obtained. One reason is thermodynamic: although not favoured, secondary gases are still formed, albeit in minor quantities. Existing thermodynamic models derived from the petroleum industry, however, cannot predict accurately the gas compositions formed, because they correspond to ideal gas/temperature equilibria that do not exist in actual faults. Large temperature gradients also occur in practice, for instance as a result of oil flow or vaporization along a hot surface. This is particularly true in the case of arcs with power follow-through, which transfer a lot of heat to the oil vapour/decomposition gas layer between the arc and the oil, probably explaining the increasing formation of ethylene observed in addition to acetylene. In addition, existing thermodynamic models do not apply to paper that turns irreversibly to carbon above 300 °C.

5.3   Types of faults

Internal inspection of hundreds of faulty equipment has led to the following broad classes of visually detectable faults:

– partial discharges (PD) of the cold plasma (corona) type, resulting in possible X-wax deposition on paper insulation;

– discharges of low energy (D1), in oil or/and paper, evidenced by larger carbonized perforations through paper (punctures), carbonization of the paper surface (tracking) or carbon particles in oil (as in tap changer diverter operation); also, partial discharges of the sparking type, inducing pinhole, carbonized perforations (punctures) in paper, which, however, may not be easy to find;

– discharges of high energy (D2), in oil or/and paper, with power follow-through, evidenced by extensive destruction and carbonization of paper, metal fusion at the discharge extremities, extensive carbonization in oil and, in some cases, tripping of the equipment, confirming the large current follow-through;

– thermal faults, in oil or/and paper, below 300 °C if the paper has turned brownish (T1), and above 300 °C if it has carbonized (T2);

– thermal faults of temperatures above 700 °C (T3) if there is strong evidence of carbonization of the oil, metal coloration (800 °C) or metal fusion (>1 000 °C).

5.4 Basic gas ratios

Each of the six broad classes of faults leads to a characteristic pattern of hydrocarbon gas composition, which can be translated into a DGA interpretation table, such as the one recommended in Table 1 and based on the use of three basic gas ratios:

$$\frac{C_2H_2}{C_2H_4} \qquad \frac{CH_4}{H_2} \qquad \frac{C_2H_4}{C_2H_6}$$

Table 1 applies to all types of equipment, with a few differences in gas ratio limits depending on the specific type of equipment.

Table 1 – DGA interpretation table

Case	Characteristic fault	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$
PD	Partial discharges (see notes 3 and 4)	NS [a]	<0,1	<0,2
D1	Discharges of low energy	>1	0,1 – 0,5	>1
D2	Discharges of high energy	0,6 – 2,5	0,1 – 1	>2
T1	Thermal fault t <300 °C	NS [a]	>1 but NS [a]	<1
T2	Thermal fault 300 °C < t <700 °C	<0,1	>1	1 – 4
T3	Thermal fault t >700 °C	<0,2 [b]	>1	>4

NOTE 1   In some countries, the ratio C_2H_2/C_2H_6 is used, rather than the ratio CH_4/H_2. Also in some countries, slightly different ratio limits are used.

NOTE 2   Conditions for calculating gas ratios are indicated in 6.1 c).

NOTE 3 CH_4/H_2 <0,2 for partial discharges in instrument transformers. CH_4/H_2 <0,07 for partial discharges in bushings.

NOTE 4   Gas decomposition patterns similar to partial discharges have been reported as a result of stray gassing of oil (see 4.3).

[a]   NS = Non-significant whatever the value.

[b]   An increasing value of the amount of C_2H_2 may indicate that the hot spot temperature is higher than 1 000 °C.

Typical examples of faults in the various types of equipment (power transformers, instrument transformers, etc.), corresponding to the six cases of Table 1, may be found in Tables A.1, A.5, A.8 and A.12.

Some overlap between faults D1 and D2 is apparent in Table 1, meaning that a dual attribution of D1 or D2 must be given in some cases of DGA results. The distinction between D1 and D2 has been kept, however, as the amount of energy in the discharge may significantly increase the potential damage to the equipment and necessitate different preventive measures. Table 1 applies to transformers. For switching equipment see Clause A.7 and reference [8] in the bibliography.

NOTE   Combinations of gas ratios that fall outside the range limits of Table 1 and do not correspond to a characteristic fault of this table can be considered a mixture of faults, or new faults that combine with a high background gas level (see 6.1).

In such a case, Table 1 cannot provide a diagnosis, but the graphical representations given in Annex B can be used to visualize which characteristic fault of Table 1 is closest to the case.

The less detailed scheme of Table 2 can also be used in such a case in order to get at least a rough distinction between partial discharges (PD), discharges (D) and thermal fault (T), rather than no diagnosis at all.

Table 2 – Simplified scheme of interpretation

Case	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$
PD		<0,2	
D	>0,2		
T	<0,2		

5.5 CO₂/CO ratio

The formation of CO_2 and CO from oil-impregnated paper insulation increases rapidly with temperature. High values of CO (e.g., 1 000 ppm) and CO_2/CO ratios less than 3 are generally considered as an indication of probable paper involvement in a fault, with possible carbonization, in the presence of other fault gases.

However, in some recent transformers of the closed-type or open (free breathing) transformers operating at constant load (i.e., with low breathing), CO can accumulate in the oil, leading to ratio CO_2/CO < 3, without any irregularities or faults if no other gases such as H_2 or hydrocarbons are formed [7].

High values of CO_2 (>10 000 ppm) and high CO_2/CO ratios (>10) can indicate mild (<160 °C) overheating of paper [6, 8] or oil oxidation, especially in open transformers. CO_2 can accumulate more rapidly than CO in open transformers operating at changing loads because of their different solubilities in oil. This, and the long term degradation with time of paper at low temperatures (<160 °C), can lead to higher CO_2/CO ratios in aged equipment.

In some cases, localized faults in paper do not produce significant amounts of CO and CO_2 and cannot be detected with these gases (the same for furanic compounds).

Involvement of faults in paper therefore shall not be based only on CO and CO_2, but shall be confirmed by the formation of other gases or other types of oil analysis.

In order to get reliable CO_2/CO ratios in the equipment, CO_2 and CO values should be corrected (incremented) first for possible CO_2 absorption from atmospheric air, and for the CO_2 and CO background values (see 6.1 and Clause 9), resulting from the ageing of cellulosic insulation, overheating of wooden blocks and the long term oxidation of oil (which will be strongly influenced by the availability of oxygen caused by specific equipment construction details and its way of operation).

Air-breathing equipment, for example, saturated with approximately 9 % to10 % of dissolved air, may contain up to 300 μl/l of CO_2 coming from the air. In sealed equipment, air is normally excluded but may enter through leaks, and CO_2 concentration will be in proportion of air present.

When excessive paper degradation is suspected, it is recommended to ask for further analysis (e.g., of furanic compounds) or a measurement of the degree of polymerization of paper samples, when this is possible.

NOTE 1   In case of equipment containing negligible amounts of paper (e.g., most modern types of on load tap changers (OLTCs)) CO and CO_2 can increase with oil oxidation under thermal stress. CO_2/CO ratios can have values quite different from those in transformers.

NOTE 2   High levels of CO can also be formed in case of high energy discharges in oil only.

NOTE 3   In instrument transformers and some bushing types, low ratios <3 are observed without any paper degradation.

5.6 O_2/N_2 ratio

Dissolved O_2 and N_2 are found in oil as a result of contact with atmospheric air in the conservator of air-breathing equipment, or through leaks in sealed equipment. At equilibrium with air, the concentrations of O_2 and N_2 in oil are ~32 000 and ~64 000 ppm, respectively [8], and the O_2/N_2 ratio is ~0,5.

In service, this ratio may decrease as a result of oil oxidation and/or paper ageing, if O_2 is consumed more rapidly than it is replaced by diffusion. Factors such as the load and preservation system used may also affect the ratio, but with the exception of closed systems, ratios less than 0,3 are generally considered to indicate excessive consumption of oxygen.

5.7 C_2H_2/H_2 ratio

In power transformers, on load tap changer (OLTC) operations produce gases corresponding to discharges of low energy (D1). If some oil or gas communication is possible between the OLTC compartment and the main tank, or between the respective conservators, these gases may contaminate the oil in the main tank and lead to wrong diagnoses. The pattern of gas decomposition in the OLTC, however, is quite specific and different from that of regular D1s in the main tank.

C_2H_2/H_2 ratios higher than 2 to 3 in the main tank are thus considered as an indication of OLTC contamination. This can be confirmed by comparing DGA results in the main tank, in the OLTC and in the conservators. The values of the gas ratio and of the acetylene concentration depend on the number of OLTC operations and on the way the contamination has occurred (through the oil or the gas).

If contamination by gases coming from the OLTC is suspected, interpretation of DGA results in the main tank should be made with caution by subtracting background contamination from the OLTC, or should be avoided as unreliable.

NOTE   Modern OLTCs are designed not to contaminate oil in the main tank.

5.8 C_3 hydrocarbons

The interpretation method of gas analysis indicated above takes into account only C_1 and C_2 hydrocarbons. Some practical interpretation methods also use the concentrations of C_3 hydrocarbons, and their authors believe that they are liable to bring complementary information that is useful to make the diagnosis more precise. Because the C_3 hydrocarbons are very soluble in oil, their concentrations are practically not affected by a possible diffusion into ambient air. Conversely, and because they are very soluble, they are difficult to extract from the oil and the result of the analysis may greatly depend on the extraction method used. Moreover, experience has shown that, in most cases, a satisfactory diagnosis can be made without taking into account these hydrocarbons and for the sake of simplification, they have been omitted from the interpretation method indicated above.

5.9   Evolution of faults

Faults often start as incipient faults of low energy, which may develop into more serious ones of higher energies, leading to possible gas alarms, breakdowns and failures.

When a fault is detected at an early stage of development, it may be quite informative to examine not only the increase in gas concentrations, but also the possible evolution with time toward a more dangerous high-energy fault resulting in failure.

For example, some current transformers have operated satisfactorily for long periods of time with very high levels of hydrogen produced by partial discharges. However, partial discharges may also cause the formation of X-wax. When the X-wax is present in sufficient quantity to increase the dissipation losses in the paper-oil insulation, a thermal fault may occur, eventually leading to catastrophic thermal runaway and breakdown.

In other occurrences, however, instant final breakdown may occur without warning.

5.10 Graphical representations

Graphical representations of gas ratios are convenient to follow this evolution of faults visually. Annex B gives examples of graphical representation of faults.

These representations are also useful in cases that do not receive a diagnosis using Table 1, because they fall outside the gas ratios limits. Using Figures B.1 or B.2, the zone or box that is closest to such an undiagnosed case can be easily visualized and attributed with caution to this case. Figure B.3 is particularly useful since it always provide a diagnosis in such cases.

6 Conditions for calculating ratios

6.1 Examination of DGA values

DGA sampling and analysis should be done in accordance with the recommendations of IEC 60475 and IEC 60567, respectively.

a) Values of 0 μl/l on a DGA report or below the analytical detection limits S shall be replaced by "below the S value for this gas" (see IEC 60567 for recommended S values).

b) If successive DGA analyses have been performed over a relatively short period of time (days or weeks), inconsistent variations (e.g. large decreases of concentrations) may have to be eliminated as an indication of a sampling or analytical problem.

c) Gas ratios are significant and should be calculated only when at least one of the gases is at a concentration and a rate of gas increase above typical values (see Clause 9). Nevertheless, it is recommended to also calculate them in cases where one or more gases show increasing or abnormal concentrations, even if they are lower than typical values. Avoid calculating ratios when gas concentrations are not high enough to be reasonably accurate according to IEC 60567.

d) If gas ratios are different from those for the previous analysis, a new fault may superimpose itself on an old one or normal ageing. In order to get only the gas ratios corresponding to the new fault, subtract the previous DGA values from the last ones and recalculate ratios. This is particularly true in the case of CO and CO_2 (see 5.4). Be sure to compare DGA values of samples taken at the same place and preferably in moving oil. Interpretation should also take into account treatments previously made on the equipment, such as repair, oil degassing or filtering, which may affect the level of gases in the oil.

NOTE　In the case of air-breathing power transformers, losses occur very slowly with time by diffusion through the conservator or as a result of oil expansion/temperature cycles, with the result that the measured gas levels can be slightly less than the gas levels actually formed in the transformer. However, there is no agreement concerning the magnitude of this diffusion loss in service, some considering it as totally negligible, others as potentially significant, depending on the type of equipment used. Typical values in open and closed transformers are relatively similar, suggesting that either gas loss in open transformers is lower than suspected, or that gas production is higher (because of higher oxygen availability) and compensated by higher gas loss. In any case, this has not been observed to significantly affect the identification of faults in open transformers.

6.2 Uncertainty on gas ratios

Because of the uncertainty on DGA values, there is also an uncertainty on gas ratios, which can be calculated using the uncertainty on DGA values described in IEC 60567.

Above 10 × S (S being the analytical detection limit), the uncertainty (precision and accuracy) is typically ±15 % on DGA values and this may also effect the uncertainty on gas ratios. Below 10 × S, the uncertainty on DGA values increases rapidly, to typically ±30 % at 5 × S.

Caution should therefore be exercised when calculating gas ratios at low gas levels (lower than 10 × S), keeping in mind the possible variations resulting from the higher uncertainty.

7   Application to free gases in gas relays

During a fault, the production rate of gases of all types is closely linked to the rate of energy liberation. Thus, the low rate of energy liberation in partial discharges, or in a low-temperature thermal fault, will cause gases to evolve slowly and there is every probability that all the gas produced will dissolve in the oil. The higher rate of energy liberation of a high-temperature core fault, for example, can cause an evolution of gas rapid enough to result in gas bubbles. These will usually partially dissolve in the oil (and exchange with gases already dissolved) but some gas may well reach the gas collecting relay or gas cushion; this gas may approach equilibrium with the gases dissolved in the oil.

A very high rate of energy liberation associated with a power arcing fault causes a rapid and substantial evolution of gas (the resulting pressure surge normally operates the surge element of the gas collecting relay). The large gas bubbles rise quickly to the relay and exchange little gas with the oil so that the gas that collects in the relay is initially far from being in equilibrium with the gases dissolved in the oil. However, if this gas is left for a long time in the relay, some constituents will dissolve, modifying the composition of the gas collected. Acetylene, which is produced in significant quantities by an arcing fault, and which is very soluble, is a noteworthy example of a gas that may dissolve comparatively quickly to produce misleading results.

In principle, the analysis of free gases from a gas-collecting relay or from a gas cushion may be evaluated in the same way as the analysis of gases dissolved in the oil. However, where the surge element has operated and gas has accumulated in substantial quantities, there is a possibility of having a serious fault, and analyses of the gases should be undertaken to identify the fault. If the rate of gas production is low, gases formed will usually dissolve entirely in oil. If it is high, or if the oil is over-saturated with gas, gas bubbles will rise rapidly in the oil and accumulate in the gas relay. The less soluble gases in bubbles (H_2, CO and CH_4) will not have time to dissolve in oil during their ascent and will be over-represented in the top oil of the tank and the gas relay, resulting in wrong fault identification.

After a Buchholz alarm it is recommended to collect the gas at the relay as soon as possible and sample the oil in the relay and in the top and bottom oil of the main tank. This will allow first to verify that the alarm is indeed due to a fault in the transformer and not to air accumulation following a combination of warm days and sudden temperature drops at night, or because of faults in oil pumps.

Where gas has accumulated slowly (e.g., as a result of coking of selector contacts or of core overheating), assessment of the gases dissolved in the oil is more informative than that of the free gases; this gas-in-oil analysis is also essential in order to determine the total rate of evolution of gases and thus check whether the fault is growing, which is the most important matter to investigate. When analysis of free gases is undertaken, it is necessary to convert the concentrations of the various gases in the free state into equivalent concentrations in the dissolved state, using Table 3, before applying the gas ratio method of Table 1, and to compare them to the dissolved gas concentrations in the oil of the relay and the main tank.

Applying the principles set out above, comparison of the actual concentrations in the oil with the equivalent concentrations in the free gas may give valuable information on how far gas bubbles may have risen through the oil and, hence, on the rate of gas evolution.

The calculation of dissolved gas concentrations equivalent to free gas concentrations is made by applying the Ostwald solubility coefficient for each gas separately. For a particular gas, the Ostwald solubility coefficient k is defined as follows:

$$k = \frac{\text{concentration of gas in liquid phase}}{\text{concentration of gas in gas phase}}$$

with concentrations in microlitres per litre.

Table 3 contains the Ostwald solubility coefficients of various gases in mineral insulating oils as given in IEC 60567:2011, Table A.1.

Table 3 – Ostwald solubility coefficients
for various gases in mineral insulating oils

Gas	k at 25 °C
N_2	0,091
O_2	0,172
H_2	0,056
CO	0,132
CO_2	1,09
CH_4	0,429
C_2H_6	2,82
C_2H_4	1,84
C_2H_2	1,24
Data given in this table represent mean values obtained on some of the current types of transformer mineral insulating oils. Actual data may differ a little from these figures. Nevertheless, data given above may be used without influencing conclusions drawn from recalculated test results.	

The Ostwald solubility coefficient is independent of the actual partial pressures of the gas concerned. The gas and liquid phases are assumed to be at the same temperature; this is rarely the case but the error introduced by any difference will not invalidate the conclusions reached.

If only free gas in the relay is analysed, gas content in oil of the relay at equilibrium may be calculated using the above equation and Ostwald solubility coefficients k for each gas given in Table 3.

When gas accumulates in the gas relay, collect and analyse as soon as possible the free gases in the relay, convert into gases in the relay oil, using k, then compare to gases in oil in the main tank. If results are comparable, this indicates equilibrium has been reached and gas has accumulated slowly. If they do not compare, this indicates that equilibrium has not been reached and gas has accumulated rapidly.

8 Gas concentration levels in service

8.1 Probability of failure in service

8.1.1 General

The probability or risk of having an incident or a failure in service is related to gas concentration levels and rates of gas formation [8].

Below certain concentration levels (quoted as typical values or normal values), the probability of having a failure is low (typically 10 % according to CIGRE [6] when using oil sampling). The equipment is considered healthy, although a failure cannot be totally ruled out, even at these low levels, but it is improbable. A first rough screening between healthy and suspect analyses can therefore be obtained by calculating typical values for the equipment.

The probability of having a failure may increase significantly at values much above typical concentration levels. The situation is then considered critical, for even though a failure may never occur at these high levels, the risk of having one is high. For detecting such failures, see [9] in the bibliography.

8.1.2   Calculation methods

Utilities with large DGA and equipment maintenance databases are able to calculate the probability of failure in service for a given type of equipment and at a given concentration level of a gas. This can be obtained by calculating the number of DGA analyses that have led to an actual failure or incident in service (gas alarm, failure, repair, outage, etc.), and comparing it to the total number of DGA analyses on this type of equipment and at this gas concentration level.

A large number of analyses is necessary to get reliable values of failure probability. Knowledge of these values, however, is useful when choosing the normality percentage most appropriate for a given network and type of equipment (see 8.2.3). Pre-failure values have thus been proposed by CIGRE [6, 8], above which the probability of failure increases very rapidly.

8.2   Typical concentration values

8.2.1   General

Typical concentration values are the acceptable gas quantities that are exceeded by only an arbitrarily low percentage of higher gas contents, for example 10 %. Typical concentration values will be referred to in such an example as the 90 % typical values. This allows concentrating maintenance efforts on the 10 % of transformers most at risk.

However, typical concentration values are preferably to be considered as initial guidelines for decision making, when no other experience is available. They shall not be used to ascertain whether or not a fault exists within the equipment. They should be viewed as values above which the rate of gas formation may permit the detection of a probable fault.

Typical concentration values are affected by a number of factors, chiefly the operating time since commissioning, the type of equipment and the nature of the fault (electrical or thermal). For power transformers, the type of oil protection, load factor and operation mode are other influencing factors.

Typical concentration values may be calculated as follows and should preferably be obtained by the equipment users on the specific types of equipment.

8.2.2   Calculation methods

The simplest method of calculation consists in gathering all the DGA results concerning a specific type of equipment. For each characteristic gas considered, the cumulative number of DGA analyses where the gas concentration is below a given value is calculated, then plotted as a function of gas concentration. Using the plotted curve, the gas concentration corresponding to a given percentage of the total cumulative number of analyses (for instance 90 %) is the 90 % typical concentration value for that gas and type of equipment.

8.2.3   Choice of normality percentages

Most organizations worldwide (IEC, IEEE) use a normality percentage of 90 % for typical values. However, other percentages can also be used.

If adequate databases are not available to calculate typical values, users may also adopt as a first step, values observed on other networks and indicated in the application notes. It is apparent from these values that, in general, typical values are lower in instrument transformers and bushings than in power transformers, especially those with a communicating OLTC.

8.2.4 Alarm concentration values

Alarm concentration values are those values of concentration above which the probability of an incident is sufficiently high to require urgent competent decisions and/or actions. Pre-failure concentration values have thus been proposed by CIGRE [8], and more recently as a function of type and location of faults [10].

Alarm concentration values should be set by users, manufacturers or independent experts, based on previous experience with equipment with similar characteristics (voltage, type, manufacturer, loading practices, age, etc.).

8.3 Rates of gas increase

If there is no increase in gas concentration over the last analysis, chances are that the fault has disappeared (or that a very small one is still there, in the case of air-breathing equipment, compensated by diffusion losses through the conservator (see 6.1).

What should be considered as a typical or alarm rate of gas increase depends very much on equipment type and age, type of identified faults, air-breathing and load patterns, and volume of the insulation involved. Ultimately the rate of increase should be decided by the user of the equipment, the manufacturer and/or other experts.

Typical rates of gas increase can be calculated as in the case of typical gas concentrations and are indicated in Table A.3. Pre-failure rates of increase have also been proposed by CIGRE [8].

On-line gas monitors, including those for hydrogen, may be particularly well-suited for detecting non-typical rates of gas increase occurring within minutes, hours or weeks, which is generally not possible with routine oil samplings done at monthly or yearly intervals [9]. However, when such increases are detected by a gas monitor, complete DGA analyses shall be made at the laboratory to confirm the monitor readings.

9 Recommended method of DGA interpretation (see Figure 1)

The procedure shall be as follows:

a) Reject or correct inconsistent DGA values (see 6.1). Calculate the rate of gas increase since the last analysis, taking into account the precision on DGA results.

   If all gases are below typical values of gas concentrations and rates of gas increase, report as "Normal DGA/healthy equipment".

   If at least one gas is above typical values of gas concentrations and rates of gas increase, calculate gas ratios and identify fault using Table 1 (see 5.4). Check for eventual erroneous diagnosis (see 4.3).

   If necessary subtract last values from present ones before calculating ratios, particularly in the case of CO, CO_2 (see 6.1).

   If DGA values are above typical values but below $10 \times S$ (S = analytical detection limit), see 6.2.

b) Determine if gas concentrations and rates of gas increase are above alarm values. Verify if fault is evolving towards final stage (see 5.9). Determine if paper is involved (see 4.2 and 5.5).

c) Take proper action according to best engineering judgment and/or with the help of Figure 1.

   It is recommended to:

   1) increase sampling frequency (quarterly, monthly or other) when the gas concentrations and their rates of increase exceed typical values;

2) consider performing complementary tests (acoustic, electrical, infrared) or reduce loading;

3) consider removing the transformer from service for inspection or repair depending on results of complementary and other tests and on advice of transformer experts;

4) consider immediate action when gas concentrations and rates of gas increase exceed alarm values.
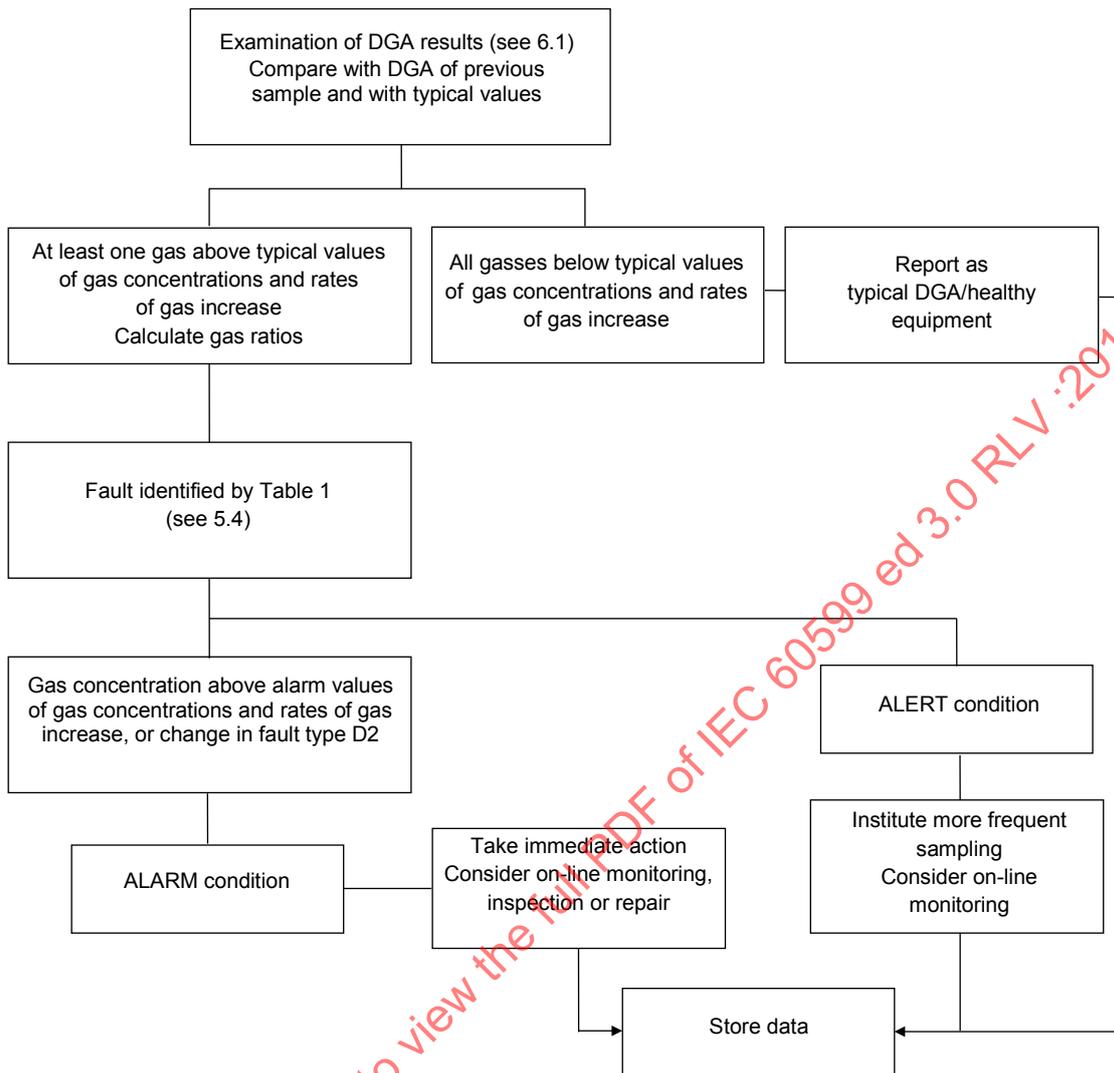
10 Report of results

The report should be adapted to the specific type of equipment considered.

The DGA interpretation report should include the following, when available:

a) analysis report, including S values, method of analysis (see IEC 60567:2011, Table A.1) and date of analysis.

   NOTE   Values of 0 ppm or μl/l on a DGA report or below the S values are replaced by "below the S value for this gas".

b) specific information on the equipment such as:

   1) date of commissioning, voltage, general type (e.g. power or instrument transformer), rated power;

   2) special features (e.g. sealed or air-breathing, type of OLTC (see A.2.1);

   3) oil volume;

   4) oil or gas sampling date;

   5) oil or gas sampling location;

c) special operations or incidents just before the oil or gas sampling, such as tripping, gas alarm, degassing, repair, outage;

d) previous DGA on the equipment;

e) indication of typical values for this specific equipment, if known;

f) indication of "Typical DGA/healthy equipment" or "Fault";

g) in case of "Fault", identification of the fault using Table 1 (see 5.4), with values of the calculated gas ratios indicated;

h) indication of paper involvement or not, with value of the CO_2/CO ratio or other methods (see 5.5);

i) recommended actions: (see 9 c).

Figure 1 – Flow chart

Annex A
(informative)

Equipment application notes

A.1   General warning

"Limit values" of gas concentrations and rates of gas increase in service are not the responsibility of TC10 but of IEC equipment committees.

"Typical values" in the following application notes **are not limit values**. They are given for information only, as a maintenance and predictive tool. In a given transformer population, they indicate for example that 90 % of DGA values in service are below the 90 % typical values and 10 % are above. When typical values are exceeded, the only action recommended in this standard is to increase the frequency of DGA analyses.

Typical values depend on several parameters (age, type and manufacturer of equipment, operating and loading practices, climate, etc.), and are not exactly the same for all electrical networks. Ranges of typical values are therefore indicated in the following application notes, covering the different individual values observed worldwide and surveyed by IEC and CIGRE.

Individual networks are strongly encouraged to calculate the typical values corresponding to their own specific transformer population, using DGA data meeting IEC 60567 specifications for accuracy and following methods indicated in Clause 8 and [6].

The ranges of typical values indicated in these application notes should be used only by default, when individual values are not available, and should not be used in a contract without a special agreement between the user and manufacturer of the equipment.

A.2   Power transformers

A.2.1   Specific sub-types

Specific sub-types of power transformers are as follows:

– air-breathing (open conservator type);

– sealed or nitrogen-blanketed;

– inter-tie transmission versus generation step-up;

– no OLTC communicating with main tank versus communicating OLTC;

– core-type or shell-type;

– reactors.

A.2.2   Typical faults

See Table A.1.

Table A.1 – Typical faults in power transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from incomplete impregnation, high-humidity in paper, oil super saturation or cavitation, and leading to X-wax formation
D1	Discharges of low energy	Sparking or arcing between bad connections of different or floating potential, from shielding rings, toroids, adjacent disks or conductors of winding, broken brazing or closed loops in the core
		Discharges between clamping parts, bushing and tank, high voltage and ground within windings, on tank walls
		Tracking in wooden blocks, glue of insulating beam, winding spacers. Breakdown of oil, selector breaking current
D2	Discharges of high energy	Flashover, tracking, or arcing of high local energy or with power follow-through
		Short circuits between low voltage and ground, connectors, windings, bushings and tank, copper bus and tank, windings and core, in oil duct, turret. Closed loops between two adjacent conductors around the main magnetic flux, insulated bolts of core, metal rings holding core legs
T1	Thermal fault $t < 300\ °C$	Overloading of the transformer in emergency situations
		Blocked item restricting oil flow in windings
		Stray flux in clamping beams of yokes
T2	Thermal fault $300\ °C < t < 700\ °C$	Defective contacts between bolted connections (particularly between aluminium busbar), gliding contacts, contacts within selector switch (pyrolitic carbon formation), connections from cable and draw-rod of bushings
		Circulating currents between yoke clamps and bolts, clamps and laminations, in ground wiring, defective welds or clamps in magnetic shields
		Abraded insulation between adjacent parallel conductors in windings
T3	Thermal fault $t > 700\ °C$	Large circulating currents in tank and core
		Minor circulation currents in tank walls created by a high uncompensated magnetic field
		Shorting links in core steel laminations

A.2.3 Identification of faults by DGA

Table 1 (see 5.4) applies directly to all transformer sub-types, except those equipped with a communicating OLTC. In the latter cases, if C_2H_2/H_2 is higher than 2 to 3, there may be contamination from the OLTC into the main tank, in which case Table 1 does not apply or applies with care, after subtracting background contamination from the OLTC (see 5.7).

Any gas formation below typical values of gas concentration and rates of gas increase should not be considered as an indication of "fault", but rather as "normal gas formation". Ratios are not significant in such a case (see Note 2 of Table 1).

In the case of air-breathing power transformers, losses of gas occur very slowly with time by diffusion through the conservator or as a result of oil expansion cycles, with the result that the measured gas levels may be slightly less than the gas levels actually formed in the transformer. However, there is no agreement concerning the magnitude of this diffusion loss in service, some considering it as totally negligible, others as potentially significant, depending on the type of equipment considered. In case of doubt, to get an idea of the volume ventilated it may be expedient to measure the gas concentration in the conservator as well. Significant diffusion losses may affect gas ratios, typical values of gas concentrations and rates of gas increase (see 6.1).

A.2.4 Typical concentration values

Important note: Clause A.1: General warning, shall be consulted before using A.2.4.

Ranges of 90 % typical gas concentration values observed in power transformers, from about 25 electrical networks worldwide and including more than 20 000 transformers, are given in Table A.2. For hydrogen, for example, one network reported a typical value of 50 μl/l, another one 150 μl/l and the 23 others reported values between 50 μl/l and 150 μl/l. These ranges of values have been reported by CIGRE SC D1 and A2 (TF11) and approved by IEC TC 10 and TC 14.

Table A.2 – Ranges of 90 % typical gas concentration values observed in power transformers, in μl/l

	C_2H_2	H_2	CH_4	C_2H_4	C_2H_6	CO	CO_2
All transformers		50 – 150	30 – 130	60 – 280	20 – 90	400 – 600	3 800 – 14 000
No OLTC	2 – 20						
Communicating OLTC	60 – 280						

"Communicating OLTC" in Tables A.2 and A.3 means that some oil and/or gas communication is possible between the OLTC compartment and the main tank or between the respective conservators. Gases produced in the OLTC compartment may contaminate the oil in the main tank and affect concentration values in these types of equipment. "No OLTC" refers to transformers not equipped with an OLTC, or equipped with a tap changer not communicating with or leaking to the main tank.

Typical values in Table A.2 apply to both breathing and sealed transformers, and correspond mostly to core-type transformers. Values in shell-type transformers are likely to be higher. In two countries, values for C_2H_6 are higher. In one country where transformers are operated below nominal load, values for CH_4 and CO and particularly for C_2H_4 are lower. In one country, values of 0,5 μl/l for C_2H_2 and 10 μl/l for C_2H_4 are reported. Values for H_2 may be higher in transformers where reactions between oil and transformer components (paints, metals) are occurring. Values in transformers frequently degassed, a practice used in a few countries, should not be compared with values of Table A.2.

A.2.5   Typical rates of gas increase

Important note: Clause A.1, General warning, shall be consulted before using A.2.5.

Ranges of 90 % typical rates of gas increase observed in power transformers, from four electrical networks and including more than 20 000 DGA analyses, are given in Table A.3. These ranges of values have been reported by CIGRE SC D1 and A2 (TF11) and approved by IEC/TC 10 and TC 14.

Table A.3 – Ranges of 90 % typical rates of gas increase observed in power transformers (all types), in μl/l/year

	C_2H_2	H_2	CH_4	C_2H_4	C_2H_6	CO	CO_2
All transformers		35 – 132	10 – 120	32 – 146	5 – 90	260 – 1 060	1 700 -10 000
No OLTC	0 – 4						
Communicating OLTC	21 – 37						

Typical values in Table A.3 are valid for large power transformers with an oil volume >5 000 l. Values in small transformers (<5 000 l) are usually lower. Values in the early and late years of the equipment tend to be higher than the average values of Table A.3.

Values of Table A.3 may be converted into ml/day when the transformer oil volume is known. In some countries, it is preferred to express rates of gas increase in ml/day. Values in Table A.3 should not be used to calculate concentration values after several years and compare them to values in Table A.2, since values in these two tables are affected differently by the shape of their respective cumulative curves and gas losses.

When calculating typical rates of increase of individual networks, intervals should be chosen to provide an acceptable accuracy of results.

A.2.6   Specific information to be added to the DGA report (see Clause 10)

Specific information to be added to the DGA report is as follows:

–   power rating;

–   transformer sub-type: air-breathing or sealed;

–   oil temperature;

–   type of cooling system: ONAN (oil natural air natural), OFAF (oil forced air forced), etc.;

–   date of manufacturing;

–   type of OLTC and whether it is communicating with the main tank or not;

–   number of OLTC operations, if known;

–   load since last DGA.

NOTE   OLTCs are often composed of a selector switch, located in the oil of the main tank, and of a diverter switch, located in a separate tank but on the same operating axle.

A.3   Industrial and special transformers

A.3.1   Specific sub-types

Specific sub-types of industrial and special transformers are as follows:

–   furnace transformers;

–   rectifier transformers;

–   railway transformers;

–   distribution transformers below 10 MVA, not from utilities.

–   submersible distribution transformers

–   wind farm transformers

A.3.2   Typical faults

See Table A.1.

A.3.3   Identification of faults by DGA.

See A.2.3.

A.3.4   Typical concentration values

See Table A.4.

The values given in table A.4 are for information only.

**Table A.4 – Examples of 90 % typical concentration
values observed on individual networks**

Values in microlitres per litre

Transformer sub-type	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Furnace	200	800	6 000	150	150	200	a
Distribution	100	200	5 000	50	50	50	5
Submersible	86	628	6 295	21	4	6	<S b

NOTE   The values listed in this table were obtained from two individual networks. Values on other networks may differ.

a   The data are influenced by the design and assembly of the on-load tap changer. For this reason, no statistically significant value can be proposed for acetylene.

b   < S means less than the detection limit.

A.4   Instrument transformers

A.4.1   Specific sub-types

CT: Current transformers (eyebolt or hairpin design)

VT: Voltage transformers

CTCV: Combined transformers (current-voltage)

CIVT: Cascade (inductive) voltage transformers

CVT: Capacitor voltage transformers

MVT: Magnetic voltage transformers (see [2]).

NOTE   Definitions of these specific sub-types can be found in [5].

A.4.2   Typical faults

See table A.5.

Failure rates have been reported as being about 1 % of the total population (see [2]), although much higher rates were observed on a limited number of sub-groups.

The most frequent final failures involve local or catastrophic dielectric breakdown of paper insulation, following lengthy partial discharge activity and/or thermal runaways.

Table A.5 – Typical faults in instrument transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from poor impregnation, humidity in paper, oil supersaturation, puckers or folds in paper, leading to X-wax deposition and increased dielectric losses
		Discharges related to switching operations from a nearby substation bus system (in the case of CTs) or to overvoltages at the edges of capacitor unit sections (case of CVTs)
D1	Discharges of low energy	Sparking around loose connections or floating metal strips
		Tracking in paper
		Arcing in static shielding connections
D2	Discharges of high energy	Local short circuits between capacitive stress grading foils, with high local current densities able to melt down foils
		General short circuits with power follow-through are often destructive, resulting in equipment breakage or explosion, and a DGA is not always possible after failure
T2	Thermal fault 300 °C < t < 700 °C	Circulating currents in paper insulation resulting from high dielectric losses, related to X-wax contamination, moisture or incorrect selection of insulating materials, and resulting in dielectric heating and thermal runaways
		Bad contacts in connections or welds
		Overheating due to the ferroresonant circuit in MVTs
T3	Thermal fault t > 700 °C	Circulating currents on steel lamination edges

A.4.3   Identification of faults by DGA

Table 1 (see 5.4) applies to all sub-types, with CH_4/H_2 lower than 0,2 instead of lower than 0,1 for partial discharges.

A.4.4   Typical concentration values

Ranges of 90 % typical values observed in instrument transformers are given in Table A.6. The 90 % normality percentage is the most frequently used. Factors of influence are equipment sub-type, fault type, and age.

The values given in Table A.6 are for information only.

**Table A.6 – Ranges of 90 % typical concentration
values observed in instrument transformers**

Values in microlitres per litre

Transformer sub-type	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
CT	6 – 300	250 – 1 100	800 – 4 000	11 – 120	7 – 130	3 – 40	1 – 5
VT	70 – 1 000					20 – 30	4 – 16
NOTE 1 The values listed in this table were obtained from several networks. Values on other networks can differ.							
NOTE 2 The value for H_2 in CTs is much lower for rubber seals (±20 μl/l) than for metal seals (±300 μl/l).							

Table A.7 provides the maximum admissible values for sealed instrument transformers without any action to be taken on the transformer, which have been proposed by IEC TC 38:

Table A.7 – Maximum admissible values for sealed instrument transformers

Values in microlitres per litre

H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
300	300	900	30	50	10	2

A.5 Bushings

A.5.1 Specific sub-types

Specific sub-types of bushings are as follows:

– condenser type;

– non-condenser type.

A.5.2 Typical faults

See Table A.8.

In a number of instances, partial discharges result in increased dielectric losses, thermal runaway and final breakdown.

Most frequent final failures are related to the breakdown of core insulation between short-circuited layers (as a result of partial discharges or thermal runaway), flashovers along the internal surface of the porcelain (often resulting in explosions) and flashovers along the core surface.

Table A.8 – Typical faults in bushings

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from humidity in paper, poor im-pregnation, oil supersaturation or contamination, or X-wax deposition. Also in loose insulating paper displaced during transportation with puckers or folds in paper
D1	Discharges of low energy	Sparking around loose connections at capacitive tap
		Arcing in static shielding connections
		Tracking in paper
D2	Discharges of high energy	Localized short-circuits between capacitive stress grading foils, with high local current densities able to melt down foils (see definition of D2 in 5.3), but not leading to the explosion of the bushing
T2	Thermal fault 300 °C < t < 700 °C	Circulating currents in paper insulation resulting from high dielectric losses, related to contamination or improper selection of insulating materials, and resulting in thermal runaways
		Circulating currents in poor connections at bushing shield or high voltage lead, with the temperature transmitted inside the bushing through conduction by the conductor

A.5.3 Identification of faults by DGA

A simplified table of interpretation is proposed as shown in Table A.9.

Table A.9 – Simplified interpretation scheme for bushings

Fault	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$	$\dfrac{CO_2}{CO}$
PD		<0,07		
D	>1			
T			>1	
TP				<1, >20

In cases where a single characteristic fault cannot be attributed using this simplified table, or when a more precise diagnosis is required, the general Table 1 should be used.

NOTE   Some modern bushings contain mixtures of mineral oil and dodecylbenzene (DDB), in proportions not known. Gas compositions evolved from DDB are not the same as from mineral oil, and DDB absorbs more gas than mineral oil.

A.5.4   Typical concentration values

The following 95 % typical values are proposed.

The values given in Table A.10 are for information only.

Table A.10 – 95 % typical concentration values in bushings

Values in microlitres per litre

H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
140	1 000	3 400	40	70	30	2

A.6   Oil-filled cables

A.6.1   Typical faults

Discharges and hot spots at cable terminations or junctions.

A.6.2   Identification of faults by DGA

Table 1 applies.

DGA is difficult to apply in cables due to the lack of representative oil samples (sampling sometimes possible only a long distance from the fault; lack of oil convection; gas trapped in paper insulation).

Also, modern cables often contain mixtures of mineral oil and dodecylbenzene (DDB), in proportions not known. Gas compositions evolved from DDB are not the same as from mineral oil, and DDB absorbs more gas than mineral oil under electric stress.

A.6.3   Typical concentration values

The values given in Table A.11 are for information only.

The data are coming from one particular network and only 95% values are available. The following 95 % typical concentration values have been observed on cables.

Table A.11 – Ranges of 95 % typical concentration values observed on cables

Values in microlitres per litre

H$_2$	CO	CO$_2$	CH$_4$	C$_2$H$_6$	C$_2$H$_4$	C$_2$H$_2$
150 – 500	40 – 100	220 – 500	5 – 30	10 – 25	3 – 20	2 – 10

NOTE   These values are examples taken from one particular network. Values on other networks and with different types of cable designs may differ.

A.7   Switching equipment

A.7.1   Specific sub-types

Specific sub-types of switching equipment are as follows:

– on-load tap-changers (OLTC) (vacuum and non-vacuum), including selector switches;

– switchgear.

A.7.2   Normal operation

The large majority of non-vacuum on-load tap-changers (OLTCs) of the reactive or resistive type produce gases of the arcing type D1 or D2 during their normal operation, because of the arc-breaking-in-oil activity on the switching contacts. Change-over selector contacts or commutation contacts of vacuum type models can produce low amounts of D1 gases.

Some vacuum or non-vacuum resistive type models can produce T2 or T3 gas patterns, respectively under certain load conditions, not indicating any thermal irregularities.

A.7.3   Typical faults

See Table A.12.

Table A.12 – Typical faults in switching equipment

Type	Fault	Examples
D1	Discharges of low energy	Normal operation of OLTC, selectors Arcing on off-load selector switch ring, OLTC connections
D2	Discharges of high energy	Switch contacts do not reach their final position but stop halfway, due to a failure of the rotating mechanism, inducing a sparkover discharge Arcing on off-load selector switch ring, OLTC connections, of high energy or with power follow-through, with failure often transmitted to transformer windings
T2, T3	Thermal fault	Increased resistance between contacts of OLTC or change-over selector, as a result of pyrolitic carbon growth, selector deficiency or a very large number of operations Transition resistor temperatures >700°C due to faulty (prolonged) switching sequence

NOTE 1   In this table are given examples of faults detected by DGA of oil samples taken from the switching compartment. NOTE 2   Switching equipment attached to transformers is complex and of various designs. The detailed description of these systems and the interpretation of DGA results can be obtained from equipment manufacturer, particularly concerning the types of discharges and degree of heating that is normal for the specific equipment.

A.7.4   Identification of faults by DGA

Two methods are used for the identification of faults in OLTCs:

1) The C_2H_4/C_2H_2 ratio represents an individual fingerprint of the application. It is up to users to define ratio value ranges for normal operation, depending on the OLTC model and operation mode. Deviations of the found range indicate irregularities.

2) The Duval-triangle-2-method (see Annex B): for the large majority of OLTCs, normal operation will show coordinates in the "N" zone. Nevertheless, some applications will show coordinates in the X3, T2 or T3 zone for normal operation [11], as described in A.7.2. As long as coordinates don't move significantly, these fingerprints don't indicate a fault. With this, the triangle method can be used to track the evolution of gas formation graphically to detect excessive arcing or heating.

NOTE   All DGA interpretations for OLTC are strongly model type and operation dependent. In case of suspect DGA results, contact the manufacturer.

A.8   Equipment filled with non-mineral fluids

Gases formed in equipment filled with non-mineral fluids (natural esters, synthetic esters, silicones) are the same as with mineral oils, however, some adjustments to zone boundaries used for mineral oils are necessary to identify faults in non-mineral oils, as indicated in [8].

Examples of typical values observed with such fluids are also indicated in [8].

Annex B
(informative)

Graphical representations of gas ratios (see 5.10)

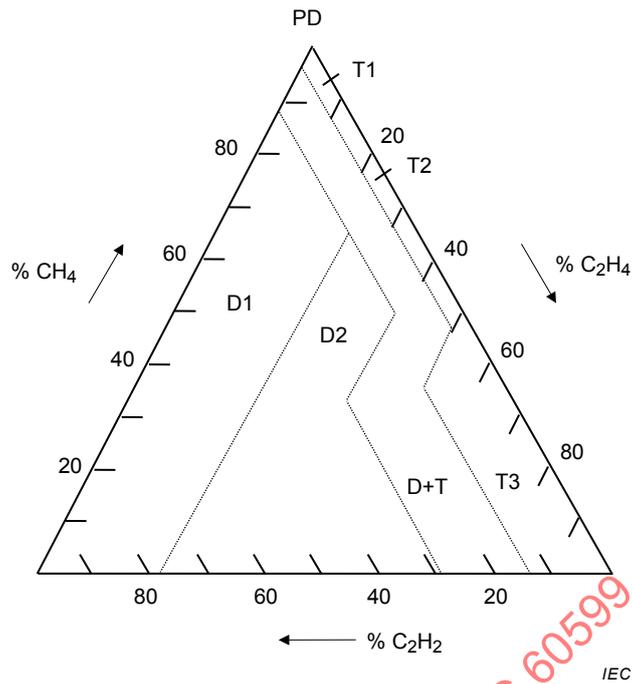Graphical representations of gas ratios are given in Figures B.1, B.2, B.3 and B.4.

Key

PD   partial discharges

D1   discharges of low energy

D2   discharges of high energy

T1   thermal fault, $t < 300\ °C$

T2   thermal fault, $300\ °C < t < 700\ °C$

T3   thermal fault, $t > 700\ °C$

NOTE 1   The arrow indicates increasing temperature.

NOTE 2   The axes are limited to values of 10 for clarification of presentation, but actually extend to unlimited values. The coordinates of each zone are the same as in Table 1 and Figure B.2.

Figure B.1 – Graphical representation 1 of gas ratios (see [3])

Key

PD partial discharges

D1 discharges of low energy

D2 discharges of high energy

T1 thermal fault, $t < 300$ °C

T2 thermal fault, 300 °C $< t < 700$ °C

T3 thermal fault, $t > 700$ °C

NOTE 1   Each of the cases defined in Table 1 is represented by a volume or "box" on the 3-D graphic.

NOTE 2   The coordinates of each box are the same as in Figure B.1 and Table 1. It is more convenient to use this representation with the help of a computer software package.

Figure B.2 – Graphical representation 2 of gas ratios

PD

T1

80

20

T2

% CH₄ 60 40 % C₂H₄

D1

D2

40 60

20 80

D+T T3

80 60 40 20

% C₂H₂

IEC

where

$$\% \; C_2H_2 = \frac{100\,x}{x+y+z} \qquad \text{for } x = \left[C_2H_2\right] \text{ in microlitres per litre}$$

$$\% \; C_2H_4 = \frac{100\,y}{x+y+z} \qquad \text{for } y = \left[C_2H_4\right] \text{ in microlitres per litre}$$

$$\% \; CH_4 = \frac{100\,z}{x+y+z} \qquad \text{for } z = \left[CH_4\right] \text{ in microlitres per litre}$$

Key

PD partial discharges

D1 discharges of low energy

D2 discharges of high energy

T1 thermal fault, $t <$ 300 °C

T2 thermal fault, 300 °C $< t <$ 700 °C

T3 thermal fault, $t >$ 700 °C

Limits of zones			
PD	98 % CH_4		
D1	23 % C_2H_4	13 % C_2H_2	
D2	23 % C_2H_4	13 % C_2H_2	40 % C_2H_4	29 % C_2H_2
T1	4 % C_2H_2	20 % C_2H_4	
T2	4 % C_2H_2	20 % C_2H_4	50 % C_2H_4
T3	15 % C_2H_2	50 % C_2H_4	

**Figure B.3 – Graphical representation 3 of gas ratios –
Duval's triangle 1 for transformers, bushings and cables(see [4])**

NOTE   See Figure B.3 for calculation of triangular coordinates.

Key

N   normal operation

T3   severe coking of contacts at $t > 700$ °C

T2   severe coking of contacts at $t > 300$ °C

X3   coking in progress or abnormal arcing D2

D1   abnormal arcing D1

X1   overheating at $t < 300$ °C

Limits of zones				
N	19 % CH_4	23 % C_2H_4	2 % CH_4	6 % C_2H_4
T3	50 % C_2H_4	15 % C_2H_2		
X3	23 % C_2H_4	15 % C_2H_2		
T2	23 % C_2H_4	15 % C_2H_2		
D1	19 % CH_4	6 % C_2H_4	2 % CH_4	23 % C_2H_4
X1	19 % CH_4	23 % C_2H_4		

**Figure B.4 – Graphical representation 4 of gas ratios –
Duval's triangle 2 for OLTCs (see A.7.2)**

NOTE   For some OLTCs mentioned in A.7.2 and A.7.3, normal gassing occurs either in zone N, T3, T2 or X3, depending on specific OLTCs models and operating conditions [11].

Bibliography

[1]   OOMMEN et al, *"New mechanisms of moderate hydrogen gas generation in oil-filled transformers", CIGRE,* Paris 1998, paper 12-206

[2]   EPRI Workshop, *Proceedings on Failed High Voltage Instrument Transformers, 1992*

[3]   DÖRNENBURG et al, *"Operational supervision by testing of insulating oil*", *Etz N° 98, 1977, pp 211-215*

[4]   DUVAL et al*, "Update on Hydro Quebec's experience in the interpretation of dissolved gas analysis in HV transformers",* CIGRE Symposium Berlin 1993*, Paper 110-14*

[5]   IEC 60050-321:1986, "*International Electrotechnical Vocabulary (IEV) – Chapter 321: Instrument transformers"*

[6]   CIGRE Technical Brochure 296, 2006, "*Recent developments on the interpretation of dissolved gas analysis in transformers"*

[7]   HOEHLEIN and FROTSCHER, *"Carbon oxides in the interpretation of dissolved gas analysis in transformers and tap changers", IEEE EI Mag., Dec. 2010*

[8]   CIGRE Technical Brochure 443: 2010, "*DGA in Non-Mineral Oils and Load Tap Changers and Improved DGA Diagnosis Criteria"*

[9]   CIGRE *Technical Brochure 409:* 2010*, "Report on Gas Monitors for Oil-Filled Electrical Equipment"*

[10]   CIGRE WG D1.47, Report to be published in 2015

[11]   DUVAL, *EuroTechCon Conference, Glasgow, "Application of Duval Triangles 2 to DGA analysis in load tapchangers", Nov. 2012*

[12]   ASTM Method D7150, "*Standard Test Method for the Determination of Gases Characteristic of Insulating Liquids under Thermal Stress", 2013*

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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**MATÉRIELS ÉLECTRIQUES REMPLIS D'HUILE MINÉRALE
EN SERVICE – LIGNES DIRECTRICES POUR L'INTERPRÉTATION
DE L'ANALYSE DES GAZ DISSOUS ET DES GAZ LIBRES**

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Cette troisième édition annule et remplace la deuxième édition parue en 1999 et l'Amendement 1:2007. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) révision de 5.5, 6.1, 7, 8, 9, 10, A.2.6, A.3, A.7 ;

b) ajout d'un nouveau paragraphe 4.3;

c) enrichissement de la Bibliographie;

d) révision de la Figure 1;

e) ajout de la Figure B.4.

Le texte de cette norme est issu des documents suivants:

FDIS	Rapport de vote
10/967/FDIS	10/973/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette norme.

Cette publication a été rédigée selon les Directives ISO/IEC, Partie 2.

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INTRODUCTION

L'analyse des gaz libres et des gaz dissous dans l'huile (AGD) est l'un des outils de diagnostic les plus couramment utilisés pour la détection et l'évaluation de défauts dans les matériels électriques remplis de liquide isolant. Cependant, l'interprétation des résultats d'AGD est souvent complexe et il convient qu'elle soit toujours faite avec prudence, en faisant appel à des personnes expérimentées en maintenance des isolants.

La présente Norme internationale fournit des informations visant à faciliter cette interprétation. La première édition, parue en 1978, a bien servi l'industrie électrique, mais a montré ses limites, comme l'absence de diagnostic dans certains cas, l'absence de niveaux de concentration et le fait de reposer principalement sur l'expérience acquise avec les transformateurs de puissance. La deuxième édition a tenté de remédier à certaines de ces insuffisances. Les schémas d'interprétation étaient fondés sur des observations résultant d'examens effectués sur un grand nombre d'appareils remplis d'huile, après un défaut en service, et sur les niveaux de concentrations résultant d'analyses recueillies dans le monde entier.

MATÉRIELS ÉLECTRIQUES REMPLIS D'HUILE MINÉRALE EN SERVICE – LIGNES DIRECTRICES POUR L'INTERPRÉTATION DE L'ANALYSE DES GAZ DISSOUS ET DES GAZ LIBRES

1 Domaine d'application

La présente Norme internationale décrit comment les concentrations de gaz dissous ou de gaz libres peuvent être interprétées pour diagnostiquer l'état des matériels électriques remplis d'huile en service et pour proposer une intervention ultérieure.

La présente norme s'applique aux matériels électriques remplis d'huile minérale isolante et isolés par des isolants solides constitués de papier ou de carton cellulosiques. Des informations relatives aux types spécifiques de matériels tels que les transformateurs (de puissance, de mesure, industriels, ferroviaires, de distribution), les réactances, les traversées, les appareillages de connexion et les câbles à huile sont données, à titre informatif seulement, dans les notes d'application (voir Annexe A).

La présente norme peut être appliquée, mais uniquement avec prudence, à d'autres systèmes d'isolation liquide-solide.

Dans tous les cas, il convient que les indications obtenues soient considérées seulement comme des lignes directrices et il convient que toute action qui en résulte ne soit entreprise qu'après un avis technique autorisé.(une confirmation technique d'un expert)

2 Références normatives

Les documents suivants sont cités en référence de manière normative, en intégralité ou en partie, dans le présent document et sont indispensables pour son application. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60050-191:1990, *Vocabulaire Électrotechnique International – Chapitre 191: Sûreté de fonctionnement et qualité de service* (disponible à l'adresse http://www.electropedia.org)

IEC 60050-192:2015, *Vocabulaire Électrotechnique International – Partie 192: Sûreté de fonctionnement* (disponible à l'adresse http://www.electropedia.org)

IEC 60050-212:2010, *Vocabulaire Électrotechnique International – Partie 212: Isolants électriques solides, liquides et gazeux* (disponible à l'adresse http://www.electropedia.org)

IEC 60050-604:1987, *Vocabulaire Électrotechnique International – Chapitre 604: Production, transport et distribution de l'énergie électrique – Exploitation* (disponible à l'adresse http://www.electropedia.org)

IEC 60475, *Méthode d'échantillonnage des liquides isolants*

IEC 60567:2011, Matériels électriques immergés – *Échantillonnage de gaz et analyse des gaz libres et dissous – Lignes directrices*

IEC 61198, *Huiles minérales isolantes – Méthodes pour la détermination du 2-furfural et ses dérivés*

3   Termes, définitions et abréviations

3.1   Termes et définitions

Pour les besoins du présent document, les termes et définitions suivants, dont certains sont basés sur l'IEC 60050-191, l'IEC 60050-192, l'IEC 60050-212 et l'IEC 60050-604, s'appliquent.

3.1.1
défaut
événement imprévu ou défectuosité (anomalie) d'un dispositif qui peut donner lieu à une ou plusieurs défaillances de ce dispositif, ou d'autres dispositifs associés

[SOURCE: IEC 60050-604:1987, 604-02-01]

3.1.2
défaut sans dommage
défaut ne nécessitant ni réparation ni remplacement à l'endroit du défaut

Note 1 à l'article: Des exemples types sont les arcs auto-extinguibles dans les matériels de coupure ou un échauffement général sans carbonisation du papier ou encore un stray gassing de l'huile.

[SOURCE: IEC 60050-604:1987, 604-02-09]

3.1.3
défaut avec dommage
défaut qui a provoqué des détériorations nécessitant une réparation ou un remplacement à l'endroit du défaut

[SOURCE: IEC 60050-604:1987, 604-02-08]

3.1.4
incident
événement, d'origine externe ou interne, se produisant dans un matériel ou dans un réseau et qui en perturbe le bon fonctionnement

Note 1 à l'article: Pour les besoins de la présente norme, le terme "incidents" est associé à des défaillances internes.

Note 2 à l'article: Pour les besoins de la présente norme, les exemples types d'"incidents" désignent des alarmes de gaz, un déclenchement du matériel ou des fuites du matériel.

[SOURCE: IEC 60050-604:1987, 604-02-03]

3.1.5
défaillance
perte de l'aptitude à fonctionner tel que requis

Note 1 à l'article: Dans les matériels électriques, une défaillance est la conséquence d'un défaut avec dommage ou d'un incident nécessitant la mise hors service, la réparation ou le remplacement du matériel, tel qu'un claquage interne, une rupture de la cuve, un incendie ou une explosion.

[SOURCE: IEC 60050-192:2015, 192-03-01]

3.1.6
défaut électrique
décharge partielle ou disruptive à travers l'isolation

3.1.7
décharge partielle
décharge électrique dont le trajet se développe sur une partie seulement de l'isolation entre des conducteurs

Note 1 à l'article: Une décharge partielle peut se produire au sein même de l'isolation, ou à partir d'un conducteur.

Note 2 à l'article: Les scintillations de faible énergie à la surface de matériaux isolants sont souvent décrites comme des décharges partielles, mais il convient plutôt de les considérer comme des décharges disruptives de faible énergie, étant donné qu'elles sont le résultat de claquages diélectriques locaux de haute densité d'ionisation, ou de petits arcs, selon les conventions de la physique.

Note 3 à l'article: Pour les besoins de la présente norme, la considération suivante peut également être ajoutée:

–   L'effet couronne est une forme de décharge partielle qui se produit dans les milieux gazeux autour des conducteurs placés loin de toute isolation solide ou liquide. Ce terme ne doit pas être employé comme terme général pour désigner toutes les formes de décharges partielles.

–   En raison de décharges d'effet couronne, de la cire-X, une substance solide composée de fragments polymérisés des molécules du liquide de départ peut se former.

[SOURCE: IEC 60050-212:2010, 212-11-39]

3.1.8
amorçage
décharge (disruptive)
passage d'un arc à la suite d'un claquage

Note 1 à l'article: Le terme "amorçage" (en anglais: "sparkover") est utilisé lorsque la décharge disruptive se produit dans un diélectrique gazeux ou liquide.

Le terme "contournement" (en anglais: "flashover ") est utilisé lorsque la décharge disruptive longe la surface d'un diélectrique solide entouré d'un gaz ou d'un liquide isolant.

Le terme "perforation" (en anglais: "puncture ") est utilisé lorsque la décharge disruptive se produit à travers un diélectrique solide.

Note 2 à l'article: Les décharges sont souvent appelées arcs, claquages ou courts-circuits. Les termes plus précis suivants sont également utilisés dans certains pays:

–   cheminement (dégradation progressive de la surface d'un matériau isolant solide par des décharges locales formant des chemins conducteurs ou partiellement conducteurs);
–   étincelles qui, selon les conventions de la physique, sont des claquages diélectriques locaux de forte densité d'ionisation ou de petits arcs.

[SOURCE: IEC 60050-604:1987, 604-03-38]

3.1.9
défaut thermique
élévation (augmentation) excessive de la température dans l'isolation

Note 1 à l'article: Les causes types sont

–   un refroidissement insuffisant;

–   des courants trop élevés circulant dans des parties métalliques adjacentes (en raison de mauvais contacts, des courants de Foucault, des pertes vagabondes ou des flux de fuite);

–   des courants trop élevés circulant dans l'isolation (en raison de pertes diélectriques élevées), conduisant à un emballement thermique;

–   un échauffement d'enroulement interne ou de jonction de traversée;

–   une surcharge.

3.1.10
valeurs typiques des concentrations de gaz
concentrations de gaz se trouvant normalement(habituellement) dans les matériels en service ne présentant aucun symptôme de défaillance, et qui ne sont dépassées que par un pourcentage arbitraire de teneurs en gaz plus élevées (par exemple 10 % (voir 8.2.1))

Note 1 à l'article: Les valeurs typiques sont différentes selon les types de matériels et les réseaux électriques, et selon les pratiques d'exploitation (niveaux de charge, climat, etc.).

Note 2 à l'article: Les valeurs typiques, dans nombre de pays et pour beaucoup d'utilisateurs, sont appelées "valeurs normales", mais ce terme n'a pas été retenu ici, pour éviter de possibles fausses interprétations.

3.2 Abréviations

3.2.1 Noms et formules chimiques

Nom	Formule
Azote	N_2
Oxygène	O_2
Hydrogène	H_2
Monoxyde de carbone	CO
Dioxyde de carbone	CO_2
Méthane	CH_4
Éthane	C_2H_6
Éthylène	C_2H_4
Acétylène	C_2H_2

NOTE   Acétylène et éthyne sont tous deux utilisés pour C_2H_2; éthylène et éthène sont tous deux utilisés pour C_2H_4

3.2.2 Abréviations générales

D1   décharges de faible énergie

D2   décharges de forte énergie

AGD: analyse des gaz dissous

CIGRE   Conseil International des Grands Réseaux Électriques

DP   décharges partielles et effet couronne

S   limite de détection analytique

T1   défaut thermique, $t < 300$ °C

T2   défaut thermique, 300 °C $< t < 700$ °C

T3   défaut thermique, $t > 700$ °C

T   défaut thermique

D   défaut électrique

TP   défaut thermique dans le papier

ppm   parties par million par volume de gaz dans l'huile, équivalent à μl(de gaz)/l(d'huile). Voir l'IEC 60567:2011, 8.7, note 1

OLTC   changeur de prises en charge

4   Mécanismes de formation des gaz

4.1   Décomposition de l'huile

Les huiles minérales isolantes sont constituées d'un mélange de molécules de différents hydrocarbures, contenant des groupements chimiques CH_3, CH_2 et CH reliés les uns aux autres par des liaisons moléculaires carbone-carbone. Des défauts thermiques ou électriques peuvent couper certaines de ces liaisons C-H et C-C avec la formation de petits fragments instables, sous une forme radicalaire ou ionique, tels que $H^\bullet$, $CH_3^\bullet$, $CH_2^\bullet$, $CH^\bullet$ or $C^\bullet$ (parmi de nombreuses autres formes plus complexes), qui se recombinent rapidement, par des réactions complexes, en molécules de gaz comme l'hydrogène (H-H), le méthane (CH_3-H), l'éthane (CH_3-CH_3), l'éthylène ($CH_2 = CH_2$) ou l'acétylène (CH $\equiv$ CH). Des hydrocarbures gazeux en C_3 et C_4, ainsi que des particules solides de carbone et des polymères hydrocarbonés (cire-X), sont d'autres produits de recombinaison possibles. Les gaz formés se dissolvent dans l'huile, ou s'accumulent sous forme de gaz libres s'ils sont produits

rapidement en grandes quantités, et peuvent être analysés par AGD conformément à l'IEC 60567.

Les défauts de faible énergie, tels que les décharges partielles de type plasma froid (décharges couronne), favorisent la coupure des liaisons C-H les plus faibles (338 kJ/mole) par des réactions d'ionisation, et l'accumulation d'hydrogène comme gaz principal de recombinaison. De plus en plus d'énergie et/ou des températures plus élevées sont nécessaires pour la coupure des liaisons C-C et leur recombinaison en gaz contenant une liaison simple C-C (607 kJ/mole), une double liaison C=C (720 kJ/mole) ou une triple liaison C≡C (960 kJ/mole), suivant des réactions présentant des similarités avec celles observées dans l'industrie du craquage du pétrole.

Ainsi, la formation d'éthylène est favorisée par rapport à celle de méthane et d'éthane à des températures supérieures à 500 °C environ (bien que l'éthylène soit toujours présent, mais en plus faibles quantités). L'acétylène exige des températures d'au moins 800 °C à 1 200 °C suivies d'une descente rapide à de plus basses températures pour pouvoir s'accumuler comme produit de recombinaison stable. L'acétylène se forme ainsi en quantités significatives principalement dans les arcs, où le canal ionisé conducteur est à plusieurs milliers de degrés Celsius, et où l'interface avec l'huile liquide avoisinante est nécessairement en dessous de 400 °C (température au-dessus de laquelle l'huile se vaporise complètement), avec une couche de vapeur d'huile et de gaz de décomposition entre les deux. L'acétylène peut toujours se former à des températures plus basses (<800 °C), mais en très faibles quantités. Les particules de carbone se forment entre 500 °C et 800 °C et s'observent effectivement après un claquage dans l'huile ou autour de points très chauds.

L'huile peut s'oxyder, avec la formation de faibles quantités de CO et de CO_2, qui peuvent s'accumuler en quantités plus importantes sur de longues durées.

4.2   Décomposition de l'isolation cellulosique

Les chaînes polymériques de l'isolation solide cellulosique (papier, carton, bois de calage) contiennent un grand nombre de noyaux anhydroglucosidiques, et des liaisons moléculaires C-O faibles et des liaisons glycosidiques qui sont thermiquement moins stables que les liaisons hydrocarbonées de l'huile, et qui se décomposent à des températures plus basses. Les vitesses de coupure de chaînes polymériques deviennent significatives à des températures supérieures à 105 °C, avec décomposition complète et carbonisation au-dessus de 300 °C (défaut avec dommage). Il se forme du monoxyde et du dioxyde de carbone, ainsi que de l'eau, et de faibles quantités d'hydrocarbures gazeux, de composés furaniques et autres composés. Les composés furaniques sont analysés conformément à l'IEC 61198, en complément à l'interprétation de l'AGD, pour confirmer si oui ou non l'isolation cellulosique est impliquée dans le défaut. La formation de CO et de CO_2 augmente non seulement avec la température, mais également avec la teneur en oxygène dissous dans l'huile et avec la teneur en eau du papier.

4.3   Stray gassing de l'huile

Le stray gassing a été défini par le CIGRE [6][1] comme la formation de gaz dans l'huile chauffée à des températures modérées (<200 °C). La formation de H_2, CH_4 et de C_2H_6 peut être observée dans tous les matériels à de telles températures, ou du fait de l'oxydation de l'huile selon sa structure chimique. Le stray gassing est un défaut sans dommage. Il peut être évalué à l'aide des méthodes décrites dans les références [6] et [12].

NOTE   Il a été observé dans certains cas que le stray gassing de l'huile est renforcé par la présence dans l'huile d'un additif passivant des métaux ou d'autres additifs.

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[1]   Les chiffres entre crochets se réfèrent à la Bibliographie.

4.4 Autres sources de gaz

Dans certains cas, des gaz peuvent se former, non pas à la suite de défauts dans le matériel, mais à cause de réactions chimiques de corrosion ou autres impliquant l'acier, les surfaces non peintes ou les peintures de protection.

De l'hydrogène peut être produit par réaction de l'acier et de l'acier galvanisé avec l'eau, tant que de l'oxygène est présent dans l'huile adjacente. Des quantités importantes d'hydrogène ont ainsi été observées dans des transformateurs qui n'avaient jamais été mis sous tension. De l'hydrogène peut aussi se former par réaction d'eau libre avec des revêtements spéciaux de surfaces métalliques, ou par réaction catalytique de certains types d'acier inoxydable avec l'huile, en particulier avec de l'huile à haute température contenant de l'oxygène dissous. De l'hydrogène, de l'acétylène et d'autres gaz peuvent aussi être présents dans de l'acier inoxydable neuf, absorbé pendant le procédé de fabrication, ou produit pendant le soudage, et libéré lentement dans l'huile. Des peintures internes du transformateur, comme les résines alkydes et les polyuréthannes modifiés, contenant des acides gras dans leur formulation, peuvent aussi former des gaz.

Des gaz peuvent aussi être produits, et de l'oxygène consommé, par exposition de l'huile à la lumière solaire.

De tels cas ne se produisent néanmoins qu'extrêmement rarement, et peuvent être détectés en effectuant des analyses d'AGD sur des matériels neufs qui n'ont jamais été mis sous tension, et par des essais de compatibilité des matériaux. La présence d'hydrogène en l'absence totale d'autres hydrocarbures gazeux peut être, par exemple, une indication d'un tel problème.

NOTE   Le cas des gaz provenant d'un défaut ancien et subsistant dans le transformateur est traité en 5.4.

5   Identification des défauts

5.1   Généralités

En service, toute formation de gaz, même minime, résulte d'une contrainte quelconque, même très faible, telle qu'un vieillissement thermique normal. Néanmoins, tant que la concentration de gaz reste en dessous des valeurs typiques et n'augmente pas de façon significative, il convient de ne pas la considérer comme l'indication d'un "défaut", mais plutôt comme le résultat d'une formation typique de gaz (voir Figure 1). Les valeurs typiques sont spécifiques à chaque type de matériel.

5.2   Composition des gaz dissous

Bien que le niveau de température atteint ou l'énergie mise en jeu dans le défaut favorisent la formation de certains gaz (voir 4.1), en pratique, des mélanges de gaz sont presque toujours obtenus. Une des raisons est thermodynamique: bien qu'ils ne soient pas favorisés, des gaz secondaires se forment toujours, mais en plus faibles quantités. Cependant, les modèles thermodynamiques existants issus de l'industrie pétrolière ne peuvent prédire avec précision la composition des gaz formés, parce que ces modèles correspondent à des équilibres idéaux de températures et de gaz qui n'existent pas dans les défauts réels. Des gradients élevés de température existent aussi en pratique, dus, par exemple à l'écoulement ou à la vaporisation de l'huile le long d'une surface très chaude. Ceci est particulièrement vrai pour les arcs de puissance qui transfèrent une grande quantité de chaleur à la couche de gaz de décomposition et de vapeur d'huile située entre l'arc et l'huile, expliquant probablement la formation accrue d'éthylène observée en plus de l'acétylène. D'autre part, les modèles thermodynamiques existants ne s'appliquent pas non plus au papier, qui se carbonise de façon irréversible au-dessus de 300 °C.

5.3   Types de défauts

L'examen interne de centaines de matériels défectueux a conduit aux grandes classes suivantes de défauts détectables visuellement:

– les décharges partielles (DP), de type plasma froid (couronne), avec dépôt possible de cire-X sur l'isolation en papier;

– les décharges de faible énergie (D1), dans l'huile et/ou le papier, mises en évidence par de plus larges perforations carbonisées à travers le papier, une carbonisation de la surface du papier (cheminement) ou des particules de carbone dans l'huile (comme dans le rupteur, suite aux manœuvres du changeur de prises); les décharges partielles de type étincelles, provoquant des microperformations carbonisées dans le papier, qui, cependant, peuvent ne pas être faciles à détecter;

– les décharges de forte énergie (D2), dans l'huile et/ou le papier, avec forts courants, mises en évidence par une destruction et une carbonisation importantes du papier, la fusion du métal aux extrémités de la décharge, une carbonisation importante de l'huile et, dans certains cas, le déclenchement du matériel, confirmant la forte intensité du courant de décharge;

– les défauts thermiques, dans l'huile et/ou le papier, en dessous de 300 °C, si le papier est devenu brun (T1), et au-dessus de 300 °C s'il s'est carbonisé (T2);

– les défauts thermiques de températures supérieures à 700 °C (T3) s'il existe une preuve solide d'une carbonisation de l'huile, d'une coloration du métal (800 °C) ou d'une fusion de métal (>1 000 °C).

5.4   Rapports fondamentaux de gaz

Chacune des six grandes classes de défauts donne naissance à une composition caractéristique en hydrocarbures gazeux, qui peut être mise sous la forme d'une table d'interprétation des AGD, telle que celle recommandée dans le Tableau 1, et en utilisant trois rapports de gaz fondamentaux:

$$\frac{C_2H_2}{C_2H_4} \qquad\qquad \frac{CH_4}{H_2} \qquad\qquad \frac{C_2H_4}{C_2H_6}$$

Le Tableau 1 s'applique à tous les types de matériels, avec quelques différences dans les limites des rapports de gaz, selon le type particulier de matériel.

Tableau 1 – Table d'interprétation d'AGD

Cas	Défaut caractéristique	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$
DP	Décharges partielles (voir notes 3 et 4)	NS [a]	<0,1	<0,2
D1	Décharges de faible énergie	>1	0,1 – 0,5	>1
D2	Décharges de forte énergie	0,6 – 2,5	0,1 – 1	>2
T1	Défaut thermique t <300 °C	NS [a]	>1 mais NS [a]	<1
T2	Défaut thermique 300 °C < t <700 °C	<0,1	>1	1 – 4
T3	Défaut thermique t >700 °C	<0,2 [b]	>1	>4

NOTE 1 Dans certains pays, le rapport C_2H_2/C_2H_6 est utilisé plutôt que le rapport CH_4/H_2. Également, dans certains pays, des limites légèrement différentes des rapports de gaz sont utilisées.

NOTE 2   Les conditions de calcul des rapports de gaz sont indiquées en 6.1 c).

NOTE 3 CH_4/H_2 <0,2 pour les décharges partielles dans les transformateurs de mesure, CH_4/H_2 <0,07 pour les décharges partielles dans les traversées.

NOTE 4   Des types de décompositions gazeuses similaires aux décharges partielles ont été observés à la suite du dégagement gazeux vagabond de l'huile (voir 4.3).

[a]   NS = Non significatif, quelle que soit la valeur.

[b]   Une valeur croissante de la quantité de C_2H_2 peut indiquer que le point chaud est à une température supérieure à 1 000 °C.

Des exemples typiques de défauts correspondant aux six cas du Tableau 1, observés dans les différents types de matériels (transformateurs de puissance, de mesure, etc.) peuvent être consultés dans les Tableaux A.1, A.5, A.8 et A.12.

Dans le Tableau 1 figure un certain recouvrement entre les défauts D1 et D2, ce qui signifie qu'une double attribution de D1 ou de D2 doit être donnée dans certains cas de résultats d'AGD. Cependant, la distinction entre D1 et D2 a été conservée parce que la quantité d'énergie de la décharge peut accroître de manière significative les dommages possibles causés au matériel et nécessiter des mesures préventives différentes. Le Tableau 1 s'applique aux transformateurs. Pour les matériels de coupure, voir l'Article A.7 et la référence [8] de la bibliographie.

NOTE Les combinaisons de rapports de gaz qui sortent des limites du Tableau 1, et ne correspondent pas à un défaut caractéristique de ce tableau, peuvent être considérées comme un mélange de défauts, ou comme de nouveaux défauts qui se superposent à un niveau élevé de gaz produit antérieurement (voir 6.1).

Dans un tel cas, le Tableau 1 ne peut pas fournir de diagnostic, mais les représentations graphiques de l'Annexe B peuvent être utilisées pour voir quel défaut caractéristique du Tableau 1 est le plus proche.

Le schéma d'interprétation simplifié, donné au Tableau 2, peut également être utilisé dans un tel cas pour obtenir au moins une distinction approximative entre décharges partielles (DP), décharges (D) et défaut thermique (T), plutôt que pas de diagnostic du tout.

Tableau 2 – Schéma d'interprétation simplifié

Cas	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$
DP		<0,2	
D	>0,2		
T	<0,2		

5.5 Rapport CO_2/CO

La formation de CO_2 et de CO à partir de l'isolation en papier imprégné d'huile augmente rapidement avec la température. Des valeurs élevées de CO (par exemple, 1 000 ppm) et des rapports CO_2/CO inférieurs à 3 sont généralement considérés comme l'indication d'une implication probable du papier dans le défaut, avec une carbonisation possible, en présence d'autres gaz de défaut.

Cependant, dans certains transformateurs récents de type scellé, ou dans les transformateurs ouverts (respiration libre) fonctionnant sous une charge constante (c'est-à-dire à respiration faible), le CO peut s'accumuler dans l'huile, produisant le rapport $CO_2/CO < 3$, sans aucune irrégularité ou aucun défaut en l'absence de formation d'autres gaz tels que le H_2 ou des hydrocarbures [7].

Des valeurs élevées de CO_2 (>10 000 ppm) et des rapports CO_2/CO élevés (>10) peuvent indiquer un léger (<160 °C) échauffement du papier [6, 8] ou une oxydation de l'huile, notamment dans le cas des transformateurs ouverts. Le CO_2 peut s'accumuler plus rapidement que le CO dans les transformateurs ouverts fonctionnant sous des charges variables du fait de leurs solubilités dans l'huile différentes. Ce phénomène, ainsi que la dégradation à long terme du papier à des températures basses (<160 °C), peut produire des rapports CO_2/CO plus élevés dans des matériels anciens.

Dans certains cas, des défauts localisés dans le papier ne produisent pas des quantités importantes de CO et de CO_2 et peuvent ne pas être détectés avec ces gaz (cas semblable avec des composés furaniques).

Par conséquent, l'implication des défauts dans le papier ne doit pas reposer uniquement sur le CO et le CO_2, mais doit être confirmée par la formation d'autres gaz ou par d'autres types d'analyses de l'huile.

Pour avoir des rapports CO_2/CO représentatifs de ce qui se passe dans le matériel, il convient tout d'abord de corriger les valeurs de CO_2 et de CO pour tenir compte de l'absorption possible du CO_2 de l'air, et des valeurs de CO_2 et de CO accumulées antérieurement (voir 6.1 et Article 9), résultant du vieillissement de l'isolation cellulosique, de l'échauffement des bois de calage ou de l'oxydation de l'huile à long terme (celle-ci étant fortement influencée par la disponibilité en oxygène due aux détails particuliers de construction du matériel et à son mode d'exploitation).

Les matériels respirants, par exemple, saturés à environ 9 % à 10 % d'air dissous, peuvent contenir jusqu'à 300 µl/l de CO_2 provenant de l'air. Dans les matériels scellés, l'air est normalement exclu, mais il peut entrer par des fuites et la concentration en CO_2 est en proportion de l'air présent.

Lorsqu'on soupçonne une dégradation anormale du papier, il est recommandé de demander une analyse supplémentaire (par exemple des composés furaniques) ou une mesure du degré de polymérisation d'échantillons de papier, quand cela est possible.

NOTE 1   Dans le cas des matériels contenant des quantités négligeables de papier (par exemple, la plupart des types modernes de changeurs de prises en charge (OLTC), la quantité de CO et de CO_2 peut augmenter avec l'oxydation de l'huile sous une contrainte thermique. Les valeurs des rapports CO_2/CO peuvent être assez différentes de celles observées avec les transformateurs.

NOTE 2   Des niveaux élevés de CO peuvent également se former dans le cas de décharges de forte énergie dans l'huile uniquement.

NOTE 3   Dans les transformateurs de mesure et dans certains types de traversées, des rapports faibles <3 sont observés, sans aucune dégradation du papier.

5.6 Rapport O_2/N_2

De l'oxygène (O_2) et de l'azote (N_2) dissous dans l'huile sont présents, en raison du contact avec l'air atmosphérique dans le conservateur des matériels respirants, ou de fuites dans les matériels scellés. À l'équilibre avec l'air, les concentrations en O_2 et en N_2 dans l'huile sont ~32 000 et ~64 000 ppm, respectivement [8], et le rapport O_2/N_2 est ~0,5.

En service, ce rapport peut diminuer par oxydation de l'huile et/ou vieillissement du papier, si l'O_2 est consommé plus rapidement qu'il n'est remplacé par diffusion. Des facteurs comme la charge et le système de préservation utilisé peuvent aussi affecter ce rapport, mais à l'exception des systèmes fermés, des rapports inférieurs à 0,3 sont généralement considérés comme l'indication d'une consommation excessive d'oxygène.

5.7 Rapport C_2H_2/H_2

Dans les transformateurs de puissance, les manœuvres du changeur de prises en charge (OLTC) produisent des gaz caractéristiques des décharges de faible énergie (D1). Si les gaz ou l'huile de l'OLTC peuvent communiquer avec la cuve principale ou entre leurs conservateurs respectifs, ces gaz peuvent contaminer l'huile de la cuve principale et conduire à des diagnostics erronés. Cependant, le type de décomposition gazeuse dans l'OLTC est très caractéristique et différent de celui des D1 habituelles dans la cuve principale.

Des rapports C_2H_2/H_2 supérieurs à 2 ou 3 dans la cuve principale sont ainsi considérés comme l'indication d'une contamination par l'OLTC. Ceci peut être confirmé par comparaison des résultats d'AGD dans la cuve principale, dans l'OLTC et dans les conservateurs. Les valeurs du rapport de gaz et de la concentration en acétylène dépendent du nombre de manœuvres de l'OLTC et de la façon dont la contamination s'est produite (à travers l'huile ou par voie gazeuse).

Si l'on soupçonne une contamination par les gaz de l'OLTC, il convient d'interpréter les résultats de l'AGD dans la cuve principale avec prudence en soustrayant la contamination antérieure due à l'OLTC, ou il convient d'éviter l'interprétation en raison de son manque de fiabilité.

NOTE   Les OLTC modernes sont conçus pour ne pas contaminer l'huile de la cuve principale.

5.8 Hydrocarbures en C_3

La méthode d'interprétation de l'analyse des gaz décrite ci-dessus ne tient compte que des hydrocarbures en C_1 et C_2. D'autres méthodes pratiques d'interprétation utilisent également les concentrations des hydrocarbures en C_3, et leurs auteurs pensent que ces derniers sont fiables pour fournir des renseignements complémentaires utiles pour réaliser un diagnostic plus précis. Comme les hydrocarbures en C_3 sont très solubles dans l'huile, leurs concentrations ne sont pratiquement pas affectées par une possible diffusion vers l'air ambiant. En revanche, comme ils sont très solubles, ils sont difficiles à extraire de l'huile, et leur analyse peut dépendre fortement de la méthode d'extraction utilisée. De plus, l'expérience a montré que, dans la plupart des cas, un diagnostic satisfaisant peut être obtenu sans tenir compte de ces hydrocarbures. C'est la raison pour laquelle, dans un but de simplification, ils n'ont pas été retenus dans la méthode d'interprétation décrite ci-dessus.

5.9 Évolution des défauts

Les défauts apparaissent souvent comme des défauts naissants de faible énergie, qui peuvent se transformer par la suite en défauts plus sévères de plus fortes énergies, conduisant à des alarmes de gaz, à des claquages ou à des défaillances possibles.

Lorsqu'un défaut est détecté à un stade d'évolution précoce, il peut être intéressant de suivre non seulement l'augmentation de la concentration des gaz, mais également l'évolution éventuelle avec le temps vers un défaut plus dangereux de forte énergie, donnant lieu à une défaillance.