Insulating Liquids for Power Transformers and their use for Condition Assessment Purposes

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Since 2003 he is with ABB AG, Transformer Service in Halle, Germany, where he has hold different national and international positions. Since 2010 he is the general manager of the Transformer Service Workshop in Halle with more than 200 employees. He is member of VDE, IEEE, DKE K 182 insulation liquids and CIGRÉ as liason officer A2 - IEC TC 10 and active in different working Groups. He is the author or co-author of more than 100 publications and owner of more than 20 patents in Asset Management, Diagnostic Methods, Monitoring and High Voltage Testing.

Insulating Liquids for Power Transformers and their use for Condition Assessment Purposes

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Leibniz Universität Hannover

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TLM

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Overview

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- **Motivation**
- **Insulation Fluids**
  Background and Basics
- **SOT Parameters and DGA**
- **DGA according to IEC / IEEE**
- **Examples, Examples, Examples…**
- **Conclusion**

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Why DGA and Diagnosis ?

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- Prevent the worst-case

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Condition Assessment

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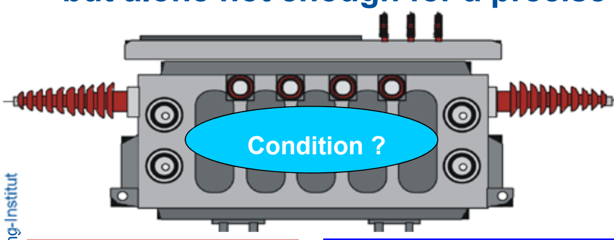
- Chemical Analysis are the most important starting point, but alone not enough for a precise condition assessment



Holistic approach

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Chemical	Electrical	Optical
Standard oil test DGA Furan DP-Estimation	Resistances Transmission ratio Isolation resistances Impedance FRA FDS / PDC / RVM PD and HV Tests	Visual Inspection Thermovision scan UV-Camera (Corona detection)

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Page 4

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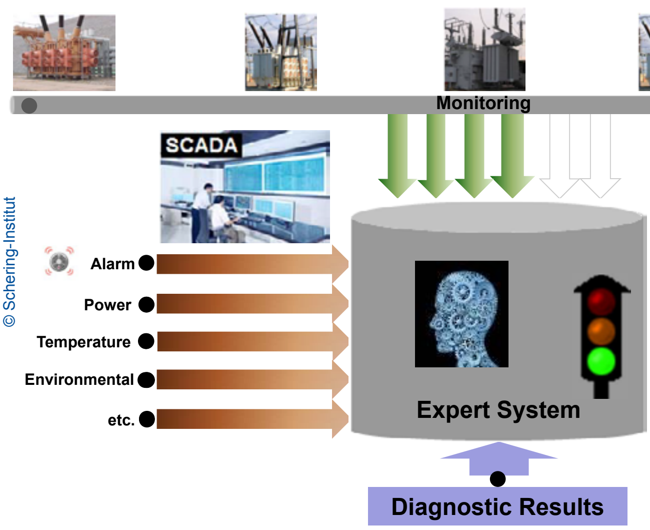
Automatic Expert Systems



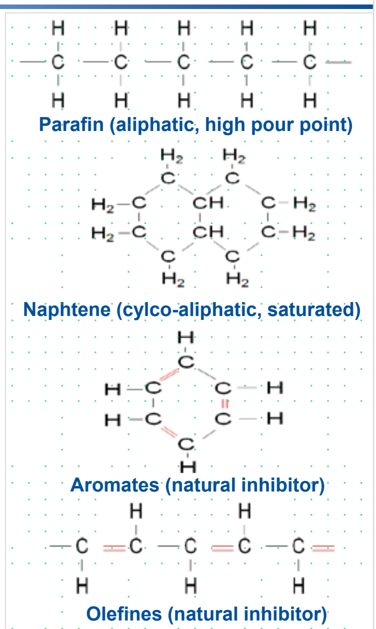
Vision:
Automatic Expert System

- Life Time Calculation
- Failure Risk

Experts by artificial Intelligence
- Fuzzy Logic
- Neural Networks
- Cluster Analysis
- Pattern Analysis
- etc.

Insulation Liquids

- Mineral oil
  - Highly refined oil from raw oil
  - Inhibited/uninhibited
    - DBPC, BHT*
  - Naphtenic/parafinic
  - New trend: GtL (Gas to Liquid)
  - Components
    - Parafin/Alkanes 40-60%
    - Naphtenes 30-50%
    - Aromates 5-20%
    - Olefines/Alkenes <1%



*2,6-ditertiarybutyl para-cresol (DBPC) and 2,6-ditertiary-butyl phenol (DBP). DBPC also known as butylated hydroxytoluene (BHT)

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Oil Analysis

- Standard Oil Test

Refraction Index
Breakdown Voltage
Moisture Content
Particles
Clearness
Colour
Inhibitor Content
Dielectric Dissipation Factor
Interfacial Tension
Acidity

Oil Analysis

- Standard Oil Test

Test	
Refraction Index	Type of the Oil
Breakdown Voltage	
Moisture Content	
Particles	
Clearness	
Colour	
Inhibitor Content	
Dielectric Dissipation Factor	
Interfacial Tension	
Acidity	

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Oil Analysis

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- Standard Oil Test

Refraction Index
Breakdown Voltage — Critical ! Insulation strength
Moisture Content
Particles
Clearness
Colour
Inhibitor Content
Dielectric Dissipation Factor
Interfacial Tension
Acidity

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Oil Analysis

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- Standard Oil Test

Refraction Index
Breakdown Voltage
Moisture Content — Critical ! Impact on BV!
Particles
Clearness
Colour
Inhibitor Content
Dielectric Dissipation Factor
Interfacial Tension
Acidity

Oil Analysis

- **Standard Oil Test**

Refraction Index	
Breakdown Voltage	
Moisture Content	
Particles	Impact on BV!
Clearness	
Colour	
Inhibitor Content	
Dielectric Dissipation Factor	
Interfacial Tension	
Acidity	

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Oil Analysis

- **Standard Oil Test**

Refraction Index	
Breakdown Voltage	
Moisture Content	
Particles	
Clearness Colour	Sludge ? Indicate Ageing
Inhibitor Content	
Dielectric Dissipation Factor	
Interfacial Tension	
Acidity	

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Oil Analysis

- Standard Oil Test

Refraction Index
Breakdown Voltage
Moisture Content
Particles
Clearness
Colour
Inhibitor Content — Critical, ageing acceleration!
Dielectric Dissipation Factor
Interfacial Tension
Acidity

Oil Analysis

- Standard Oil Test

Refraction Index
Breakdown Voltage
Moisture Content
Particles
Clearness
Colour
Inhibitor Content
Dielectric Dissipation Factor
Interfacial Tension
Acidity

(Dielectric Dissipation Factor, Interfacial Tension: Ageing !)

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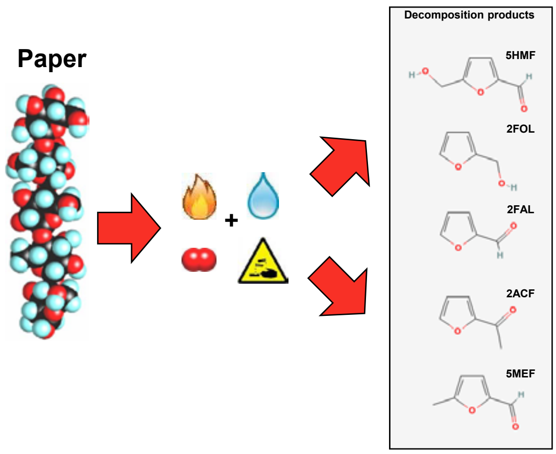
Oil Analysis

- Standard Oil Test

Refraction Index	
Breakdown Voltage	
Moisture Content	
Particles	
Clearness	
Colour	
Inhibitor Content	
Dielectric Dissipation Factor	
Interfacial Tension	
Acidity	Aggressive to paper !

Oil Analysis

- Furan Analysis
  - Degradation of the paper due to heat, humidity, oxygen and acidity
  - DP value as function of 2FAL is not precise enough
  - DP profile depending on temp. and moisture, but typically low DP on top, higher DP on buttom



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

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Fault Gas Generation

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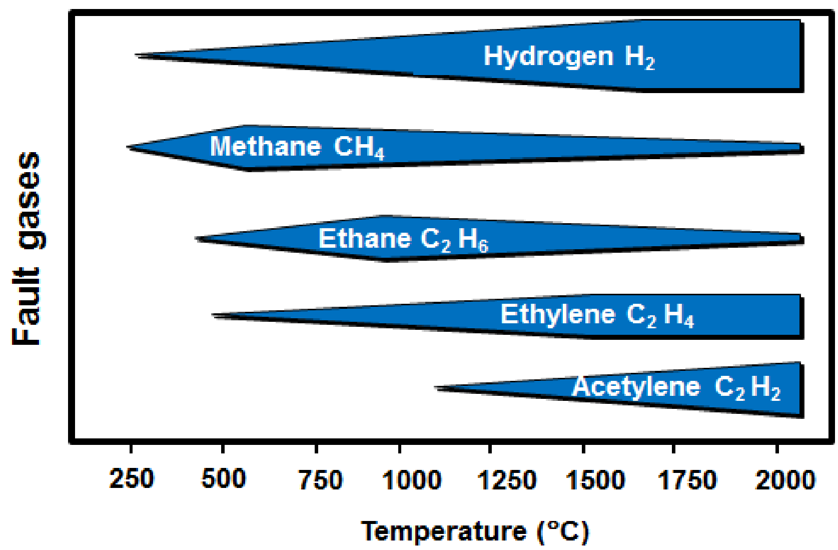

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Considered Gases

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- Nitrogen N_2
- Oxygen O_2
- Hydrogen H_2
- Carbon Monoxyd CO
- Carbon Dioxyd CO_2
- Methane CH_4
- Ethane C_2H_6
- Ethylene C_2H_4
- Acethylene C_2H_2
- Propane C_3H_8
- Propene C_3H_6

According to IEEE:

Combustible Gases

Not Combustible Gases

Not considered in IEEE

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IfES

Considered Gases

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- Nitrogen N_2
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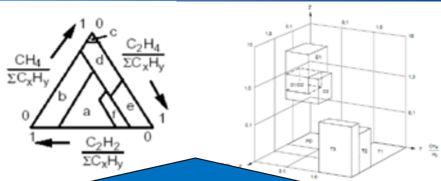

Ratios

Graphical

IEEE C57.104
IEC 60599
Other…

Failure

IEC	Electrical (PD, Discharges with low or high energy)
FAULTS	Thermal (Temperatures < 300°C, < 700°C or > 700°C)

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Oil Analysis

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- The basis of any DGA is a correct oil sampling – therefore separate standards have been developed
- If the oil sampling is not performed exactly, the DGA result will not be reliable or wrong
- About 1 Million DGA are performed per year in approx. 600 labs around the world
- In addition 40.000 online monitoring systems are installed in total (from simple gas sensors to “all gas” sensor systems)
- The sampling is usually an advantage of online monitoring systems

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IEC 60599

- DGA Interpretation
  - Performed only if gas amounts or gas rates are suspicious
    - Limits are not directly given, only typical values and the recommendation to develop own limits based on own operated transformer fleet
  - Beside the main fault gases special gases or ratios are considered
- Carbon Oxides
  - The ration CO_2/CO should be considered
  - If this ratio is smaller 3 or larger 10 paper involvement in the failure has to be considered, but has to be proven by additional measurements (e.g. furans)
  - High levels of CO is 1000ppm, of CO_2 is 10000ppm

IEC 60599

- Atmospheric gases
  - O_2 and N_2 are important indicators for open transformers (free breathing)
  - The ratio O_2/N_2 should be approx. 0,5, where O_2 is in a range of 32000ppm and N_2 is in a range of 64000ppm
  - Ratios smaller than 0,3 indicate strong oxidation
- OLTC faults
  - C_2H_2/H_2 ratios higher than 2 to 3 in the main tank are considered as an indication of OLTC contamination
  - Cases to be confirmed by additional measurements: e.g. comparing DGA from tank and conservator – however, interpretation becomes more difficult
- C_3 hydrocarbons
  - These hydrocarbons have a very good solubility in oil and might therefore be useful (thermal history)

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IEC 60599

- Interpretation scheme

Table 2 – DGA interpretation table

If $H_2 > CH_4$ – electrical failure ! otherwise – thermal problem !

Hints about failure root cause are given for each failure type (e.g. thermal failure <300°C: overloading, blocked oil cooling flow, stray flux in clamping system)

		$\frac{C_2H_2}{C_2H_4}$	[illegible]	[illegible]
PD	Partial discharges (see notes 3 and 4)	[illegible]	[illegible]	<0,2
D1	Discharges of lo[illegible]	[illegible]	0,1 – 0,5	>1
D2	Discharg[illegible]	[illegible] – 2,5	0,1 – 1	>2
T1	[illegible]	NS 1)	>1 but NS 1)	<1
[illegible]	[illegible] fault [illegible] < t < 700 °C	<0,1	>1	1 – 4
[illegible]	Thermal fault t > 700 °C	<0,2 2)	>1	>4

Source IEC 60599

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IEEE

- **DGA Interpretation**
  - Also some special gases ratios are mentioned
    - The ratio CO_2/CO often indicate a paper ageing (normally>7) Levels should have a certain value to improve certainty factor (CO 500ppm, CO_2 5000ppm)
  - Interpretation only if limits are exceeded (first absolute values, afterwards rates to be checked)
  - TCG (Total Combustible Gas) and TDCG (Total Dissolved Combustible Gas) are important parameters

Table 1—Dissolved gas concentrations

Status	Dissolved key gas concentration limits [μL/L (ppm)[a]]							
	Hydrogen (H_2)	Methane (CH_4)	Acetylene (C_2H_2)	Ethylene (C_2H_4)	Ethane (C_2H_6)	Carbon monoxide (CO)	Carbon dioxide (CO_2)	TDCG[b]
Condition 1	100	120	1	50	65	350	2 500	720
Condition 2	101–700	121–400	2–9	51–100	66–100	351–570	2 500–4 000	721–1920
Condition 3	701–1800	401–1000	10–35	101–200	101–150	571–1400	4 001–10 000	1921–4630
Condition 4	>1800	>1000	>35	>200	>150	>1400	>10 000	>4630

Source IEEE C57.104 - 2008

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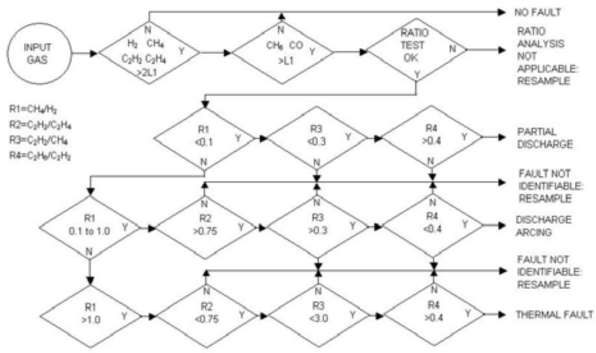
- Interpretation
  - Ratios are defined according to Dörnenburg (R1, R2, R3, R4) and Rogers (R1, R2, R5 – similar to IEC 60599)
  - Based on these ratios tables and flow charts are given

Ratio 1 (R1) = CH_4/H_2
Ratio 2 (R2) = C_2H_2/C_2H_4
Ratio 3 (R3) = C_2H_2/CH_4
Ratio 4 (R4) = C_2H_6/C_2H_2
Ratio 5 (R5) = C_2H_4/C_2H_6



Source IEEE C57.104 - 2008

Figure 4—Doernenburg ratio method flow chart

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Example 1

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- 110kV / 40MVA – YoM 2013
  - DGA after 1,5 years

Fehlergas	Wert
H_2 [ppm]	3
O_2 [ppm]	28354
N_2 [ppm]	97150
CO_2 [ppm]	453
CO [ppm]	44
CH_4 [ppm]	2
C_2H_6 [ppm]	1
C_2H_4 [ppm]	1
C_2H_2 [ppm]	0
C_3H_8 [ppm]	2
C_3H_6 [ppm]	3
Total Gas Content [%]	9,5

Is this Transformer be OK ?

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Example 2

- 110kV / 40MVA

What about this Transformer ?

Measurement	Result
SOT	OK
Furans	None
Resistance	No deviations
Insulation resistance	good
DGA	No deviations

Gas	ppm
H_2 [ppm]	<1
O_2 [ppm]	25354
N_2 [ppm]	67143
CO_2 [ppm]	253
CO [ppm]	54
CH_4 [ppm]	<1
C_2H_6 [ppm]	<1
C_2H_4 [ppm]	<1
C_2H_2 [ppm]	<1

Transformer has a membrane – broken !

Example 3

- Reactor

Property	Value
Voltage	120 kV
YoM	1979
Reactive Power	60 MVAr

Measurement	Result
SOT	normal
Furans	low
Resistances	No deviations
Insuation Resistances	good
FDS	Middle moisture
FRA	No deviations
DGA	increased

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Example 3

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- Reactor

Gas	ppm
H_2 [ppm]	60
CO_2 [ppm]	5229
CO [ppm]	769
CH_4 [ppm]	406
C_2H_6 [ppm]	116
C_2H_4 [ppm]	439
C_2H_2 [ppm]	1
C_3H_8 [ppm]	16
C_3H_6 [ppm]	177

According to IEC thermal problem between 300 and 700°C

Example 3

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- Investigation in the Workshop
  - Dissassembly of windings necessary

DGA Interpretation was correct, but even a more detailed analysis could be possible using experience !

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Example 4

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- Lab experiment using different mineral oils
  - Identical failures and failure energies

Gas content in ppm	A	B
CO_2	153	222
C_2H_4	1602	1766
C_2H_2 ➡	7418	10712
C_2H_6	<1	5,3
C_3H_6 ➡	585	807
C_3H_8	32,8	35,6
CH_4 ➡	811	1126
CO	2,4	3,1
H_2 ➡	7830	9064

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Example 4

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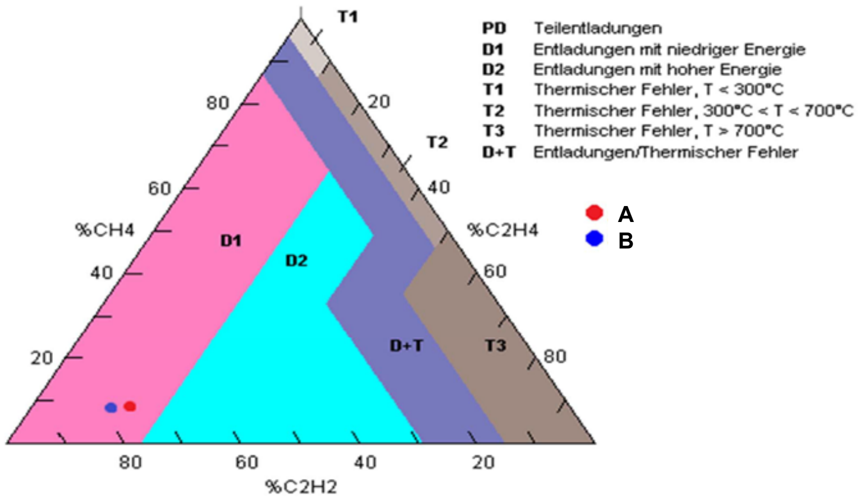
- Lab experiment using different mineral oils
  - Identical failures and failure energies



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Example 5

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- Lab experiment using identical mineral oils
  - Oil aged and degassed (A) and in addition reclaimed (B)
  - Thermal stress of 140°C for 72h

	A in ppm	B in [illegible]
Methane	78	[illegible]
Carbon monoxid	98	[illegible]
Carbon dioxid	17[illegible]	[illegible]
Ethylene	[illegible]	17
Ethane	[illegible]	5
Acetylen	[illegible]	0
Hyd[illegible]	0	0
[illegible]	[illegible]rmal problem	Thermal problem
[illegible]g	Thermal problem	No failure
[illegible]gers	Thermal problem >700°C	Thermal problem low temperature

SOT parameters might be taken into consideration, thus the ageing of the oil and therefore a relation to the gassing tendency of the aged oil is taken into account !

Conclusion

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- Oil Analysis is one of the most important tools for condition assessment of power transformers
- For DGA different standards using different limits and different evaluation criteria
- Different mineral oils / different ageing states show different gassing and stray gassing behavior – thus SOT parameters might be used in addition to DGA
- Actual DGA interpretation algorithms can lead to a wrong or "not precise enough" result
- Research work is still necessary in order to optimize DGA interpretation (all liquids, free breathing, hermetic, stray gassing, oil condition, etc.)

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