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Mineral oil-impregnated electrical equipment in service – Guide to the interpretation of dissolved and free gases analysis

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Matériels électriques imprégnés d'huile minérale en service – Guide pour l'interprétation de l'analyse des gaz dissous et des gaz libres

IEC 60599:1999

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CONTENTS

FOREWORD.....	3
INTRODUCTION.....	4
1 Scope.....	5
2 Normative references	5
3 Definitions and abbreviations	5
4 Mechanisms of gas formation	8
5 Identification of faults.....	9
6 Conditions for calculating ratios	14
7 Application to free gases in gas relays	15
8 Gas concentration levels in service	16
9 Recommended method of DGA interpretation (figure 1).....	19
10 Report of results	19
Annex A (informative) Equipment application notes	22
Annex B (informative) Graphical representation of gas ratios (see 5.9)	32
Annex C (informative) Bibliography	35
Figure 1 – Flow chart	21
Figure B.1 – Graphical representation 1 of gas ratios	32
Figure B.2 – Graphical representation 2 of gas ratios	33
Figure B.3 – Graphical representation 3 of gas ratios – Duval's triangle	34

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**MINERAL OIL-IMPREGNATED ELECTRICAL EQUIPMENT IN SERVICE –
GUIDE TO THE INTERPRETATION OF DISSOLVED AND
FREE GASES ANALYSIS**

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This consolidated version of IEC 60599 consists of the second edition (1999) [documents 10/450/FDIS and 10/460/RVD] and its amendment 1 (2007) [documents 10/685/FDIS and 10/693/RVD].

The technical content is therefore identical to the base edition and its amendment(s) and has been prepared for user convenience.

It bears the edition number 2.1.

A vertical line in the margin shows where the base publication has been modified by amendment 1.

Annexes A, B and C are for information only.

INTRODUCTION

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

This guide 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. This second edition attempts to address some of these shortcomings. Interpretation schemes are 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.

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MINERAL OIL-IMPREGNATED ELECTRICAL EQUIPMENT IN SERVICE – GUIDE TO THE INTERPRETATION OF DISSOLVED AND FREE GASES ANALYSIS

1 Scope

This International Standard is a guide describing 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 guide 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).

The Guide may be applied 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 normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050(191):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 191: Dependability and quality of service*

IEC 60050(212):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 212: Insulating solids, liquids and gases*

IEC 60050(604):1987, *International Electrotechnical Vocabulary (IEV) – Chapter 604: Generation, transmission and distribution of electricity – Operation*

IEC 60567:1992, *Guide for the sampling of gases and of oil from oil-filled electrical equipment and for the analysis of free and dissolved gases*

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

3 Definitions and abbreviations

3.1 Definitions

For the purpose of this International Standard, the following definitions, some of them based on IEC 60050(191), IEC 60050(212) and IEC 60050(604) apply:

3.1.1

fault

an unplanned occurrence or defect in an item which may result in one or more failures of the item itself or of other associated equipment [IEV 604-02-01]

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

3.1.2

non-damage fault

a fault which does not involve repair or replacement action at the point of the fault
[IEV 604-02-09]

NOTE Typical examples are self-extinguishing arcs in switching equipment or general overheating without paper carbonization.

3.1.3

damage fault

a fault which involves repair or replacement action at the point of the fault
[IEV 604-02-08, modified]

3.1.4

incident

an event related to an internal fault which temporarily or permanently disturbs the normal operation of an equipment [IEV 604-02-03, modified]

NOTE Typical examples are gas alarms, equipment tripping or equipment leakage.

3.1.5

failure

the termination of the ability of an item to perform a required function [IEV 191-04-01]

NOTE In the 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.

3.1.6

electrical fault

a partial or disruptive discharge through the insulation

3.1.7

partial discharge

a discharge which only partially bridges the insulation between conductors. It may occur inside the insulation or adjacent to a conductor [IEV 212-01-34, modified]

NOTE 1 Corona is a form of partial discharge that occurs in gaseous media around conductors which are remote from solid or liquid insulation. This term is not to be used as a general term for all forms of partial discharges.

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 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.

3.1.8

discharge (disruptive)

the passage of an arc following the breakdown of the insulation [IEV 604-03-38, modified]

NOTE 1 Discharges are often described as arcing, breakdown or short circuits. The more specific following terms are also used:

- 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 which, 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).

3.1.9**thermal fault**

excessive temperature rise in the insulation

NOTE 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.

3.1.10**typical values of gas concentrations**

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

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

NOTE 2 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**

Name	Symbol
Nitrogen	N ₂
Oxygen	O ₂
Hydrogen	H ₂
Carbon monoxide	CO
Carbon dioxide	CO ₂
Methane	CH ₄
Ethane	C ₂ H ₆
Ethylene	C ₂ H ₄
Acetylene	C ₂ H ₂

3.2.2 General abbreviations

DGA: Dissolved gas analysis

CIGRE: Conférence Internationale des Grands Réseaux Électriques

S: Analytical detection limit

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 ($\text{CH}_3\text{-H}$), ethane ($\text{CH}_3\text{-CH}_3$), ethylene ($\text{CH}_2 = \text{CH}_2$) or acetylene ($\text{CH} \equiv \text{CH}$). 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 analyzed 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/mole) 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/mole), C=C double bond (720 kJ/mole) or C≡C triple bond (960 kJ/mole), 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. Mostly carbon monoxide and dioxide, as well as water, are formed, in much larger quantities than by oxidation of oil at the same temperature, together with minor amounts of hydrocarbon gases and furanic compounds. The latter can be analyzed 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 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 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 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).

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

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

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 5.3.

5 Identification of faults

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 is below typical values, it should not be considered as an indication of a "fault", but rather as "typical gas formation" (see figure 1).

5.1 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 which 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, which turns irreversibly to carbon above 300 °C.

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

5.2 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);
- 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, $t < 300\text{ °C}$
T2	Thermal fault, $300\text{ °C} < t < 700\text{ °C}$
T3	Thermal fault, $t > 700\text{ °C}$

5.3 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 2 and based on the use of three basic gas ratios:

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

Table 2 applies to all types of equipment, with a few differences in gas ratio limits depending on the specific type of equipment.

Table 2 – DGA interpretation table

Case	Characteristic fault	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
PD	Partial discharges (see notes 3 and 4)	NS ¹⁾	<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 ¹⁾	>1 but NS ¹⁾	<1
T2	Thermal fault 300 °C < $t < 700$ °C	<0,1	>1	1 – 4
T3	Thermal fault $t > 700$ °C	<0,2 ²⁾	>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 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 of thin oil film between overheated core laminates at temperatures of 140 °C and above (see 4.3 and [1] of annex C).

¹⁾ NS = Non-significant whatever the value.

²⁾ 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 2, may be found in tables A.1, A.5, A.7 and A.11.

Some overlap between faults D1 and D2 is apparent in table 2, 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.

NOTE Combinations of gas ratios which fall outside the range limits of table 2 and do not correspond to a characteristic fault of this table may be considered a mixture of faults, or new faults which combine with a high background gas level (see 6.1).

In such a case, table 2 cannot provide a diagnosis, but the graphical representations given in annex B may be used to visualize which characteristic fault of table 2 is closest to the case.

The less detailed scheme of table 3 may 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 3 – Simplified scheme of interpretation

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

5.4 CO₂/CO ratio

The formation of CO₂ and CO from oil-impregnated paper insulation increases rapidly with temperature. Incremental (corrected) CO₂/CO ratios less than 3 are generally considered as an indication of probable paper involvement in a fault, with some degree of carbonization.

In order to get reliable CO₂/CO ratios in the equipment, CO₂ and CO values should be corrected (incremented) first for possible CO₂ absorption from atmospheric air, and for the CO₂ 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 10 % of dissolved air, may contain up to 300 µl/l of CO₂ coming from the air. In sealed equipment, air is normally excluded but may enter through leaks, and CO₂ concentration will be in proportion of air present.

When excessive paper degradation is suspected (CO₂/CO < 3), it is advisable to ask for a furanic compounds analysis or a measurement of the degree of polymerization of paper samples, when this is possible.

5.5 O₂/N₂ ratio

Dissolved O₂ and N₂ may be 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 the relative solubilities of O₂ and N₂, the O₂/N₂ ratio in oil reflects air composition and is close to 0,5.

In service, this ratio may decrease as a result of oil oxidation and/or paper ageing, if O₂ 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 ratios less than 0,3 are generally considered to indicate excessive consumption of oxygen.

5.6 C₂H₂/H₂ 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.