SERVERON®
A QUALITROL Company

Practicing DGA

Agenda

Serveron Corporate Background

Transformer Reliability and DGA

Diagnostic tools

Gas levels

Laboratory DGA

On-Line DGA

Your cases of DGA

Serveron Corporate Background

Beaverton, OR USA Headquarters

- Branch offices in Beijing and London

Incorporated in 2001

- EPRI and proprietary GC based technology
- Siemens investment and “re-branding” agreement-2006
- Qualitrol acquired in August 2013

Fully integrated operation

- Engineering
- Manufacturing
- Sales & Marketing
- Field Service
- Secure Data Center

Customer Base

- Over 3500 On-line DGA monitors
- Over 80 major utilities worldwide
- Most major transformer manufacturers

Michel Duval

Dr Michel Duval obtained a B.Sc. in chemical engineering in 1966 and a Ph.D. in polymer chemistry in 1970. He has joined IREQ (Institut de recherche d'Hydro Québec) in 1970. Since then, he has made significant contributions in 3 main fields of R&D: dissolved gas-in-oil analysis (DGA), electrical insulating materials and lithium-polymer batteries.

In the field of DGA, M. Duval:

- Is well-known for his Triangle method of DGA interpretation, used worldwide.
- Has developed and promoted the use of gas-in-oil standards in the IEC and ASTM standards
- Has established the typical and critical levels of gas formation observed in various types of electrical equipment in service, now used as a reference by the industry
- Has been the Convenor of several IEC working groups and CIGRE task forces and is the principal author of several IEC international standards on DGA (60567, 60599, 61181).

Michel Duval

In the field of electrical insulating oils, M.Duval has researched and published in the areas of:

- Metal passivators
- Oil reclamation timing
- Unstable oil detection and prevention
- Paraffinic content of oils
- The characterization of XLPE in HV cables and of HV outdoors insulators

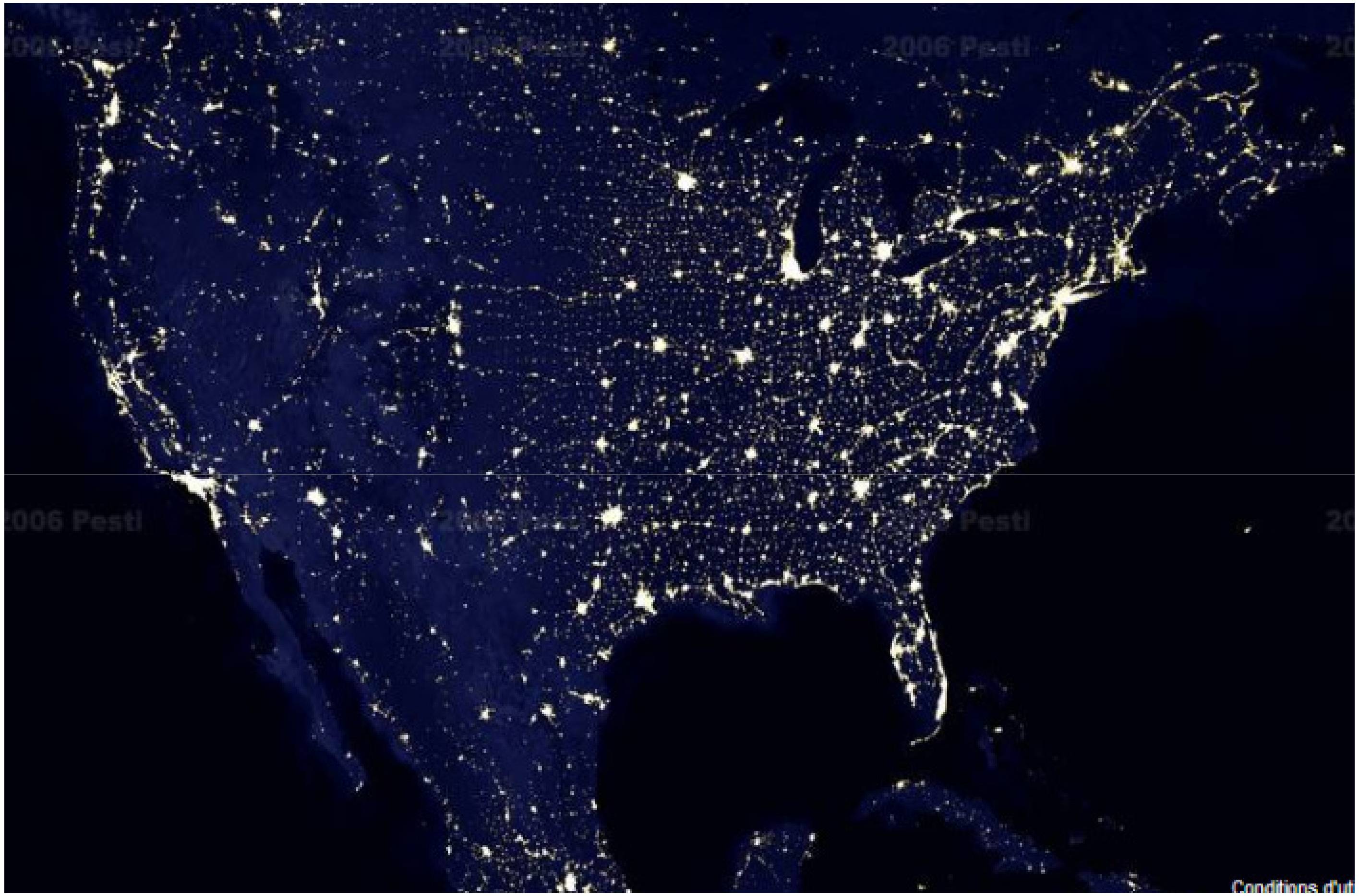
M. Duval holds 16 patents and is the author of more than 95 scientific and technical papers and books , 5 international standards (IEC, ASTM), and numerous technical reports and presentations in conferences.

He is a Life Fellow of IEEE, a Fellow of the Chemical Institute of Canada, and the recipient of the IEEE 2012 Herman Halperin Transmission and Distribution Award.

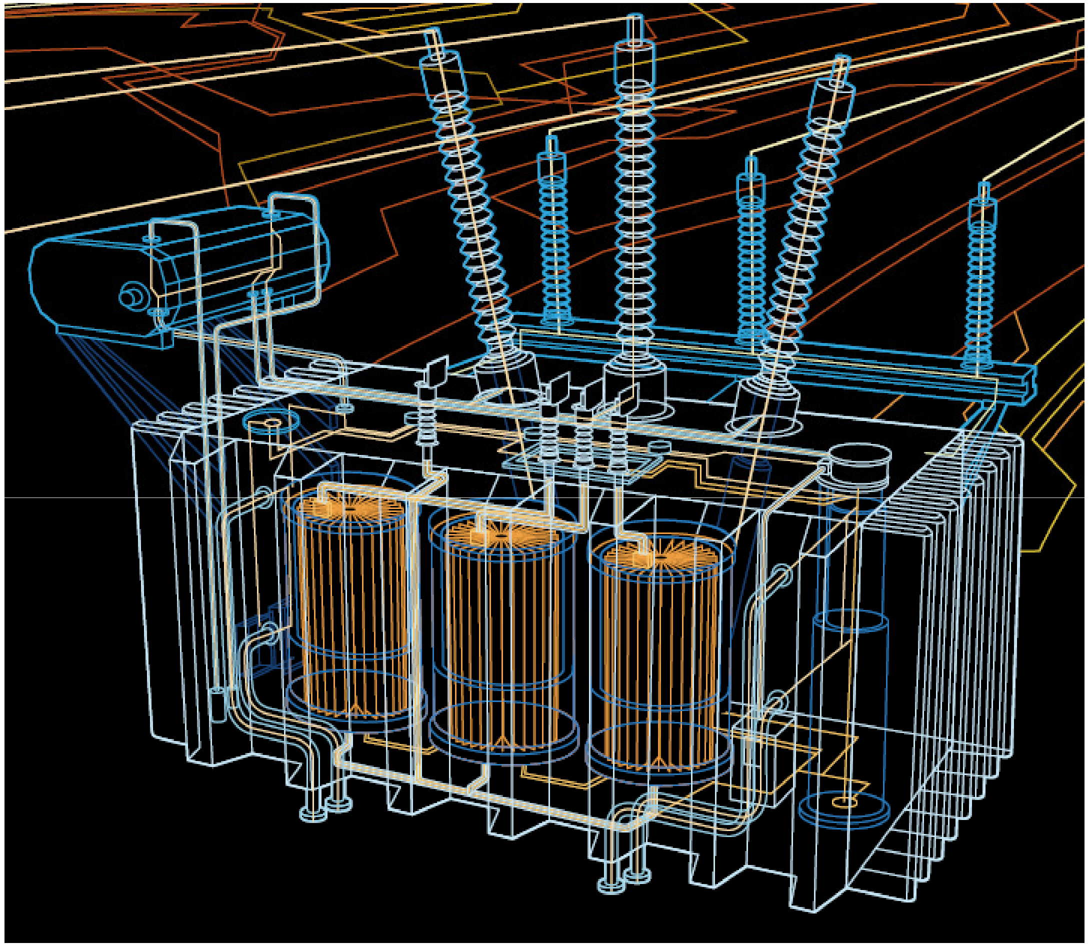
He may be contacted at duvalm@ireq.ca.

Transformer Reliability

Electric Power



Power Transformers



Failures – They Happen!

One Example

True Story: 520 MVA GSU Transformer

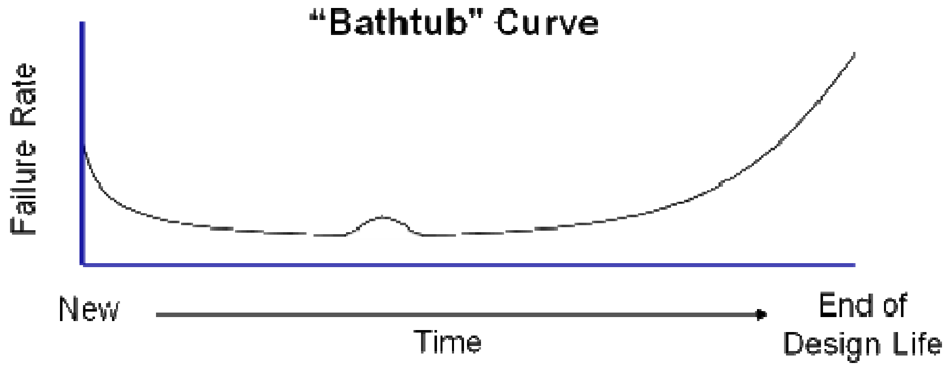
$3.5 million replacement cost

$0.5 million environmental cleanup

$1.5 million/day spot market buy

$17 million loss in eight days!!

Transformer Asset Management

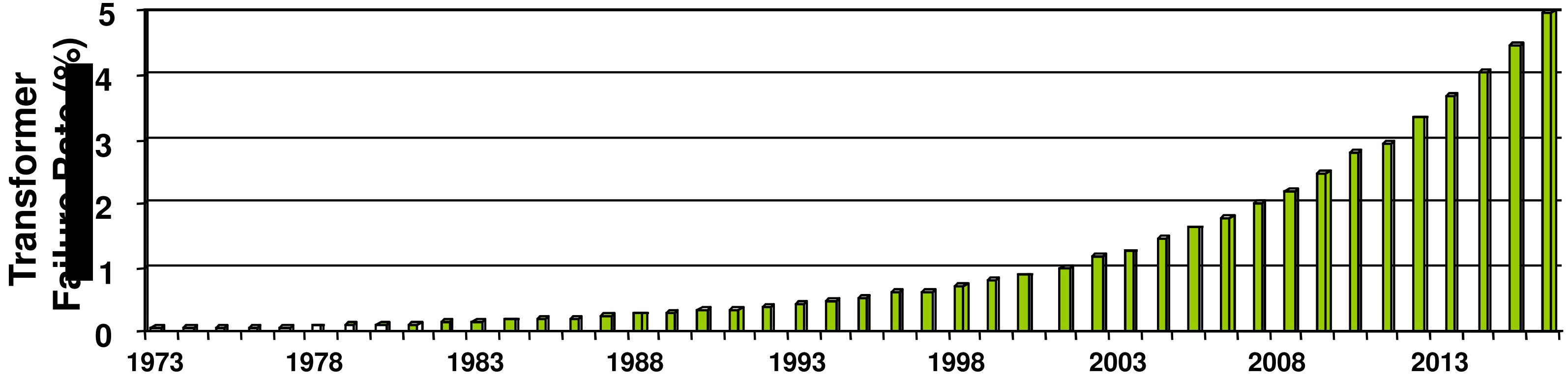


Transformers are a critical and costly element in the electrical grid

Unplanned failures at any point in the transformer lifecycle have major consequences

DGA condition assessment has been recognized for over 40 years for improving reliability and lowering transformer asset maintenance costs

Increasing Failure Rates



William H. Bartley P.E., Hartford Steam Boiler Inspection & Insurance Co.,
"Life Cycle Management of Utility Transformer Assets,"

Projected rates will reach unacceptable levels if nothing is done to improve the system;

- Replacing the fleet is not an alternative
- One solution is increased monitoring
- Published reports in the news validate an increasing failure rate

Factors Leading to Increased Failures

Stress with age: The average age of US power transformers is >42 yrs, increasing 0.7 yrs./yr.

- Age itself is not a cause of failure

Increased energy demand: Transformer peak and average loading has increased

Stress experienced:

- Mechanical
- Thermal
- Electrical
- Chemical

Tight budgets:

- Cutbacks in O&M
- Deferred capital replacement

Modes of Stress

MECHANICAL STRESS

Failures due to internal stress, weather, accidents:

- Tank failure
- Radiator failure
- Winding buckling
- Core damage
- Insulation damage
- LTC failures
- Lead failures
- Bushing failures

ELECTRICAL STRESS

Failures initially categorized into areas such as over-voltage or partial discharge, typically accompanied by thermal or chemical failure:

- Switching surges
- Lightning

THERMAL STRESS

Failures due to insulation destruction or conductor burn-through as the result of:

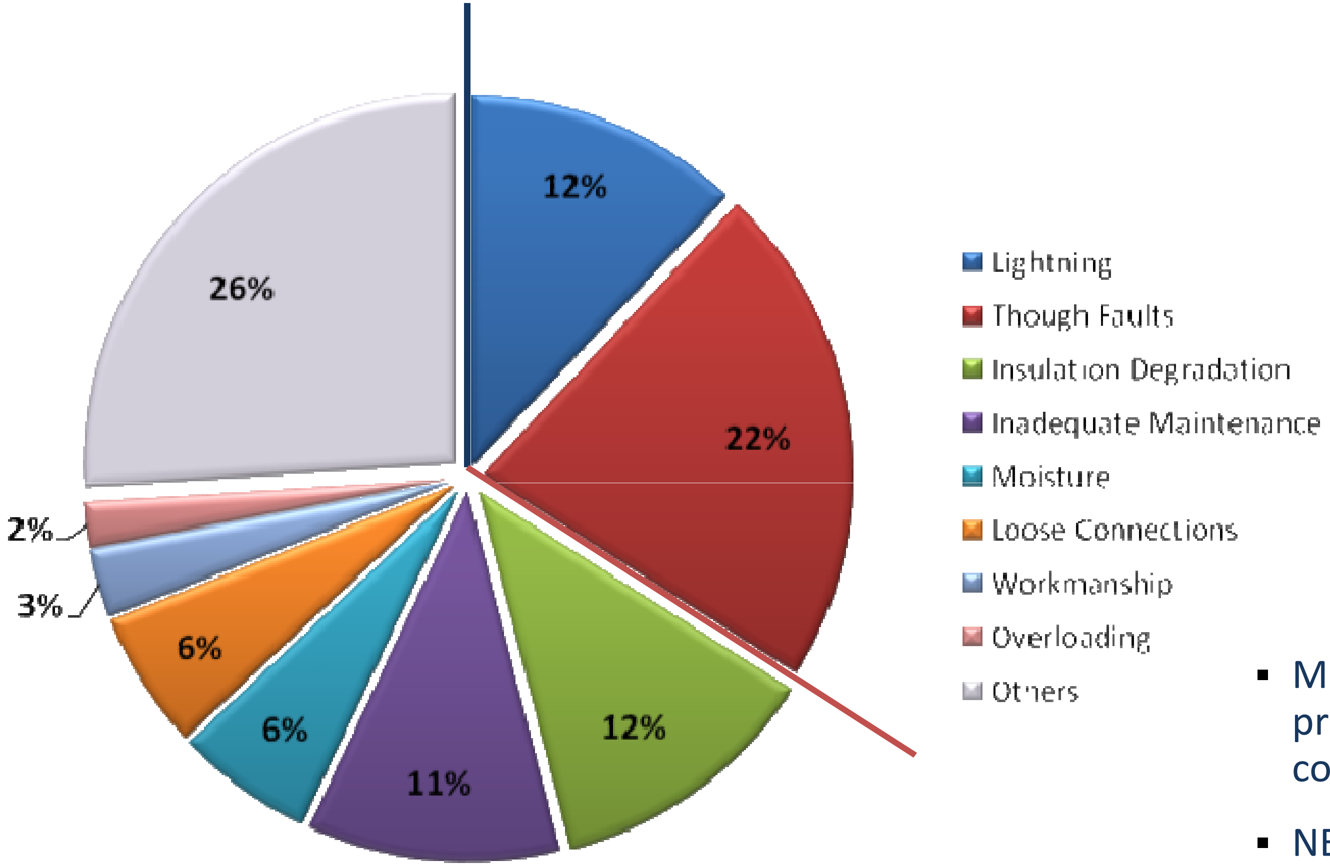
- Short or long-term overloading
- Faults
- Undersized leads
- Contact coking
- Bad joints
- Loss of cooling
- Design issues

CHEMICAL STRESS

Failures due to:

- Ingress of water
- Ingress of oxygen
- Loss of insulating oil
- Paper degradation due to heat or aging

Types of Faults



- Most failures can be prevented with continuous condition assessment.
- NEIL offers insurance credits to clients when installing 8 gas monitors

Failures in Service

-the failure rate of power transformers in service (internal failures needing repairs) typically is 0.3% per year.

-for a population of 2000 transformers, this means 6 transformers will fail in the next year.

-however, less than 1 will fail catastrophically.

-1994 will not fail.

-200 (i.e., 10% of the population at or above IEEE/IEC condition 1) may develop signs of abnormal operation and faults.

The Monitoring Dilemma

-nobody knows which 6 of the 2000 transformers will fail next year and when.

-to identify them, all the transformers need to be monitored, including the 1800 operating normally, just for the purpose of detecting the 6 that will fail and need repairs, and the less than 1 that may eventually fail catastrophically.

-in economic terms, the cost of monitoring is justified as long as it does not exceed the cost of not detecting the 6 failures and the catastrophic one (typically, 20M$).

Monitoring Tools

-general tools for monitoring oil temperature, pressure, partial discharges, etc, are available, e.g., from Qualitrol.

-however, for the early detection of faults and failures, the main monitoring tool is dissolved gas analysis (DGA).

-more than 1 million DGA analyses are performed by ~600 laboratories and ~ 40,000 on-line gas monitors each year worldwide.

Dissolved Gas Analysis

Monitoring of Gases in Transformers

As insulating material breaks down due to stress, gases are formed which dissolve in the transformer oil

Levels and combinations of the gases formed are used to detect incipient faults

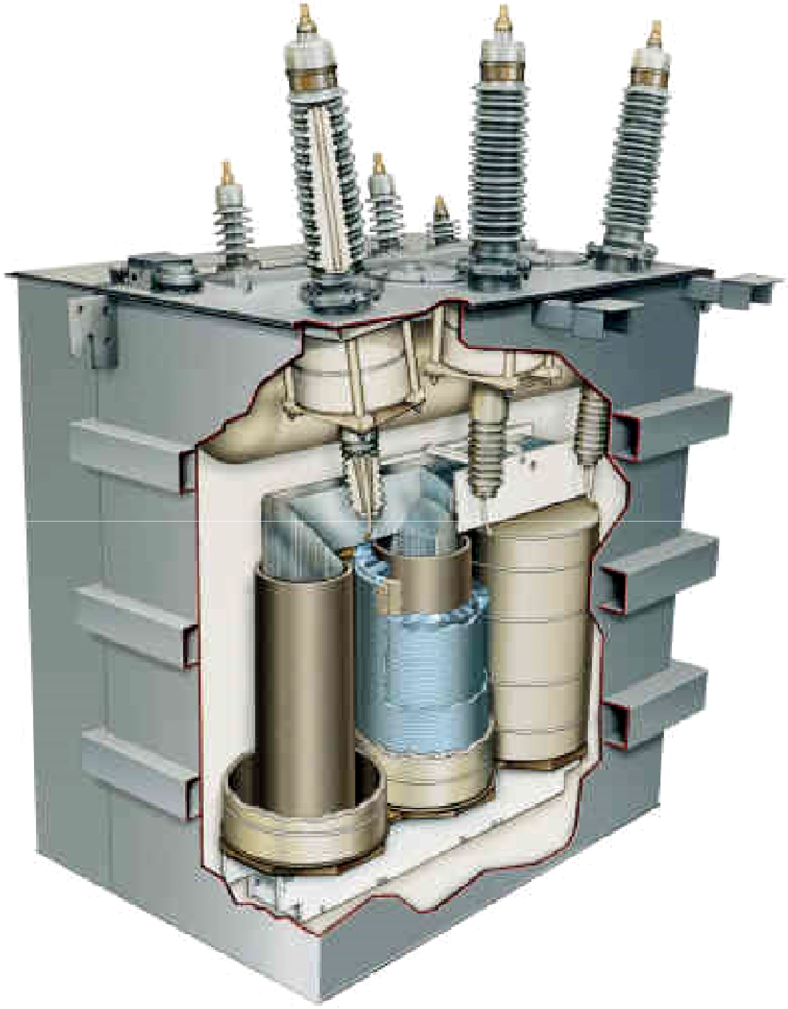
For over 50 years, DGA has been the leading tool to assess transformer condition

DISSOLVED

GAS

ANALYSIS

Monitoring of Gases in Transformers



Gas originates from many places:

- Mineral insulating oil
- Conductor paper insulation
- Pressboard barriers
- Other materials

Gas generation is related to high material temperatures (150°C to 1,000°C).

Gases are symptoms of:

- Poor design or construction
- Too much electrical stress
- Too much thermal stress
- Too many short circuits
- Overall poor condition

The Importance of DGA to Reliability

DGA enables the detection of the presence and severity of faults:

- Hot metal faults
- Arcing and partial discharges

DGA may help to indirectly detect root cause of faults in:

- Windings (short circuits, insulation failure)
- Cleats and leads (high contact resistance, loose contacts)
- Tanks (ground problems, circulating currents)
- Tap changer (resistive contacts, leaks into main tank)
- Core (magnetic flux problems)
- Oxidation of materials (mostly CO, CO_2)

DGA Interpretation

Standards and Guideline Groups

IEEE is a worldwide organization (historically focused on North & South America) that develops guides & standards for all types of electrical & electronic equipment

- There has been increased effort in recent years to “harmonize” with IEC but long-established equipment standards & practices involve un-reconcilable differences.

ASTM is one of the largest voluntary standards development organizations in the world; a source for technical standards for materials, products, systems, and services.

CIGRE is a worldwide organization doing technical work in the field of HV equipment and corresponds approximately to IEEE in the US.

IEC issues international standards and corresponds to ASTM in the US.

Standards and Guidelines Governing the Interpretation of DGA

IEEE Std. C57.104.1991 IEEE Guide for the Interpretation of Gases Generated in Oil Immersed Transformers

IEC 60599-1999 Mineral Oil Impregnated Electrical Equipment in Service: Guide to the Interpretation of Dissolved and Free Gas Analysis.

IEC 60599-1999, Amendment 1, 04/2007

The Fault Gases

Gas Sources

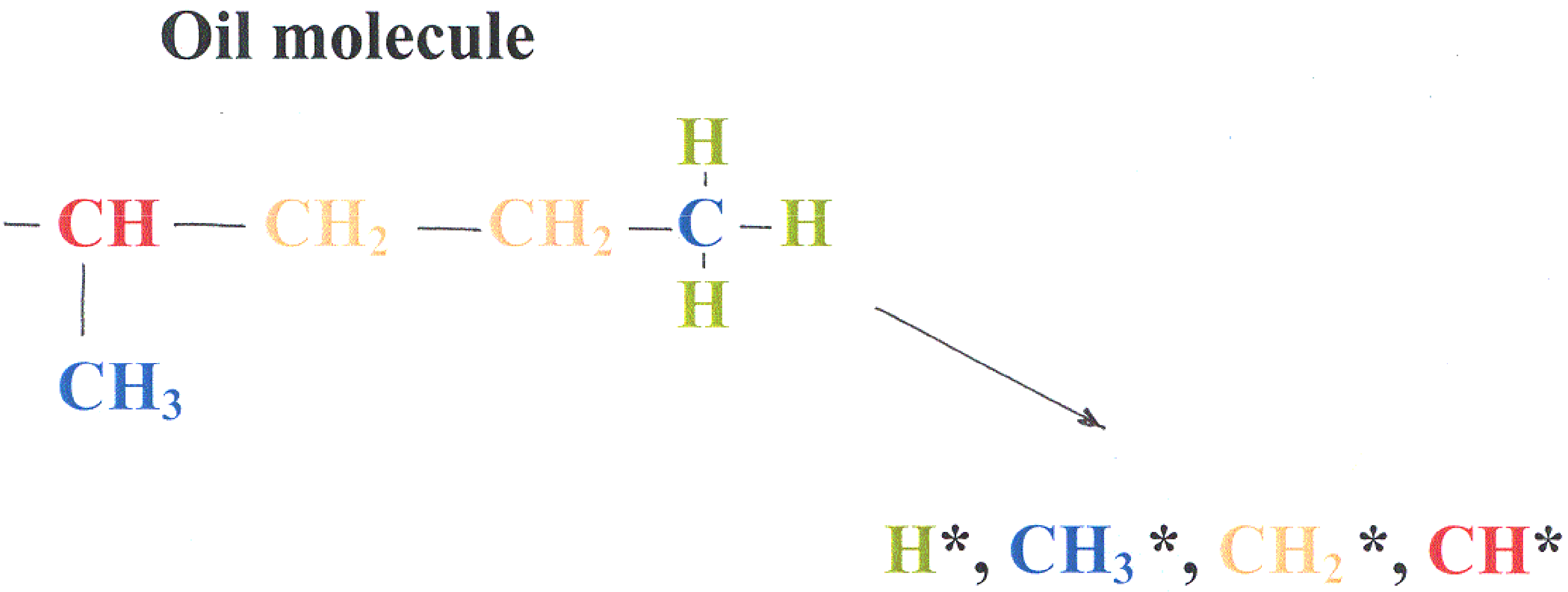
Gases in oil always result from the decomposition of electrical insulation materials (oil or paper), as a result of faults or chemical reactions in the equipment

For example:

- Oil is a molecule of hydrocarbons, i.e., containing hydrogen and carbon atoms, linked by chemical bonds (C-H, C-C)

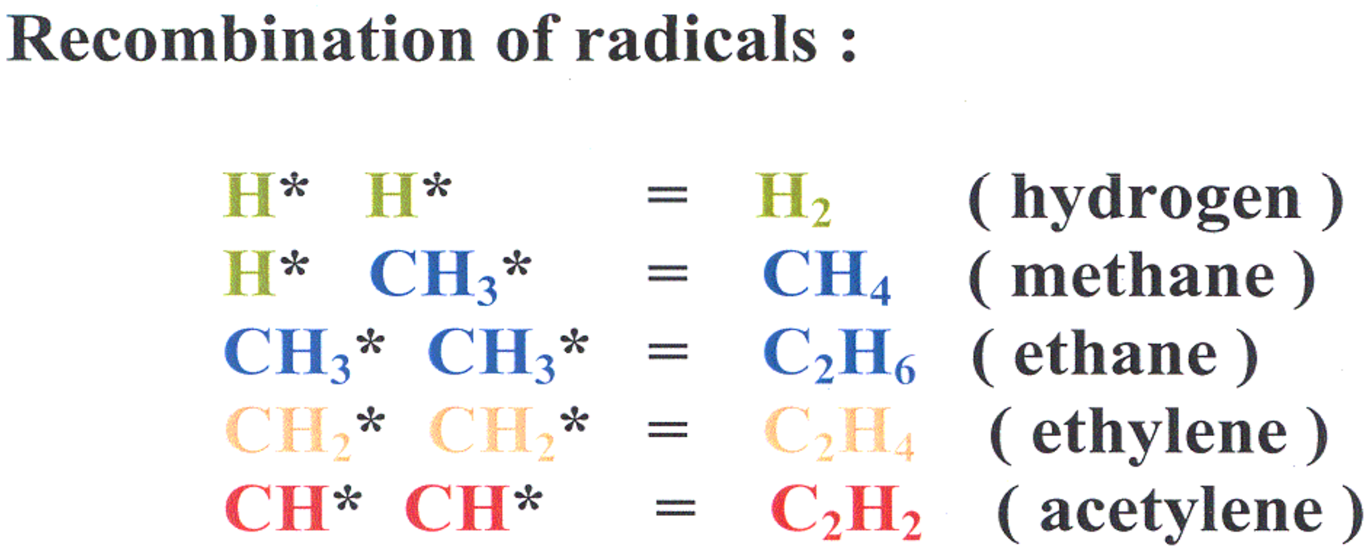
Gas Formation

Some of these bonds may break and form H*, CH_3*, CH_2* and CH* radicals.



Gas Formation

- All these radicals then recombine to form the fault gases observed in oil:



Recombination of radicals :

H^* H^* = H_2 (hydrogen)

H^* CH_3^* = CH_4 (methane)

CH_3^* CH_3^* = C_2H_6 (ethane)

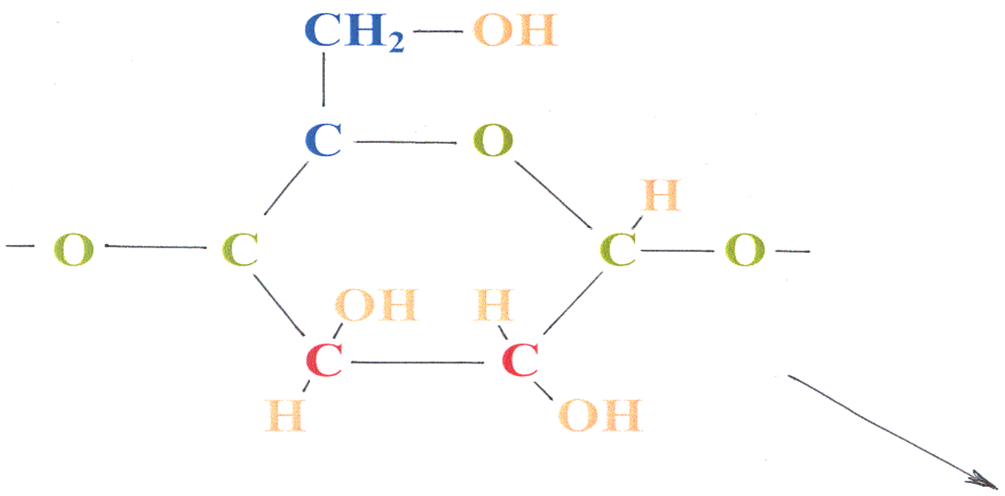
CH_2^* CH_2^* = C_2H_4 (ethylene)

CH^* CH^* = C_2H_2 (acetylene)

Gas Formation

In addition to these gases, the decomposition of paper produces CO_2, CO and H_2O, because of the presence of oxygen atoms in the molecule of cellulose:

Cellulose (paper)



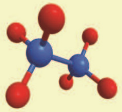
CO_2, CO, H_2O
H_2, CH_4, C_2H_6
C_2H_4, C

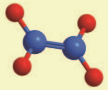
The Main Gases Analyzed by DGA

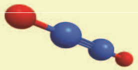
Hydrogen	H_2
Methane	CH_4
Ethane	C_2H_6
Ethylene	C_2H_4
Acetylene	C_2H_2
Carbon monoxide	CO
Carbon dioxide	CO_2
Oxygen	O_2
Nitrogen	N_2

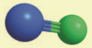
Gas	**HYDROGEN**
Formula	H_2
Structure	
Molecular Weight	2.016
Solubility in Oil @ 25°C	0.06
Solubility in Oil @ 70°C	0.07
Temperature at which Gas forms significant amount	<150°C for "cold plasma" ionization; (corona in oil) >250°C for thermal & electrical faults
Source of Gas	Partial-discharge; thermal faults; power discharges; rust, galvanized parts; stainless steel; sunlight

Gas	**METHANE**
Formula	CH_4
Structure	
Molecular Weight	16.043
Solubility in Oil @ 25°C	0.44
Solubility in Oil @ 70°C	0.44
Temperature at which Gas forms significant amount	<150° - 300° C
Source of Gas	Corona partial-discharge; low & medium temperature thermal faults

Gas	**ETHANE**
Formula	C_2H_6
Structure	
Molecular Weight	30.069
Solubility in Oil @ 25°C	2.59
Solubility in Oil @ 70°C	2.09
Temperature at which Gas forms significant amount	200° - 400°C
Source of Gas	Low & medium temperature thermal faults

Gas	**ETHYLENE**
Formula	C_2H_4
Structure	
Molecular Weight	28.054
Solubility in Oil @ 25°C	1.76
Solubility in Oil @ 70°C	1.47
Temperature at which Gas forms significant amount	300° - 700°C
Source of Gas	High-temperature thermal fault

Gas	**ACETYLENE**
Formula	C_2H_2
Structure	
Molecular Weight	26.038
Solubility in Oil @ 25°C	1.22
Solubility in Oil @ 70°C	0.93
Temperature at which Gas forms significant amount	>700°C
Source of Gas	Very hot spot; low- energy discharge (spitting from floating part); high-energy discharge (arc)

Gas	**CARBON MONOXIDE**
Formula	CO
Structure	
Molecular Weight	28.010
Solubility in Oil @ 25°C	0.13
Solubility in Oil @ 70°C	0.12
Temperature at which Gas forms significant amount	105° - 300°C (complete decomposition & carbonization occurs > 300°C)
Source of Gas	Thermal fault involving cellulose (paper, press-board, wood blocks); slowly from oil oxidation

Gas	**CARBON DIOXIDE**
Formula	CO_2
Structure	
Molecular Weight	44.010
Solubility in Oil @ 25°C	1.17
Solubility in Oil @ 70°C	1.02
Temperature at which Gas forms significant amount	105° - 300°C
Source of Gas	Normal aging (accelerated by amount of O_2-in-oil & H_2O-in-paper); thermal fault involving cellulose (paper, pressboard, wood blocks); accumulation from oil oxidation

Gas	**OXYGEN**
Formula	O_2
Structure	
Molecular Weight	31.999
Solubility in Oil @ 25°C	0.18
Solubility in Oil @ 70°C	0.17
Temperature at which Gas forms significant amount	Following drop in oil temperature (vacuum)
Source of Gas	Exposure to atmosphere (air); leaky gasket (under vacuum); air-breathing conservator; leaky bladder

Fault Gas Formation

- Most of the time, all these gases are present in DGA results. However, some are formed in larger or smaller quantities depending on the energy content of the fault

- Example; Low energy faults such as Corona Partial Discharges in gas bubbles, or low temperature hot spots, will form mainly Hydrogen, H_2 and Methane, CH_4

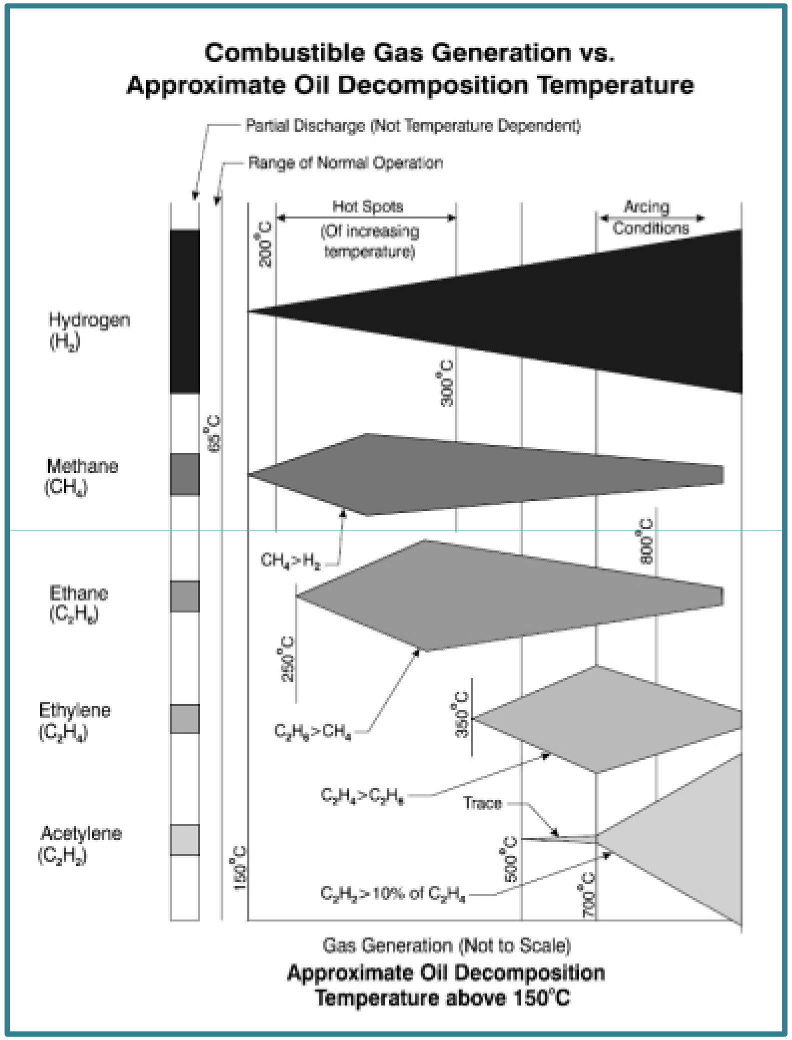
Fault Gas Formation

- Faults of higher temperatures are necessary to form large quantities of Ethylene, C_2H_4

- Finally, it takes faults with a very high energy content, such as in electrical arcs, to form large amounts of Acetylene, C_2H_2

- By looking at the relative proportion of gases in the DGA results it is possible to identify the type of fault occurring in a transformer in service

Fault Gas Formation



Source:

FIST 3-30 Facilities Instructions, Standards and Techniques; October 2000

Transformer Maintenance Guide

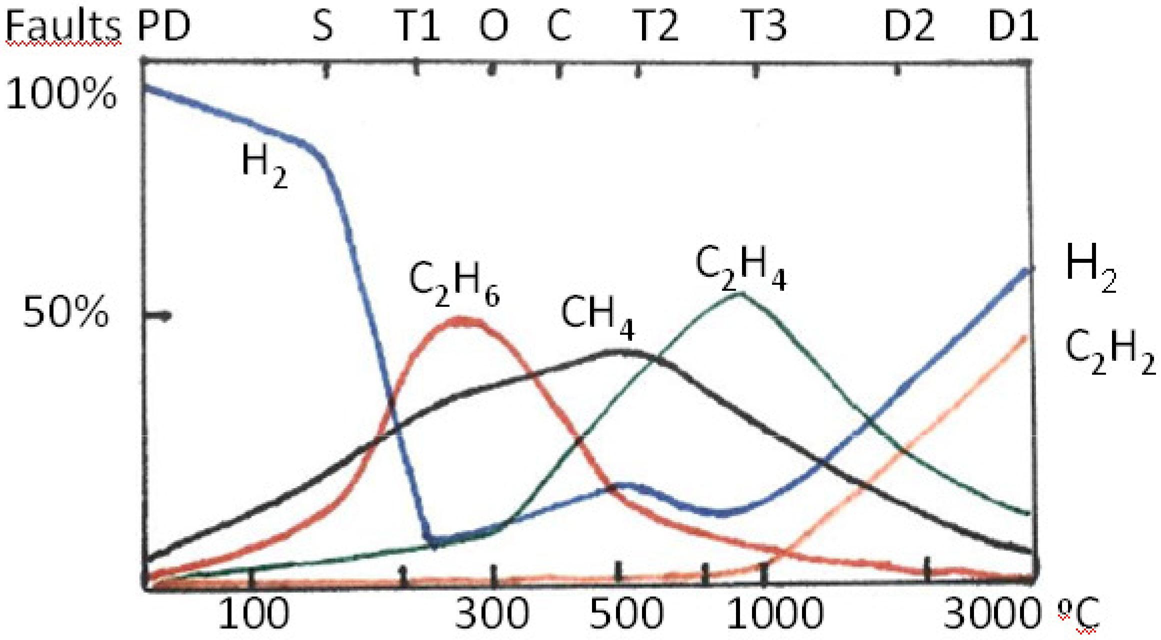
United States Department of the Interior
Bureau of Reclamation

(originally Rogers)

	TM8								
			TM3					TM1	
INDICATION / FAULT GAS	CO	CO_2	CH_4	C_2H_2	C_2H_4	C_2H_6	O_2	H_2	H_2O
Cellulose aging	◉	◉							◉
Mineral oil decomposition			◉	◉	◉	◉		◉	
Leaks in oil expansion systems, gaskets, welds, etc.		◉					◉		◉
Thermal faults – Cellulose	◉	◉	◉				◉	◉	
Thermal faults in Oil @ 150°C - 300°C			◉		TRACE	◉		◉	
Thermal faults in Oil @ 300°C - 700°C			◉	TRACE	◉	◉		◉	
Thermal faults in Oil @ >700°C			◉	◉	◉			◉	
Partial Discharge			◉	TRACE				◉	
Arcing			◉	◉	◉			◉	
Guidelines for surveillance range[1] for Type 1 transformers (IEEE PC57.104 D11d)	N <350 C 350 - 570 W >570		N <120 C 120 - 400 W >400	N <2 C 2 - 5 W >5	N <50 C 50 - 100 W >100	N <65 C 65 - 100 W >100		N <100 C 100 - 700 W >700	

[1] ppm for Normal (N), Caution (C), Warning (W) – alarm thresholds

Fault Gas Formation



Note: For faults T3 in paper (C), curve for H2 is a bit higher.
Ref: Duval, TSUG 2013.

Gas Formation Patterns

Are related only to the materials used and faults involved

Are the same in all equipment where these materials are used:

- Sealed or air-breathing power transformers
- Reactors
- Instrument transformers
- LTCs
- Etc.

Fault Types

Fault Types

Partial discharges of the corona-type (PD)

- Typical examples:
  - Discharges in gas bubbles or voids trapped in paper
  - A result of poor drying or poor oil-impregnation

Discharges of low energy (D1)

- Typical examples:
  - Partial discharges of the sparking-type
  - Inducing carbonized punctures in paper
  - Low-energy arcing, inducing surface tracking of paper and carbon particles in oil

Fault Types

Discharges of high energy (D2)

- Typical Examples
  - High Energy Arcing
  - Flashovers
  - Short Circuit with power follow through

- These result in;
  - Extensive damage to paper
  - Large formation of carbon particles in oil
  - Metal Fusion
  - Tripping of the equipment or gas alarms

Ref. IEC 60599-1999

Fault Types

Thermal faults of temperatures <300°C (T1)

- Typical Examples:
  - Overloading
  - Blocked oil ducts
  - Insufficient cooling

- Evidenced by paper turning:
  - Brown (>200°C)
  - Black or carbonized (>300°C)

Fault Types

Thermal faults of temperatures between 300 and 700℃ (T2)

- Typical Examples:
  - Defective contacts
  - Defective welds
  - Circulating currents
- Evidenced by:
  - Carbonization of paper
  - Formation of carbon particles

Ref. IEC 60599-1999

Fault Types

Thermal faults of temperatures >700°C (T3)

- Typical Examples:
  - Large circulating currents in tank and core
  - Short circuits in laminations

- Evidenced by:
  - Extensive formation of carbon particles in oil
  - Metal coloration (800°C) or metal fusion (>1000°C)

Fault Types

Mixtures of faults

- Mixtures of faults sometimes occur rather than « pure » faults and may be more difficult to identify with certainty.

- For instance, mixtures of faults D1 and T3 may appear as faults D2 in terms of gas formation.

Fault Types

New faults vs. old faults:

•When a new fault appears, as evidenced by a change in gas pattern, a more precise identification of the new fault may be obtained by subtracting the gas concentrations corresponding to the old fault from those corresponding to the new one (incremented values).

•This, however, introduces additional uncertainty on the subtracted value.

•The evolution of faults with time is best followed graphically with the Triangle.

BREAK

Diagnostic Tools

Factors Influencing the Interpretation of Results

- Type of fault (electrical, thermal)
- Location of fault (paper, oil)
- Gas concentrations, gassing rates
- Gas limits are influenced by type and location of fault

Diagnostic Tools for DGA

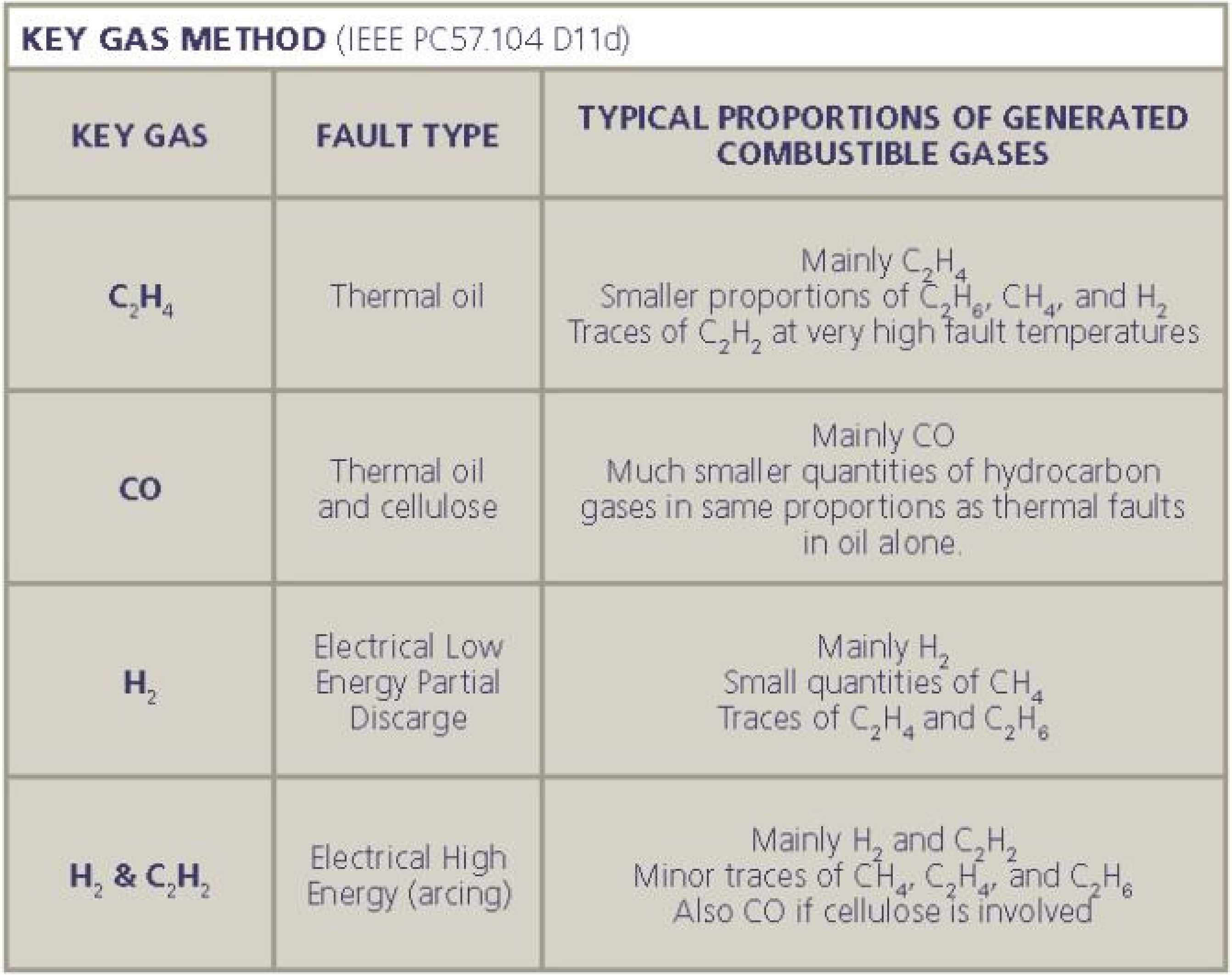
Tool	Reference Standard		
	IEEE C57. 104-1991	IEEE PC57. 104 D11d	IEC 60599-1999
Dornenburg Ratios	✓		
TDCG Procedure	✓	✓	
Key Gas Procedure	✓	✓	
TCG Procedure	✓		
Rogers Ratios	✓	✓	
IEC Gas Ratios			✓
Duval Triangle			✓
CO_2/CO Ratio		✓	✓
O_2/N_2 Ratio			✓
C_2H_2/H_2 Ratio			✓

Fault Identification Methods

- Key gas
- Rogers
- Duval Triangle 1

- CO and CO_2 (paper involvement in faults)
- O_2/N_2 (hot spots, membrane leaks)
- C_2H_2/H_2 (OLTC leaks)
- Duval Triangles 4 and 5 for more information about thermal faults

Key Gas Procedure

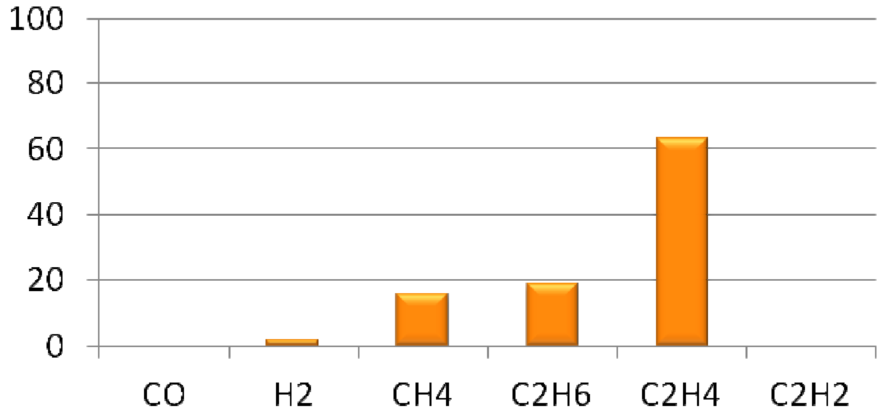


KEY GAS METHOD (IEEE PC57.104 D11d)

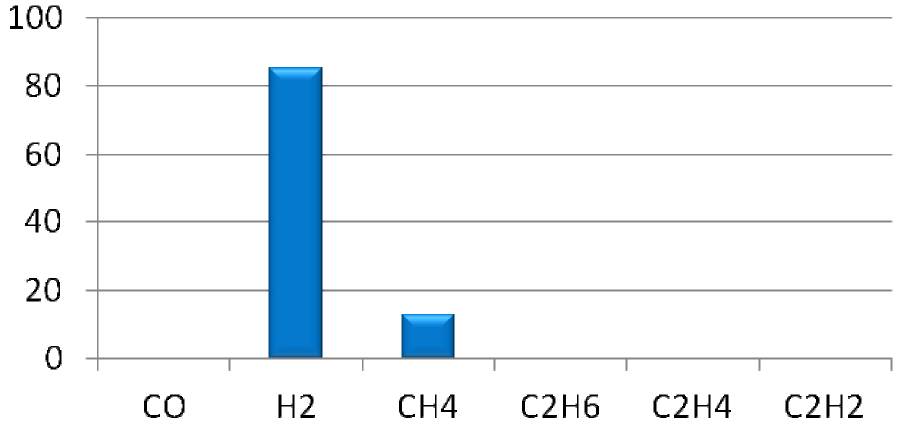
KEY GAS	FAULT TYPE	TYPICAL PROPORTIONS OF GENERATED COMBUSTIBLE GASES
C_2H_4	Thermal oil	Mainly C_2H_4 Smaller proportions of C_2H_6, CH_4, and H_2 Traces of C_2H_2 at very high fault temperatures
CO	Thermal oil and cellulose	Mainly CO Much smaller quantities of hydrocarbon gases in same proportions as thermal faults in oil alone.
H_2	Electrical Low Energy Partial Discarge	Mainly H_2 Small quantities of CH_4 Traces of C_2H_4 and C_2H_6
H_2 & C_2H_2	Electrical High Energy (arcing)	Mainly H_2 and C_2H_2 Minor traces of CH_4, C_2H_4, and C_2H_6 Also CO if cellulose is involved

Key Gas Examples

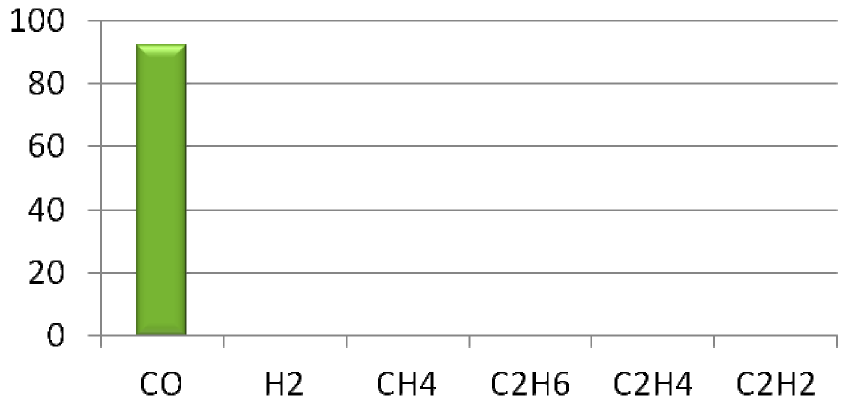
Thermal Oil Fault



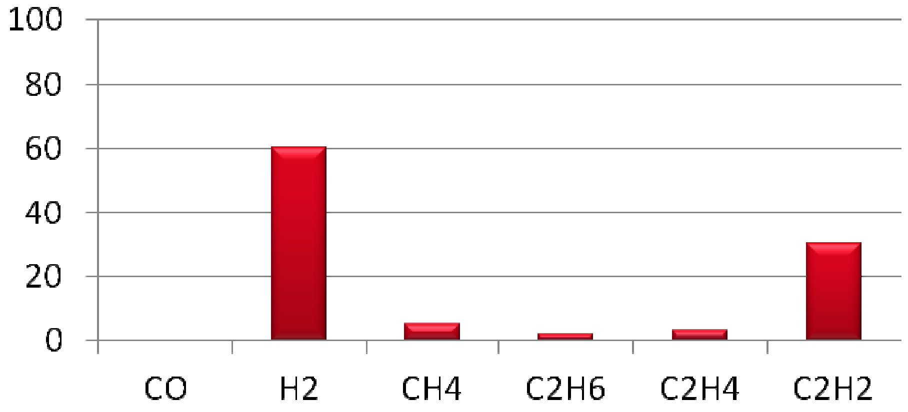
Low Energy Partial Discharge



Thermal Oil and Cellulose Fault



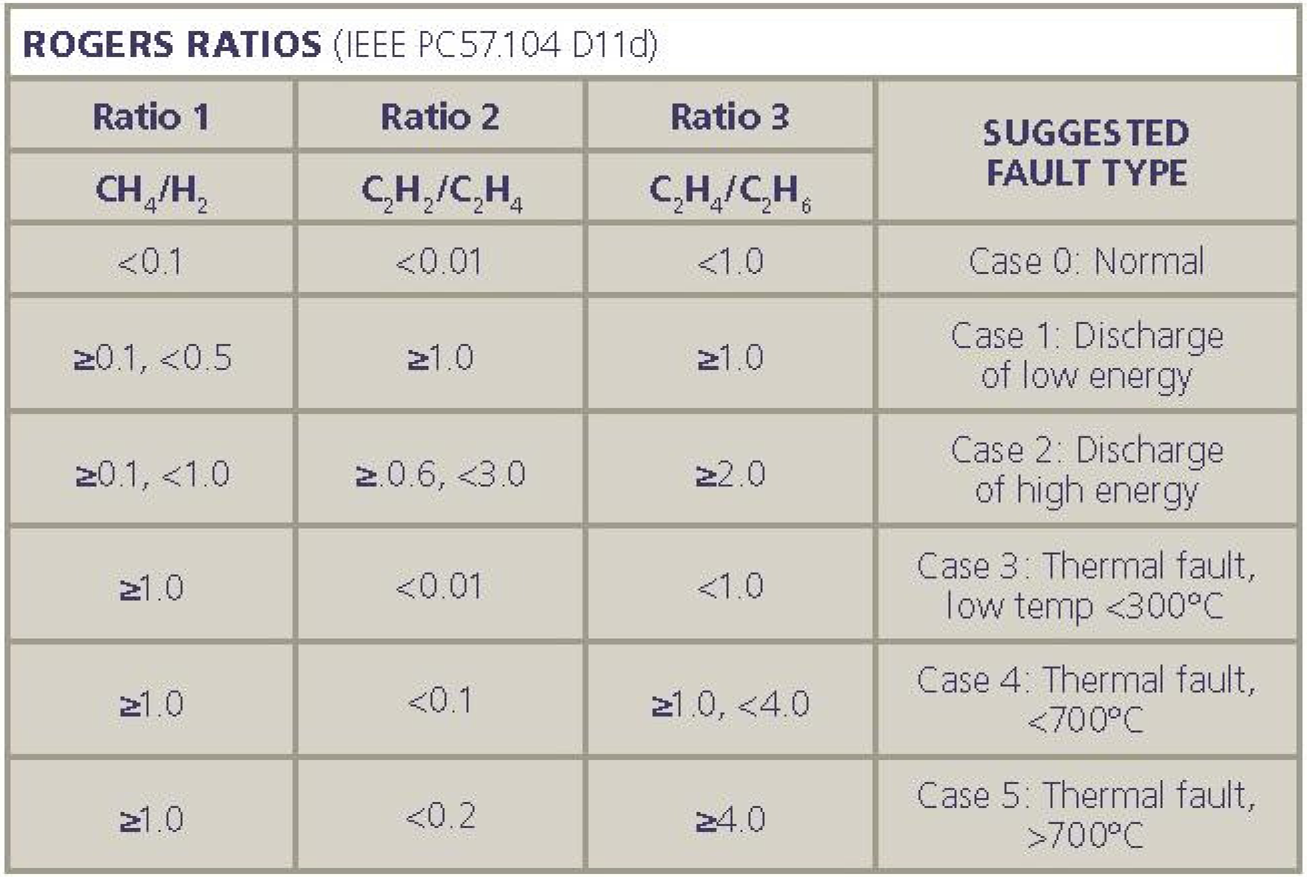
High Energy Arcing



Key Gas Method - Limitations

- High tendency to return inconclusive or wrong results if done automatically with software.
- May be used manually by experienced personnel only.
- Often difficult to determine which gas is predominant, and how secondary gases should be taken into account.
- Predominant gas often is not one of the 4 key gases.
- Carbon monoxide is often used wrongly as an indication of paper involvement in faults.

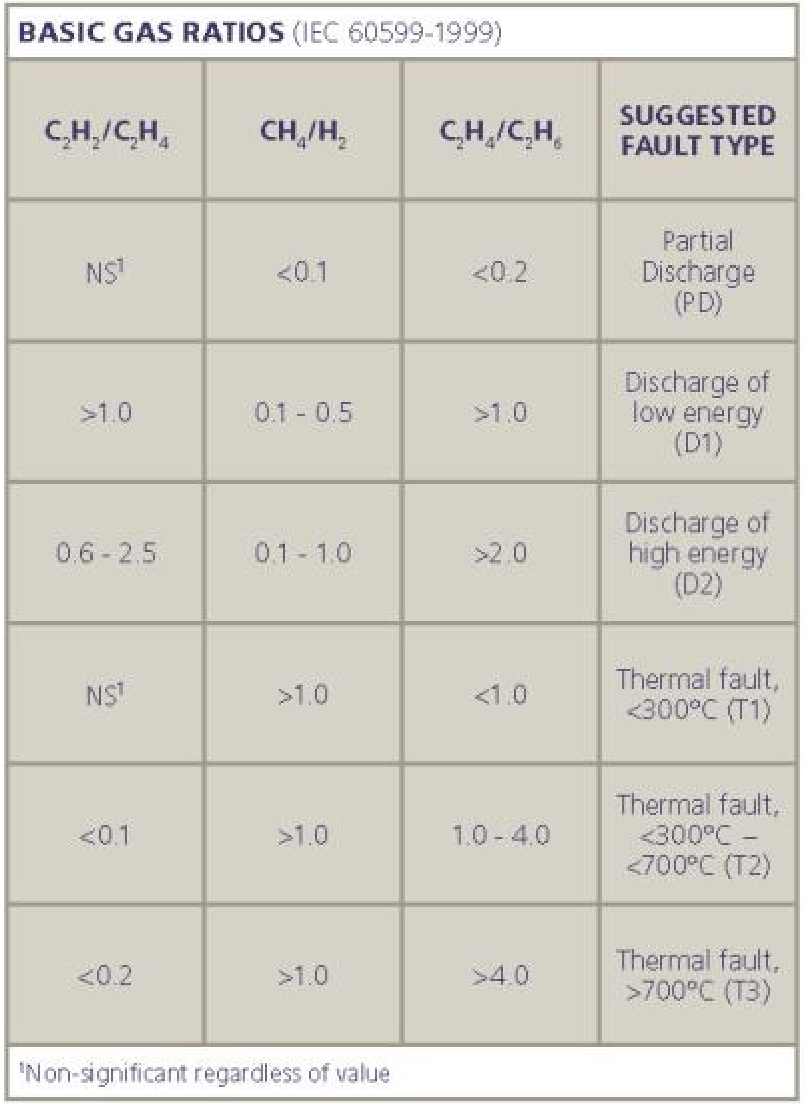
Rogers Ratios Method



ROGERS RATIOS (IEEE PC57.104 D11d)

Ratio 1	Ratio 2	Ratio 3	SUGGESTED FAULT TYPE
CH_4/H_2	C_2H_2/C_2H_4	C_2H_4/C_2H_6	
<0.1	<0.01	<1.0	Case 0: Normal
≥0.1, <0.5	≥1.0	≥1.0	Case 1: Discharge of low energy
≥0.1, <1.0	≥0.6, <3.0	≥2.0	Case 2: Discharge of high energy
≥1.0	<0.01	<1.0	Case 3: Thermal fault, low temp <300°C
≥1.0	<0.1	≥1.0, <4.0	Case 4: Thermal fault, <700°C
≥1.0	<0.2	≥4.0	Case 5: Thermal fault, >700°C

IEC Gas Ratio Method



BASIC GAS RATIOS (IEC 60599-1999)

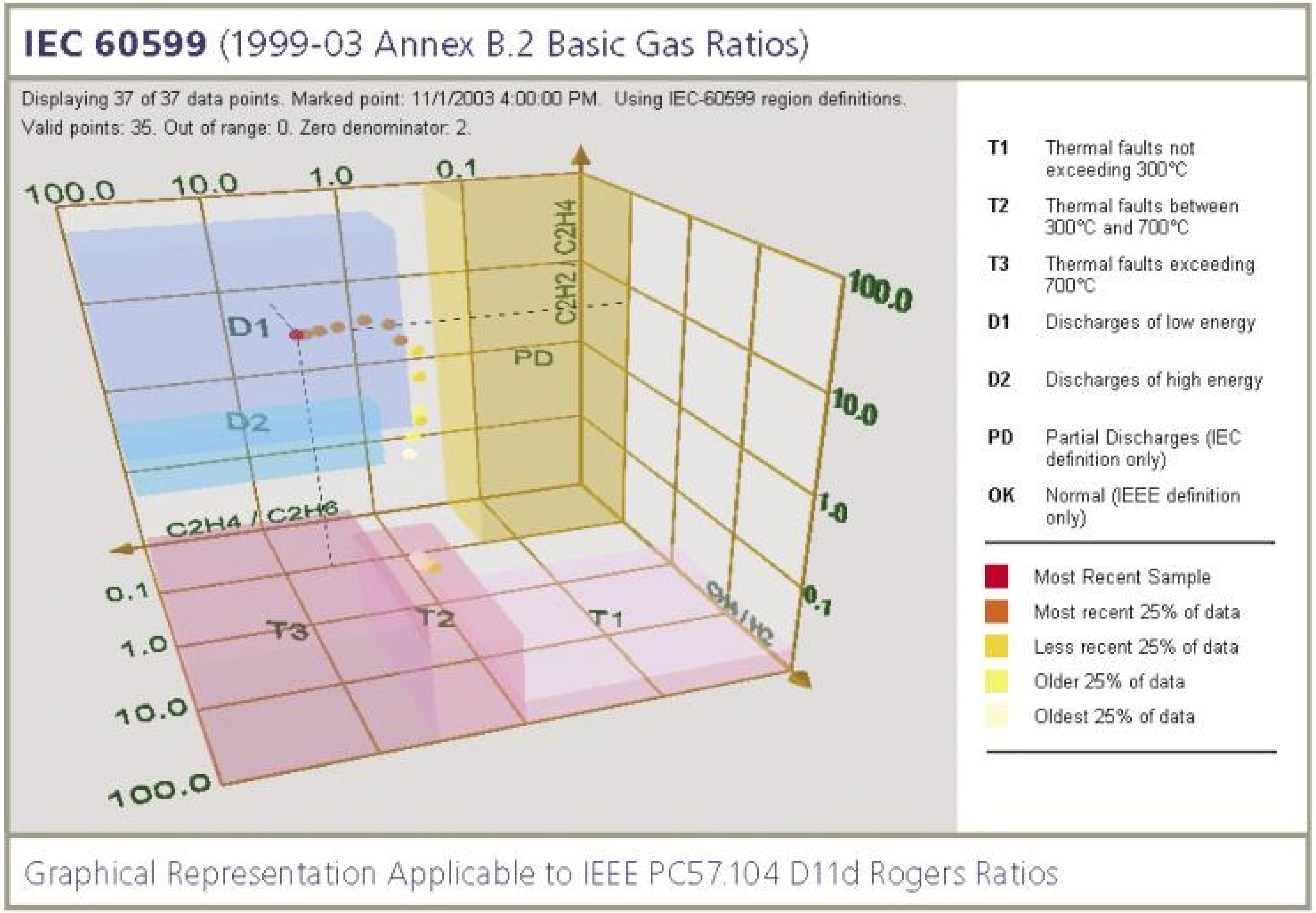
C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	**SUGGESTED FAULT TYPE**
NS[1]	<0.1	<0.2	Partial Discharge (PD)
>1.0	0.1 - 0.5	>1.0	Discharge of low energy (D1)
0.6 - 2.5	0.1 - 1.0	>2.0	Discharge of high energy (D2)
NS[1]	>1.0	<1.0	Thermal fault, <300°C (T1)
<0.1	>1.0	1.0 - 4.0	Thermal fault, <300°C – <700°C (T2)
<0.2	>1.0	>4.0	Thermal fault, >700°C (T3)

[1] Non-significant regardless of value

Rogers / IEC ratio methods - Limitations

In a significant number (typically, 33%) of cases, no diagnosis can be given because the DGA point falls outside of defined zones.

3-D IEC Gas & Rogers Ratio Methods



IEC 60599 (1999-03 Annex B.2 Basic Gas Ratios)

Displaying 37 of 37 data points. Marked point: 11/1/2003 4:00:00 PM. Using IEC-60599 region definitions.
Valid points: 35. Out of range: 0. Zero denominator: 2.

T1	Thermal faults not exceeding 300°C
T2	Thermal faults between 300°C and 700°C
T3	Thermal faults exceeding 700°C
D1	Discharges of low energy
D2	Discharges of high energy
PD	Partial Discharges (IEC definition only)
OK	Normal (IEEE definition only)

🟥	Most Recent Sample
🟧	Most recent 25% of data
🟨	Less recent 25% of data
🟨	Older 25% of data
▢	Oldest 25% of data

Graphical Representation Applicable to IEEE PC57.104 D11d Rogers Ratios

Fault Method Comparisons

	% Correct Diagnoses	% Unresolved Diagnoses	% Wrong Diagnoses
IEEE Key Gas Method	42	0	58
Rogers Ratio	62	33	5
Doernenburg Ratios	71	26	3
IEC Gas Ratio	77	15	8
IEC Duval Triangle	96	0	4

Duval Triangle

Triangle Method

The Triangle was developed empirically in the early 1970s, and is used by the IEC.

Based upon 3 gases (Methane, CH_4, Ethylene, C_2H_4 and Acetylene, C_2H_2) corresponding to the increasing energy levels of gas formation.

One advantage of this method is that it always provides a diagnosis, with a low percentage of wrong diagnoses.

There are no indeterminate diagnostics using the Triangle method.

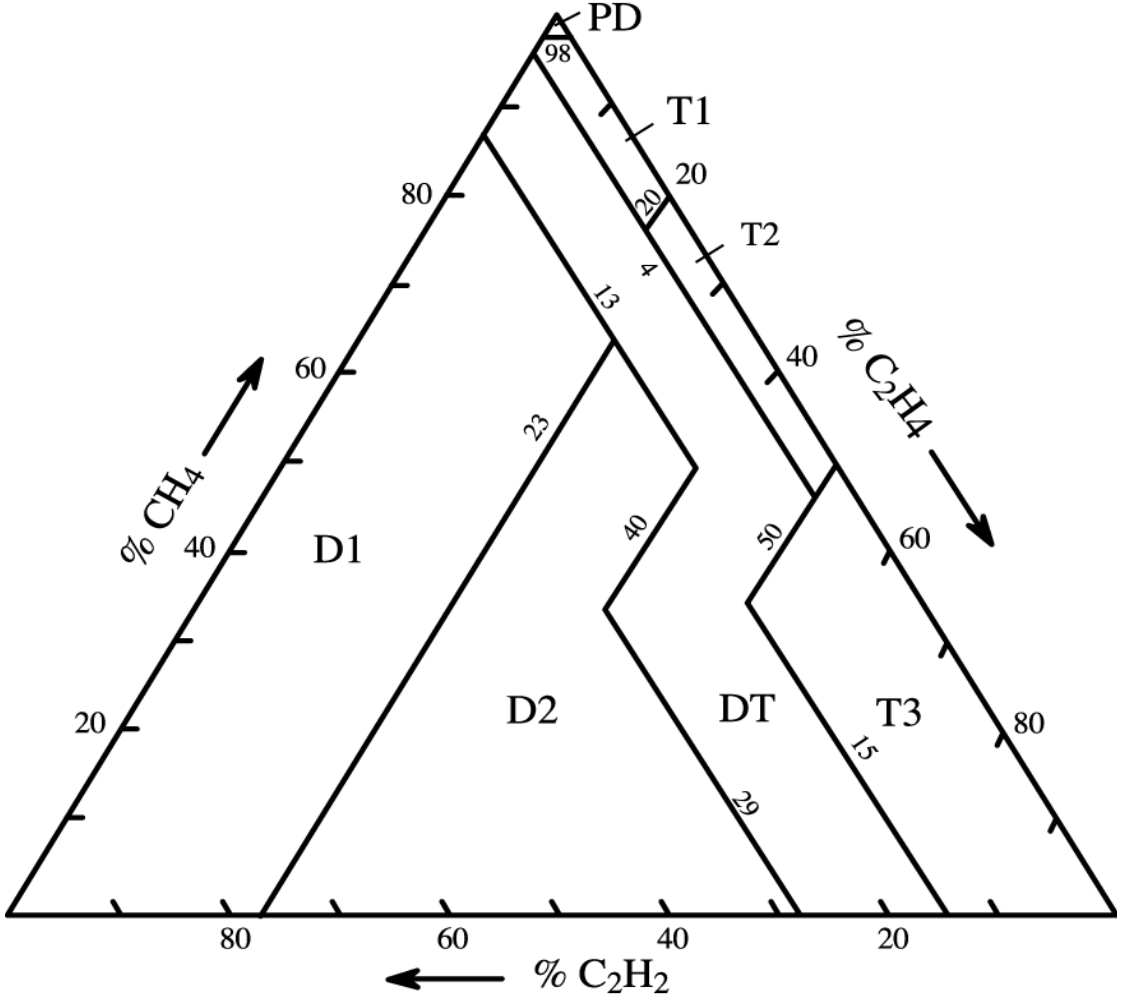
Triangle Method

The triangle method plots the relative % of the 3 gases on each side of the triangle, from 0% to 100%.

The 6 main zones of faults are indicated in the triangle, plus a DT zone (mixture of thermal and electrical faults)

Approximately 200+ inspected cases in service were used to develop the Triangle

Triangle Method

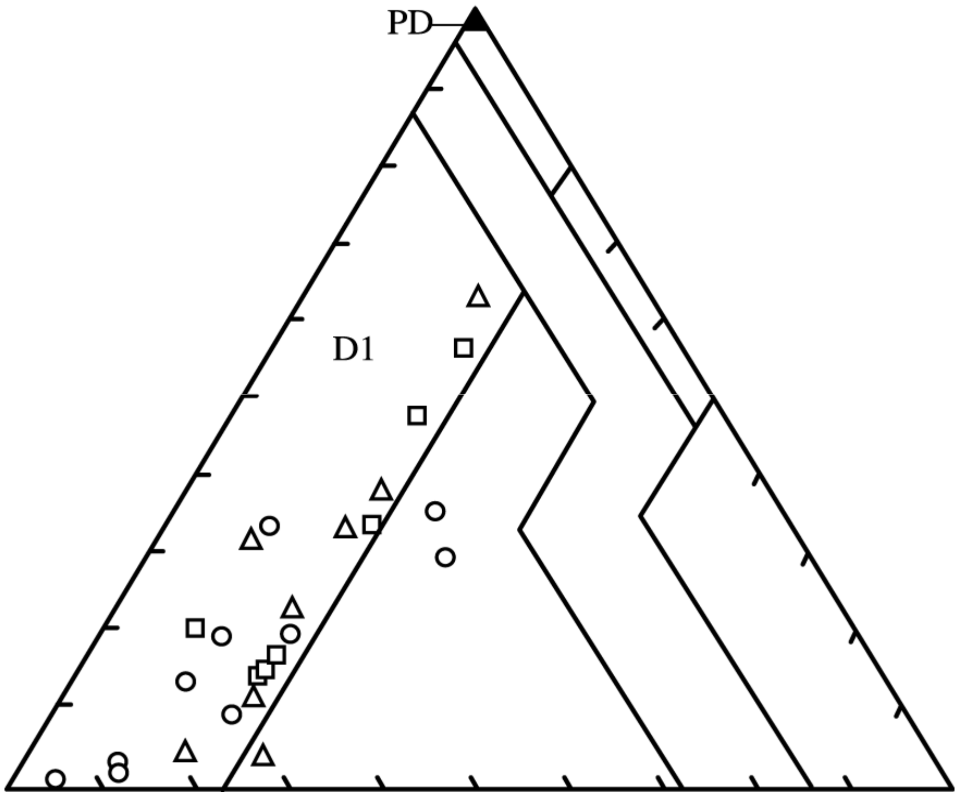


Triangle Method

- Fault zones in the Triangle are based on a large number of cases of faulty transformers in service which have been inspected visually.
- The root cause of the failure was determined and matched to the DGA data.
- The Triangle was tested with all these cases and correctly identifies the zone that matches the root cause of failure at a very high percentage.

Triangle Method

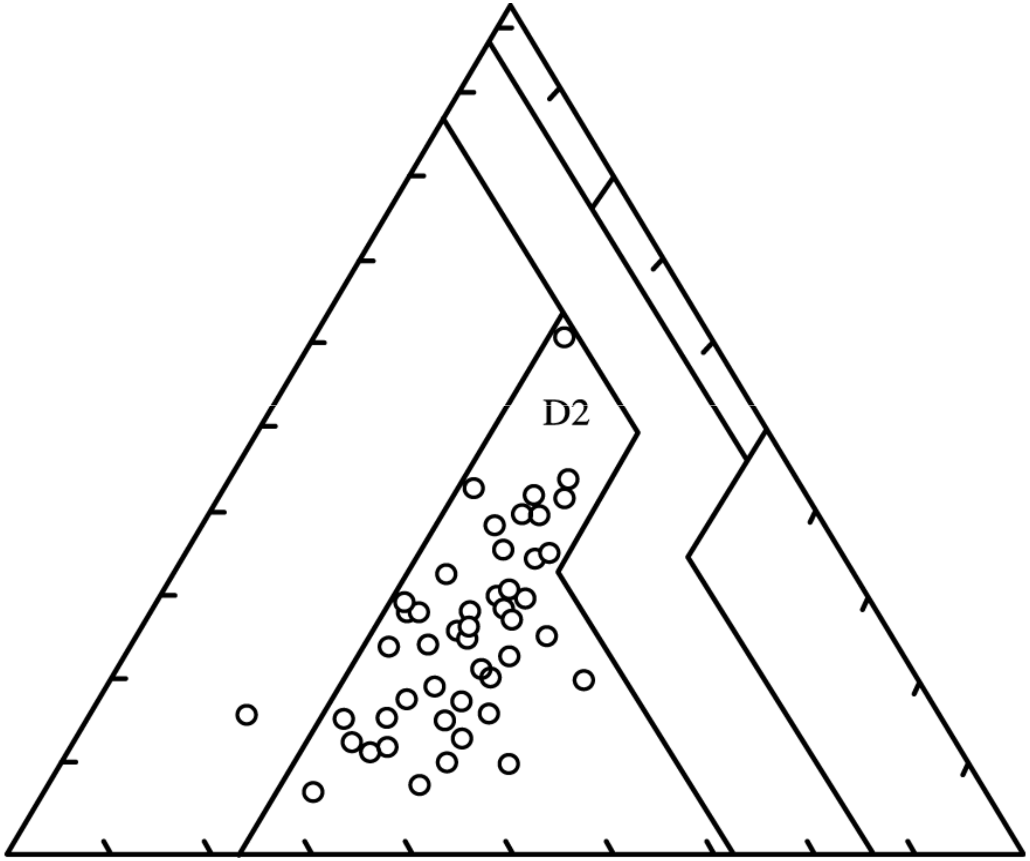
Cases of faults PD and D1



Tracking; △ Sparking; ○ Small Arcing

Triangle Method

Cases of faults D2



Material Of Dr. Duval
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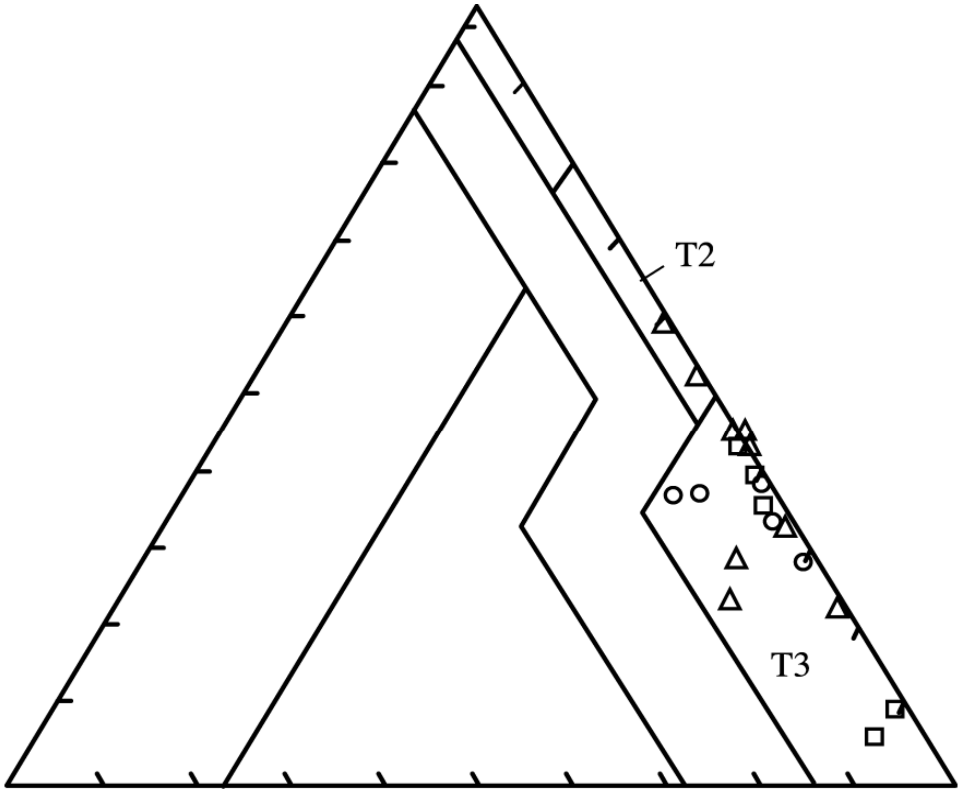
Triangle Method

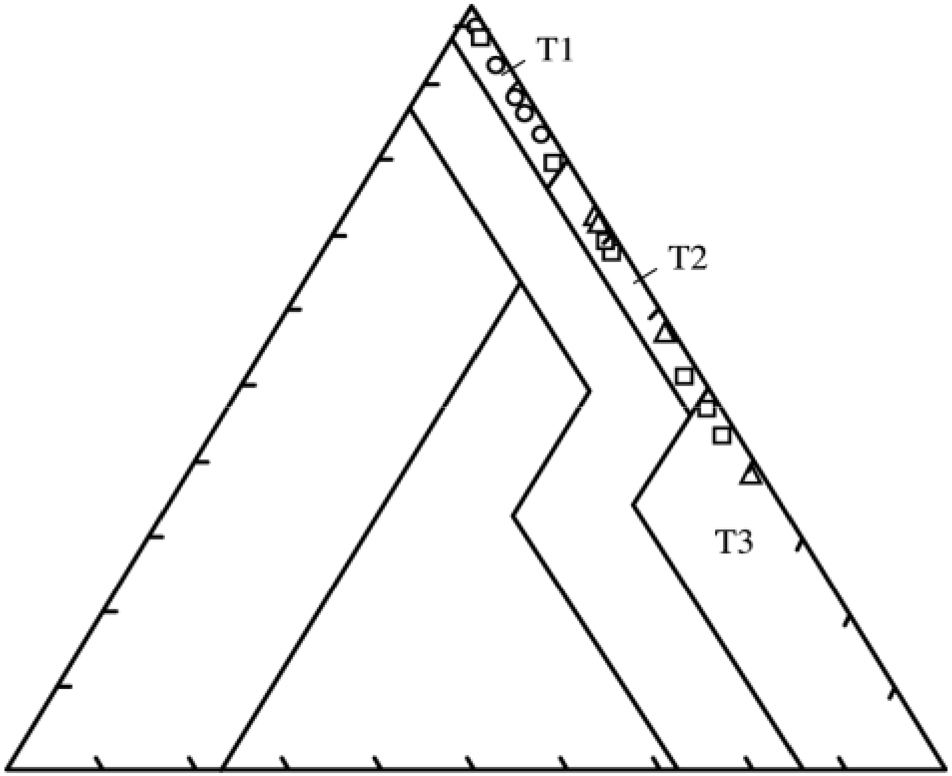
Cases of thermal faults in oil only



Circulating Currents; ○ Laminations; △ Bad Contacts

Triangle Method

Cases of thermal faults in paper

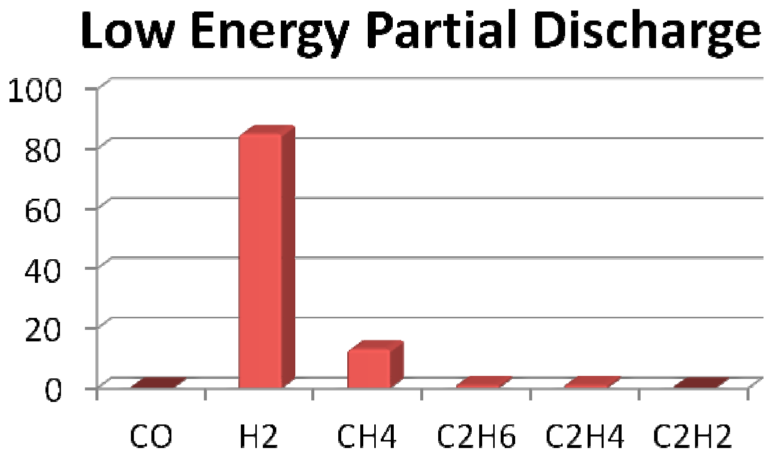


○ **Brownish Paper; Carbonized Paper; △ Not Mentioned**

Triangle Method FAQ's

How are corona PDs, which form a lot of Hydrogen, H_2, identified in the Triangle without using this gas?

- Answer: In such faults, Methane, CH_4 is indeed formed in smaller amounts than Hydrogen, H_2 (typically 10 to 20 times less), but which can still be measured easily by DGA



Triangle Method FAQ's

In the Triangle method, why not use Hydrogen, H_2 rather than Methane, CH_4 to represent low energy faults?

- Answer: Because CH_4 provides better overall diagnoses for all types of faults (of low and high energy)

New Triangle 4 using H_2, CH_4 and C_2H_6 has indeed been developed since for low energy faults

Using the Triangle Method

If, for example, the DGA lab results are:

- Methane, CH_4 = 100 ppm
- Ethylene, C_2H_4 = 100 ppm
- Acetylene, C_2H_2 = 100 ppm

First calculate: $CH_4 + C_2H_4 + C_2H_2 = 300$ppm

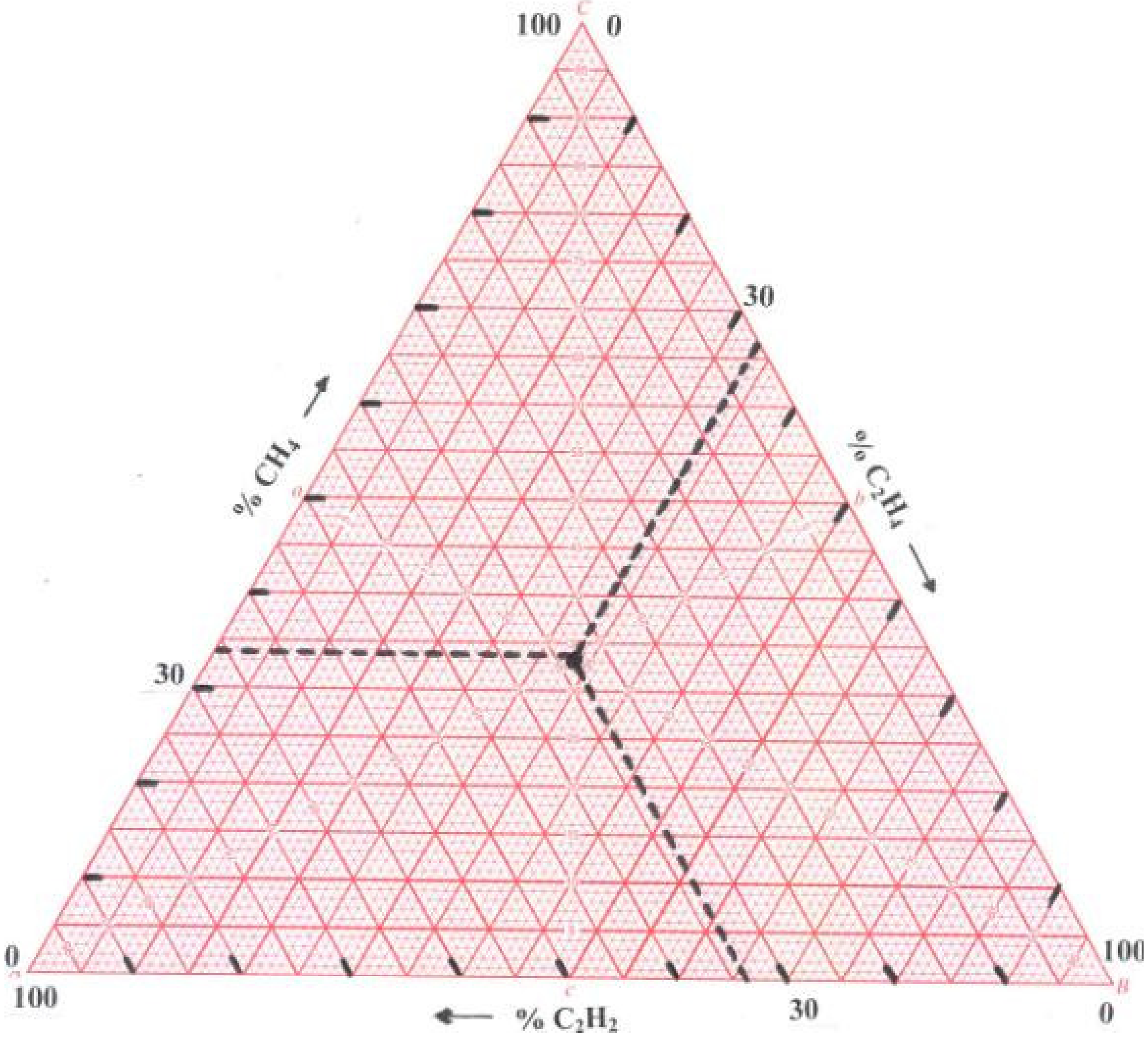
Then calculate the relative % of each gas:

- Relative % of CH_4 = 100/300 = 33.3 %
- Relative % of C_2H_4 = 100/300 = 33.3 %
- Relative % of C_2H_2 = 100/300 = 33.3 %

These values are the triangular coordinates to be used on each side of the triangle

To verify that the calculation was done correctly, the sum of these 3 values should always give 100%, and should correspond to only one point in the triangle

Triangle Method Example



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Using the Triangle Method

The calculation of triangular coordinates can easily be done manually, or with the help of a small algorithm or software

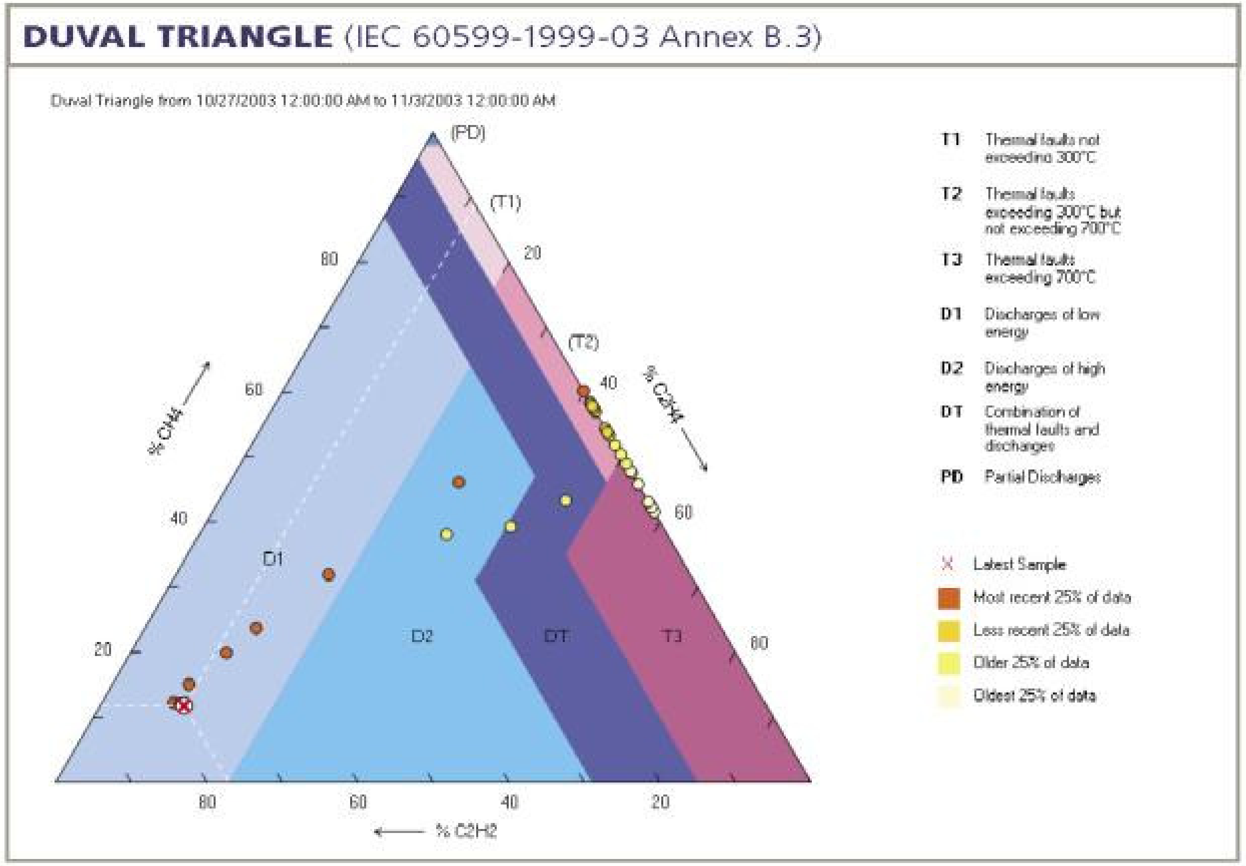
Errors are often made when developing such an algorithm, so check it first with the free algorithm available. (duvalm@ireq.ca)

For those familiar with computer graphics, it is also possible to develop a software displaying the point and the fault zones graphically in the triangle

Software from vendors is available for that purpose

An example of the software follows, Courtesy of Serveron

Using the Triangle Method



Note: This is the same data as shown using Roger's Ratio example

Fault Severity

The most severe faults:

- Faults D2 in paper and in oil (high-energy arcing)
- Faults T2-T3 in paper (>300℃)
- Faults D1 in paper (tracking, arcing)
- Faults T3 in oil (>700℃)

The less severe faults:

- Faults PD/ D1 in oil (sparking)
- Faults T1 in paper (<300℃)
- Faults T2 in oil (<700℃)
- Are difficult to find by inspection

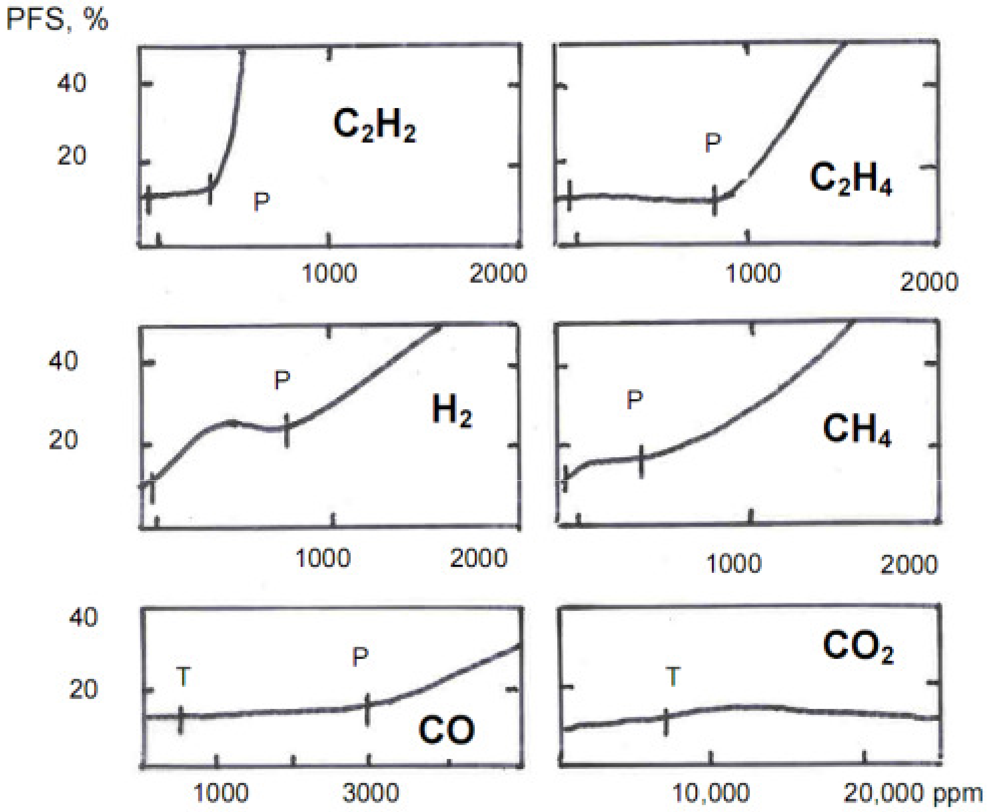
A fault in paper is generally considered as more serious than a fault in oil only, because paper is often placed in a HV area (windings, barriers), and damage is irreversible

Risk of failure vs. type and location of fault

FAULT	IN PAPER		IN OIL	
	Main products formed	RISK of failure	Main products formed	RISK of failure
D2	C, C_2H_2	Very high	C_2H_2, C	Very high
D1	C, C_2H_2	Very high	C_2H_2, C	Moderate
T3	C, C_2H_4	Very high	C_2H_4, C	Moderate
T2	C, CH_4	High	CH_4	Low
T1, O	C_2H_6, CO	Moderate	C_2H_6	Zero
PD	H_2	Low	H_2	Very low
T<200C Aging	CO_2 Furans, alcohols Low DPs of paper	Very low	H_2	Zero

Risk of failure vs. gases formed at CIGRE

(PFS = Probability
of Failure in Service)



Risk of failure vs. CO_2 and DP of paper

- The risk of failure is very low at high CO_2 values, which are strongly correlated with paper degradation and low DPs of paper.

- This suggests that the risk of failure at low DPs of paper is also very low, not very high as generally assumed.

- Indeed, large numbers of transformers have been observed at CIGRE to operate quite normally with DPs of paper < 200.

- And no cases have been reported so far of transformers with DPs < 200 that failed because of the mechanical weakness of paper, even when subjected to external short-circuits.

Transformers at risk of failure

•So, in most cases, low DPs of paper do not mean the « end-of life » of transformers as generally believed.

•Transformers actually most at risk are abnormally gassing (sick) transformers with electrical or thermal faults.

•The main concern with low DPs of paper is the shrinkage of paper and loosening of windings, not the mechanical strength of paper.

•This, however, can easily be mitigated by reclamping transformers with low DPs of paper. How easy or difficult is it for you to reclamp transformers?

Paper involvement in faults

It is generally believed that CO and CO_2 are good indicators of paper involvement in faults.

However, very often this is not the case, as shown in the following two examples.

Example 1: CO_2 and CO from closed transformers

Gas		Probe
H_2	Hydrogen	14
CH_4	Methane	10
C_2H_6	Ethane	2
C_2H_4	Ethylene	3
C_2H_2	Acetylene	< 1
CO	Carbon Monoxide	1075
CO_2	Carbon Dioxide	1369
O_2	Oxygen	1705
N_2	Nitrogen	8896

56 MVA, 220kV

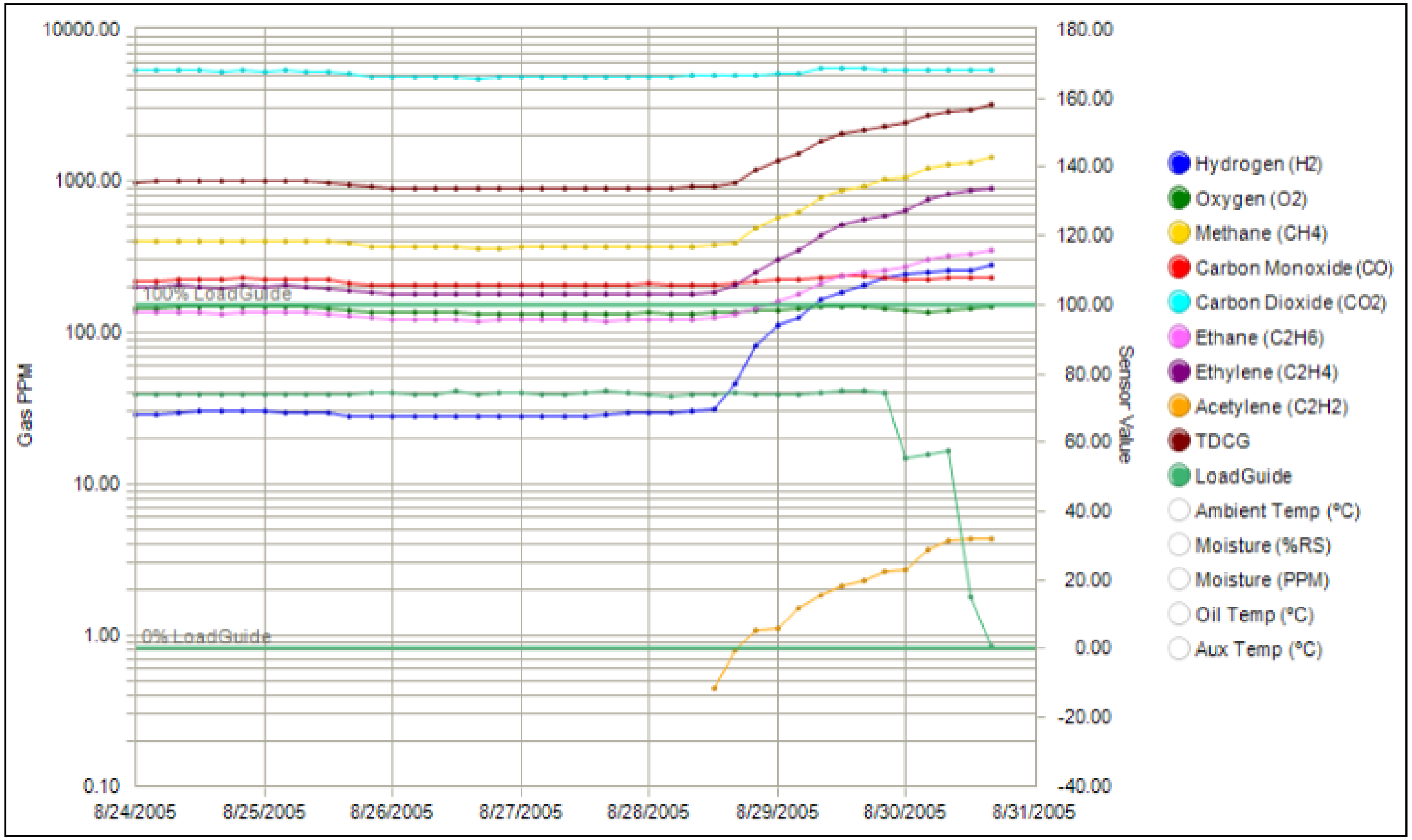
Manufactured 2006

Rubber Bag

Ref: I.Hoehlein, CIGRE TF15 (2010)

Example 2 of fault in paper

Example of fault in paper



The other gases are often more sensitive and reliable than CO to detect paper involvement

CO_2 and CO from Overheated Paper

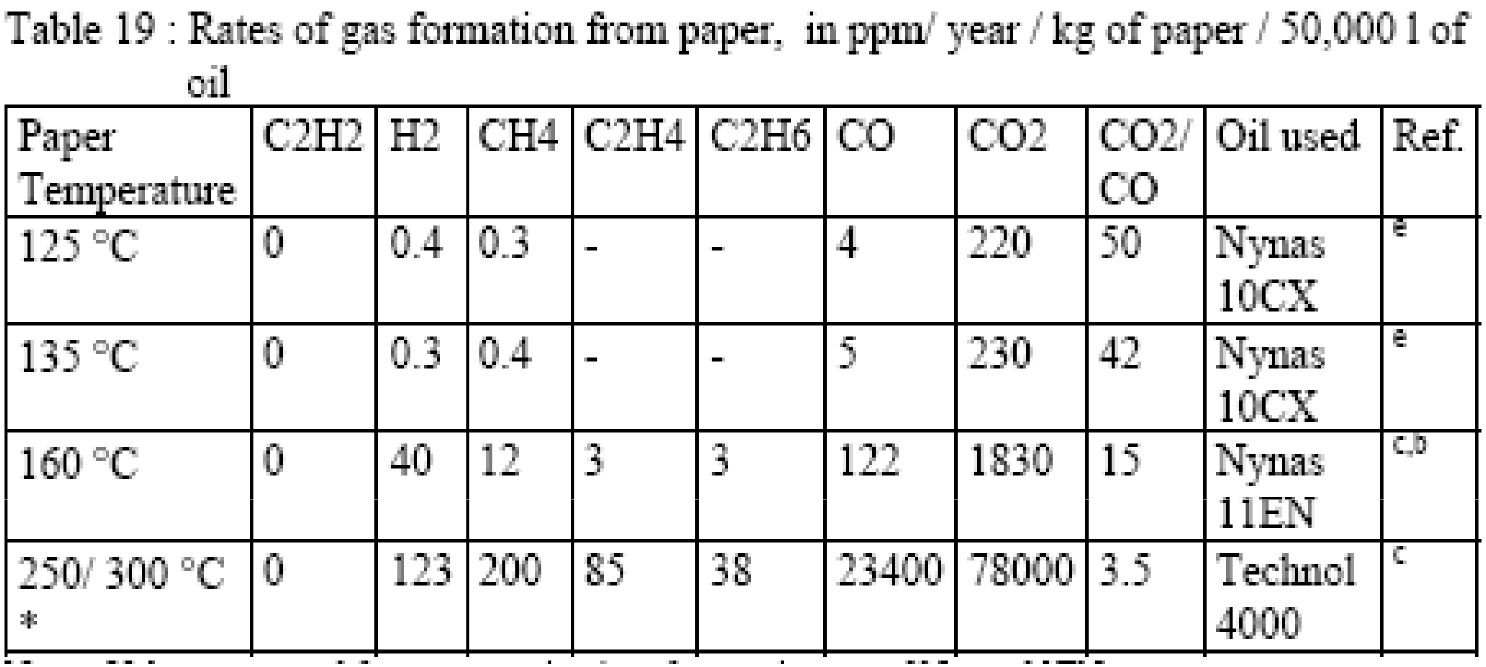


Table 19 : Rates of gas formation from paper, in ppm/ year / kg of paper / 50,000 l of oil

Paper Temperature	C2H2	H2	CH4	C2H4	C2H6	CO	CO2	CO2/ CO	Oil used	Ref.
125 °C	0	0.4	0.3	-	-	4	220	50	Nynas 10CX	e
135 °C	0	0.3	0.4	-	-	5	230	42	Nynas 10CX	e
160 °C	0	40	12	3	3	122	1830	15	Nynas 11EN	c,b
250/ 300 °C *	0	123	200	85	38	23400	78000	3.5	Technol 4000	c

Ref: CIGRE Technical Brochure # 296 (2006)

Note: CO_2/CO ~ 18 for laboratory oxidized oil at 110C.

Distribution of CO_2/CO Ratios in Transformers

	Open	Closed
> 50	1-3	3-6
50-20	6-30	14-21
20-4	63-86	69-72
< 4	3-6	3-11

Note: distribution is relatively similar in all types of transformers

Ref: CIGRE TF15 (2010)

Interpretation of CO and CO_2

-High values of CO (> 1000 ppm) and/or low CO_2/CO ratios (< 4) in closed transformers, together with no significant formation of the other hydrocarbon gases, are not an indication of a fault in paper, but an indication of oil oxidation under condition of low oxygen availability.

-They are not a concern for the transformer, which will continue to operate normally for quite a long time if gases formed do not change.

Interpretation of CO and CO_2

-High values of CO (> 750 ppm) and/or low CO_2/CO ratios (< 4), together with significant amounts of the other hydrocarbon gases, may indicate a hot spot in paper > 250 °C, with possible carbonization of paper.

-Such faults are potentially dangerous but need complementary information from Triangles 4 and 5 and furans content to be confirmed.

-If these faults involve only a small volume of paper, they may not be detectable by CO and CO_2 but only by the other hydrocarbon gases.

Interpretation of CO and CO_2

-Intermediate values of CO (between 750 and 1200 ppm) and/or intermediate values of the CO_2/CO ratio (between 4 and 20), with no significant amounts of the other hydrocarbon gases formed, are more likely due to oil oxidation and not a concern.

-values of CO and CO_2 below condition 1 values (750 and 7500 ppm, respectively), are not a concern at all.

Interpretation of CO and CO_2

-High values of the CO_2/CO ratio (>20) and/or high values of CO_2 (> 10,000 ppm), and/or high furan contents (several ppm) are an indication of the slow degradation of paper at low temperatures (< 140°C), and of low estimated degrees of polymerization DPs of paper (down to 200 and below).

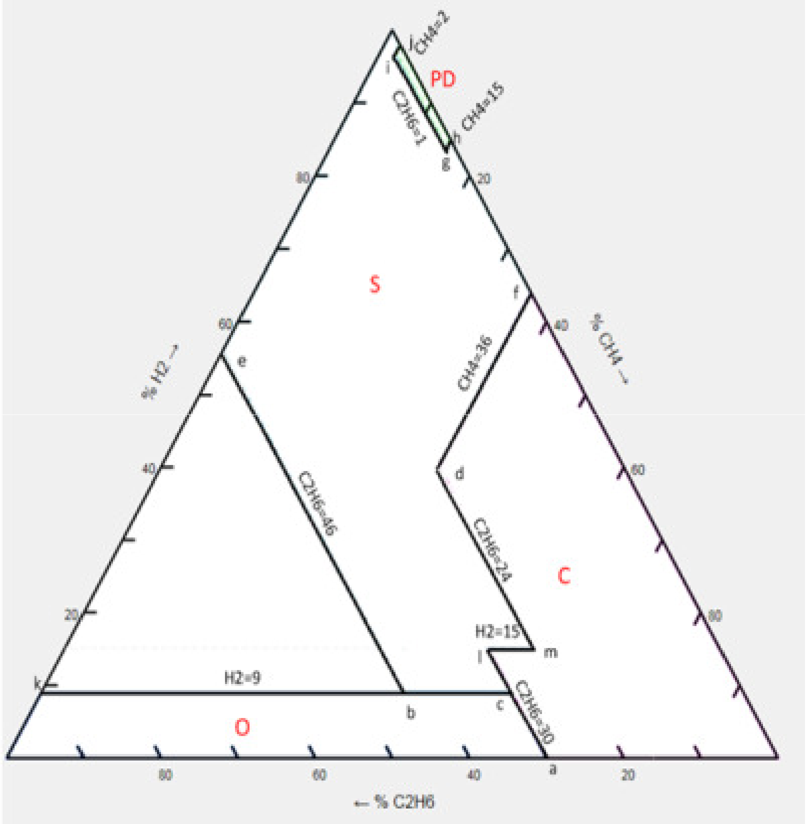
-In the very large majority of cases, the corresponding transformers will continue to operate normally during a large number of years, even when subjected to external short-circuits. When possible, however, re-clamping them would be advisable.

Interpretation of CO and CO_2

-Intermediate values of CO_2 (between 7500 and 10,000 ppm) and/or intermediate values of the CO_2/CO ratio (between 20 and 4) and/or intermediate values of furans, may indicate a slow degradation of paper (DPs between 500 and 200), and are not a concern at all.

-hydrocarbon gases are often better indicators of paper involvement in faults than carbon oxides. Triangles 4 and 5, for example, allow to determine if faults are in oil only (in zones S or T3/T2) or if they might involve paper (in zones C).

Triangle 4 (using H_2, CH_4 and C_2H_6) Results of physical inspections



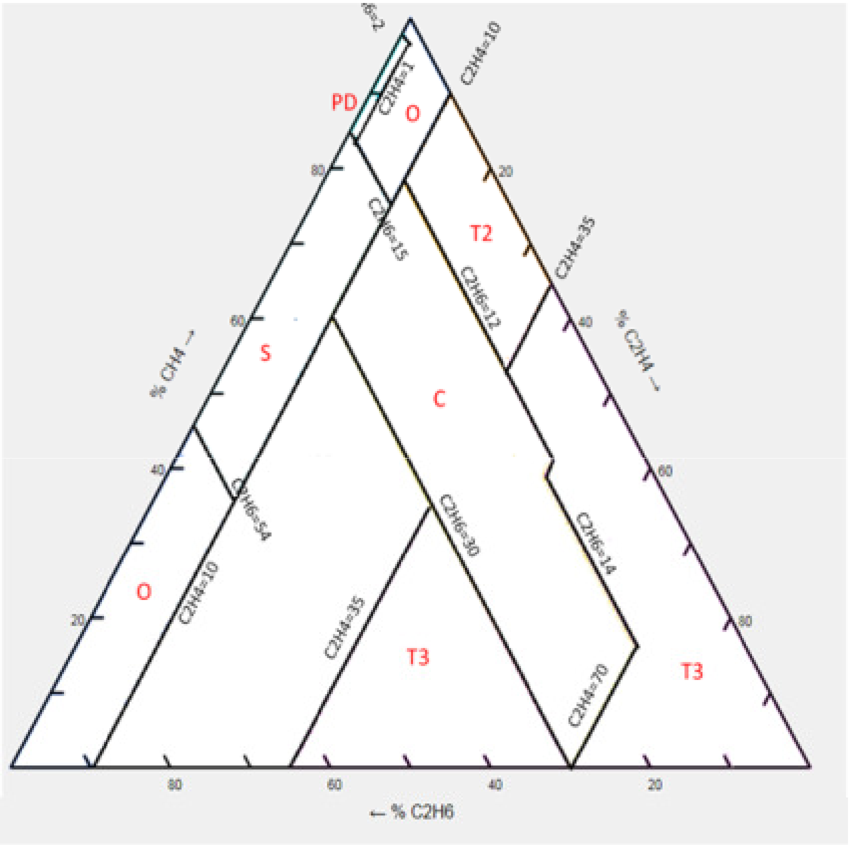
S: Stray gassing at 120°C and 200°C;

O: Overheating (T < 250°C);

C: Possible carbonization of paper (T > 300°C), with a probability of 80%, not 100%.

PD: Corona partial discharges.

Triangle 5 (using CH_4, C_2H_4 and C_2H_6)
Results of physical inspections



T3 and T2: Hot spots in oil only (at T > 300°C and 300°C).

C: Possible carbonization of paper (with a probability of 90%, not 100%).

O, S, PD: use rather Triangle 4.

Use of Triangles 4 and 5

Triangle 4 is used to have more information about low temperature faults (corona PDs, T1 or T2).

Triangle 5 is used to have more information about medium-to-high temperature faults (T2 or T3).

Both Triangles 4 and 5 are used to determine if the fault involves carbonization of paper or oil only.

Sometimes Triangles 4 and 5 do not agree, either because there is a mixture of faults, or because of laboratory inaccuracies on some gases.

Use of Triangles 4 and 5

Triangle 4 should be used only for faults identified first with Triangle 1 as faults PD, T1 or T2, or when there is a high level of H_2.

Triangle 5 should be used only for faults identified first as thermal faults T2 or T3.

Neither Triangle 4 nor Triangle 5 should be used in case of electrical faults D1 (including sparking PDs) or D2.

Other Useful Gas Ratios

O_2 / N_2: a decrease of this ratio indicates excessive heating

Acetylene/ Hydrogen (C_2H_2 / H_2)

- A ratio >3 in the main tank indicates contamination by the LTC compartment

Gassing not related to faults in service

Catalytic reactions on metal surfaces:

-formation of H_2 only

“Stray” gassing of oil:

-the “unexpected gassing of oil at relatively low temperatures (80 to 200°C)”

Both can be identified with Triangles 4 and 5.

BREAK

Gas Levels in Service

Equivalence of IEEE and CIGRE/IEC terms

IEEE Condition 1 = CIGRE/IEC “Typical” values.

IEEE Condition 4 = CIGRE/IEC “Prefailure” values.

IEEE Guide for the Interpretation of Gases

IEEE Std C57.104-1991

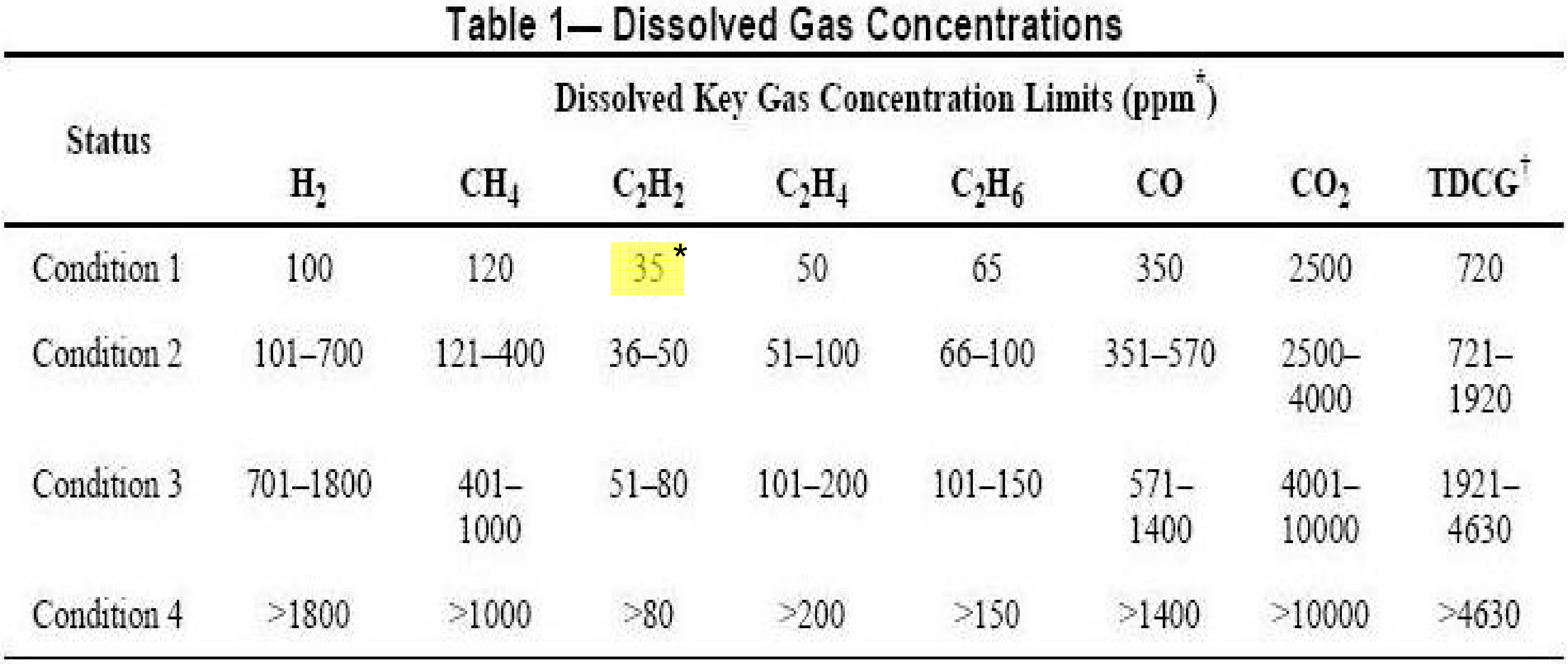


Table 1— Dissolved Gas Concentrations

Status	Dissolved Key Gas Concentration Limits (ppm[‡])							
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG[†]
Condition 1	100	120	35 *	50	65	350	2500	720
Condition 2	101–700	121–400	36–50	51–100	66–100	351–570	2500–4000	721–1920
Condition 3	701–1800	401–1000	51–80	101–200	101–150	571–1400	4001–10000	1921–4630
Condition 4	>1800	>1000	>80	>200	>150	>1400	>10000	>4630

* C_2H_2 Condition 1 Changed to 2 ppm in 2008

Problems with present Table 1

Limits for CO and CO_2 condition 1 are too low, leading to many false warnings or alarms.

Limits for conditions 2 – 4 are outdated and would also need to be revised.

IEEE Guide for the Interpretation of Gases
IEEE Std C57.104-1991

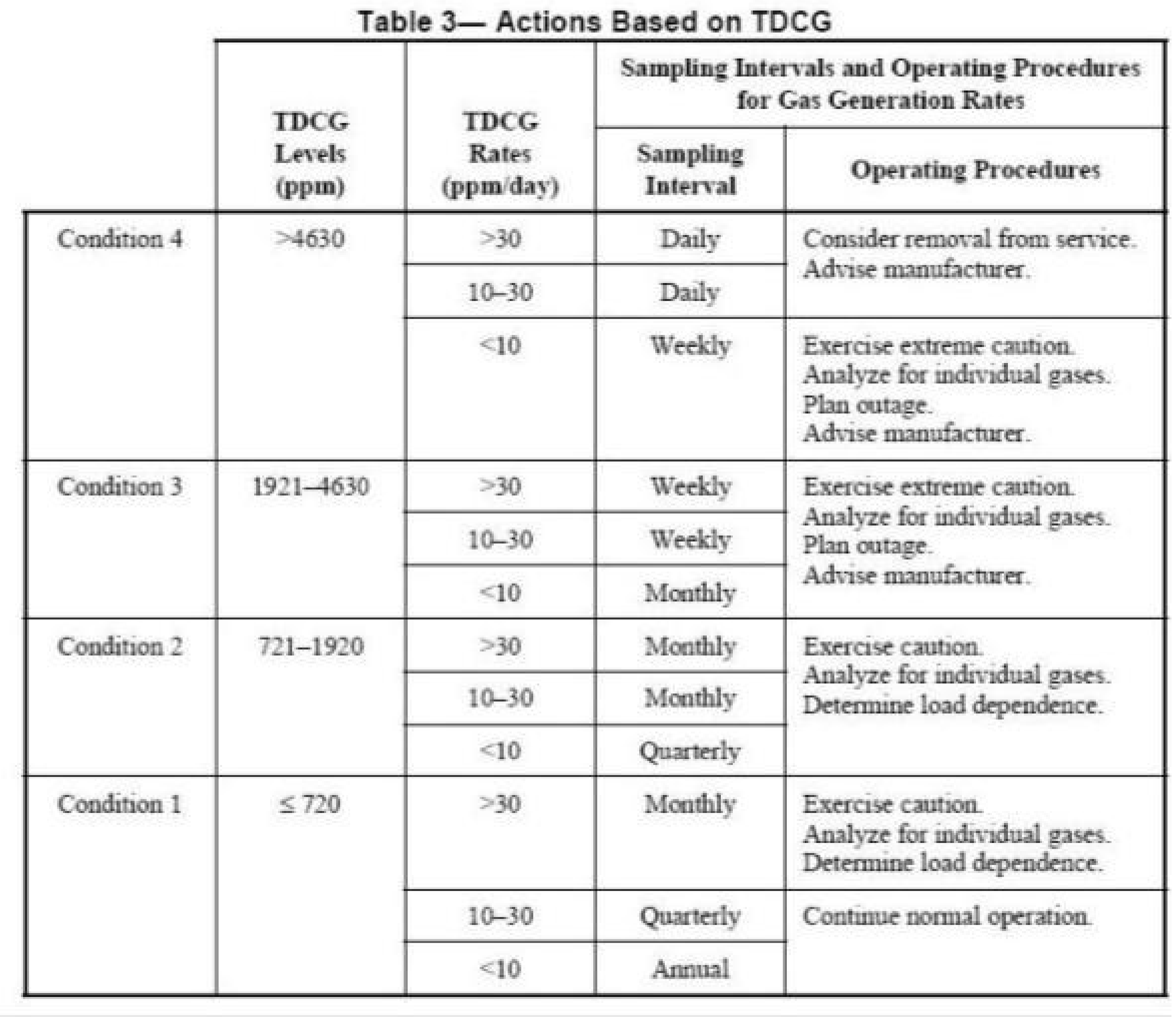


Table 3— Actions Based on TDCG

	TDCG Levels (ppm)	TDCG Rates (ppm/day)	Sampling Intervals and Operating Procedures for Gas Generation Rates	
			Sampling Interval	Operating Procedures
Condition 4	>4630	>30	Daily	Consider removal from service. Advise manufacturer.
		10–30	Daily	
		<10	Weekly	Exercise extreme caution. Analyze for individual gases. Plan outage. Advise manufacturer.
Condition 3	1921–4630	>30	Weekly	Exercise extreme caution. Analyze for individual gases. Plan outage. Advise manufacturer.
		10–30	Weekly	
		<10	Monthly	
Condition 2	721–1920	>30	Monthly	Exercise caution. Analyze for individual gases. Determine load dependence.
		10–30	Monthly	
		<10	Quarterly	
Condition 1	≤ 720	>30	Monthly	Exercise caution. Analyze for individual gases. Determine load dependence.
		10–30	Quarterly	Continue normal operation.
		<10	Annual	

Problems with present Table 3

- Limits of concentrations and gassing rates are given for Total Dissolved Combustible Gases (TDCG) only.

- TDCG levels are influenced mostly by CO and will not detect dangerous gassing rates of C_2H_2 and the other individual gases.

- Table 3 would therefore need to be revised to include gassing rate limits for the individual gases.

Condition 1 and IEC Typical Values

Typical / Condition 1 Values

- Typical /Condition 1 Values correspond to a given percentile (90%) of the population of DGA results

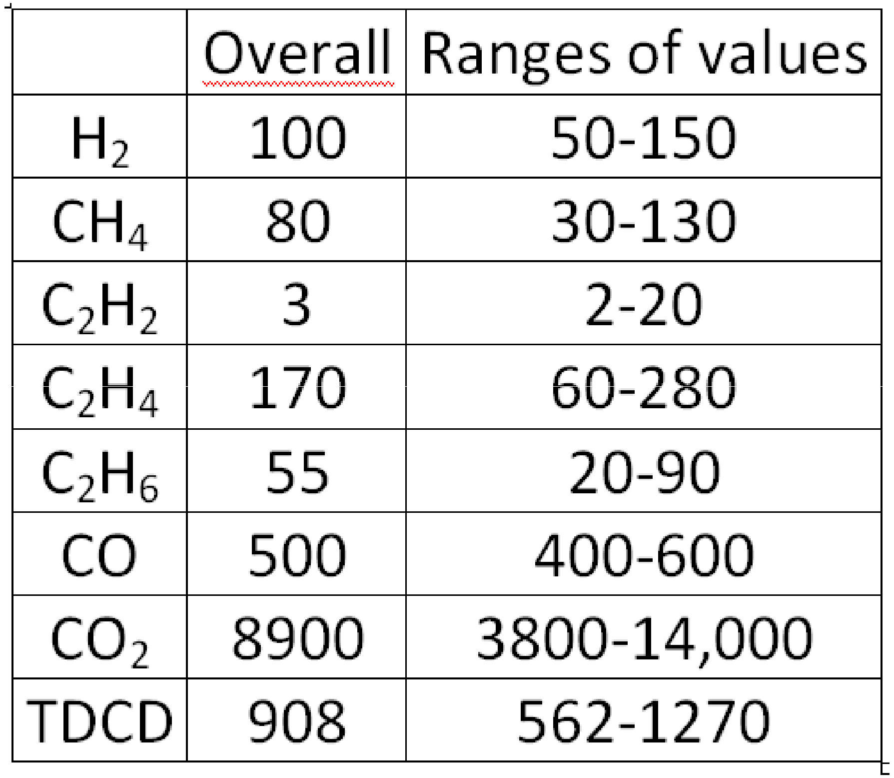
- They mean that 90% of DGA results for dissolved gases are below these 90% Typical values

- They are used to concentrate maintenance efforts on the 10% of the population with the highest gas levels and therefore most at risk

Typical / Condition 1 Values

- Below Typical/ Condition 1 Values, gas formation is considered by IEC and IEEE not to be a concern for the equipment.
- Below these values, it is recommended to use “normal” sampling frequency (monthly, semi-annual, etc.,..) and not to attempt a diagnosis.
- Above these values, it is recommended to use ‘increased’ sampling frequency (e.g., monthly or weekly) and a DGA diagnosis may be attempted.

90% Typical (condition 1) values for concentrations at IEC, in ppm



	Overall	Ranges of values
H_2	100	50-150
CH_4	80	30-130
C_2H_2	3	2-20
C_2H_4	170	60-280
C_2H_6	55	20-90
CO	500	400-600
CO_2	8900	3800-14,000
TDCD	908	562-1270

(vs. source)

90% Typical (condition 1) values at IEEE

- Calculated on the new IEEE database of 500,000+ DGA results, as 90% percentile values.

- Ranges of values vs. (kV, MVA, age, % O2) presented at IEEE meeting in Munich in March 2013.

90% Typical (condition 1) values for concentrations at IEEE, in ppm

	Overall	Ranges of values
H_2	100	48-235
CH_4	90	23-193
C_2H_2	1	0-3
C_2H_4	55	16-135
C_2H_6	90	16-208
CO	750	474-1034
CO_2	7500	3221-9673
TDCD	1086	673-1391

(vs. kV, MVA, age, $\%O_2$)

Ranges of 90% Typical Values

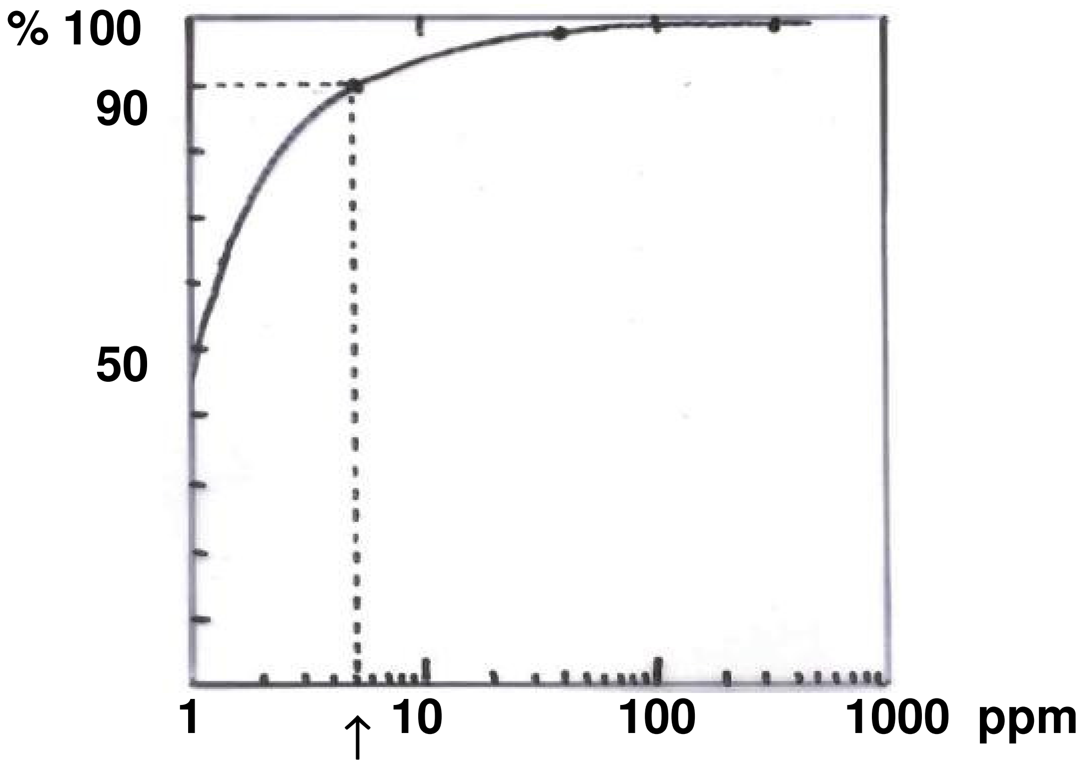
Ranges of typical/ condition 1 values are an indication of the small differences between individual networks, depending on types of equipment used, loading practices, climate.

Each individual network is therefore encouraged to calculate its own 90% typical values.

By default, CIGRE/IEC or IEEE values can be used

Calculation of 90% Typical Values

Cumulative curves of DGA results (concentrations **or** gassing rates)



90% typical concentration value

Factors influencing 90% Typical Values

Transformer Age

- Values are significantly higher in young equipment (suggesting some unstable chemical bonds in new oil and paper)
- Values are a bit higher in very old equipment

Transformer Type

- Values are higher in shell-type and shunt reactors (operating at higher temperatures), lower in instrument transformers
- Typical values are very similar in air-breathing and in sealed or nitrogen blanketed equipment, contrary to a common belief

Transformer Oil Volume

- Values are not affected by oil volume (suggesting that larger faults are formed in larger transformers)

90% Typical (Condition 1) Values

Ranges of typical (condition 1) values may influence the frequency of monitoring for DGA.

However, they are still far from condition 4 values, and therefore not very significant concerning actions on the equipment.

90% Typical (condition 1) values for gassing rates, in ppm/month

	IEEE	IEC
H_2	4	7
CH_4	2	5
C_2H_2	0	0.2
C_2H_4	2	7
C_2H_6	1	4
CO	21	55
CO_2	217	487

Gas Levels above Typical Values

Gas Levels above Typical Values
Risk of Failure in Service

Probability of Failure in Service (PFS);

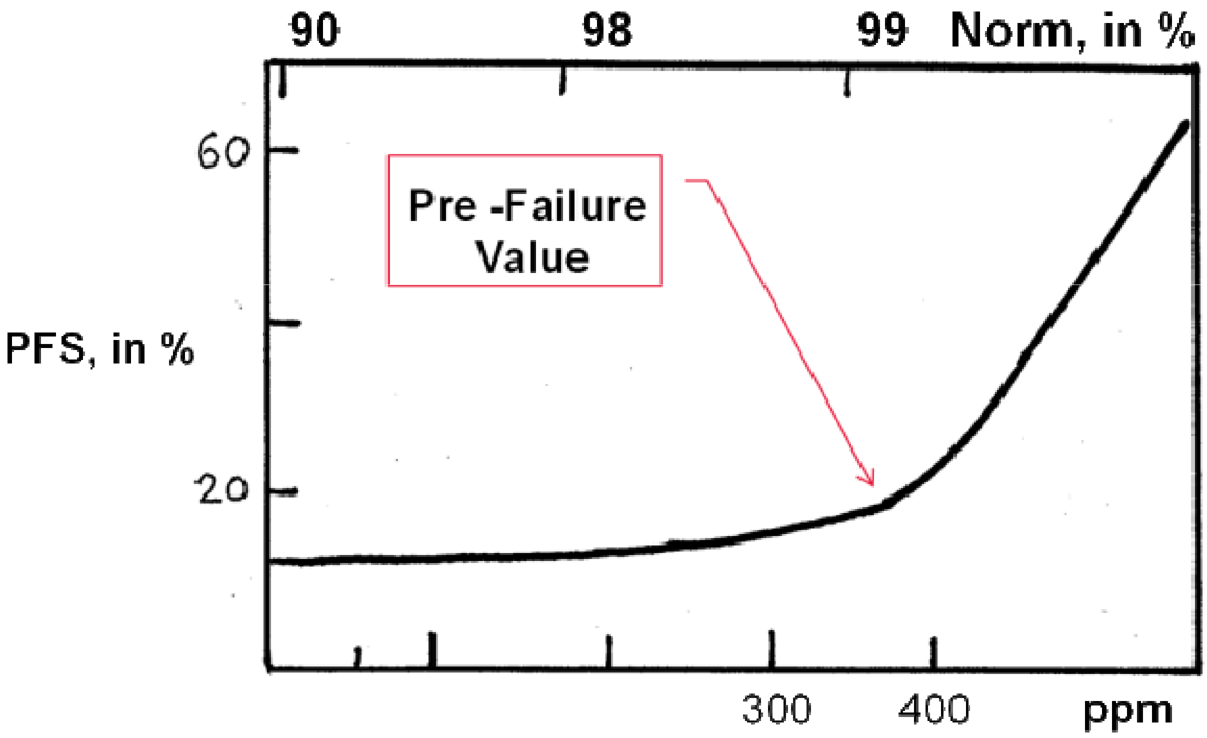
Probability of having a failure related event in service, such as any tripping, fault gas alarm, fire, etc. event

PFS has been defined at CIGRE as:

PFS = Number of DGA analyses followed by a failure related event/Total number of Analyses@ each gas concentration value

Gas Levels above Typical Values
Risk of Failure in Service

Probability of having a failure-related event (PFS, %) vs. the concentration of C_2H_2 in ppm at HQ



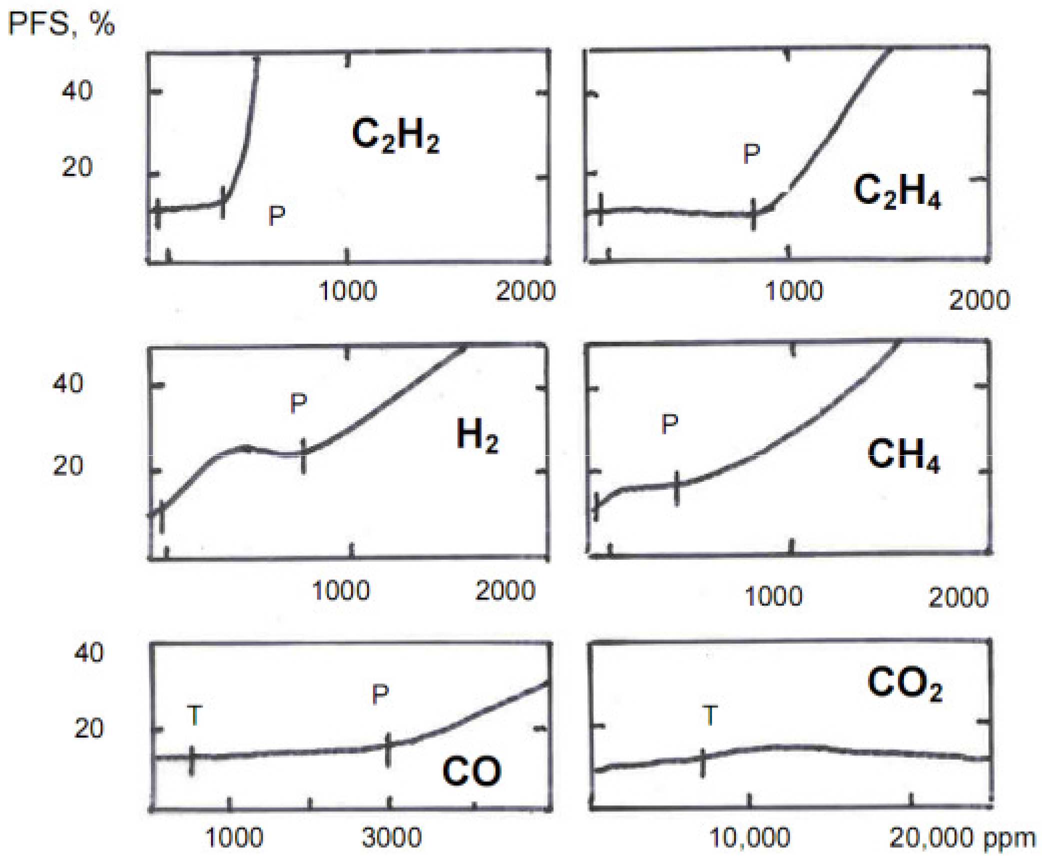
Gas Levels above Typical Values
Pre-Failure Values

The PFS remains almost constant below and above the 90% typical value, until it reaches an inflexion point on the curve (Pre-Failure Value)

DGA monitoring should be done more and more frequently as gas concentrations increase from typical to Pre-Failure Value

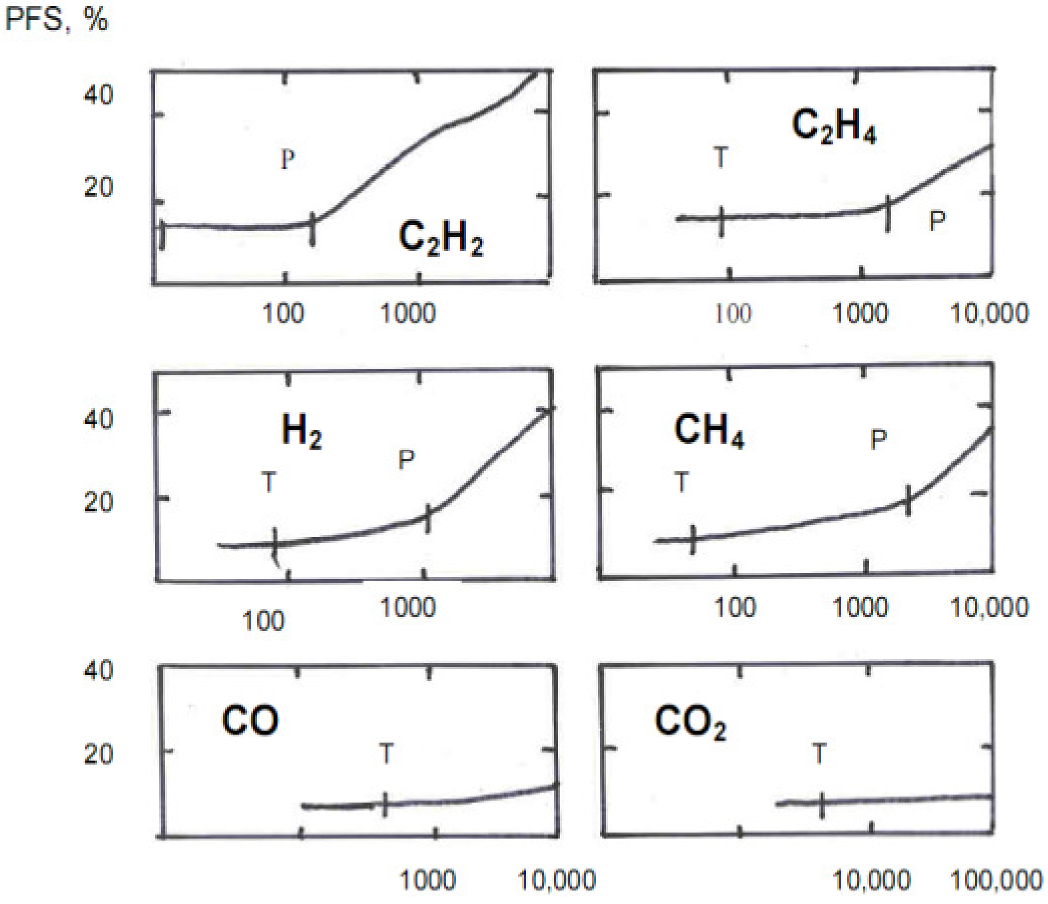
Time to reach the Pre-Failure Value is unknown, could be Hours, Days, Weeks or Months.

The IEC/CIGRE Approach (Gas Concentrations)



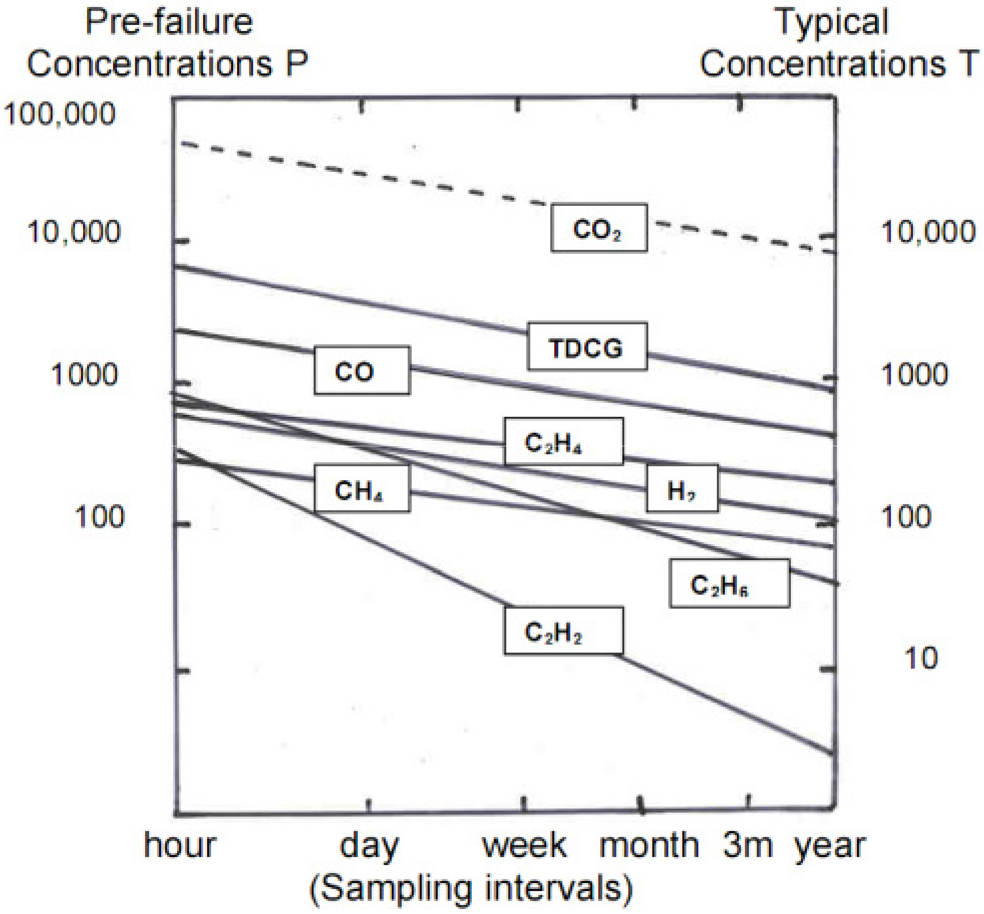
Probability of having a failure-related event in service (PFS) in %, vs. the concentration of all gases in ppm. T = 90% typical value; P = pre-failure value.

The IEC/CIGRE Approach (rates of Gas Increase)



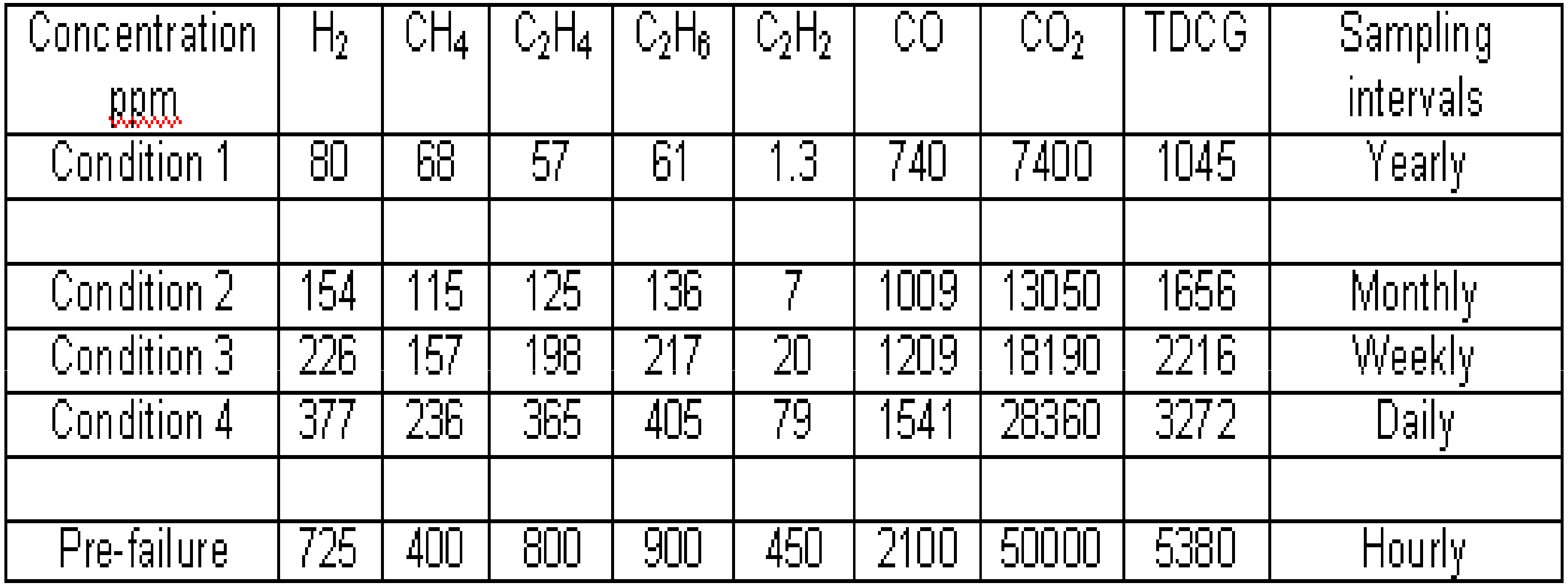
Probability of having a failure-related event in service (PFS) in %, vs. the rate of increase of all gases in ppm/ yr.

Sample Intervals & Concentration Limits



Sampling intervals and gas concentration limits in ppm, calculated for an average US power transformer

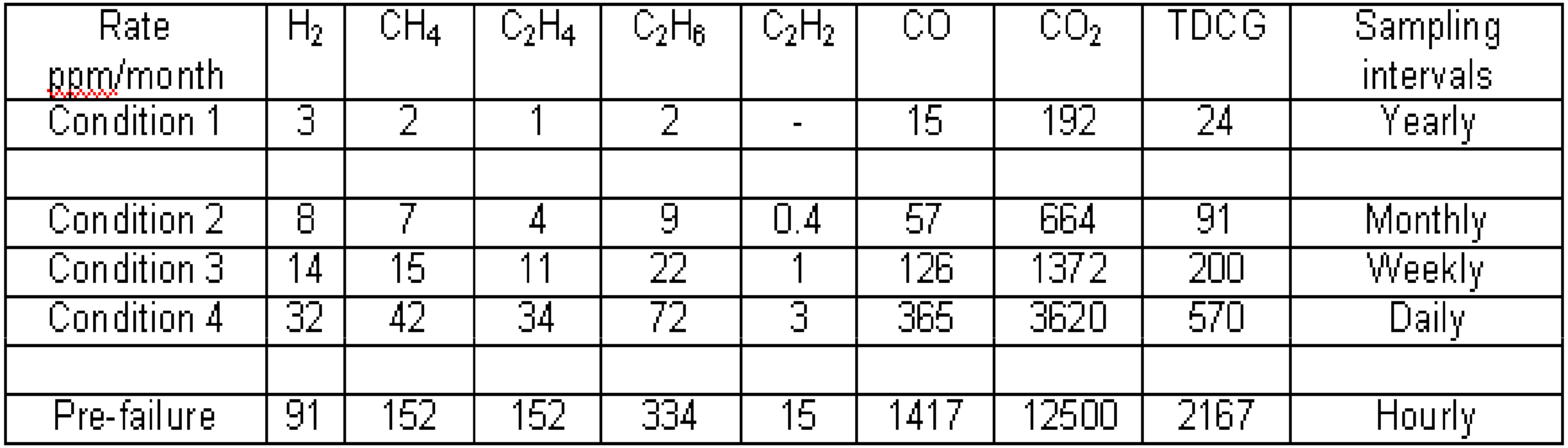
Sampling intervals and level of attention vs. Concentrations in service, in ppm



Concentration ppm	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2	TDCG	Sampling intervals
Condition 1	80	68	57	61	1.3	740	7400	1045	Yearly
Condition 2	154	115	125	136	7	1009	13050	1656	Monthly
Condition 3	226	157	198	217	20	1209	18190	2216	Weekly
Condition 4	377	236	365	405	79	1541	28360	3272	Daily
Pre-failure	725	400	800	900	450	2100	50000	5380	Hourly

(based on revised condition 1 values in the US of 2010 and pre-failure values of CIGRE)

Sampling intervals and levels of attention vs. gassing rates, in ppm/month



Rate ppm/month	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2	TDCG	Sampling intervals
Condition 1	3	2	1	2	-	15	192	24	Yearly
Condition 2	8	7	4	9	0.4	57	664	91	Monthly
Condition 3	14	15	11	22	1	126	1372	200	Weekly
Condition 4	32	42	34	72	3	365	3620	570	Daily
Pre-failure	91	152	152	334	15	1417	12500	2167	Hourly

(based on gassing rates for condition 1 in the US and pre-failure gassing rates of CIGRE)

Sampling Intervals based on Combined Gas Rate and Gas Concentration Levels of Individual Gases (IEC/CIGRE approach)

		Sampling Intervals based on Combined Gas Rate and Concentration Levels				
Rate Level #	Conc. Level #	Daily	Weekly	Monthly	Quarterly	Yearly
4	4	X				
4	3	X				
4	2		X			
4	1		X			
3	4	X				
3	3		X			
3	2		X			
3	1			X		
2	4		X			
2	3			X		
2	2			X		
2	1				X	
1	4			X		
1	3			X		
1	2				X	
1	1					X

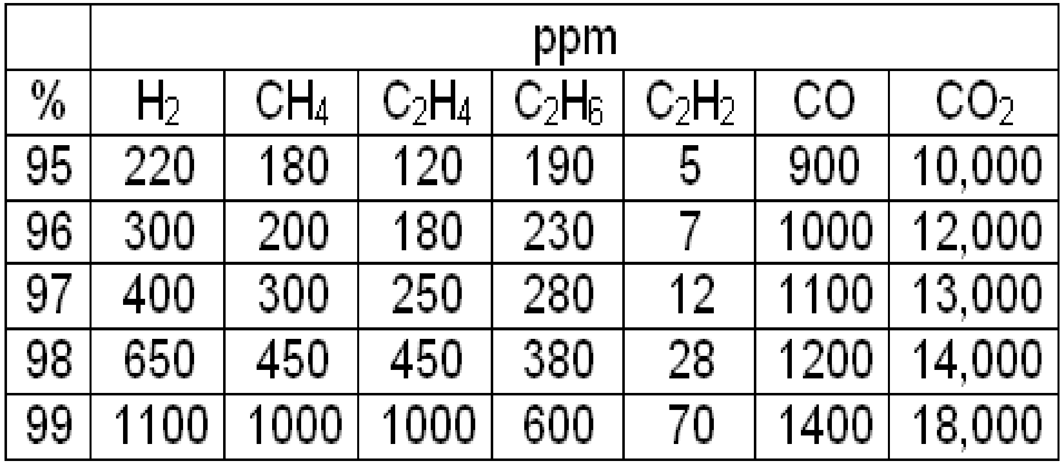
IEEE Conditions 2 to 4

Are under consideration by the IEEE WG for conditions 2 to 4:

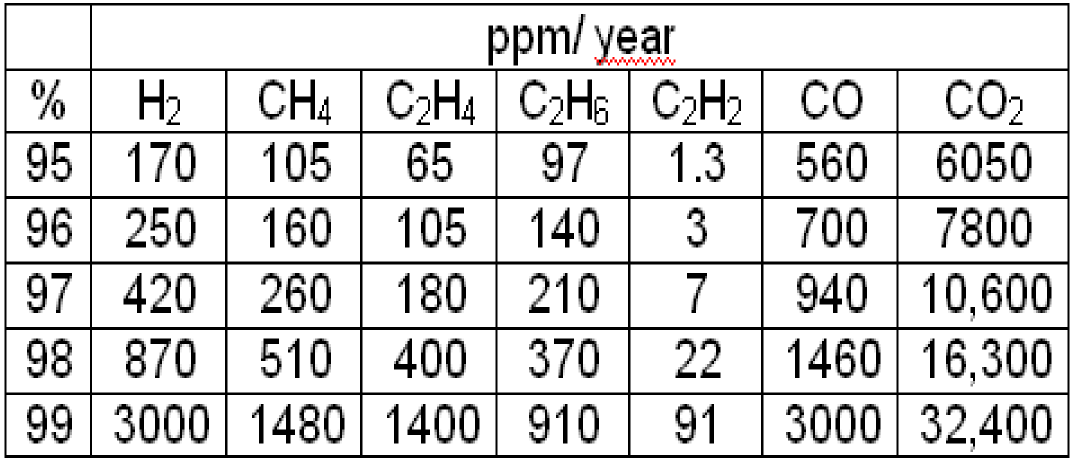
- The 95% to 98% percentile values for each gas. However, the actual risk of failure of transformers at these values is not known.

- The « survival » values of J.Dukarm, still under investigation.

IEEE percentile values (95-99%)



	ppm						
%	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2
95	220	180	120	190	5	900	10,000
96	300	200	180	230	7	1000	12,000
97	400	300	250	280	12	1100	13,000
98	650	450	450	380	28	1200	14,000
99	1100	1000	1000	600	70	1400	18,000



	ppm/ year						
%	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2
95	170	105	65	97	1.3	560	6050
96	250	160	105	140	3	700	7800
97	420	260	180	210	7	940	10,600
98	870	510	400	370	22	1460	16,300
99	3000	1480	1400	910	91	3000	32,400

Condition 4 concentrations values, in ppm

	IEEE Cond.4	CIGRE Pre-failure	Dukarm Survival
H_2	1800	725	-
CH_4	1000	400	1160
C_2H_2	35	450	100
C_2H_4	200	800	900
C_2H_6	150	900	1400
CO	1400	2100	-
CO_2	10,000	50,000	-
TDCD	4630	-	-

Condition 4 gassing rate values, in ppm/month

(CIGRE pre-failure values)

	CIGRE
H_2	90
CH_4	150
C_2H_2	15
C_2H_4	150
C_2H_6	330
CO	1400
CO_2	12,500

Significance of gassing rates and gas concentrations

Gassing rates indicate:

-that the fault is still active

-the local intensity of the fault

Gas concentrations indicate:

-the volume and duration of the fault

-the amount of insulation destroyed

-that faults having disappeared may reappear later (a common observation in service)

Effect of type of fault on gas limits:

- Under investigation at CIGRE for:

- Conventional faults PD, D1, D2, T1, T2, T3.

- Faults identified with Triangles 4 and 5:
  - T3/T2 in oil only.
  - C carbonization of paper.
  - O overheating at T<250C.
  - S stray gassing of oil at T<200C.

Occurrence of faults in service at CIGRE

Fault	Oil	Paper	Triangle used	Occurrence in %
T3			1	32
T2			1	26
T1			1	25
T3	x		5	32
C		x	5	15
S	x		4	22
O			4	14
T			1+4	90
D2			1	3.8
D1			1	1.4
PD			1+4	0.3

90% percentile (condition 1) values vs. type of thermal fault at CIGRE:

Fault	Oil	Paper	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2	Adjustment factor
All			100	90	50	80	1	750	6500	
T3	x				200					X4
T3-C		x			300				10,000	X6
T2										
T2-C		x						1000	10,000	X1.5
T1						300				X4
O						200		400		X2.5
S	x		300							X3

(ppm)

(ppm)

Percentile (condition 1) values vs. type of electrical fault at CIGRE:

Fault	Percentile% used	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	Adjustment factor
All	60					5	
All	40					2	
D2	60					**11**	X2
D1	40					**12**	X6

(after deleting $C_2H_2 < 2$ ppm)

Fault	Percentile% used	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	Adjustment factor
All	30	3					
PD	30	**300**					X100

(ppm) (ppm)

Condition 4 (pre-failure) values vs. type of fault at CIGRE:

Fault	Oil	Paper	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2
All			725	400	800	900	450	2100	50,000
T3	x				3200				
T3-C		x			4800				75,000
T1						3600			
O						2250			
S	x		2200						
D2							(450)		
D1							(450)		
PD			72,500						

(in ppm, using previous adjustment factors)

Comparison with cases of high gas levels without failure at CIGRE:

Fault	Oil	Paper	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2	Number of cases
T3	x				3500-162,000				(90,000)	16
T3-C		x			4800-11,200			(3600)	(103,000)	6
T2-C		x		300-1900					(14,000)	6
O						[400-1200]		(2400)	(31,000)	5
S	x		8400-55,000							9+
PD			[5000-33,000]							7+
D1	x						[200]-1055			8
D1		x					**50-120**			5

(in ppm)

Example of fault D1 in oil (on a bakelite plate) with 480 ppm C_2H_2 and no failure yet!

Condition 4 values vs. type of fault :

•Condition 4 values of CIGRE vs. type of fault , although not based on strict statistical calculations, are supported by large numbers of cases without failure in service.

•They suggest that significantly higher gas levels can sometimes be tolerated in service when the type of fault is known.

•Other examples are needed for arcing faults in paper just before failure.

•Thermal faults T1, T2 and T3 in paper with high levels of C_2H_4, C_2H_6 or CH_4 and no failure.

DGA Monitoring Techniques

DGA Monitoring Off-Line:

-also called manual DGA or laboratory DGA
-consists in taking oil samples from transformers and sending them to the laboratory for DGA analysis
-"normal" sampling frequency is typically one year,
-every month or week in case of abnormal gassing.

DGA Monitoring On-Line:

-does not require oil sampling
-provides a DGA analysis every 1 or 4 hours.

Advantages and Limitations of Laboratory DGA

-less expensive than on-line monitoring
-uses IEC/ASTM standardized techniques
-data comparable to those in existing DGA databases.

-will miss faults occurring between two oil samplings
-some laboratories are not accurate and reliable because of sampling and laboratory errors (“bad” laboratories).

Advantages and Limitations of On-Line Gas Monitors

-will catch abnormal formation of gases monitored and quick-developing faults
-are not affected by sampling errors
-more reliable for evaluating gassing rates (ROC).

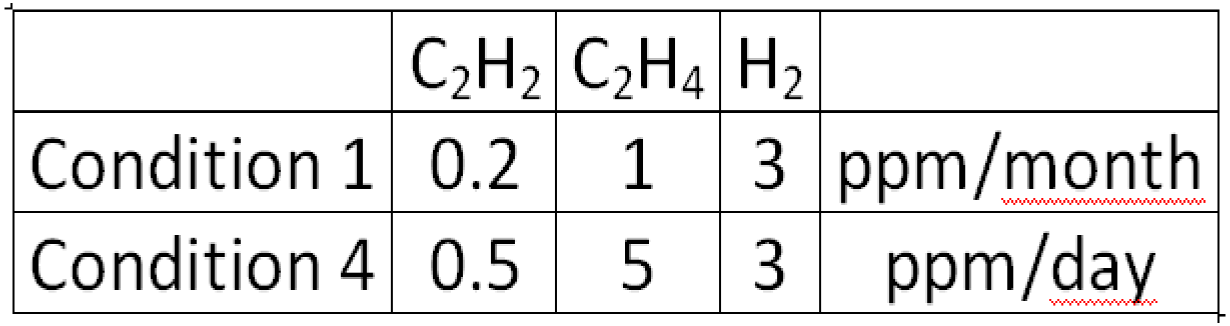
-more expensive than laboratory DGA
-some monitors are not accurate for some gases
-some monitors are not calibration-free and maintenance-free as claimed by their manufacturers.

Abnormal and Quick-Developing Faults

-Abnormal gas formation (above condition 1 of IEEE/IEC) will occur in 200 of a 2000 transformer population.

-Quick-developing faults (above condition 4/ pre-failure values of IEEE/ CIGRE) will occur in 20 to 40 of them (CIGRE TF11, 2003).

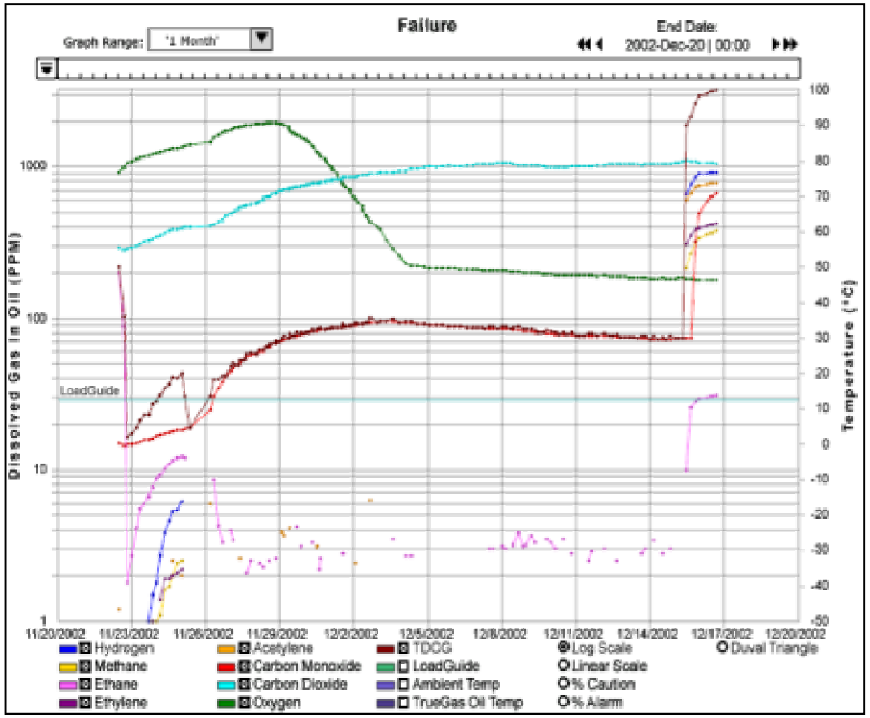
-Gassing rates corresponding to conditions 1 and 4:

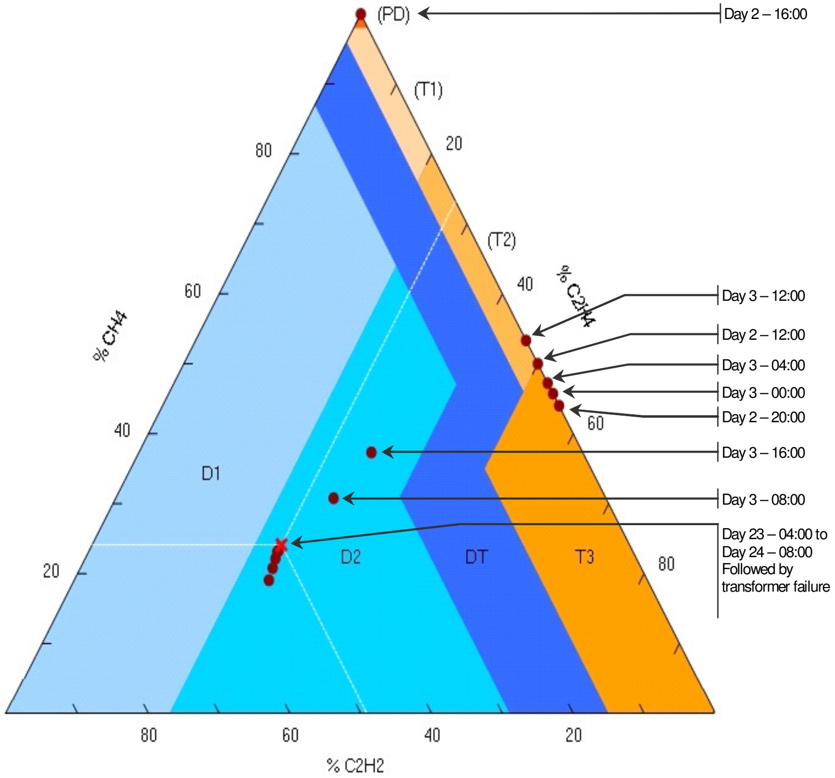


	C_2H_2	C_2H_4	H_2	
Condition 1	0.2	1	3	ppm/month
Condition 4	0.5	5	3	ppm/day

(CIGRE Technical Brochure # 443, 2010)

Detection of Quick-Developing Faults with a Multi-Gas Monitor in a 3-Phase GSU Transformer





Day 2 – 16:00

Day 3 – 12:00

Day 2 – 12:00

Day 3 – 04:00

Day 3 – 00:00

Day 2 – 20:00

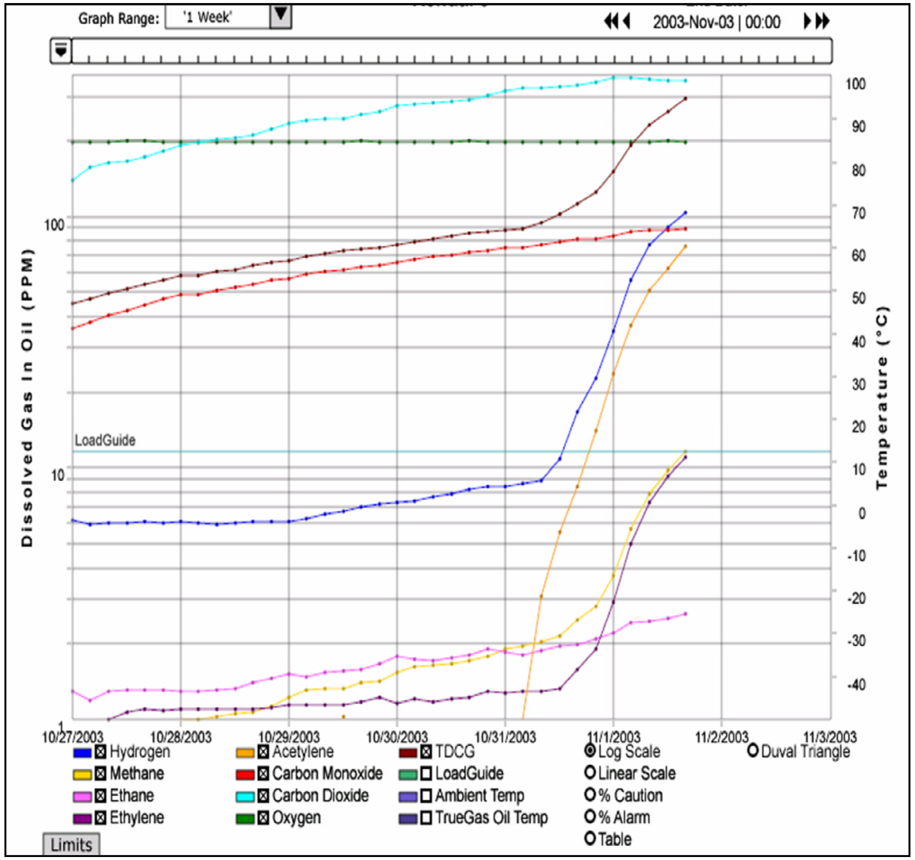
Day 3 – 16:00

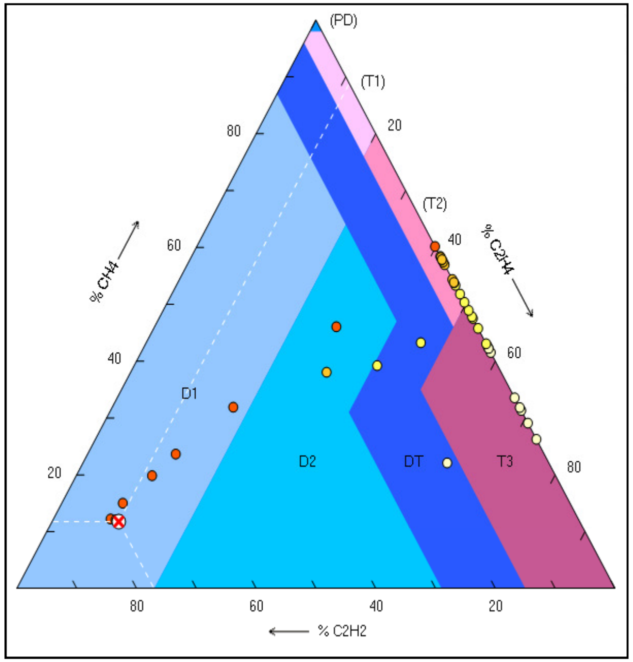
Day 3 – 08:00

Day 23 – 04:00 to
Day 24 – 08:00
Followed by
transformer failure

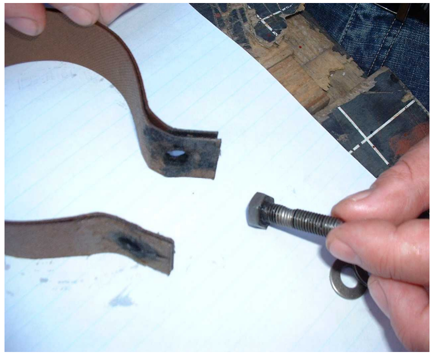
C_2H_2 = 800 ppm/day!

700 MVA Transformer



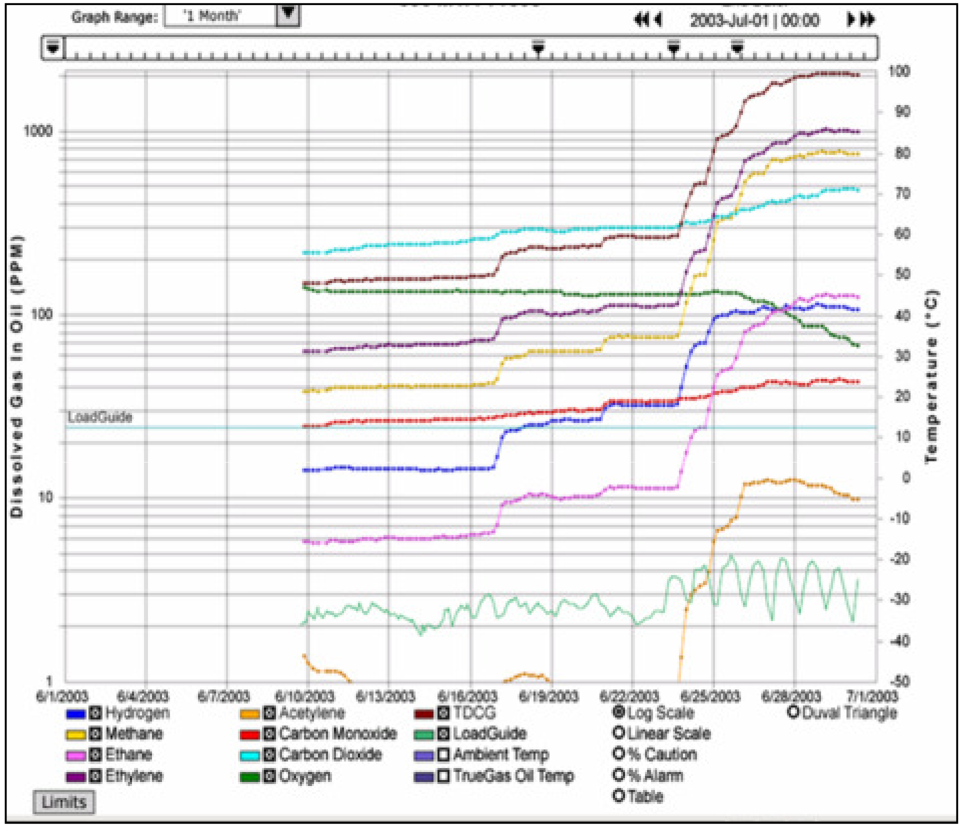


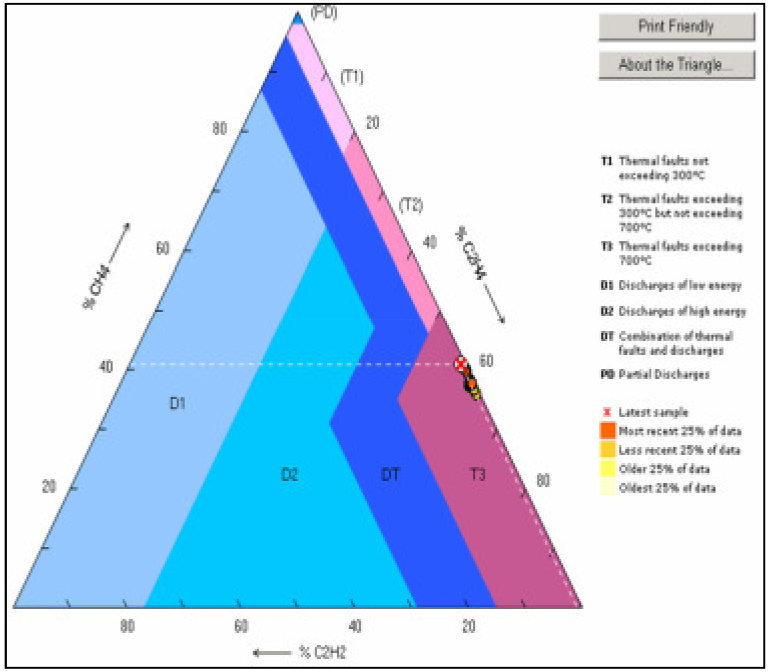
C_2H_2 = 45 ppm/day!



336 MVA Transformer

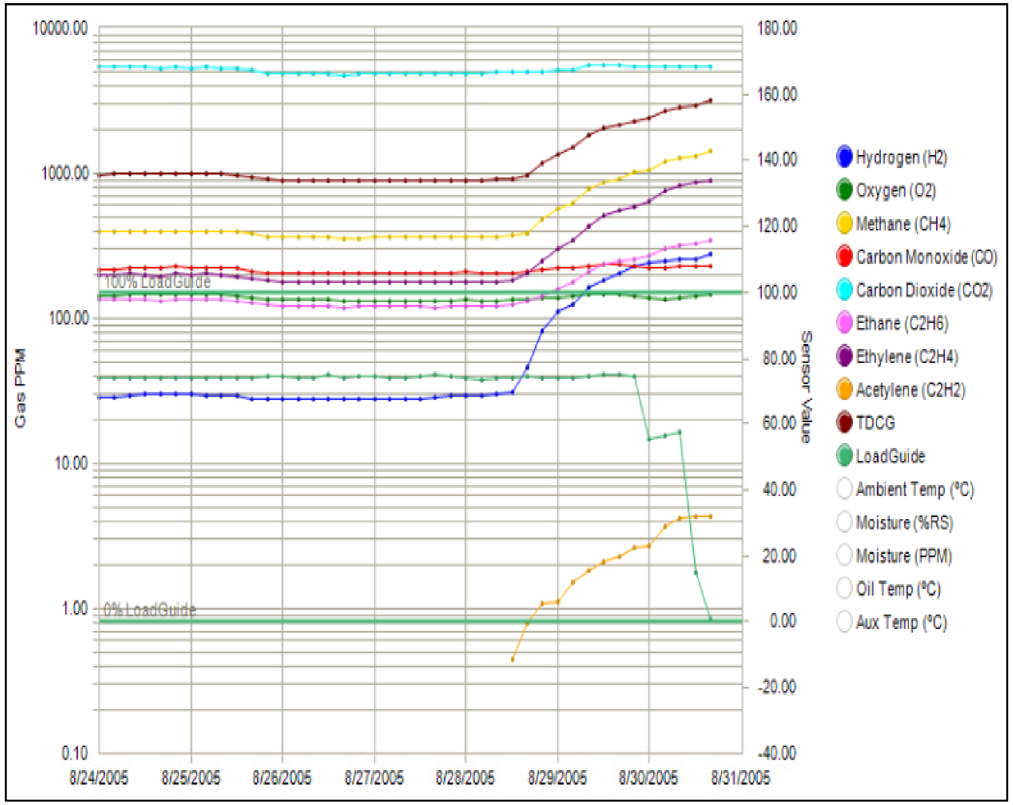
(Placed in Service -1969)

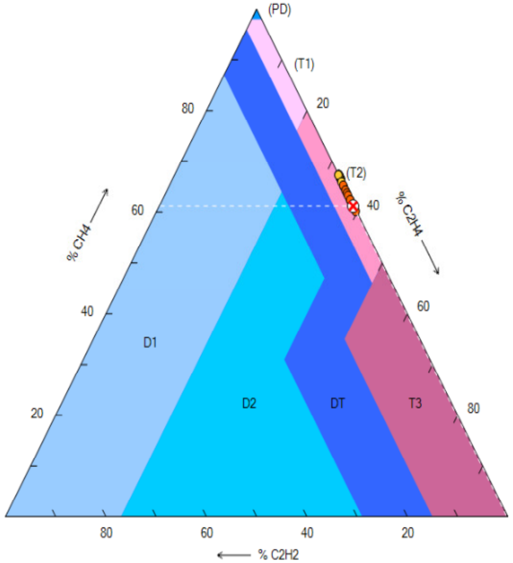




C_2H_4 = 300 ppm/day!

1100 MVA Transformer





C_2H_4 = 300 ppm/day!

Reviewed Transformer Failures

-Gassing rates were all significantly above condition 4 values.

-The corresponding transformers were removed from service 1 to 3 days after looking at monitor readings, before potential catastrophic failure.

-However, it would have been better to remove them from service earlier.

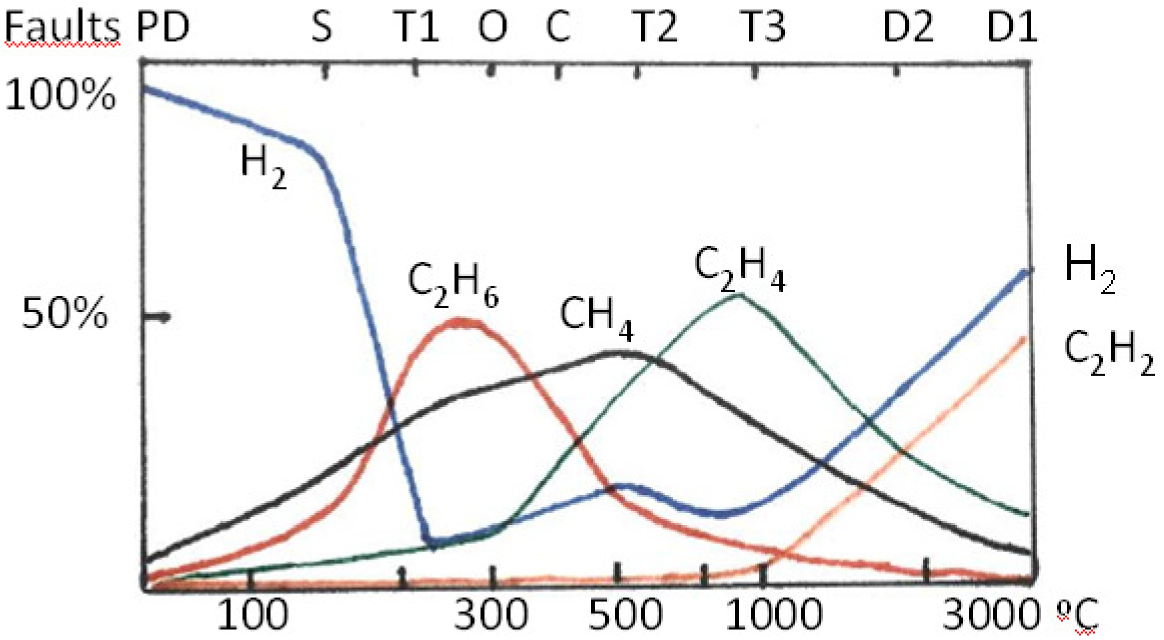
-Without an on-line monitor, these transformers would likely have suffered unplanned severe damage.

On-Line Monitoring with Multi-Gas Monitors

-Multi-gas monitors will detect all types of faults, even in their early stages at condition 1, and without false alarms since they provide DGA diagnosis on-line. However, they are more expensive than hydrogen only monitors.

-The recommendation of CIGRE (TB # 409, 2010) is therefore to use multi-gas monitors in critical transformers (GSU, nuclear, transmission) and in abnormally gassing transformers.

Fault Detection with Hydrogen Monitors



Note: for faults T3 in paper (C), curve for H_2 is a bit higher.
Ref: Duval, TSUG 2013.

Fault Detection with Hydrogen Monitors

-Hydrogen monitors are most sensitive to stray gassing of oil S (occurring in ~ 25% of cases), and to corona partial discharges PD (occurring in only 0.3% of cases).

-Such faults will commonly produce thousands of ppm of H_2 without being a concern for the transformers. If the limit in hydrogen monitors is set at average condition 1 value for H_2 (100 ppm), this may result into false alarms.

Fault Detection with Hydrogen Monitors

-Faults D1/D2 at dangerous condition 4 of CIGRE will produce 0.5 ppm/day of C_2H_2 together with only 1 or 2 ppm/day of H_2.

-If the limit for H_2 is set at 100 ppm, the monitor will detect these faults only in their late stages (condition 3 or 4), when dangerous levels of 25 to 50 ppm of C_2H_2 have already accumulated.

Fault Detection with Hydrogen Monitors

-In case of thermal faults T3/T2/T1/O the main gas formed is C_2H_4, CH_4 or C_2H_6, together with 3 to 10 times less of H_2. If the limit for H_2 is set at 100 ppm, the monitor will detect these faults only in their late stages (condition 3 or 4).

-Decreasing the limit for H_2 in the monitor (e.g., to 50 or 20 ppm) will increase the number of false alarms due to faults S or corona PD of lesser concern.

On-Line Monitoring with Hydrogen Monitors

-The recommendation of CIGRE (in TB # 409, 2010) is therefore to use hydrogen monitors in non-critical transmission and distribution transformers, and in transformers with no previous gassing history.

Examples of On-Line Gas Monitors

Basic Principles of Gas Monitors

-based on headspace principle for the extraction of gases from oil (partition of dissolved gases between oil and gas phase).

-partition coefficients must be known exactly at all temperatures of extraction.

-extracted gases are analyzed by different types of detectors.

-monitors available in 2008 have been tested in CIGRE TB # 409, those available since will be tested by CIGRE WG47.

Multi-Gas Monitors

Monitors of the chromatographic type:

-after gas extraction, will separate individual gases on a GC column, then measure them with GC detectors.

-TM8, TM3 (Serveron)

-Calisto 9 (Morgan Schaffer)

Monitors of the Chromatographic-Type:

-use the same standardized, NIST-traceable techniques as laboratories.

-provide automatic recalibration at fixed intervals as laboratories do.

-require some maintenance (change of carrier gas, calibration gas mixture, GC columns every 3 to 5 years).

Monitors of the Infrared-Type:

-after gas extraction, will measure directly individual gases with an infrared detector, and H_2 with a solid state sensor.

-Transfix 8, Transport-X 7 (GE-Kelman) use a photo-acoustic (PAS) detector.

-LumaSense 9 uses a non-dispersive IR detector.

Monitors of the infrared type:

-do not require change of carrier gas and gas mixture.

-cannot measure H_2 , O_2 by infrared, requiring the use of relatively inaccurate solid state sensors for that purpose.

-some may need recalibration because of contaminants in ambient air (SF_6, oil vapours, solvents) and lamp fade with time; some cannot be recalibrated in the field.

-require change of infrared lamp ~ every 5 years.
-contain several moving parts.

Hydrogen Monitors

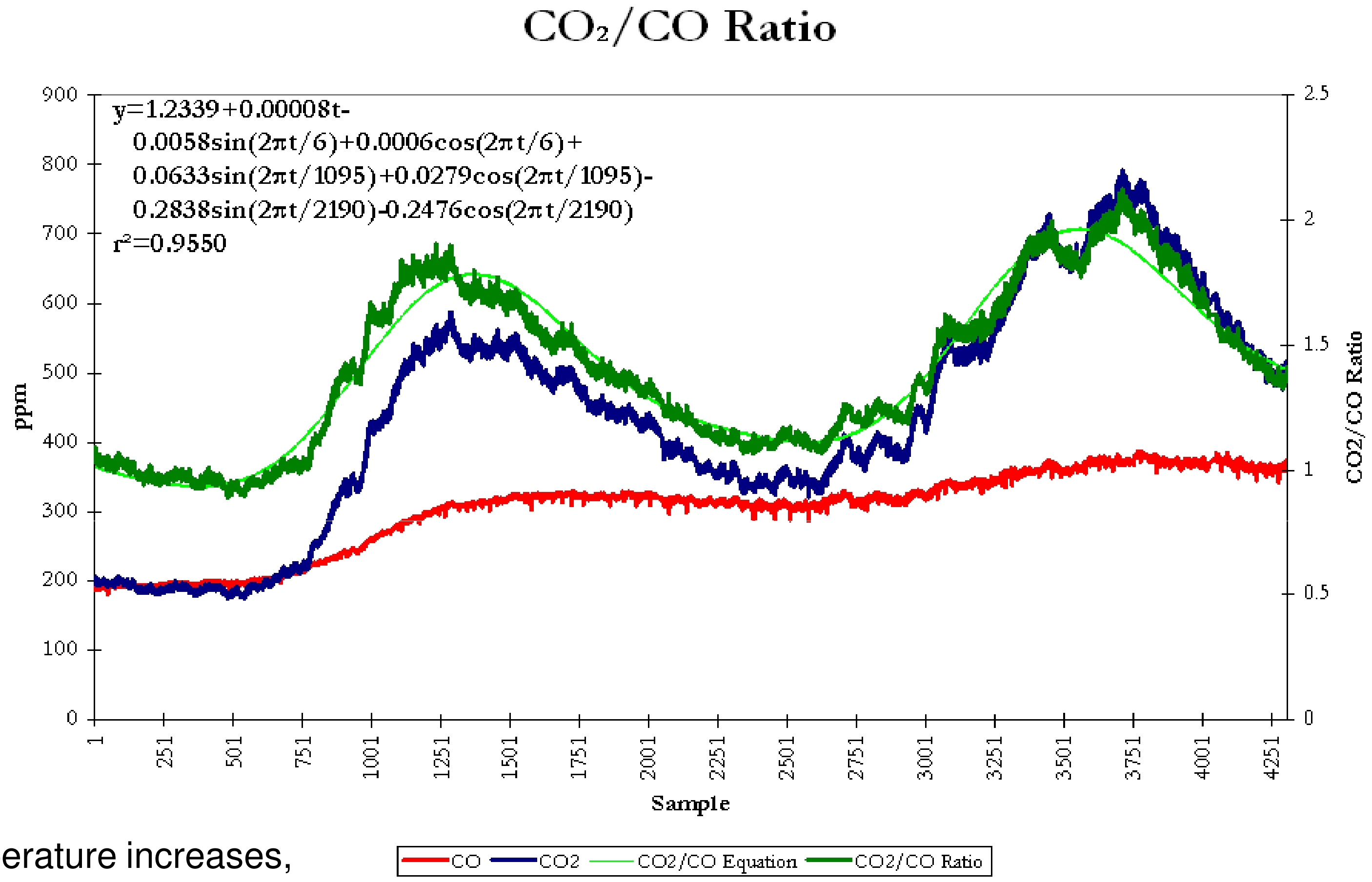
-Hydran (GE): measures 100% of the H_2 + 18% of the CO present in oil with a PTFE membrane and fuel cell detector.

-Calisto 2 (Morgan Shaffer): measures H_2 only with a PTFE membrane, GC and TCD detector.

-Serveron, Qualitrol, Weidmann: measure H_2 only with an H_2Scan Pd solid state sensor covered with an inorganic coating (no membrane).

-TM1 (Serveron): "improved" version with patent applications for temperature control and oil circulation.

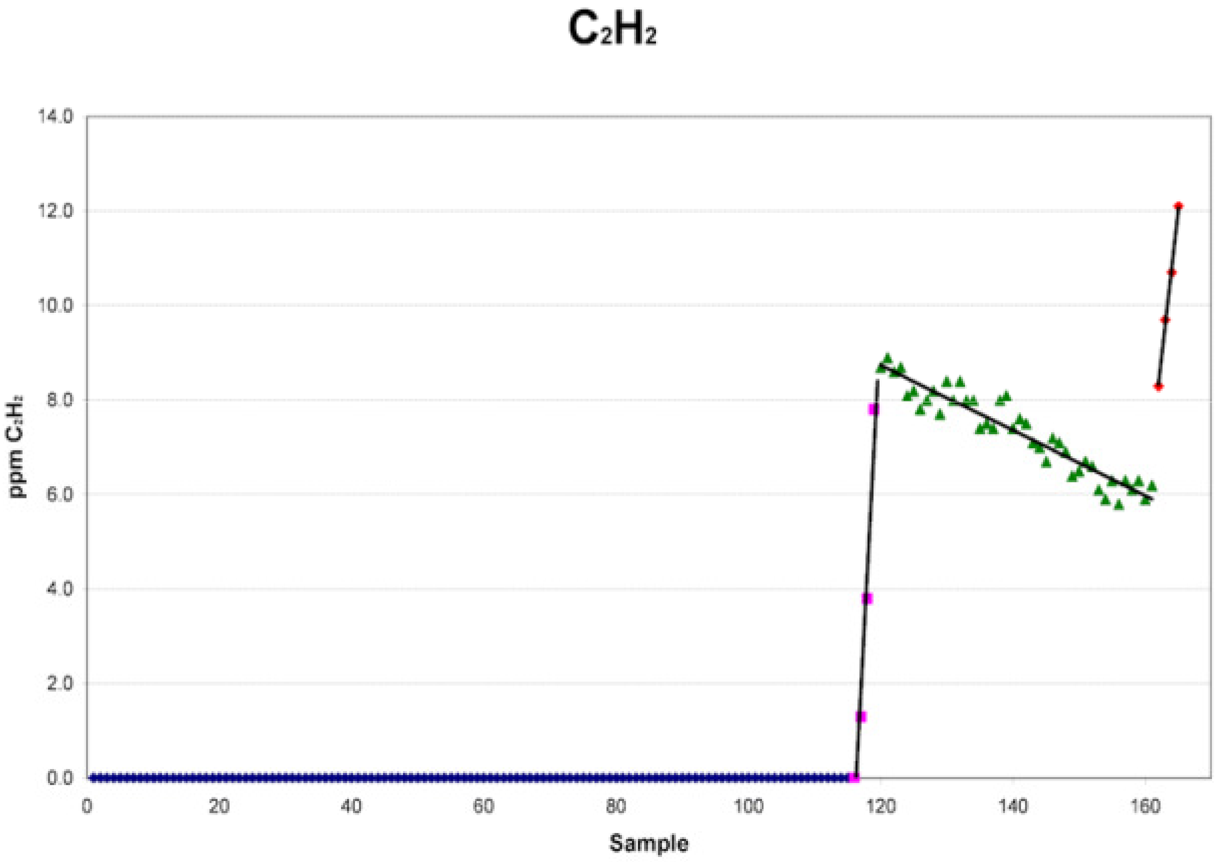
Seasonal variations of CO_2:



When temperature increases, CO_2 is pushed out of the paper and into the oil. This reverses when the temperature decreases.

(Ref: D.Lamontagne 2011)

Calculation of gassing rates with gas monitors:



(Ref: D.Lamontagne 2011)

Diagnosis methods for gas monitors:

The same DGA interpretation methods and algorithms used for laboratory results can be applied to monitor readings (gas levels, type and location of faults).

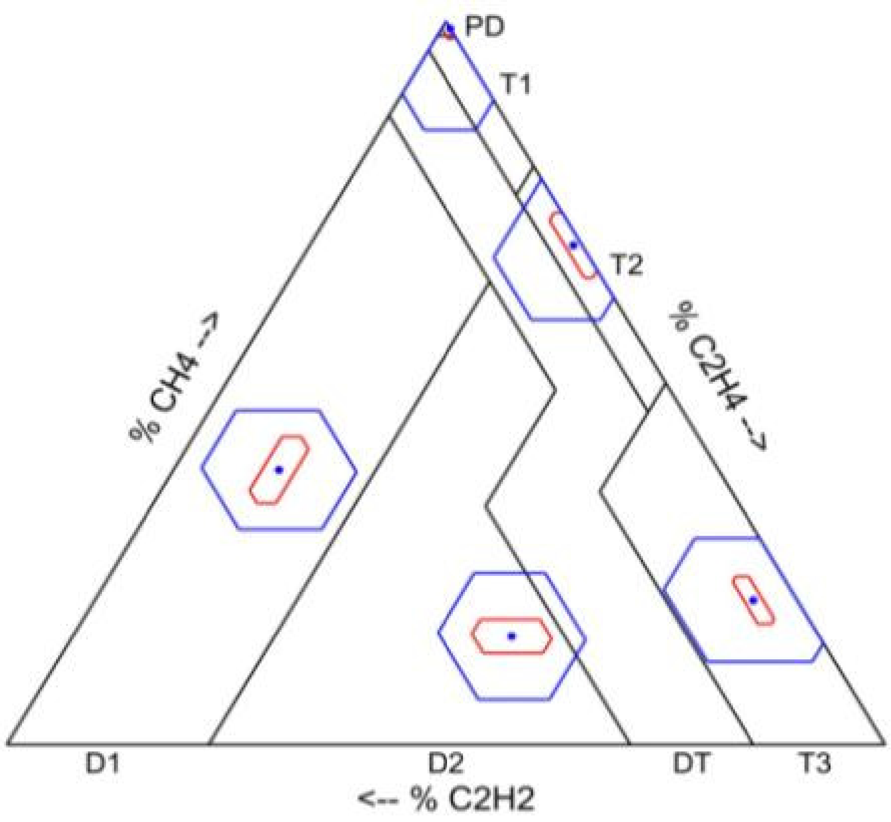
The Importance of DGA Accuracy

-accurate concentration values from both laboratories and gas monitors (15% accurate or better) are needed for reliable DGA diagnosis, and for comparison with concentration limits.

-an accuracy of 15% means that if 100 ppm are measured, the actual value may be anywhere between 85 and 115 ppm.

-low concentration values (< 5 or 10 times the analytical detection limit of the laboratory or gas monitor) are usually quite inaccurate and unreliable and should not be used for DGA diagnosis.

Lab Accuracy & Diagnostics

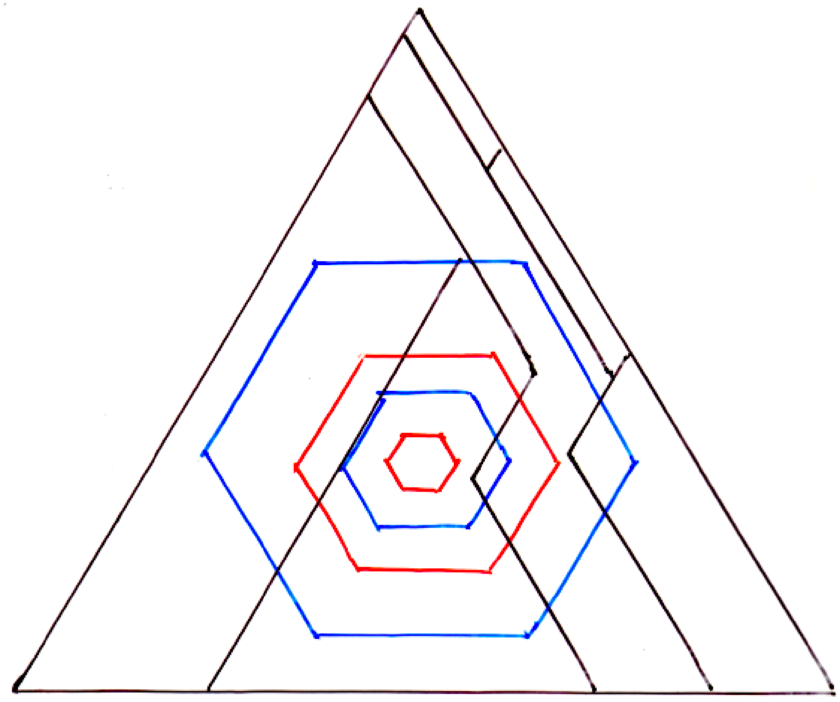


Effect of lab accuracies of 15% (in RED) and 30% (in BLUE) on DGA diagnosis uncertainty.

When an area of uncertainty crosses several fault zones, a reliable diagnosis cannot be given.

This is particularly true for lab accuracies > 30%.

Lab Accuracy & Diagnostics

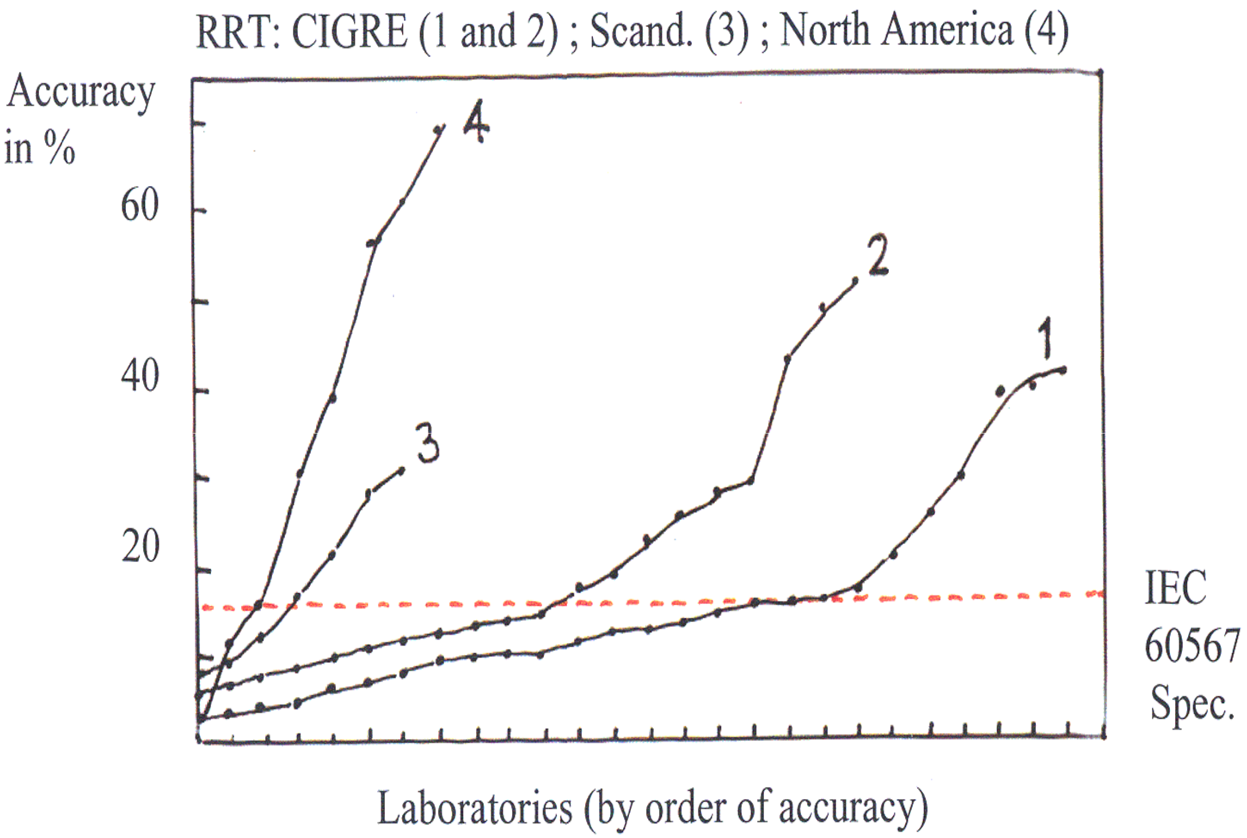


Diagnosis uncertainties corresponding to lab inaccuracies of ± 15, 30, 50 and 75 % (at 10, 6, 4 and 3 ppm for the average lab):

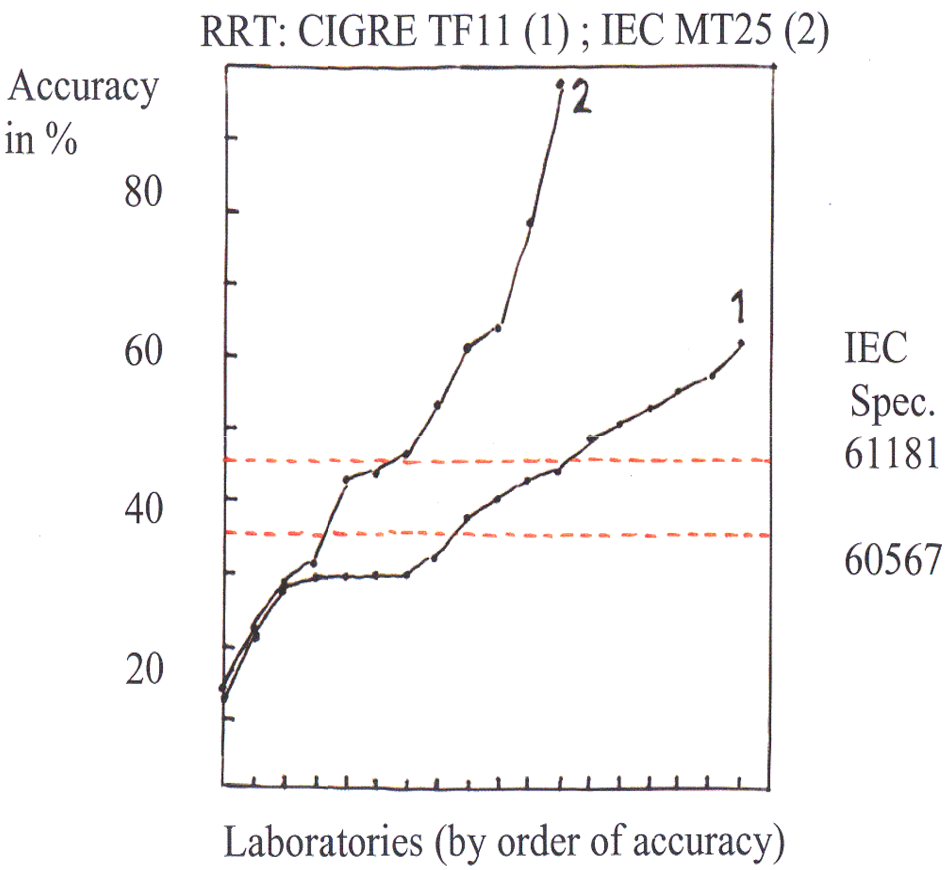
This applies not only to the triangle but to *all diagnosis methods*

Lab Accuracy & Gas Concentrations

(medium gas concentrations of >10 ppm)

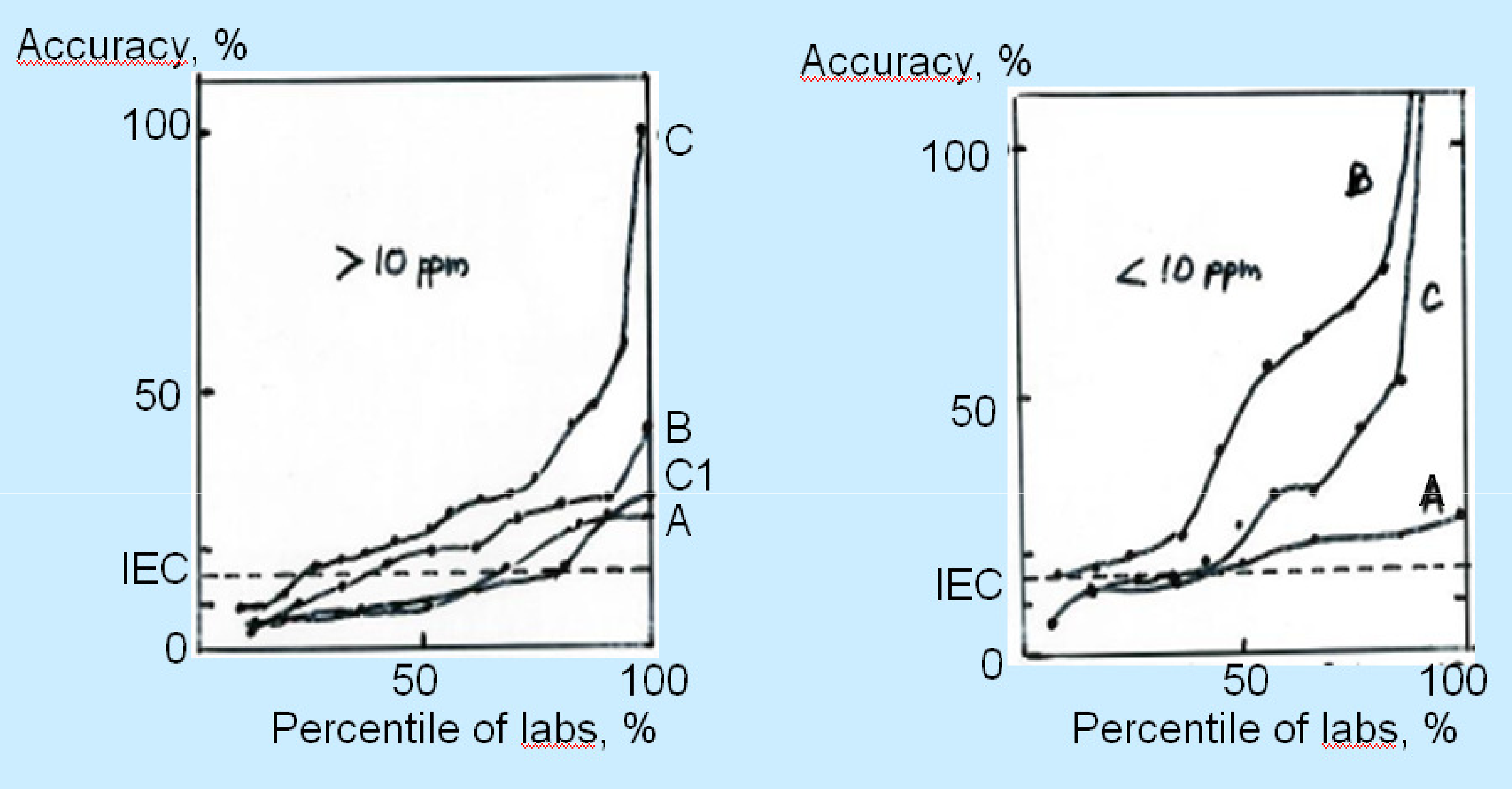


Lab Accuracy & Gas Concentrations
(low gas concentrations of <10 ppm)



The accuracy of the average laboratory decreases to ~ ± 30% at 6 ppm, and ± 100% near the lab detection limit (2 ppm)

Lab Accuracy & Gas Concentrations



Using ASTM Methods A, B and C and IEC Headspace Method (C1).

Lab Accuracy & Gas Concentrations

- This suggests that the calibration method recommended in ASTM D3612 for Method C (using gas-in-gas standards, slope intercept method and Ostwald coefficients) is not quite appropriate and should be replaced by the new calibration method of IEC 60567 (using gas-in-oil standards).

- If differences of more than 15% are observed between DGA results coming from different laboratories and/or on-line monitors, it is therefore advisable to verify the accuracy of results, using samples of gas-in-oil standard as a reference.

Accuracy & Diagnostics

The actual accuracy of your laboratory and monitors can be obtained by using gas-in-oil standards, which can be prepared in the lab or available commercially for instance from Morgan Schaffer (“TrueNorth”)

If lab accuracy is worse than 15%, a calculation of diagnosis uncertainty should be done, and commercial software are available for that purpose, for instance from Delta-X Research (TOA4)

Concentration accuracy of gas monitors:

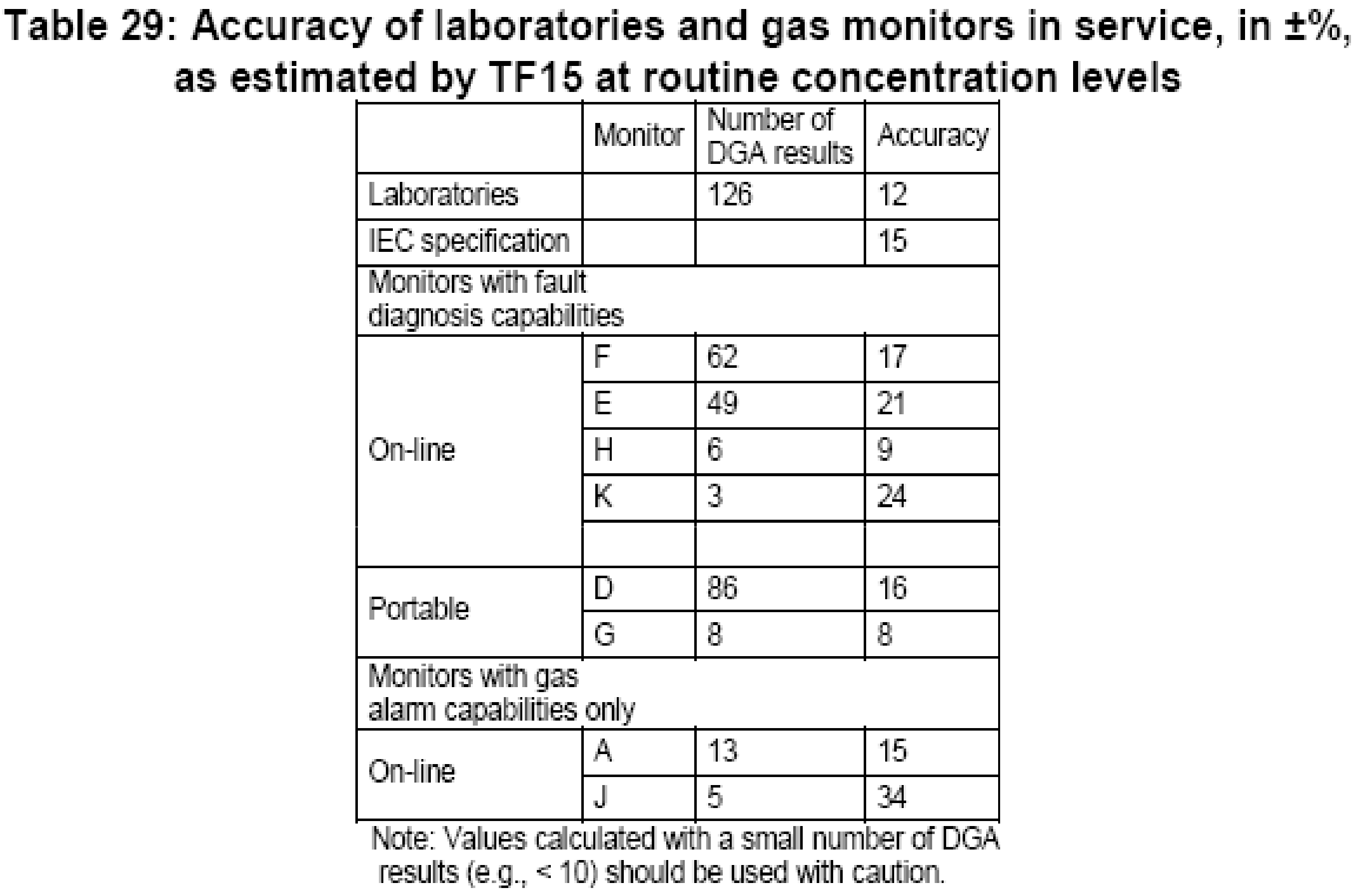


Table 29: Accuracy of laboratories and gas monitors in service, in ±%, as estimated by TF15 at routine concentration levels

	Monitor	Number of DGA results	Accuracy
Laboratories		126	12
IEC specification			15
Monitors with fault diagnosis capabilities			
On-line	F	62	17
	E	49	21
	H	6	9
	K	3	24
Portable	D	86	16
	G	8	8
Monitors with gas alarm capabilities only			
On-line	A	13	15
	J	5	34

Note: Values calculated with a small number of DGA results (e.g., < 10) should be used with caution.

Ref: CIGRE Technical Brochure # 409 (2010)

Accuracy of gassing trends:

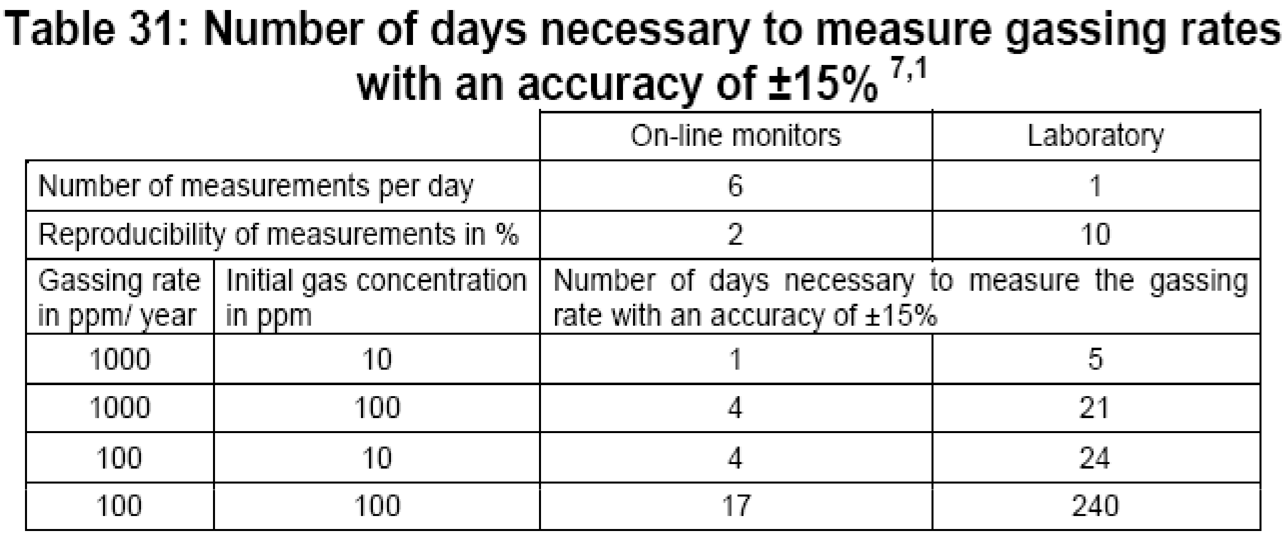


Table 31: Number of days necessary to measure gassing rates with an accuracy of ±15% [7,1]

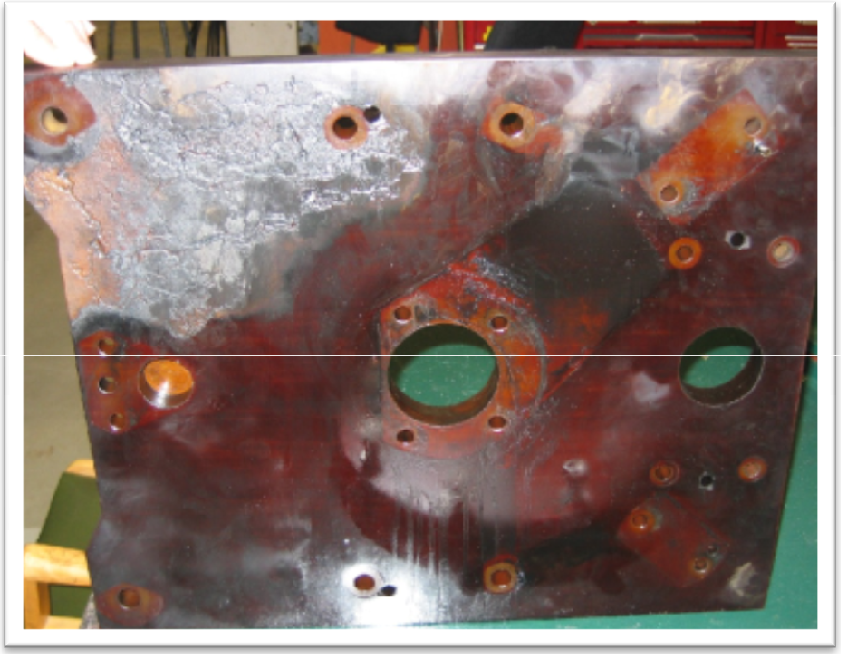
		On-line monitors	Laboratory
Number of measurements per day		6	1
Reproducibility of measurements in %		2	10
Gassing rate in ppm/ year	Initial gas concentration in ppm	Number of days necessary to measure the gassing rate with an accuracy of ±15%	
1000	10	1	5
1000	100	4	21
100	10	4	24
100	100	17	240

Ref: CIGRE Technical Brochure # 409 (2010)

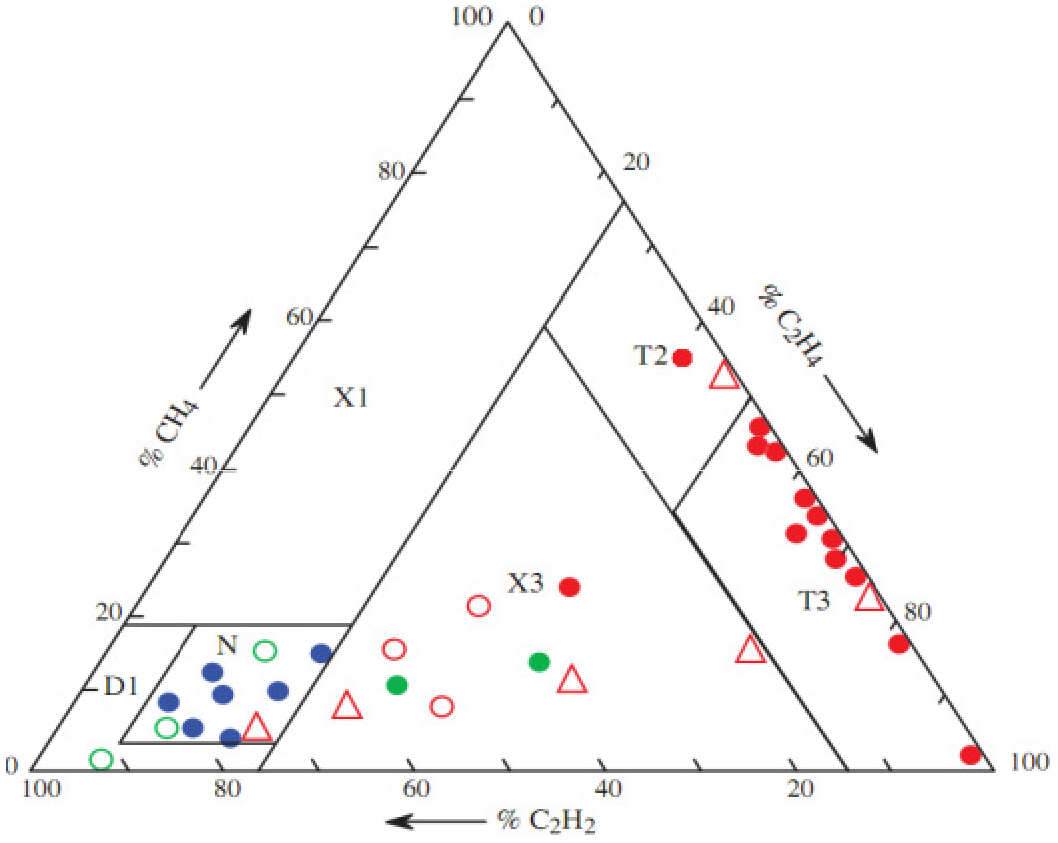
New Applications of the Triangle

LTC's of the Compartment Oil-type
(UZB, UBB, URS, UTT, URT, 550, 394, TLH, TC, LR, LRT, etc)

LTC's of the Compartment Oil-type
(UZB, UBB, URS, UTT, URT, 550, 394, TLH, TC, LR, LRT, etc)



Triangle 2 for LTC’s of the Conventional Oil-type (UZB, UBB, URS, UTT, URT, 550, 394, TLH, TC, LR, LRT, etc)



●: Normal operation; ●: Severe coking; ○: Light coking; △: “Heating”; ●: Strong arcing D2; ○: Arcing D1

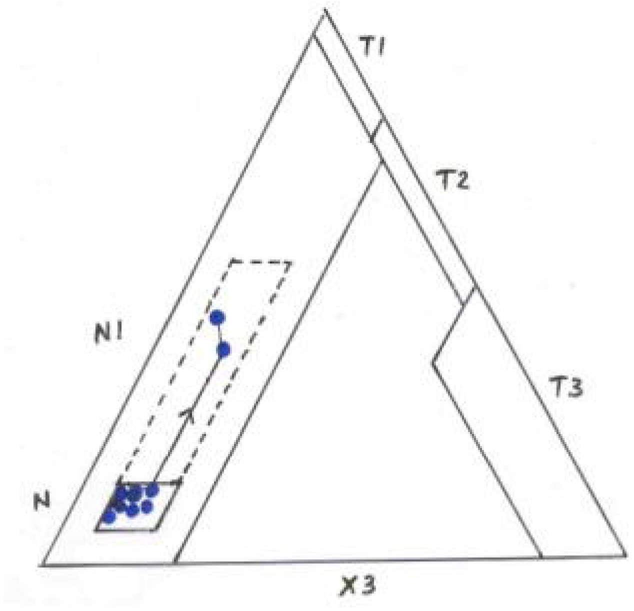
DGA in LTCs at IEEE and IEC

- Triangles 2 for LTCs will be introduced in revised C57.139 (also in revised IEC 60599):

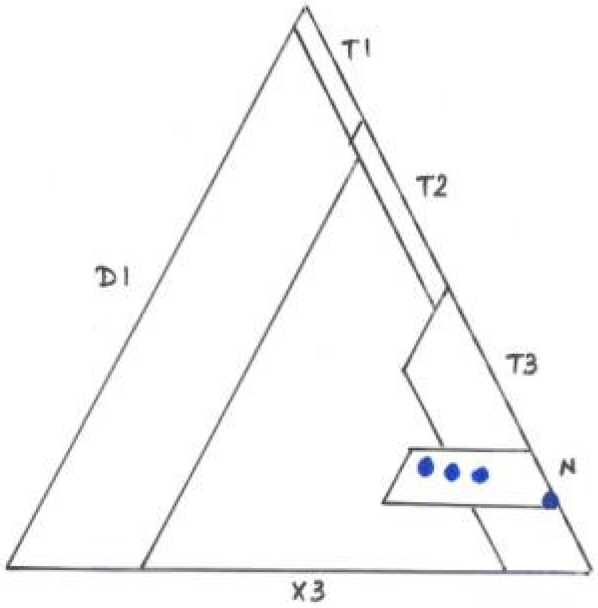
- With a single zone N of normal operation for most compartment-type LTCs.

- With several possible zones of normal operation for in-tank types (MR).

Triangle 2 for Reinhausen OLTCs



Types R, V

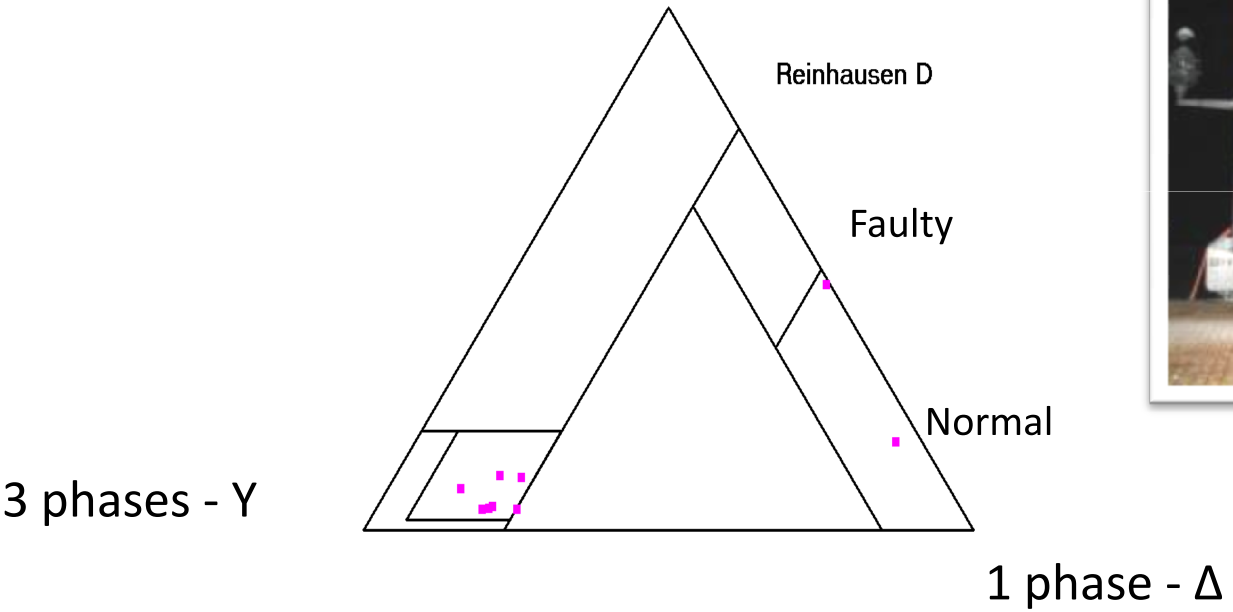


Types M

Ref: CIGRE TF15 (2010)

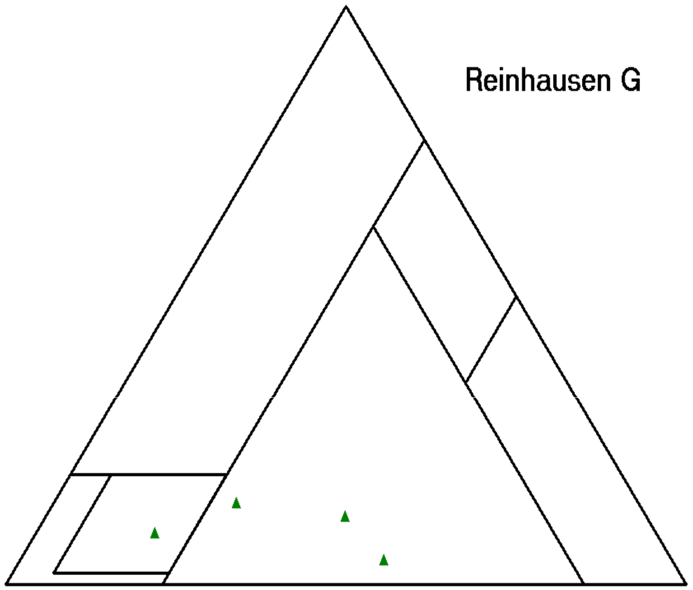
Triangle 2 for Reinhausen OLTCs

OilTap D



Ref: MRcademy (2010)

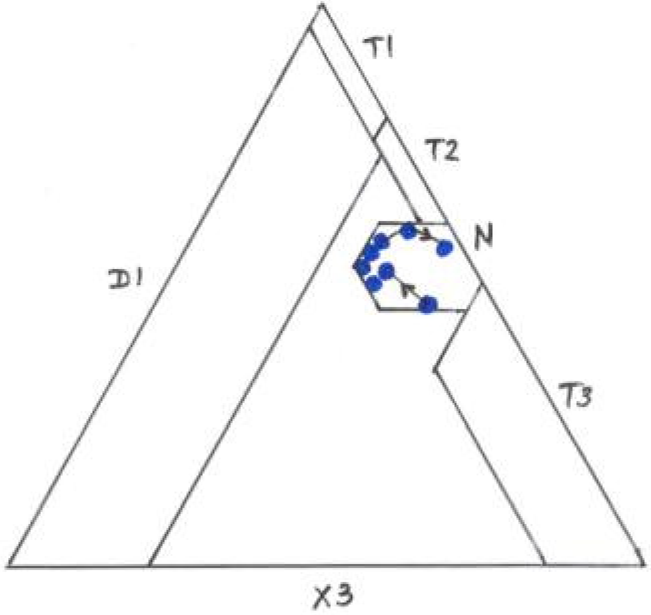
Triangle 2 for Reinhausen OLTCs



OilTap G

Ref: MRcademy (2010)

Triangle 2 for Reinhausen OLTCs

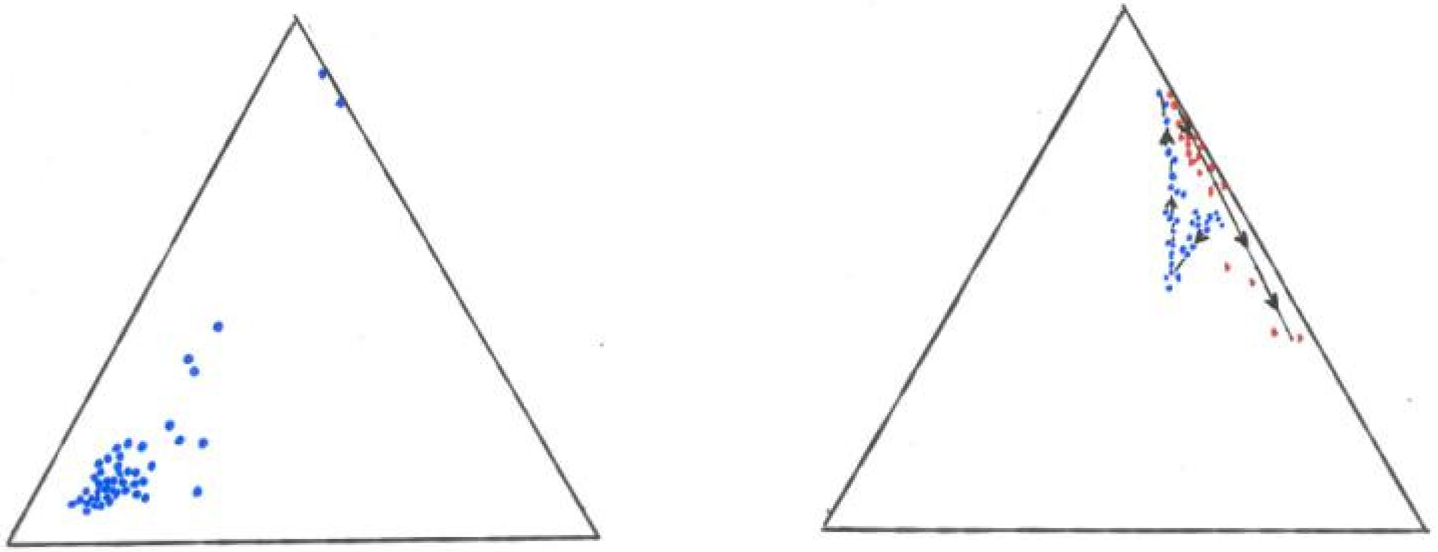


Types VR

Ref: CIGRE TF15 (2010)

Triangle 2 for Reinhausen OLTCs

Types VV



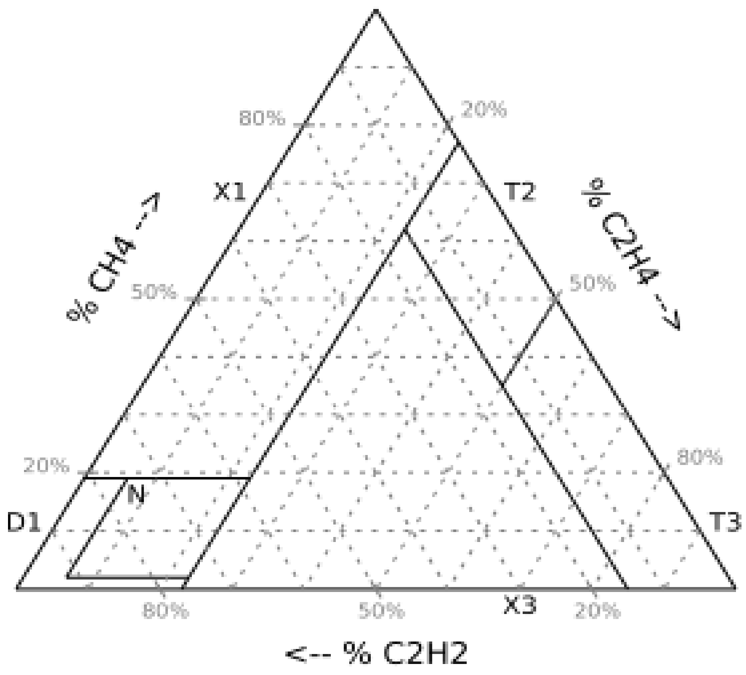
In service

During power switching tests

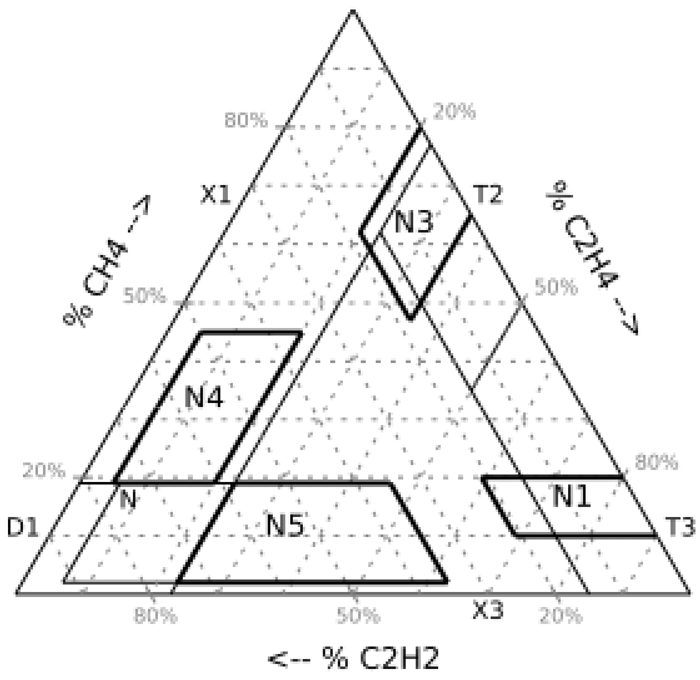
● Normal operation ● High temperature hot spot

Ref: CIGRE TF15 (2010)

DGA in LTCs at IEEE:



Triangle 2 for compartment types



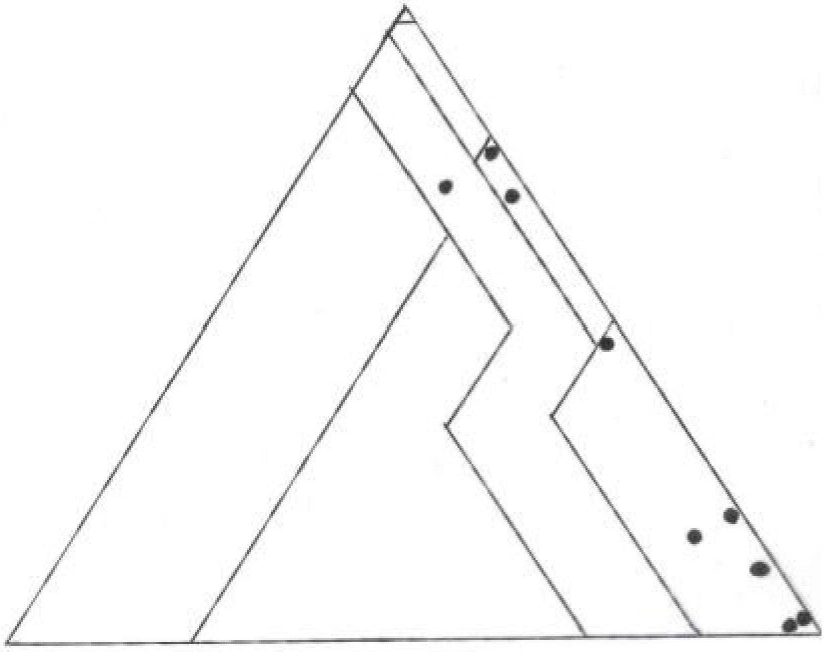
Triangles 2 for in-tank types

Normal operation zones for in-tank types:

- N or N1 for MR types M and D.
- N or N3 for MR types VR and VV.
- N or N4 for MR types R and V.
- N or N5 for MR types G and UZDs.
- Depending on operating conditions.

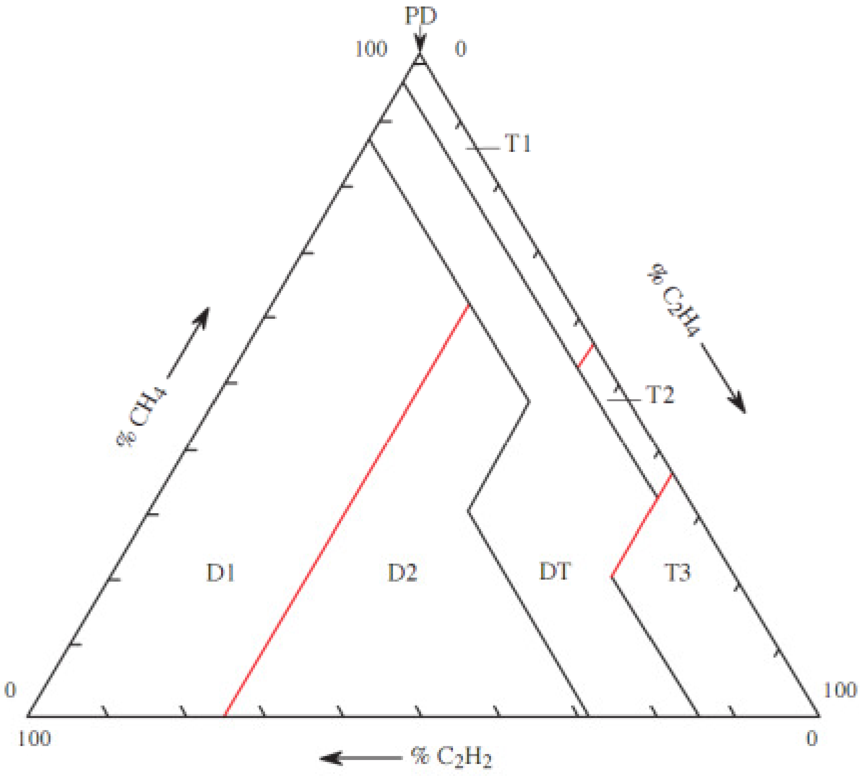
- Other DGA examples would be needed for the normal and faulty operation of these LTCs.

Triangle 1 for LTC's of the Conventional Vacuum Type (LRT, UVT)

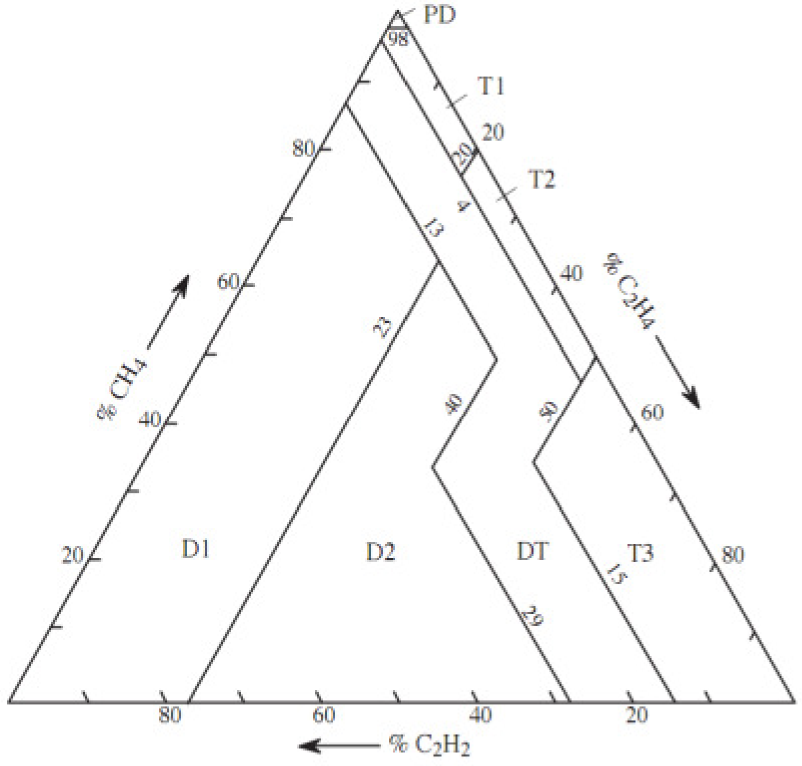


- ● No inspection made

Triangle 3 for Non-Mineral oils

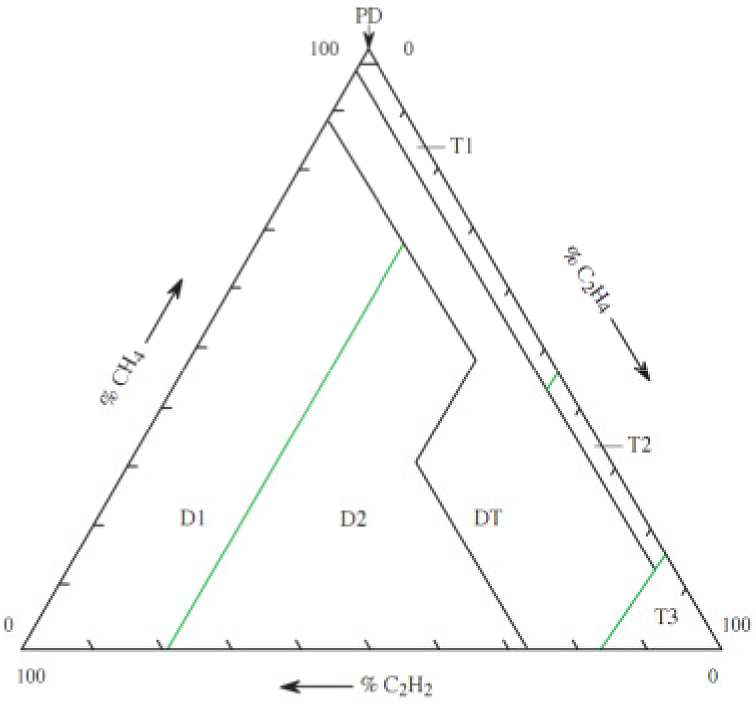


FR3

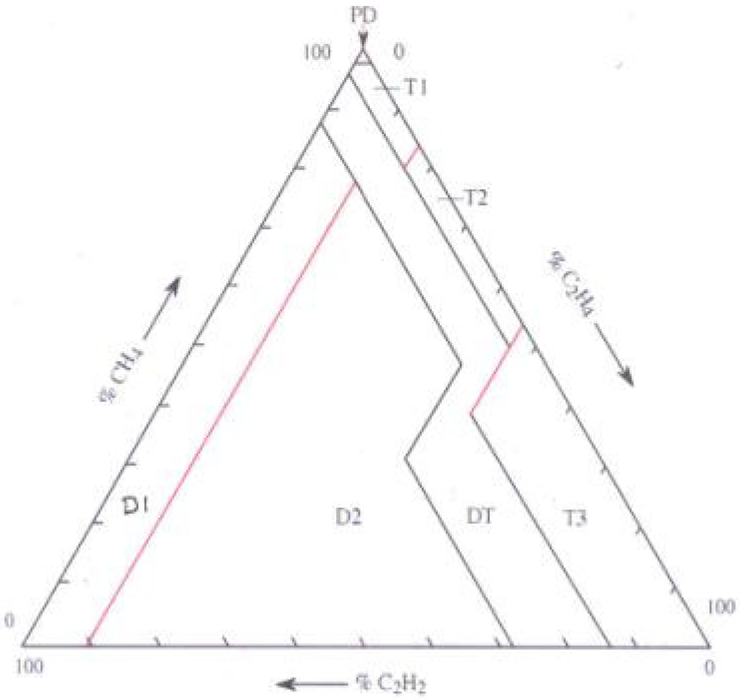


Mineral oil

Triangle 3 for Non-Mineral oils

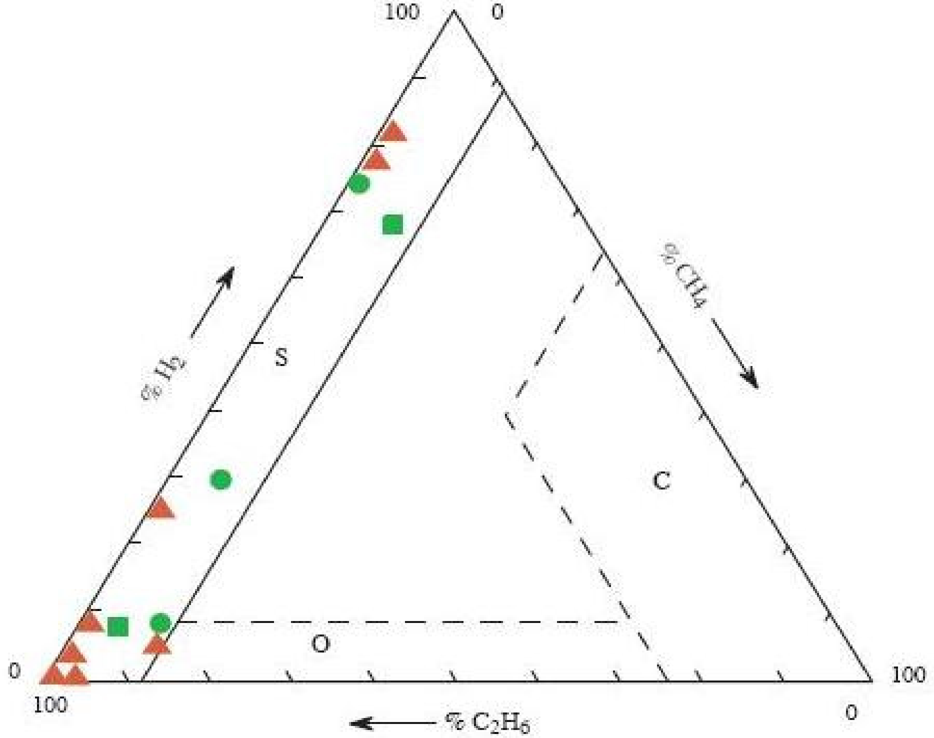


BioTemp



Silicone oil

Triangle 6 for Low-Temperature Faults in FR3 Oils

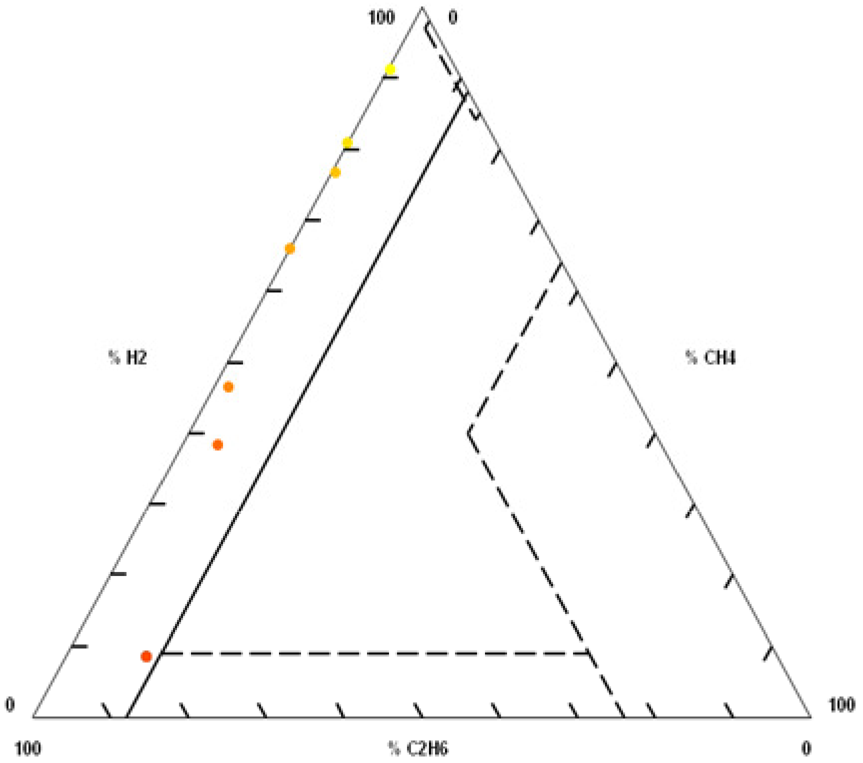


● stray gassing at T < 150 °C;

■ stray gassing at T > 200°C;

▲ gas formation in Alliant transformers

Stray gassing of FR3 (Triangle 6)



% H2	% CH4	% C2H6	Fault	Color	Date	Record No.
91,2	0,3	8,4	S	●	55 C	1
80,9	0,0	19,1	S	●	80 C	2
76,6	0,7	22,7	S	●	90 C	3
66,1	0,0	33,9	S	●	100 C	4
46,4	2,0	51,6	S	●	120 C	5
38,3	4,5	57,1	S	●	150 C	6
8,6	10,4	81,0	S	●	200 C	7

DGA in wind farm transformers at CIGRE

Because they are usually Padmount transformers not designed for that purpose, many tend to form lots of gases as a result of:

- Corona PDs, because of poor oil impregnation.
- Or stray gassing of oil, because of abnormal overheating.

Stray gassing of oil at CIGRE

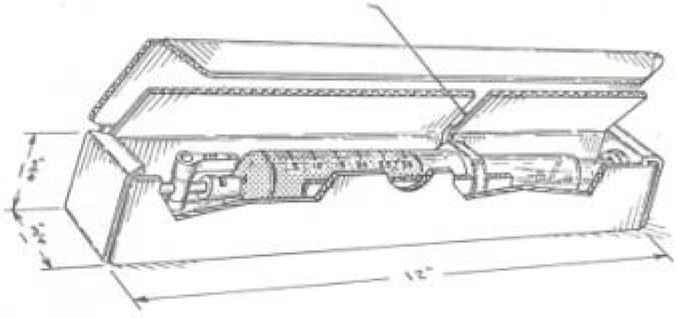
- With mineral oil, H_2 at T<120C and CH_4, C_2H_6 at T>200C.
- With vegetable oils (e.g.,FR3), H_2 at T<70C and C_2H_6 at higher temperatures (Triangles 6 and 7).
- With silicone oils, H_2 at T>200C.

Laboratory DGA

Traditional DGA Methods

DGA labs use Gas Chromatography (GC)

Samples of oil are manually taken on a set schedule.



Samples are sent to Accredited Labs

Standards and Guidelines Governing Laboratory DGA

ASTM D3612-2002 Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography

IEC 60567-2005 Oil-filled electrical equipment - Sampling of gases and of oil for analysis of free and dissolved gases

Some other ASTM standards are available;

- D3613-1998 - Standard Practice for Sampling Insulating Liquids for Gas Analysis and Determination of Water Content
- D3305-95 (1999) – Standard Practice for Sampling Small Gas Volume in a Transformer
- D2759-2000 – Standard Practice for Sampling Gas from a Transformer under Positive Pressure

Oil Sampling

Manual Sampling

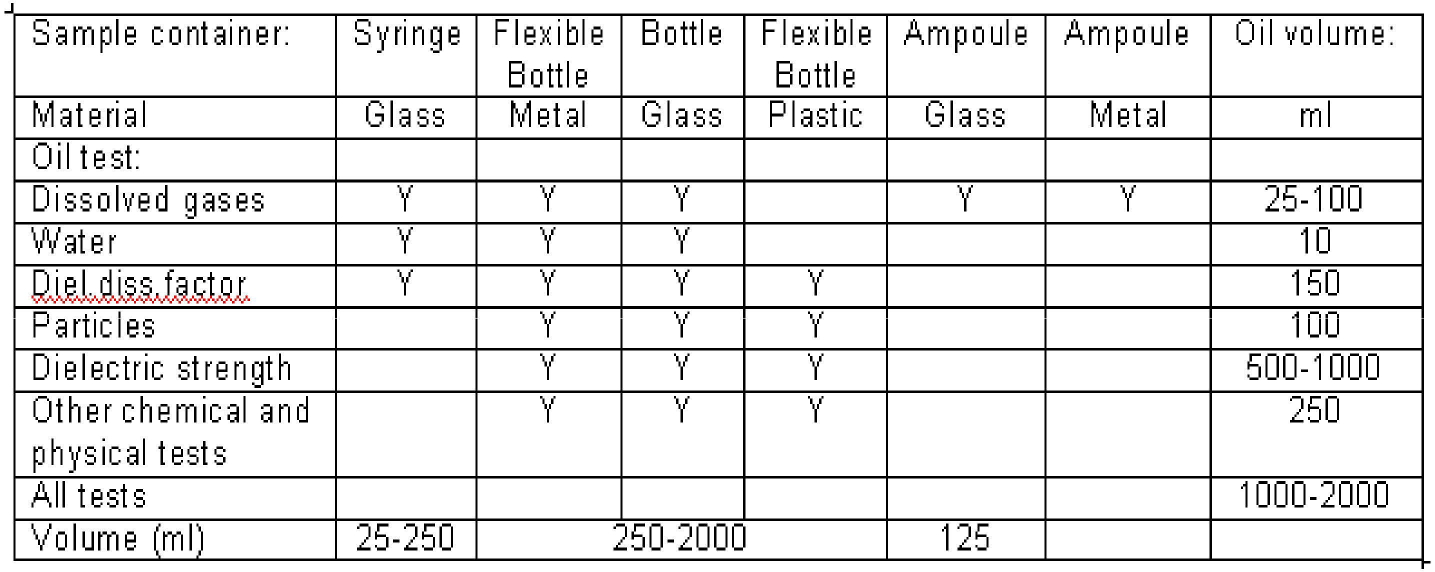
- A small volume of oil (30 mL) is collected in a gas-tight syringe, using a 3-way valve, then transported to the laboratory
- ASTM method D3613 details procedures for oil sample handling

On-Line Sampling

- A small volume of oil is continuously circulated through the monitor and then returned to the transformer
- The oil is sampled and analyzed for gas content by the monitor
- On-Line monitors offer a closed-loop repeatable oil sampling process, with no possibility for contamination

Laboratory Oil Sampling

Sampling devices used:



Sample container:	Syringe	Flexible Bottle	Bottle	Flexible Bottle	Ampoule	Ampoule	Oil volume:
Material	Glass	Metal	Glass	Plastic	Glass	Metal	ml
Oil test:							
Dissolved gases	Y	Y	Y		Y	Y	25-100
Water	Y	Y	Y				10
Diel.diss.factor	Y	Y	Y	Y			150
Particles		Y	Y	Y			100
Dielectric strength		Y	Y	Y			500-1000
Other chemical and physical tests		Y	Y	Y			250
All tests							1000-2000
Volume (ml)	25-250	250-2000			125		

Ref: IEC 60475 (2010)

Gas Extraction

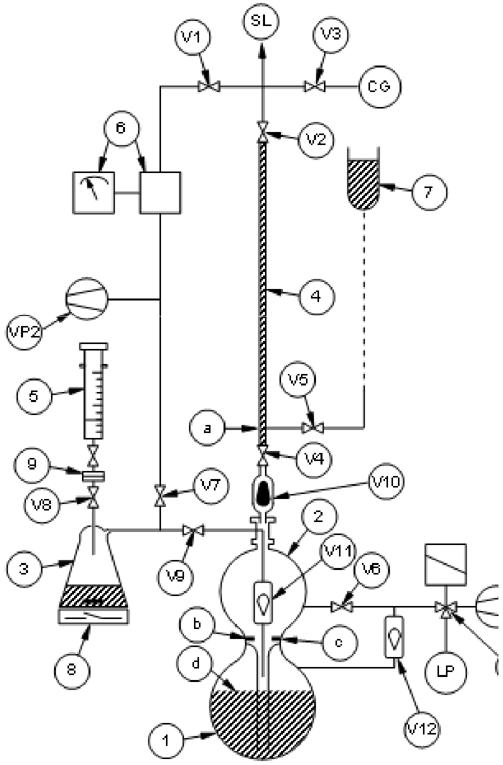
Dissolved gases are present in transformer oil at concentrations from <1 part-per-million (ppm) up to a few percent of oil volume.

ASTM method D3612 specifies three methods to extract dissolved gases from the Transformer Oil

- Method A (Vacuum Extraction)
    - Partial De-Gassing method
- Method B (Stripper Column Extraction)
- Method C (Headspace method)

Laboratory Method A (Partial Degassing/ Toepler)

- The oil sample is introduced into a pre-evacuated vessel
- The extracted gases are compressed to atmospheric pressure and the total volume measured
- The gases are then analyzed by gas chromatograph

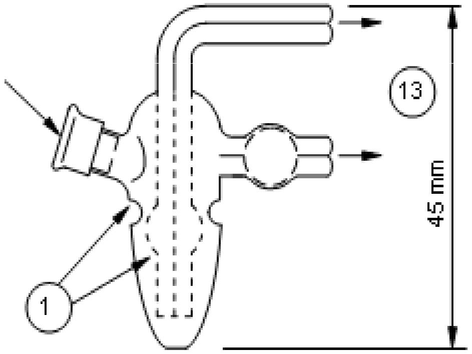


1	Mercury reservoir – 2 litres
2	Gas collection flask – 1 litre
3	Degassing flask – 250 ml or 500 ml
4	Gas collecting burette – 25 ml (0,05 ml divisions)
5	Introduction of oil sample via syringe
6	Pirani vacuum gauge
7	Mercury levelling vessel
8	Magnetic stirrer
9	Septum
10	Oil sampling bottle
11	Jet

(IEC 60567)

Laboratory Method B (Stripping)

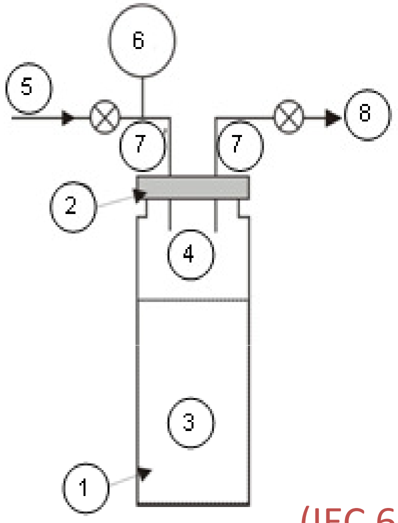
- The oil is sparged with a carrier gas in a glass stripper or column
- The gases are then flushed from the stripper column into a gas chromatograph for analysis



(IEC 60567)

Laboratory Method C (Headspace)

- The oil sample is introduced in a glass vial with a headspace gas phase of argon above it.
- Some of the gases migrate from the oil to the headspace and equilibrate according to Henry’s law.
- At equilibrium, a portion of the headspace is transferred to a sample loop then introduced into a gas chromatograph



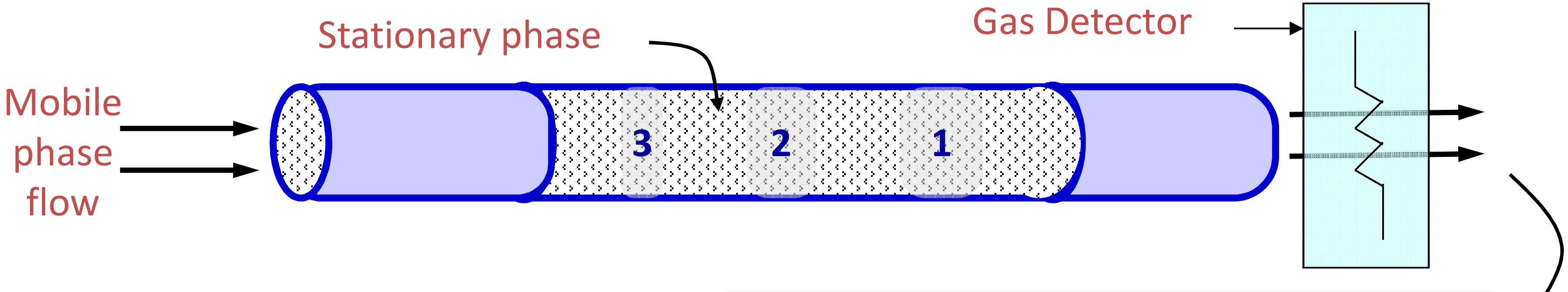
(IEC 60567)

Laboratory extraction of dissolved gases

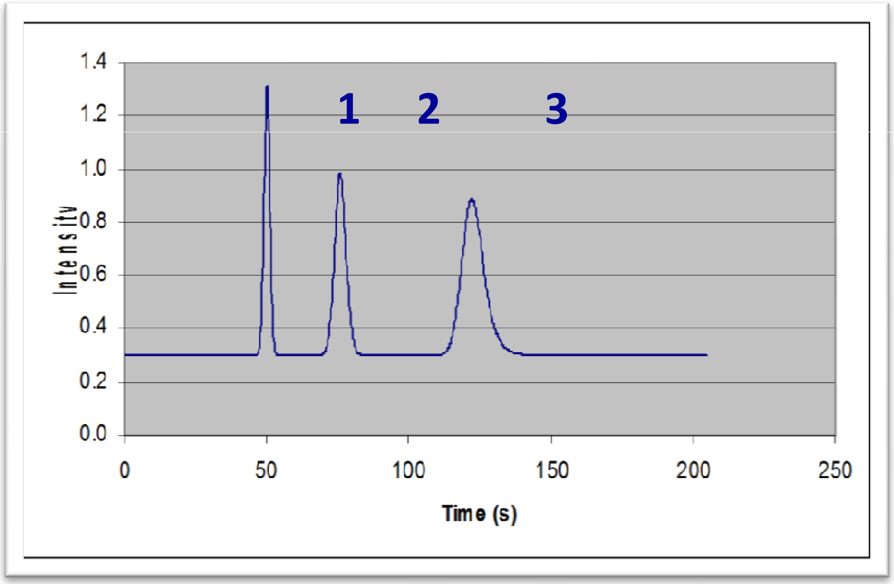
- CIGRE TF07 (2001): all these 3 methods of gas extraction provide satisfactory results if used correctly.

- CIGRE TF15 (2008): headspace results tend to be more repeatable, partial degassing and Toepler more accurate (reference methods), stripping leads to more dispersion of results.

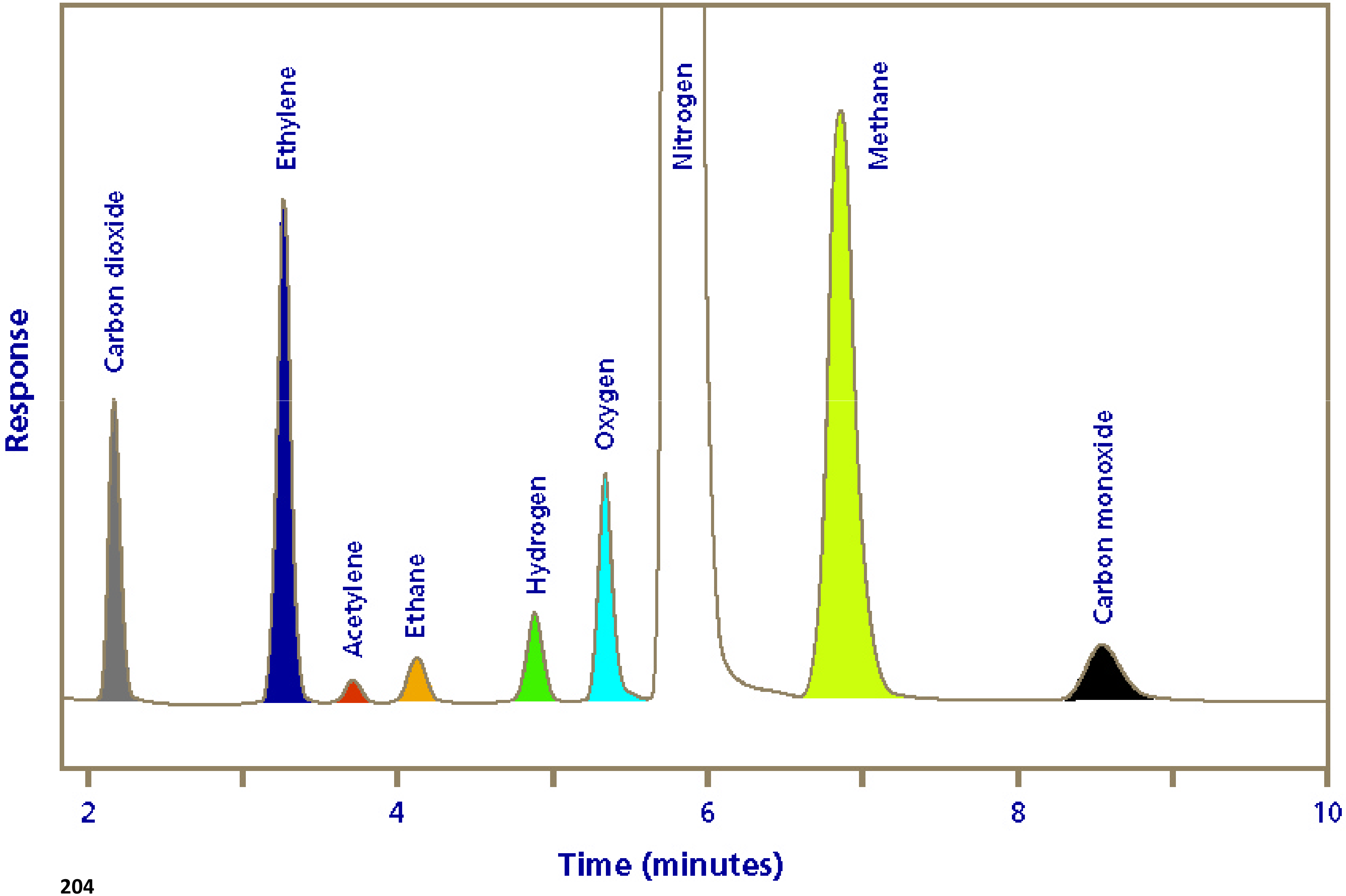
Gas Chromatography



- Mobile phase = gas
- Stationary phase = solid adsorbent or liquid
- Mobile gas phase flows through the column under pressure



TRANSFORMER GAS SEPARATION BY GAS CHROMATOGRAPHY



Laboratory analysis of gases extracted from oil:

- PLOT capillary columns often used at low gas concentrations or with Headspace.
- HID (Helium Ionization Detector) was added to revised 60567 in 2010 (more sensitive).

Gas Solubility Coefficients

Some gases dissolve into the oil more than others

- This is known as <u>Solubility</u>
- In the following graph, Ethane, C_2H_6 dissolves the most and Hydrogen, H_2 the least.

Solubility coefficients change over temperature

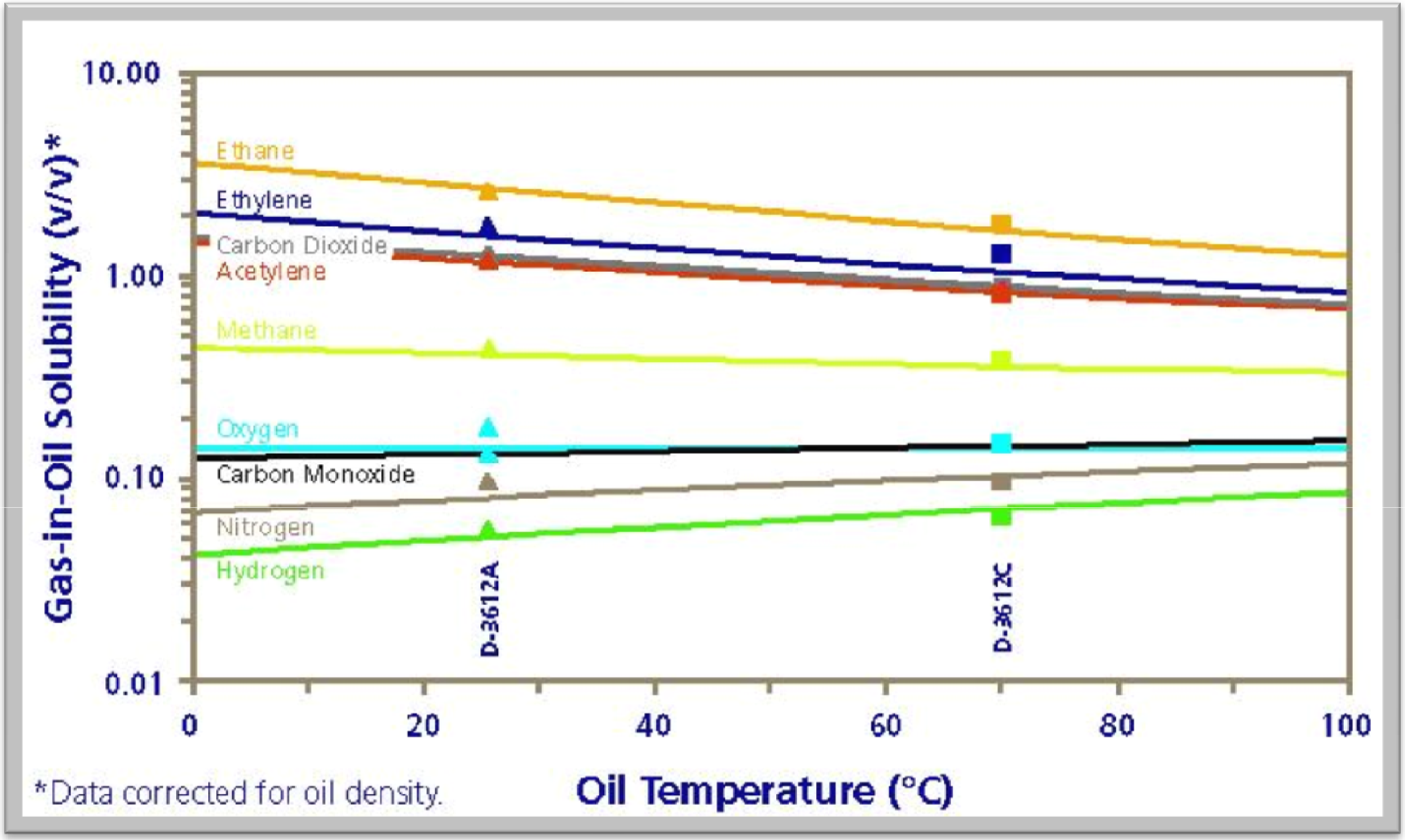
- Gases dissolve into oil in different amounts as temperature changes

Solubility coefficients are required because all Laboratory gas measurement systems measure gas-in-gas and these concentrations are different than the gas-in-oil

Note:

- <u>Temperature of the Oil</u> during a ‘manual’ sample is required only for Lab “Moisture-in-Oil” calculations
- <u>Temperature of the Oil</u> during the gas extraction process is required to determine the ‘Solubility Coefficient”

Gas Solubility Coefficients



*Data corrected for oil density.

The triangles and squares in the graph represent ASTM solubility coefficients at selected temperatures used in the Laboratory DGA process

Gas Solubility Coefficients

Solubility coefficients are applied to the laboratory measured gas-in-gas values to derive the true gas-in-oil concentration in transformer oil.

Example

"Method C" headspace sampling formula (from ASTM D3612)

$C_L = C_G (K + V_G/V_L)$

- C_L = Gas-in-Oil value, ppm
- C_G = Gas-in-Gas value, ppm
- K = Solubility Coefficient
- V_G = Volume of Oil space, 7 mL*
- V_L = Volume of Gas space, 15 mL*

(*)Typical Laboratory values

Example for Hydrogen, H2

- C_G = 40 ppm K = 0.0558 V_G/V_L = 7/15 = 0.467 mL
- C_L = 40 (0.0558 + 0.467)
- C_L = 40 (0.5225)

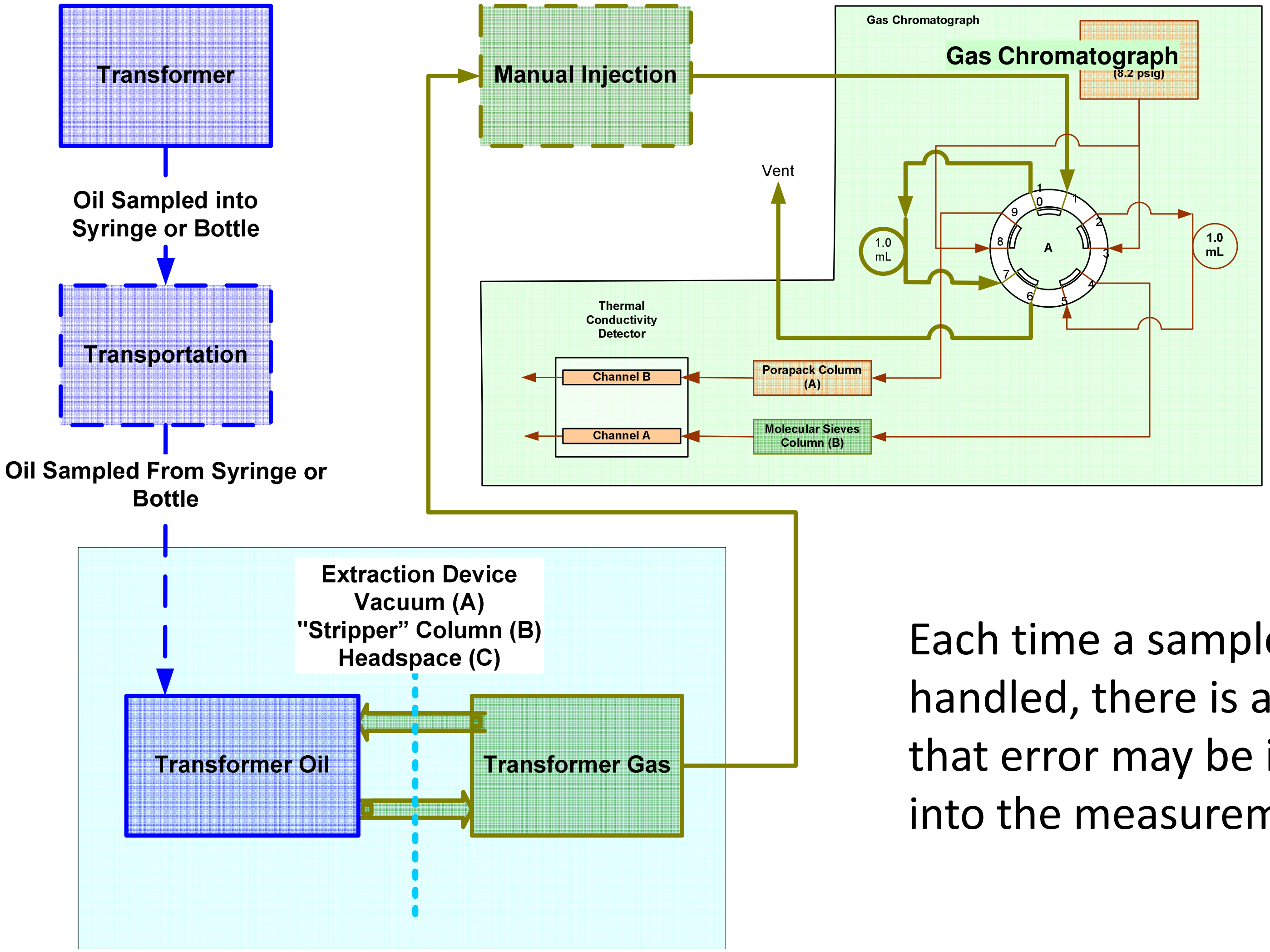
$\underline{C_L = 20.9 \text{ ppm is the Gas-in-Oil value}}$

Laboratory analysis of extracted gases:

- Calibration method recommended for Headspace in revised 60567 (2010) is with gas-in-oil standards rather than (gas-in-gas standards + partition coefficients).

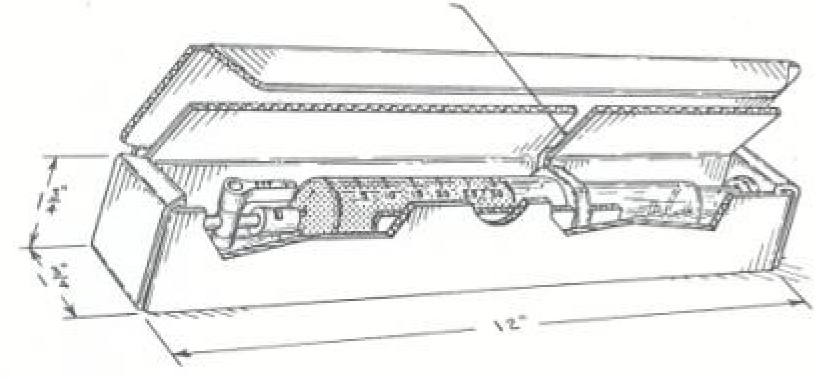
- Method recommended in revised 60567 (2010) for the determination of partition coefficients is with gas-in-oil standards rather than with slope/intercept method.

Manual DGA Process



Each time a sample is handled, there is a chance that error may be introduced into the measurement

Concerns with Laboratory DGA



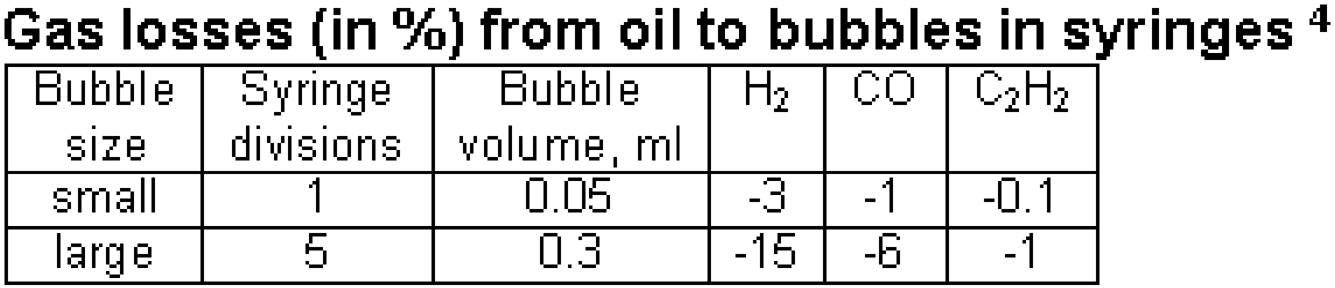
<u>Sampling</u>:

- If not done according to standard procedures by experienced personnel, the samples may lead to erroneous results.
- For instance, if low-quality syringes are used, additional O_2 & CO_2 may be introduced or key gases (e.g. H_2) may be lost. Exposure to light may also affect DGA results.

<u>Transport</u>:

- If procedures are not followed properly, transportation may introduce contaminations or even breakage.

Laboratory oil sampling



Gas losses (in %) from oil to bubbles in syringes [4]

Bubble size	Syringe divisions	Bubble volume, ml	H_2	CO	C_2H_2
small	1	0.05	-3	-1	-0.1
large	5	0.3	-15	-6	-1

Gas bubbles, however, are formed in only 20% of glass syringes received by laboratories, and large bubbles in only 2% of cases.

Ref: CIGRE TF15 (2010)

Good sample versus bad sample

It is sometimes very clear to the laboratory performing the analysis if it was taken improperly.

- The presence of free water or foreign objects such as insects, pipe sealant, tape or putty are strong indicators that the drain valve was not adequately flushed out prior to sampling.

Materials used for collecting samples;

- Galvanic fittings (zinc coated) used in the drain valve assembly such as the drain plug, can create a galvanic reaction with water, and cause very high levels of hydrogen to be produced.

Good sample versus bad sample

Sample ports should have Brass Fittings or Stainless Steel

Compatible tubing is necessary for sample collecting (Tygon, Viton or silicone rubber for mineral oils; PTFE or metal for non-mineral oil)

- Tubing should only be used once and then discarded as the walls of the tubing have a memory (can hold gases, water and other chemicals compounds in the wall of the tubing)
- Incompatible tubing such as natural rubber or PVC will contaminate a sample with unwanted materials.

Concerns with Laboratory DGA

Laboratory handling is a concern the sample may be contaminated in the process of being analyzed

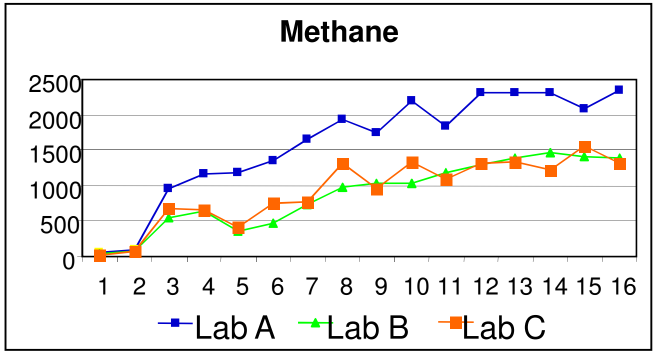
Gas Chromatography analysis in the laboratory is another source of errors if not done by experienced personnel and not following QA/QC procedures.

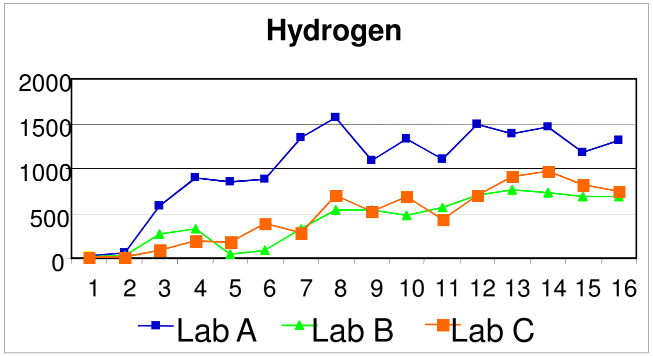
The accuracy required for laboratory analysis is +/- 15 % on gas concentrations, but several laboratories are much less accurate than that.

Differences Among Lab DGA Results

Independent studies have shown lab-to-lab DGA differences can be large, with some results necessarily not accurate

This study consisted of Sixteen (16) samples from the same Transformer - All samples were collected by the same individual using the same process.





All samples were sent to 3 different laboratory's simultaneously.

Possible causes of differences are:

- Even with the same sampler and sample process, contamination could have occurred
- Transportation may have affected the samples
- Laboratory accuracies are ±15% on average; some are much worse

Interpretation of DGA results (Summary)

#1 - Examine DGA laboratory values

- Eliminate zero values (replace them by the detection limits of the laboratory, e.g., 2 or 1 ppm)
- Compare with previous values in ppm on the same transformer (DGA history)
- Check for inconsistencies which might indicate contamination during sampling or a laboratory analytical error. Consider suspect values with caution or discard them

#2 - Attempt a fault diagnosis

- Compare lab results or monitor readings with in-house typical values of concentration and gassing rate, or compare with published values (e.g., from IEEE and CIGRE)

- If measured DGA values are above typical values, a fault diagnosis may be attempted

- If measured values are below routine concentration values (10 ppm for hydrocarbons), a fault diagnosis should be attempted only after calculating the uncertainty on the diagnosis, based on the accuracy of the laboratory at these low concentration levels

#3a - Evaluate the severity of the fault

The severity of the fault will depend on:

- The rate of gas formation
- The concentration of gases
- How far measured values are from typical values, and how close they are to pre-failure values
- The nature of the fault (electrical or thermal)
- The location of the fault (paper or oil only)

#4 - Actions on the equipment

Increase the frequency of oil sampling

- (as values move from typical values to pre-failure values)

Determine the dependence of gas formation on load

Consider complementary tests

- (UHF detection of partial discharges, detection of hot spots by infra-red cameras and acoustic tests)

For critically located or severely affected equipment, install on-line gas monitors

For the most severe cases, plan the replacement of the transformer and/or its removal from service and inspection

Ask for advise of DGA experts

On-line DGA

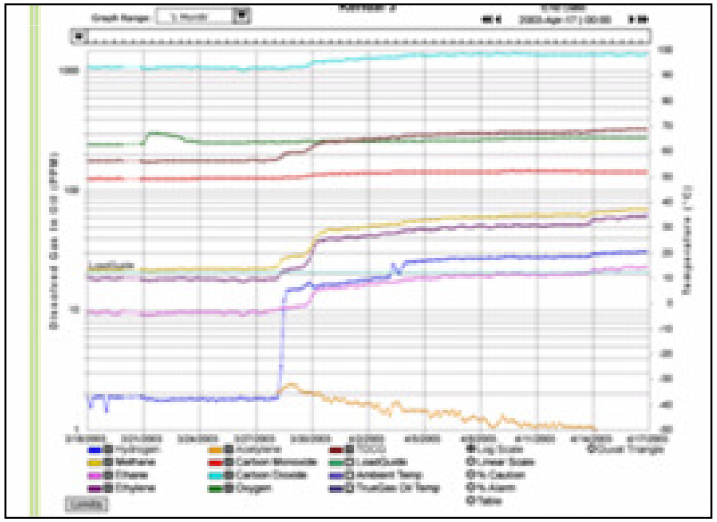
Benefits of On-Line DGA

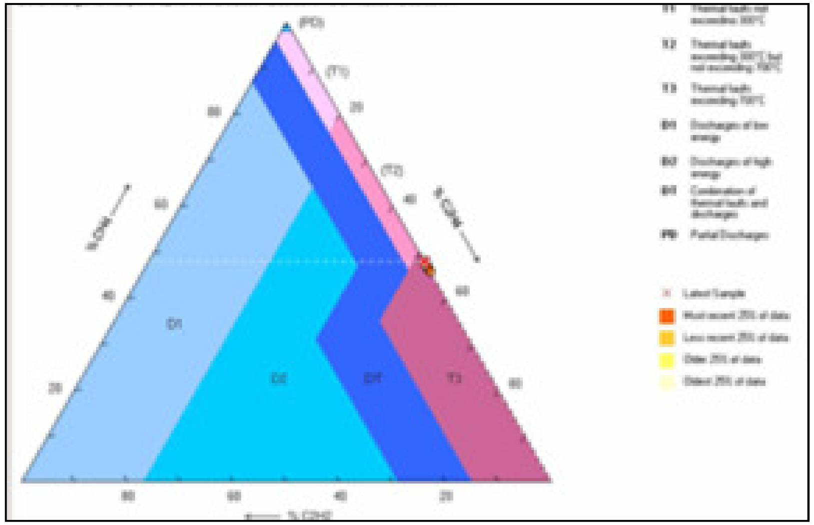
Detects both gradual and sudden trends in all gases

Correlates gassing events with external events such as transformer load, oil temperature, LTC changes, etc.

Provides historic trail for delayed analysis of gassing events

May provide diagnosis on-line





Advantages of On-Line DGA

Oil is sampled automatically via closed-loop GC:

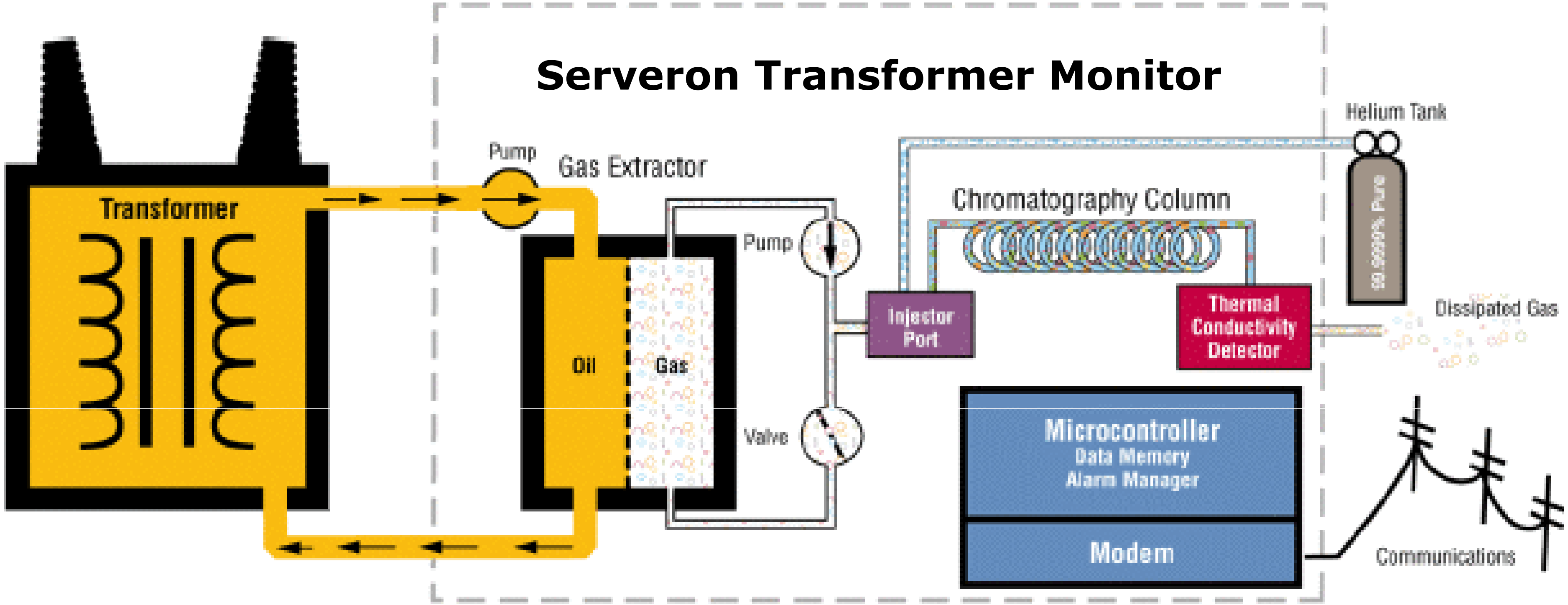
- No risk of human intervention
- Repeatable sampling technique
- No atmospheric exposure

Data is collected up to hourly:

- Resulting in faster, more accurate determination of trends

All 8 fault gases + moisture are monitored and correlated with oil temperature and load

On-Line DGA


Serveron Transformer Monitor
Helium Tank
Pump
Gas Extractor
Transformer
Chromatography Column
Pump
99.9999% Pure
Injector Port
Thermal Conductivity Detector
Dissipated Gas
Oil
Gas
Valve
Microcontroller
Data Memory
Alarm Manager
Modem
Communications

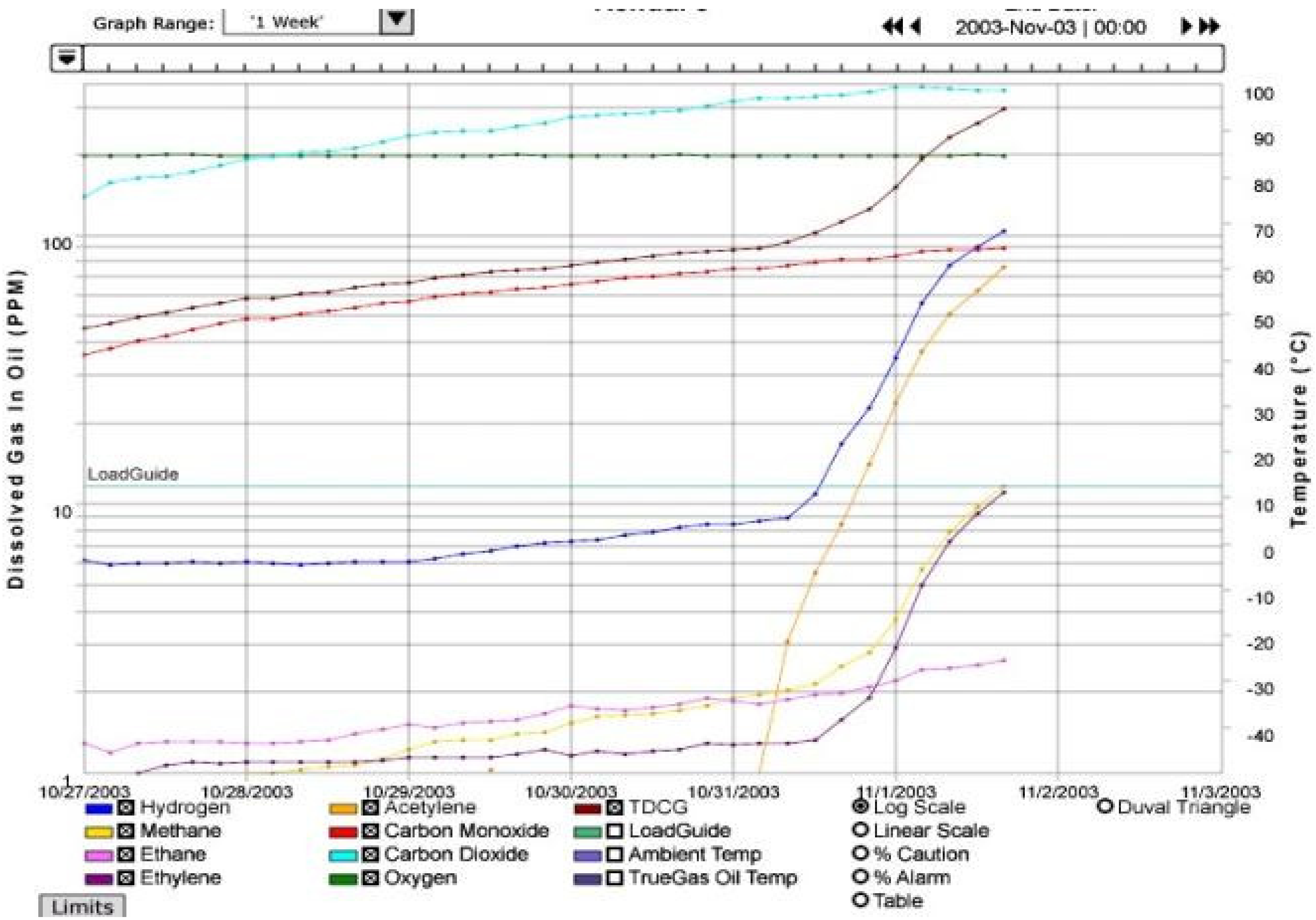
On-line DGA

On-line gas monitors

- Are best suited for measuring rates of gas increase (trends)
- Will detect faults between regular oil samplings
- May now also provide on-line diagnosis

On-line DGA Case Studies

Serveron Story #11



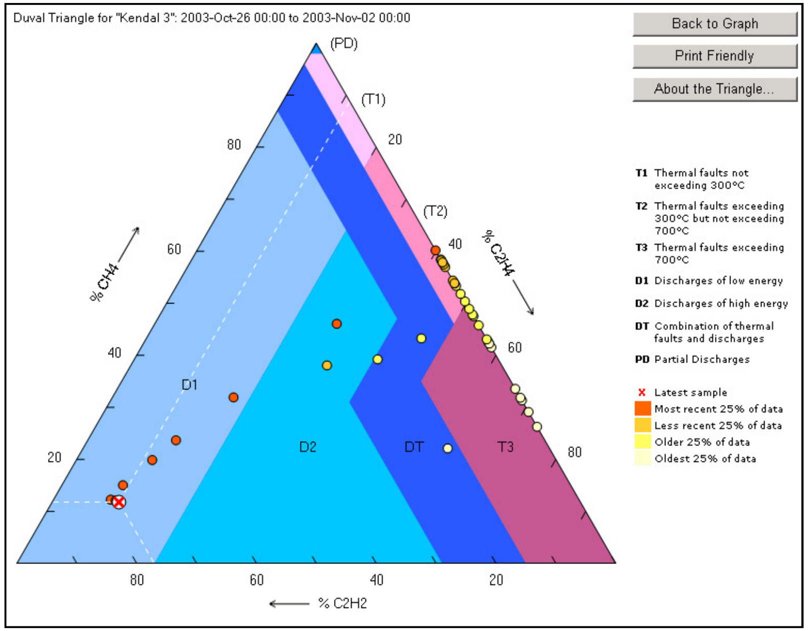
Three-phase 700 MVA ,

400 kV GSU transformer

Hints:

- Increasing Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4)
- Sudden increase in Acetylene (C_2H_2)
- Transformer refurbished and re-commissioned 10/27/03

Serveron Story #11 Analysis:



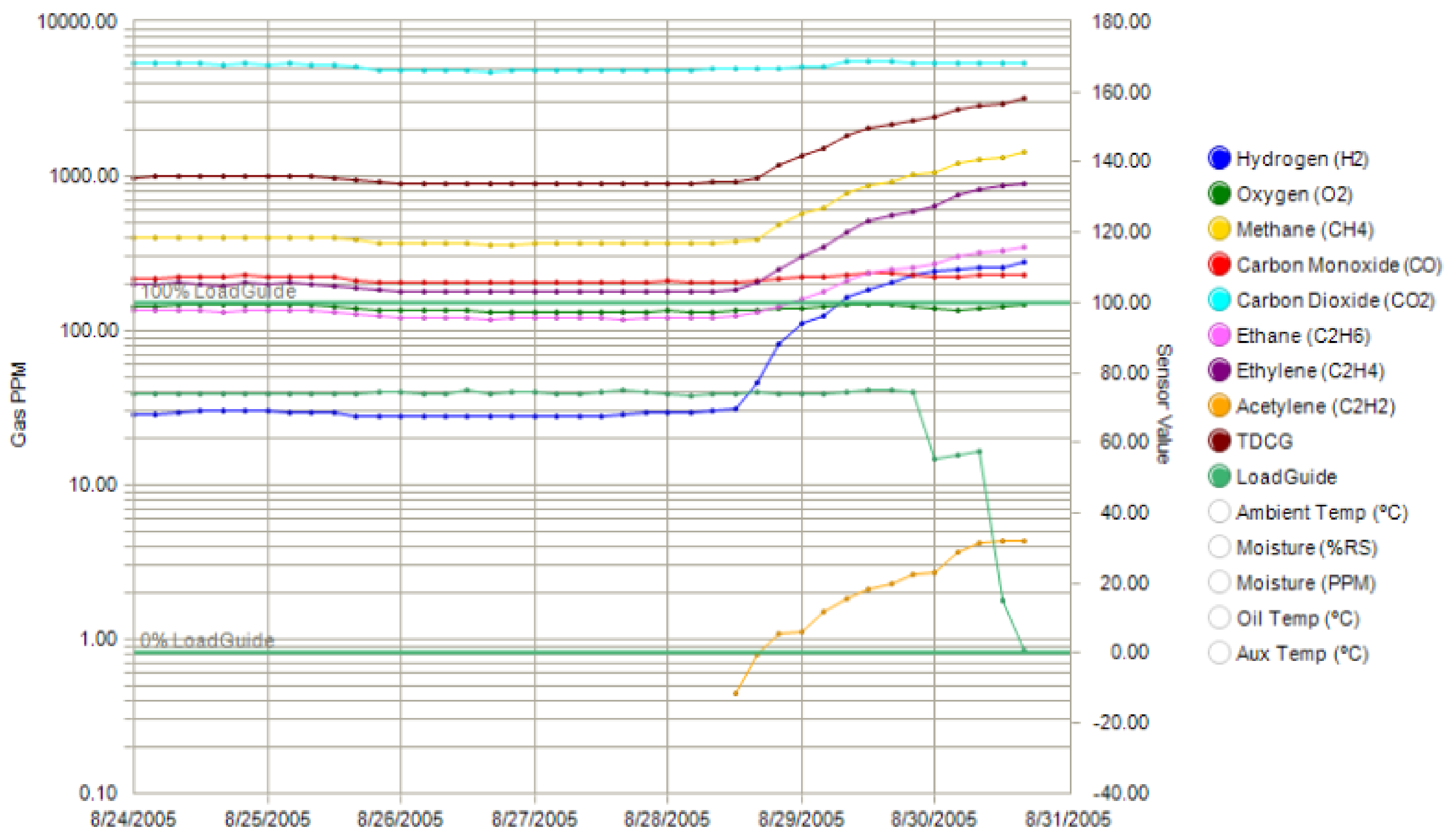
The Duval Triangle is a DGA tool included in the IEC 60599 Gas Guide.

1. The Duval Triangle shows problem evolving from a T3 Thermal Fault to D1 Discharge of low energy
2. Intermittent grounding was provided by the fastening bolt causing a transient potential rise and subsequent discharges occurring between the corona ring and the main tank ground point.
3. An on-site repair was performed and the transformer was returned to service.

HV lead corona ring shield connection

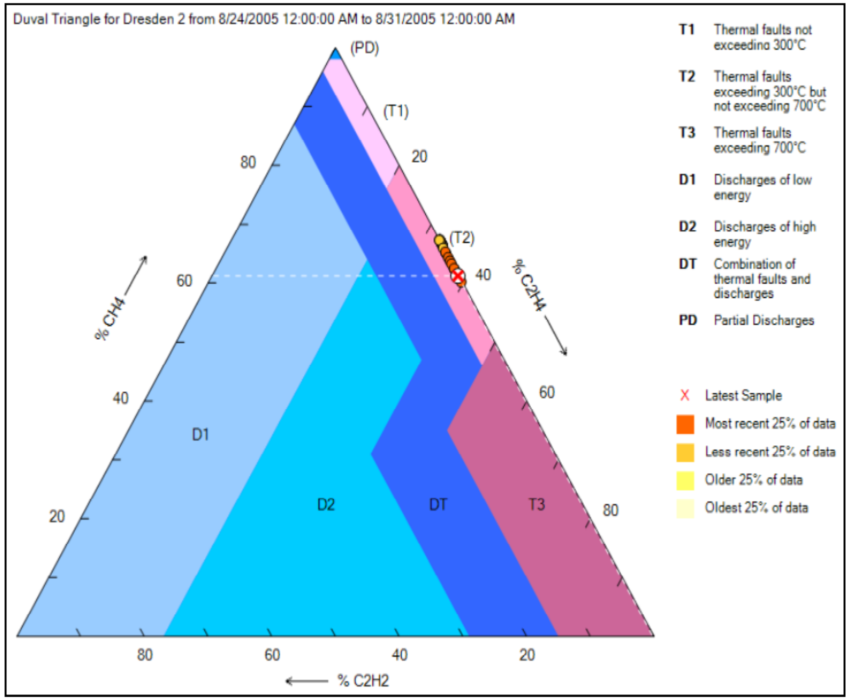
(note burn mark on corona ring material & eroded bolt)

Serveron Story #12

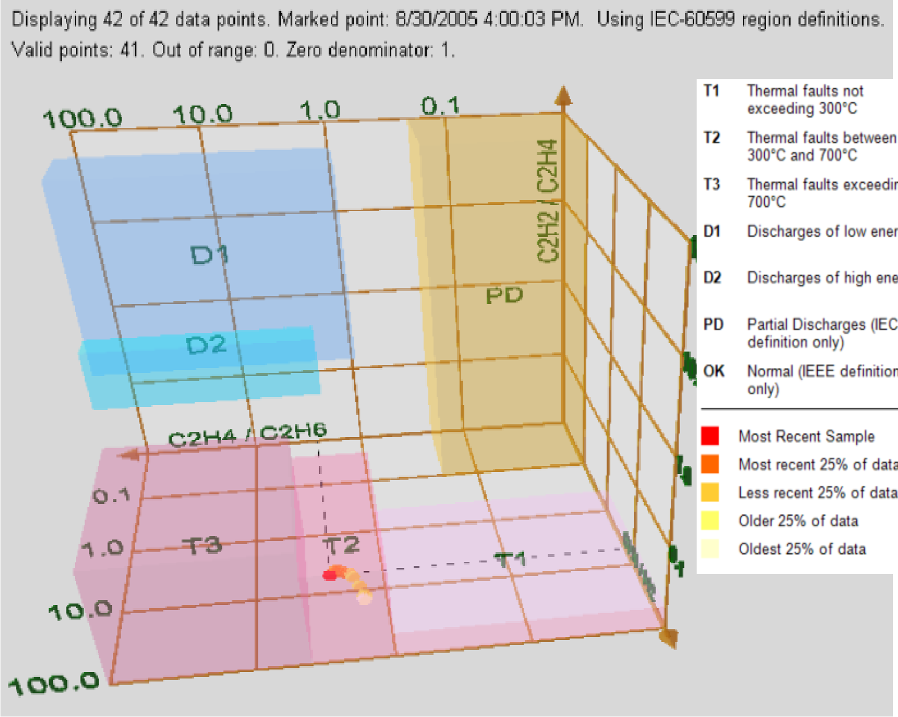


3-phase, 1100 MVA, 345 kV GSU transformer

Serveron Story #12 Analysis:



The Duval Triangle is a DGA tool included in the IEC 60599 Gas Guide.


Displaying 42 of 42 data points. Marked point: 8/30/2005 4:00:03 PM. Using IEC-60599 region definitions. Valid points: 41. Out of range: 0. Zero denominator: 1.

Rogers Ratios are included in IEEE 57.104 Gas Guide (similar to Basic Gas Ratios in IEC-60599)

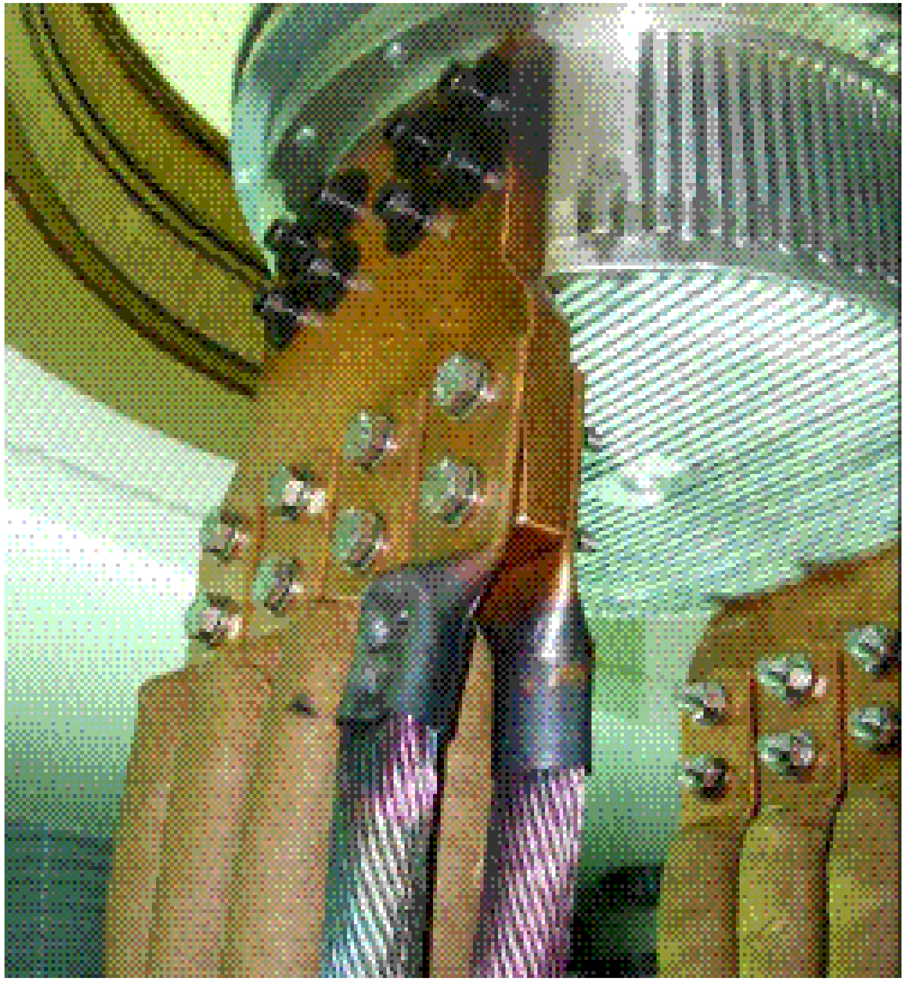
1. Both the Duval Triangle and Rogers Ratio analysis shows the fault condition is in T2 indicating a thermal problem getting worse in the range of 300°C to 700°C

2. Combustible gas levels were rising very quickly, exceeding preset rate of change limits. Transformer load reduction began approximately 32 hours after levels began to change and was fully de-energized within approximately 52 hours

3. Root cause of the problem was insulation design issues around HV and LV leads

Serveron Story #12

Serveron Story #12



How to proceed with DGA results coming from the on-line gas monitor

- No need to check for errors or inconsistencies in DGA values
- Diagnosis may be available on-line using the main diagnosis methods
- What should still be evaluated is the reliability of the diagnosis, depending on gas level, and the severity of the fault as in the case of manual DGA
- Also, decide on appropriate actions on the equipment as in the case of manual DGA, once the diagnosis is confirmed

The TM series monitors

Transformer Mounted

Your Special Cases of DGA…