Dissolved Gas Analysis and the Duval Triangle

By

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Abstract

Dissolved gas analysis (DGA) is widely used to detect incipient faults in transformers. A brief review on the interpretation of DGA in transformers is presented, with a special emphasis on the Duval Triangle method. It is shown how the accuracy of DGA laboratory results can affect the reliability of DGA diagnosis. The minimum gas levels in service above which diagnoses may be attempted are indicated, as well as the gas levels observed before failure.

Introduction

Several methods of interpretation of DGA in transformers in service are provided in IEC Standard 60599[1], the IEEE Guide C57.104[2], as well as in published reviews on the subject[3-5]. The Duval Triangle method is described in the IEC Standard and in these published reviews, however, users sometimes are not quite at ease with the use of triangular coordinates. One purpose of this paper is therefore to indicate in more detail how to use such coordinates. Another purpose is to present the most recent developments made at CIGRE concerning gas levels in service.
This paper is limited to DGA in transformers. It does not address the case of DGA in load tap changer (LTC) accessories, for which specialized diagnostic programs are available[6], or which is treated elsewhere[3].

Gas formation in service

Mineral insulating oils are complex mixtures of hydrocarbon molecules, in linear (paraffinic) or cyclic (cycloaliphatic or aromatic) form, containing CH_3, CH_2 and CH chemical groups bonded together. Scission of some of the C-H and C-C bonds as a result of thermal or electrical discharges will produce radical or ionic fragment such as H*, CH_3*, CH_2*, CH* or C*, which will recombine to form gas molecules such as hydrogen (H-H), methane (CH_3-H), ethane (CH_3-CH_3), ethylene (CH_2=CH_2) or acetylene ($CH\equiv CH$).
More and more energy is required to form the above chemical bonds. Hydrogen (H_2), methane (CH_4) and ethane (C_2H_6) are thus favoured at low energy level, such as in corona partial discharges or at relatively low temperatures (< 500 °C), ethylene (C_2H_4) at intermediate temperatures, and acetylene (C_2H_2) at very high temperatures (> 1000 °C) such as in arcs.

Paper insulation is composed of complex cellulosic molecules, mostly in cyclic form, containing CH_2, CH and CO chemical groups. The C-O molecular bonds are weaker, resulting in gas formation at temperatures as low as 100 °C, and complete carbonization of paper at 300 °C. The formation of CO_2 is favoured at the lower temperatures and CO above 200 °C, but significant amounts of the other gases (H_2, hydrocarbons) are also formed.

Oxygen is also present in oil, mainly in the case of air breathing transformers, but also in sealed or nitrogen-blanketed ones because of leaks. A decrease in oxygen content usually indicates an excessive temperature in the transformer.

The main gases formed by decomposition of oil and paper are summarized in Table 1. These gases dissolve in oil or accumulate above it and are analyzed by DGA. Some laboratories also report the contents of C_3 and C_4 hydrocarbon gases formed.

Table 1
Main gases analyzed by DGA

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

DGA is the most widely used technique for detecting and monitoring faults in electrical equipment. About one million DGA analyses are performed each year by more than 400 laboratories worldwide.

Faults detectable by DGA

The internal inspection of hundreds of faulty equipment has led to the broad classes of faults indicated in Table 2, detectable by visual inspection and by DGA:

Table 2
Examples of faults detectable by DGA

Symbol	Fault	Examples
PD	Partial discharges	Discharges of the cold plasma (corona) type in gas bubbles or voids, with the possible formation of X-wax in paper.
D1	Discharges of low energy	Partial discharges of the sparking type, inducing pinholes, carbonized punctures in paper. Low energy arcing inducing carbonized perforation or surface tracking of paper, or the formation of carbon particles in oil.
D2	Discharges of high energy	Discharges in paper or oil, with power follow-through, resulting in extensive damage to paper or large formation of carbon particles in oil, metal fusion, tripping of the equipment and gas alarms.
T1	Thermal fault, T <300 °C	Evidenced by paper turning brownish (> 200 °C) or carbonized (> 300 °C).
T2	Thermal fault, 300 <T<700 °C	Carbonization of paper, formation of carbon particles in oil.
T3	Thermal fault, T >700 °C	Extensive formation of carbon particles in oil, metal coloration (800 °C) or metal fusion (> 1000 °C).

Fault diagnosis

If DGA values are above typical concentration values and/or rates of increase, an actual fault in the transformer is probable, and diagnostic methods may be used for its identification.

The main diagnostic methods used are :
-the IEEE methods (Dornenburg, Rogers and key gases methods)
-the IEC ratio codes
-the Duval Triangle

The Dornenburg, Rogers and IEC codes compare gas ratios such as CH_4/H_2 , C_2H_2/C_2H_4 and C_2H_4/C_2H_6. The key gas method is based on the 2 or 3 main gases formed. And the Duval Triangle on the relative proportions of 3 gases (CH_4, C_2H_4 and C_2H_2).

The relative performance of these methods is summarized in Table 3. One drawback of the gas ratio methods (Dornenburg, Rogers, IEC) is that some DGA results may fall outside the ratio codes and no diagnosis can be given (unresolved diagnoses). This does not occur with the Triangle method because it is a closed system rather than an open one.

Table 3
Comparison of diagnostic methods

	% Unresolved diagnoses	% Wrong diagnoses	% Total
Key gases	0	58	58
Rogers	33	5	38
Dornenburg	26	3	29
IEC	15	8	23
Triangle	0	4	4

The Duval Triangle

The Duval Triangle was first developed in 1974 [7]. It uses three hydrocarbon gases only (CH_4, C_2H_4 and C_2H_2). These three gases correspond to the increasing levels of energy necessary to generate gases in transformers in service. The Triangle method is indicated in Figure 1. In addition to the 6 zones of individual faults mentioned in Table 2 (PD, D1, D2, T1, T2 or T3), an intermediate zone DT has been attributed to mixtures of electrical and thermal faults in the transformer.

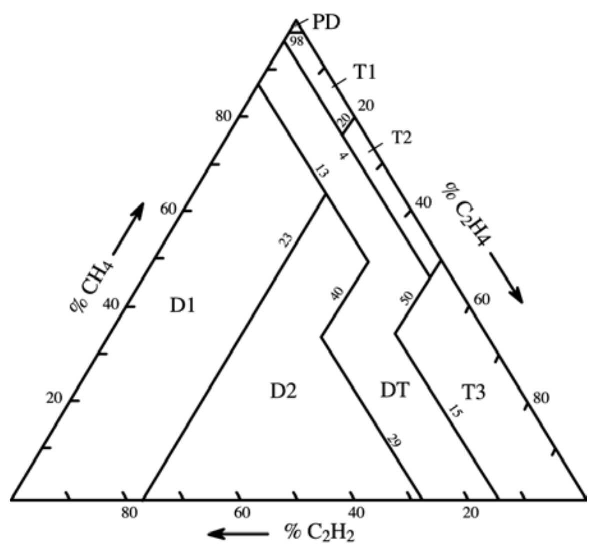


Figure 1
Duval Triangle method

C_2H_2 and C_2H_4 are used in all interpretation methods to represent high energy faults (such as arcs) and high temperature faults. H_2 is preferred in several of these methods to represent very low energy faults such as PDs, where it is produced in large quantities.
CH_4, however, is also representative of such faults and always formed in addition to H_2 in these faults, in smaller but still large enough amounts to be quantified. CH_4 has been chosen for the

Triangle because it not only allows to identify these faults, but provides better overall diagnosis results for all the other types of faults than when using H_2.

This good performance of the Triangle with CH_4 might be related to the fact that H_2 diffuses much more rapidly than the hydrocarbon gases from the oil through gaskets and even metal welds. Therefore, gas ratios using H_2 are probably more affected by the loss of this gas than those using hydrocarbons gases only, which have much lower and comparable diffusion rates.

The three sides of the Triangle are expressed in triangular coordinates (X,Y,Z) representing the relative proportions of CH_4, C_2H_4 and C_2H_2, from 0% to 100% for each gas.

In order to display a DGA result in the Triangle, one must start with the concentrations of the three gases, $(CH_4) = A$, $(C_2H_4) = B$ and $(C_2H_2) = C$, in ppm.
First calculate the sum of these three values: $(CH_4 + C_2H_4 + C_2H_2) = S$, in ppm, then calculate the relative proportion of the three gases, in %:
$X = \%\ CH_4 = 100\ (A/S)$, $Y = \%\ C_2H_4 = 100\ (B/S)$, $Z = \%\ C_2H_2 = 100\ (C/S)$.
X, Y and Z are necessarily between 0 and 100%, and (X + Y + Z) should always = 100 %.
Plotting X, Y and Z in the Triangle provides only one point in the Triangle.

For example, if the DGA results are A = B = C = 100 ppm, X = Y = Z = 33.3%, which corresponds to only one point in the centre of the Triangle, as indicated in Figure 2.

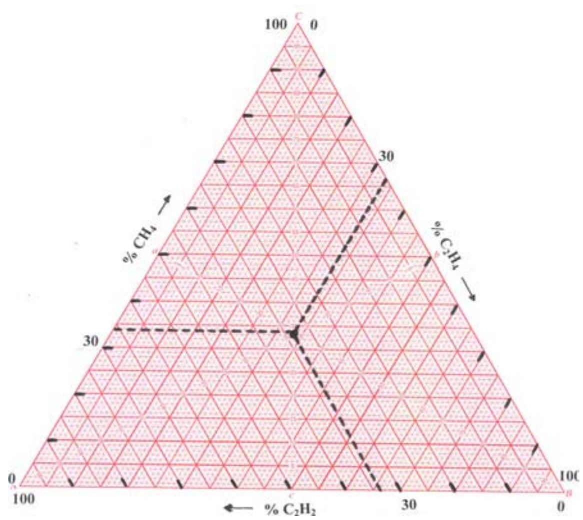


Figure 2:
Example of triangular graphical plot

The zone in which the (X,Y,Z) point falls in the Triangle in Figure 1 allows to identify the fault responsible for the DGA results. The example of Figure 2 would indicate a fault D2 (when transferred in Figure 1).

The X, Y and Z values can easily be calculated manually, or through the use of a small algorithm, available free of charge in electronic form by email from duvalm@ireq.ca. Plotting the (X,Y,Z) point in the Triangle can also be done manually, preferably using a triangular graphical paper such as in Figure 2 for better precision. Such a paper is not available commercially any more, but it can also be obtained free of charge in electronic form by email from duvalm@ireq.ca.

For those familiar with computer graphics, the (X,Y,Z) point, as well as the points from previous DGA results on the same transformer, can also be plotted and displayed automatically in the Triangle as part of a DGA report. The Kelman company in UK and Serveron the US, for example, provide such software with their on-line gas monitors, as shown in Figures 3-4. The Delta-X Research company in Canada also provides such a display (see for example Figure 7). Several individual DGA users have also developed their own graphical software.

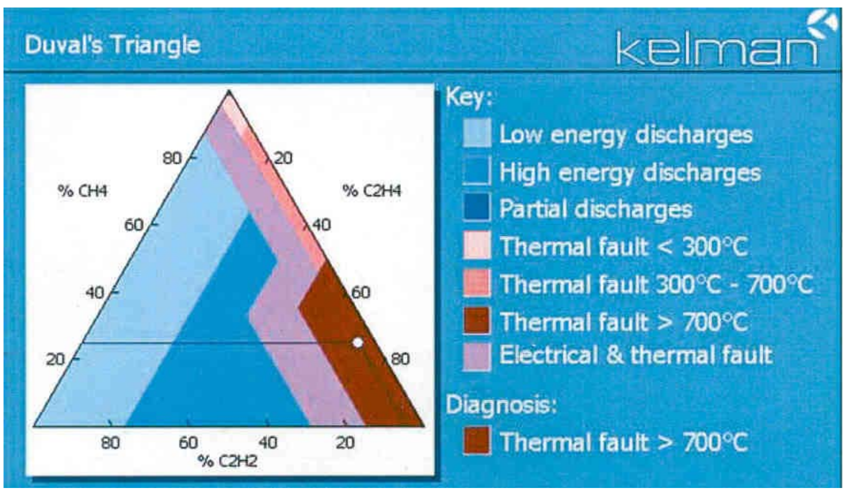


Figure 3: Example of automatic graphical representation by Kelman

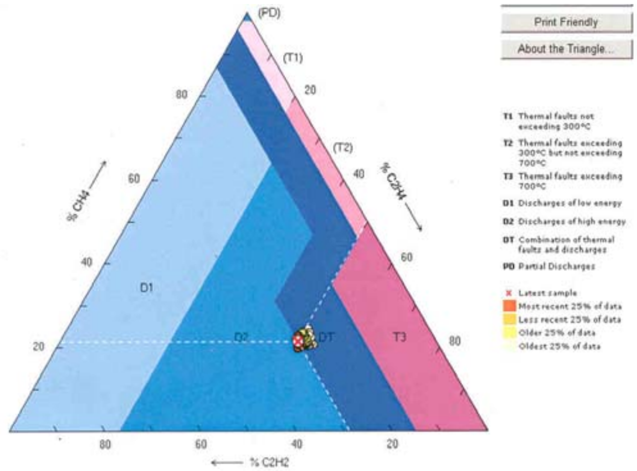
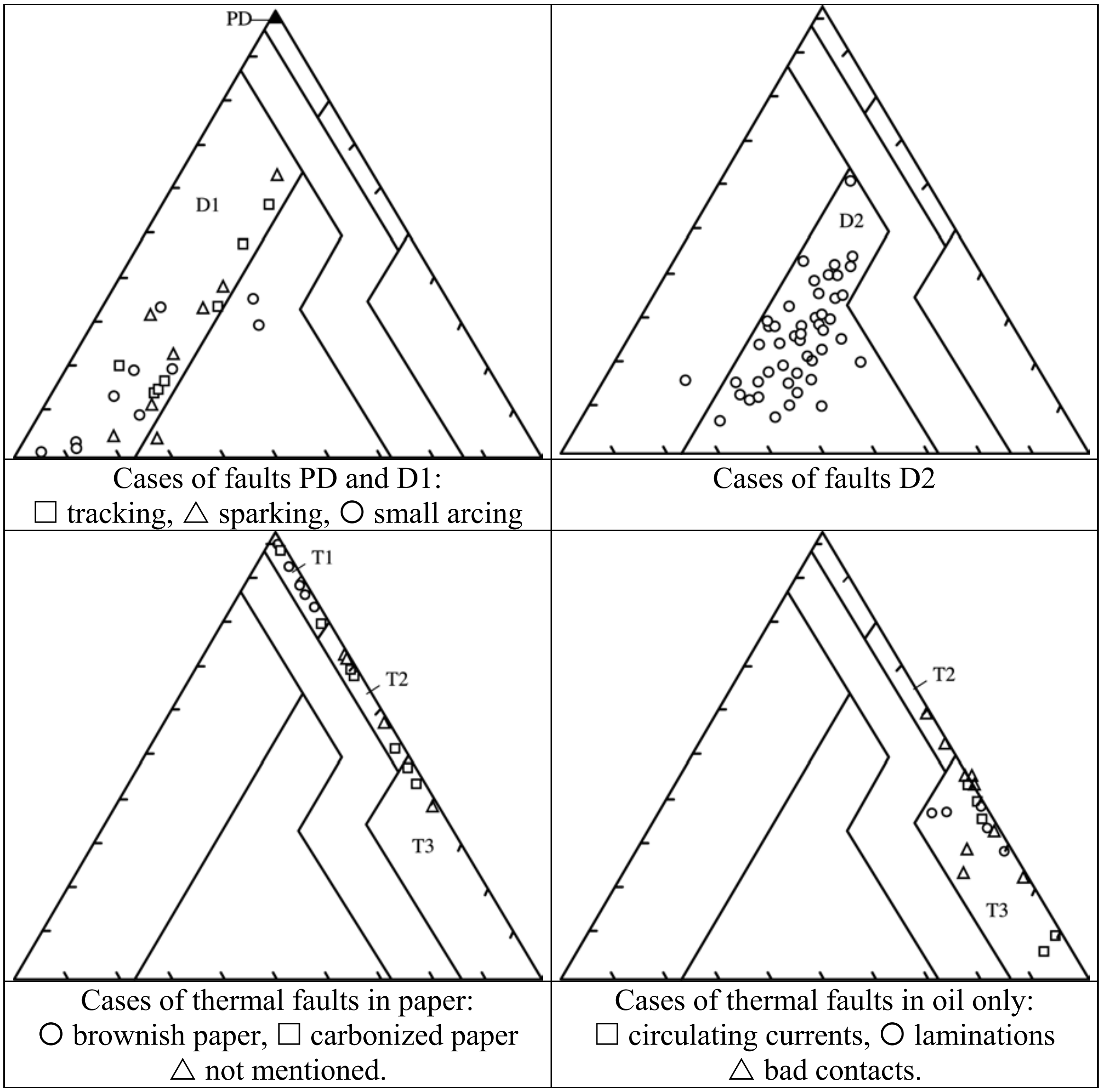


Figure 4: Example of automatic graphical representation by Serveron

Zone boundaries in the Triangle

Zone boundaries in the Triangle have been deduced empirically from a large number of cases of faults visually inspected in transformers worldwide over the last 60 years, as reported for example in [3,4] and in Figure 5. The present position of zone boundaries is indicated in Figure 1. Well documented and reliable new cases of faults inspected in service may be used to confirm or re-adjust slightly these boundaries.



Cases of faults PD and D1: □ tracking, △ sparking, ○ small arcing

Cases of faults D2

Cases of thermal faults in paper: ○ brownish paper, □ carbonized paper △ not mentioned.

Cases of thermal faults in oil only: □ circulating currents, ○ laminations △ bad contacts.

Figure 5: Actual cases of faults visually inspected in transformers

Faults in paper vs. faults in oil

Faults in paper are generally considered as more serious than faults in oil, because paper is often located in areas of high electric field (in the windings, or as voltage barriers), and the destruction of paper insulation may lead to short circuits or severe arcing.

Faults in paper, fortunately, are much less frequent than faults in oil (typically, in 10 % of cases only), however, because of the more serious consequences, their detection by DGA or other means is of great interest.

A popular way of detecting faults in paper by DGA is by looking at the CO_2 to CO ratio. Values < 3 are a good indication of faults in paper of a temperature > 200 to 300 °C (including arcing), where paper degrades very rapidly or even carbonizes. However, there is always a large background of CO and CO_2 in oil (except in the first years of operation of the transformers), so that caution should be exercised when interpreting the value of this ratio. Using increment values of CO and CO_2 over the last analysis is preferable, but the uncertainty on the incremented ratio is high and should be calculated to determine its reliability.

Values of the CO_2 to CO ratio > 10 are also an indication of thermal faults in paper at temperatures < 150 °C, but such temperatures have only a long term aging effect on paper and on the reduction of transformer life, which can be more precisely evaluated by furans formation, (when regular kraft, not thermally-upgraded paper, is used).

DGA results appearing in the T1 and T2 zones may also be an indication of paper involvement, since most inspected cases of thermal faults in paper have been observed in these zones, as shown in Figure 5. One should verify, however, that the oil used is not stray gassing, since stray gassing also produces gases in these zones (see below). Thermal faults in oil, by comparison, are observed mostly in the T3 zone.

A sharp increase in the formation of furans may in some cases be a confirmation of faults in paper at temperatures > 250 °C.

Evolution of faults with time

The Triangle method being a graphical method, it can be used to follow visually whether a fault evolves from a relatively harmless thermal fault into a potentially more severe electrical one. This can be done easily manually, or automatically with a software. Figure 6, extracted from [8], illustrates such a case.

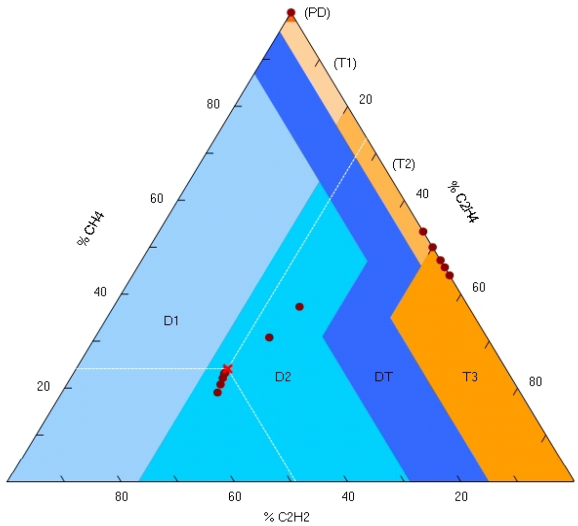


Figure 6
Evolution from a thermal fault to strong arcing D2

The most severe faults, in terms of type and location, are generally considered as :

- high-energy arcing D2 in paper (and in oil).
- medium-to-high temperature faults T2-T3 in paper (> 250 °C)
- low energy arcing D1 in paper (tracking, arcing)
- high temperature faults T3 in oil (> 700 °C)

The less severe faults, which can often be tolerated for relatively long periods of time as long as they don't evolve into a more severe one are :

- low-energy discharges PD/D1 in oil (corona, sparking)
- low temperature faults T1 in paper (< 150 °C)
- medium temperature faults in oil (< 500 °C).
- these faults are difficult to find by visual inspection.

Other useful gas ratios

In breathing transformers, the normal O_2 to N_2 ratio is around 0.5. In sealed and nitrogen blanketed ones, this ratio should be zero but in reality it often has a significant value because of leaks in gaskets, tank covers, etc.
A reduction in the value of the O_2 to N_2 ratio, below 0.3 in the case of breathing transformers, is usually an indication of excessive heating inside the transformer.

A C_2H_2 / H_2 ratio > 3 in the main tank is a probable indication of contamination from current-breaking activity in the LTC compartment.

Gas formation not related to faults in service

Some new insulating oils on the market tend to be "stray gassing", meaning that they form significant amounts (and unexpected until recently) of H_2 and CH_4 at temperatures as low as 100 °C, as a result of inadequate refining processes leaving weak chemical groups on the oil molecules. Typical examples of a non-stray gassing oil and of a strongly stray gassing one, heated at 120°C during 16h in the laboratory, are indicated in Table 7.

Table 4
Typical examples of stray gassing behaviour of oils (in ppm)

Oil	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2
Non-stray gassing	3	1	-	-	-	3	43
Strongly stray gassing	1088	172	11	27	-	500	1880

This is generally a non-recurrent process, i.e., it occurs mainly in the first year of operation. However, it should be taken into account to avoid misinterpretation of DGA results. An extensive study of stray gassing oils has been made by CIGRE TF11 [10].

A few older oils also tend to form abnormal quantities of H2 only, in contact with wet steel surfaces or internal paints, through catalytic decomposition. However, such a behaviour has not been reported in the past 10 years, possibly because such oils are not used any more in the equipment.

The influence of laboratory accuracy on fault diagnosis

The accuracy of DGA diagnosis, whatever the diagnosis method used, depends greatly on the accuracy and reliability of the DGA results coming from the laboratory. Note that, by convention among chemists, accuracy is represented by the difference with actual value (the analytical error in %), so that higher (better) accuracies are represented by a smaller number in %.

A few laboratories worldwide provide very accurate results, with an accuracy higher (or error lower) than ±5% at routine gas concentration levels (typically, above 10 ppm for hydrocarbon gases). Some others are known to provide very inaccurate results (±50%). In-between, the average accuracy of laboratories worldwide has been evaluated by CIGRE TF11 as ~ ±15% at routine levels. The average accuracy worsens rapidly to ~ 35% at lower concentration levels (between 2 and 10 ppm for hydrocarbon gases), and even more so (to 100% and more) as concentrations approach analytical detection limits.

This is illustrated in Figure 7, where the diagnosis uncertainty corresponding to the various DGA cases of Table 5 is represented by the coloured polygons [11]. The more inaccurate the laboratory results, the larger the uncertainty on the diagnosis, as illustrated in Figure 8.

Table 5: Examples of DGA cases (concentrations in ppm)

Fault	CH4	C2H4	C2H2
PD	99	1	0
	9.9	0.1	0
D1	38	12	50
	3.8	1.2	5
D2	15	50	35
	1.5	5	3.5
T2	69	30	1
	6.9	3	0.1
T3	20	75	5
	2	7.5	0.5

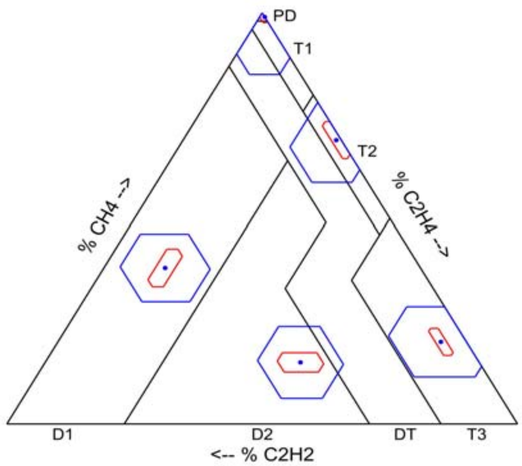


Figure 7: Uncertainty on diagnoses for cases of Table 5

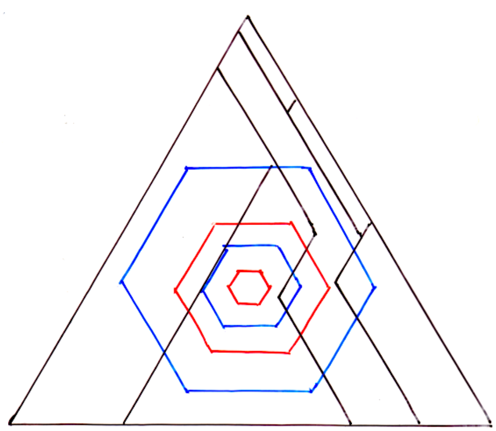


Figure 8: Diagnosis uncertainties corresponding to laboratory analytical accuracies of ± 15, 30, 50 and 75 %

When a polygon crosses two or more zones, a wrong or uncertain diagnosis may result. This may have serious consequences for the equipment if for example an arcing problem is mistakenly diagnosed as a less severe thermal fault. In order to get good reliable diagnoses, laboratory accuracy should below ±10%. Between ±10% and ±40%, diagnoses will likely become more and more uncertain, and above ±40% they are totally meaningless.

DGA users are therefore strongly recommended to verify the accuracy of their laboratories, using samples of gas-in-oil standards (the only way to do that correctly). Such standards are now available commercially[12].

DGA users should also always look at inconsistencies in the DGA results, for instance values going up and down within short periods of time for no explainable reason. These are often an indication of a gross laboratory or sampling error rather than just inaccurate results.

Rates and levels of gas formation in service

Typical values

Most transformers in service are healthy. In these transformers, dissolved gas concentration levels and rates of gas increase are low. When a fault occurs in service, rates and levels of gas formation start increasing, more or less rapidly depending on the severity of the fault, up to very high values before failure. This is illustrated schematically in Figure 9, where the three gas concentration levels and rates of gas increase in oil defined by CIGRE and the IEC (typical, alarm and pre-failure values) are indicated as a function of time.

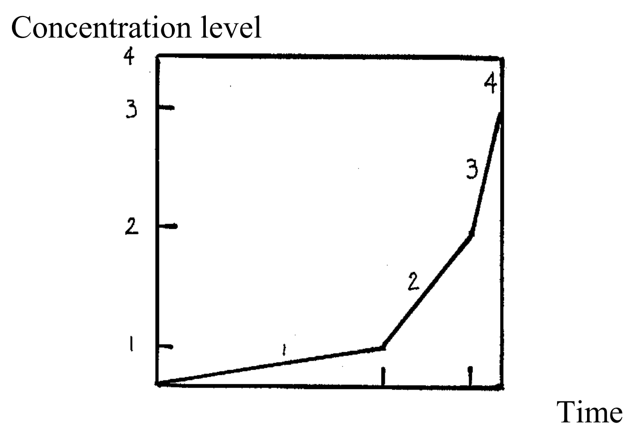


Figure 9
Schematic representation of gas formation in service

The first part of the curve (1) corresponds to typical gas concentration values and typical rates of increase. It concerns the majority of transformers (typically, 90 % of them). Its time scale is very long, generally several years or even the whole life of transformers. Typical values observed worldwide are quite comparable and there is a relatively good agreement today in the electrical community concerning these values.

The second part of the curve corresponds to alarm gas concentration levels and alarm rates of increase (2). It concerns a much smaller portion of transformers (typically, less than 5 %). Its time scale is much shorter, months or days, depending on how alarm values are defined.

The third part of the curve corresponds to "pre-failure" gas concentration levels and rates of increase (3). It concerns a very small minority of transformers (typically, less than 1 %). Its time scale is considerably shorter, days or hours. Pre-failure concentration values also appear to be comparable worldwide.

The fourth part of the curve corresponds to failure (4). It concerns typically 0.3 % of transformers. Its time scale is almost instantaneous and often catastrophic. DGA generally is meaningless at this stage because of fire or tank rupture, even using on-line gas monitors.

Calculation of typical values

Since typical values are influenced by such factors as transformer age and type and loading practices, each individual network is encouraged to calculate the typical values corresponding to its own transformer population.

This can be done easily by listing DGA results by increasing order of values, for each of the fault gases (e.g., H_2). The value corresponding to 90 % of the cumulative number of DGA analyses is the 90 % typical value. Said differently, 90 % of H_2 values in the transformer population of the network are below this typical value, and 10 % (the upper percentile) are above. This can be done for both concentrations values and rates of gas increase[10].

By default, if typical values cannot be calculated, for example because of an insufficient DGA data bank, the typical gas concentration levels and rates of increase reported in various countries by CIGRE an the IEC[10] may be used as a rough approximation (Tables 6,7):

Table 6 : Ranges of 90 % typical values for power transformers, in ppm

	C2H2	H2	CH4	C2H4	C2H6	CO	CO2
All transformers		50-150	30-130	60-280	20-90	400-600	3800-14000
No OLTC	2-20						
Communicating OLTC	60-280						

Table 7: Ranges of 90 % typical rates of gas increase for power transformers, in ppm/year

	C2H2	H2	CH4	C2H4	C2H6	CO	CO2
All transformers		35-132	10-120	32-146	5-90	260-1060	1700-10,000
No OLTC	0-4						
Communicating OLTC	21-37						

Values in Tables 6-7 are coming from both air-breathing transformers and sealed or nitrogen blanketed equipment. This indicates that, contrary to an often heard assumption, gas levels in sealed or nitrogen-blanketed transformers are not higher than in air-breathing ones.

The ranges of values in Tables 6-7 reflect the small differences in typical values observed on different networks worldwide.

Influence of some factors on typical values

Typical values for hydrocarbons (except C_2H_2) are markedly higher in power transformers of the shell-type and in shunt reactors than in the mostly core-type transformers of Tables 6-7, possibly because they operate at higher temperatures.
Typical values in instrument transformers are much lower than in power transformers.

Typical values are higher in the early years of the transformers, suggesting that some unstable chemical bonds in the paper or oil insulation are broken in the early years, then the remaining ones are more stable afterwards. Typical values are also slightly higher for faults in oil than in paper.

Contrary to another often heard assumption, typical values are not dependent on oil volume, suggesting that smaller amounts of gases (and smaller faults) are formed in smaller equipment.

Pre-failure and alarm values

Pre-failure concentration values and pre-failure rates of gas increase can be obtained by calculating the probability of having a failure-related event (PFS, in %) in a transformer in service, as a function of gas concentration level in oil [5,10]. This is done by calculating the following ratio, for each individual gas, at different concentrations : number of DGA analyses followed by an event such as tripping, tank rupture, fire or explosion, divided by the total number of analyses.

In Figure 10, the PFS value is indicated as a function of the concentration of C_2H_2, in power transformers without a communicating OLTC at Hydro Quebec. It can be seen that even at low concentration values (near the 90 % typical value of 5 ppm), the PFS is not zero but around 12 %. In such cases, a fault probably developed in the transformer very rapidly after the DGA analysis, without advanced warning. Above a value of around 350 ppm, there is an inflexion point in the curve above which the PFS increases rapidly.

This corresponds approximately to the 99 % typical value and to 1 % of DGA analyses, which is not far from the annual failure rate of transformers (0.3 %). This value has been defined as the pre-failure gas concentration value (PFGC). The PFGC values observed for the other gases are indicated in Table 8.

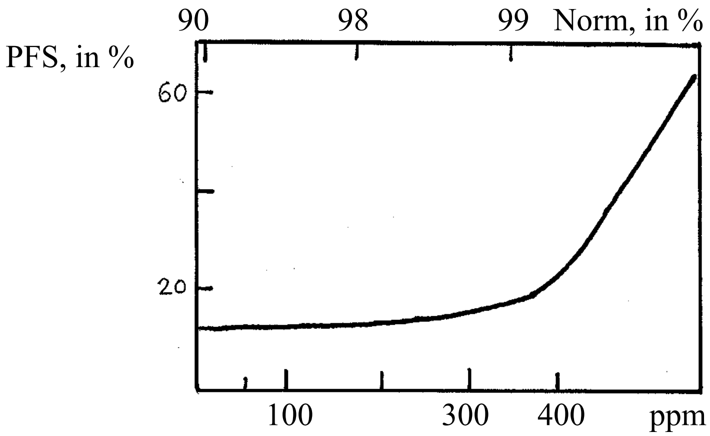


Figure 10
Probability of having a failure-related event (PFS, in %) as a function of C_2H_2 concentration in service in ppm, and of Norm in %

Table 8
Pre-failure gas concentration values at CIGRE for core-type power transformers

H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO
550-1320	340-460	750-1050	700-990	310-600	980-3000

By combining pre-failure values and actual rates of increase in service, one may have an idea of how long it may take to reach failure (if rates do not accelerate), and plan appropriate actions.

Alarm gas concentration values may be defined as the values corresponding to x times the PFGC population. For example, in Figure 10, if x = 2, the alarm value corresponds to the 98 % typical value, or 170 ppm. Alarm values thus calculated for the other gases can be found in [10].

Pre-failure and alarm rates of gas increase are in preparation by CIGRE TF15.

On-line monitors

On-line monitors are particularly useful to detect alarm and pre-failure rates of increase, since these occur over a short time scale (weeks or hours), and may often be missed by regular oil samplings performed over longer periods of time (years or months).

About 25,000 on-line monitors have been installed so far in service worldwide, while an increasing number of commercial equipment are available today (e.g., Hydran, Calisto, TNU, Serveron, Transfix), in addition to portable on-site instruments (e.g., Hydran, Shake test, TransportX, Energy Support). The accuracy and reliability of these monitors is presently under evaluation by CIGRE TF15.

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Biography

Michel Duval is a senior scientist with Hydro Quebec's Institute of Research (IREQ) in Canada since 1970. His main topics of interest have been dissolved gas analysis, electrical insulating oils and lithium polymer batteries.

A senior member of IEEE, he holds 13 patents, has authored over 70 scientific papers, book chapters or international standards and is very active in several CIGRE and IEC working groups.

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