



The world of DGA – and its uncertainties

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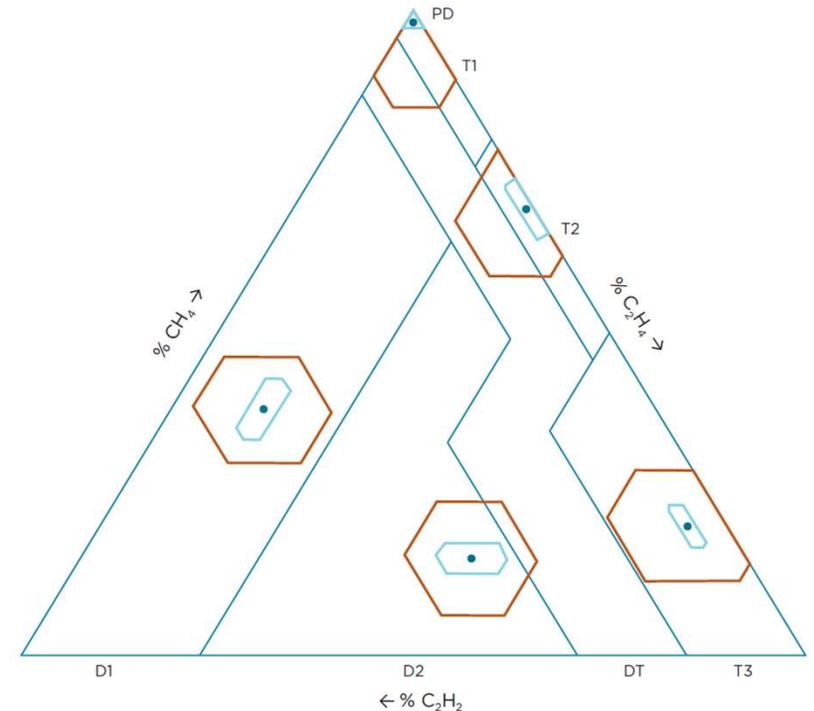
Dissolved gas analysis

- DGA and its utilization in transformer diagnostics is not exact science, but rather an evaluation method based on statistics and empirical data from transformers.
- One main challenge is that there is no explicit international reference available for DGA, but all methods include some calculation and oil-specific parameters.
- Even various mineral oils are not equal from a DGA perspective.



Why is accuracy needed?

- Online monitors have proven their value in gas trending and detecting quickly evolving faults.
- Adequate accuracy is also important, because inaccurate DGA results may lead to
 - erroneous fault diagnoses.
 - wrong action being taken on a transformer.



Effect of accuracy on fault diagnosis uncertainty when using Duval Triangles.
Accuracy $\pm 15\%$ in blue and $\pm 30\%$ in red, respectively.

(Ref. CIGRE TB783)

How accurate is a measurement?

- Simple question - answer is not
- The agreement of the measured value with the true value is often called “accuracy”.
- Challenge with DGA is that neither measured value nor true value is known precisely.
- The true value is often considered as laboratory DGA
 - Its uncertainty is seldom reported or even defined.



A measurement cannot be more accurate than the reference used in its calibration.

Laboratory-DGA related uncertainties

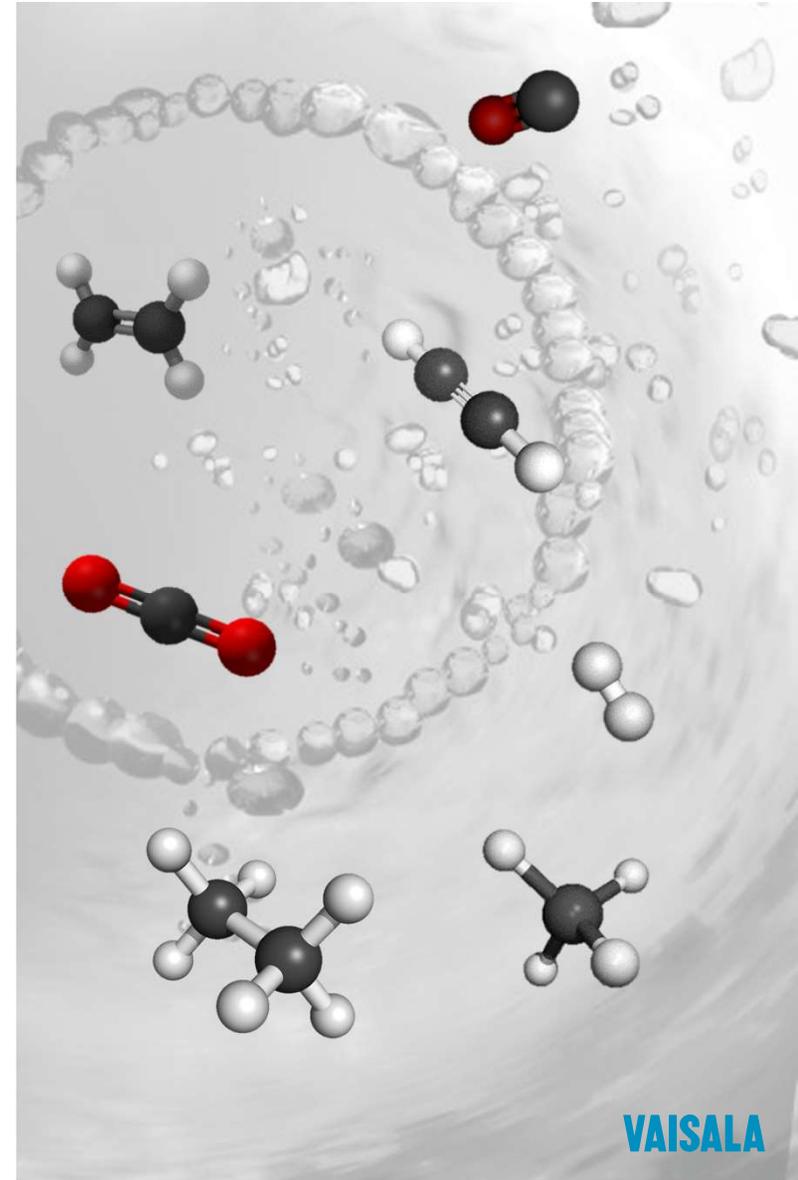
- Oil-sampling method and quality
 - Gas-extraction method
 - Standards used (IEC vs ASTM)
 - Human factor
 - Sample preparation and GC signal repeatability
 - Calibration and calibration sample preparation uncertainty
 - Partition coefficient uncertainty (K)
 - Vial volume uncertainty
 - Sample mass uncertainty
 - Oil density uncertainty
- } Varies depending
how oil vs gas
volume is defined



Gas extraction methods

Gas extraction methods and their efficiency

- Toppler ~100% efficiency
- Partial vacuum, 90-99% efficiency
- Headspace (HS), efficiency = $1/(1 + K * \frac{V_{OIL}}{V_{GAS}})$
- The efficiency depends also on gas composition, because some gases are easier to extract.



Partition coefficients (Ostwald)

- Gases have different tendency to stay in oil: some prefer to stay there whereas others will 'escape' immediately if possible.
- This tendency is gas solubility in oil, and it is defined by so-called partition coefficients (K), which vary by gas, oil type, oil quality, and temperature etc.

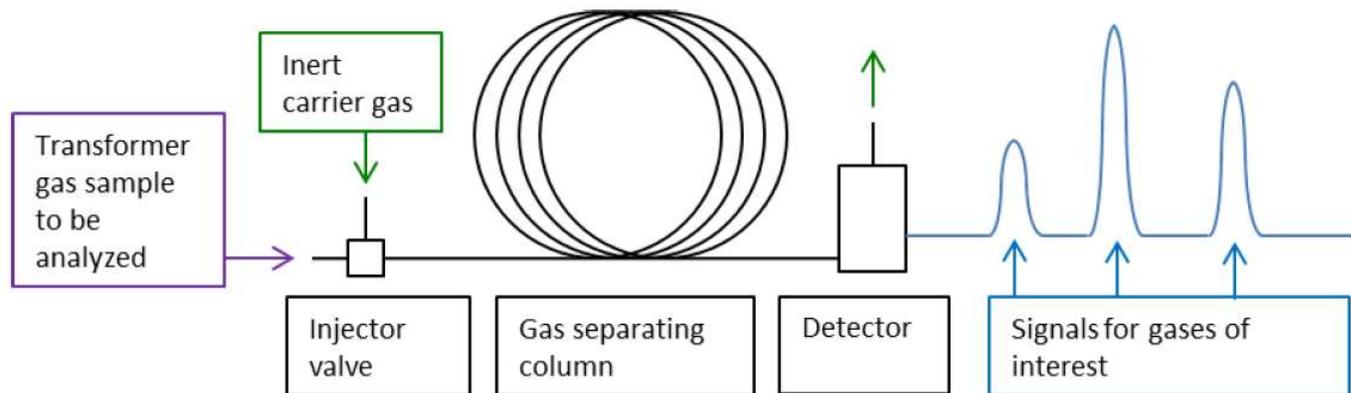
$$C_{OIL} = C_{GAS} \left(K + \frac{V_{GAS}}{V_{OIL}} \right)$$

	Example of naphthenic oil	Example of paraffinic oil
Density	0,864	0,849
H ₂	0,074	0,036
O ₂	0,17	0,18
N ₂	0,11	0,12
CH ₄	0,44	0,37
CO	0,12	0,073
CO ₂	1,02	0,64
C ₂ H ₂	0,93	0,89
C ₂ H ₄	1,47	1,27
C ₂ H ₆	2,09	1,73
C ₃ H ₆	5,04	4,36
C ₃ H ₈	5,37	4,72
C ₄ H ₆	10,10	

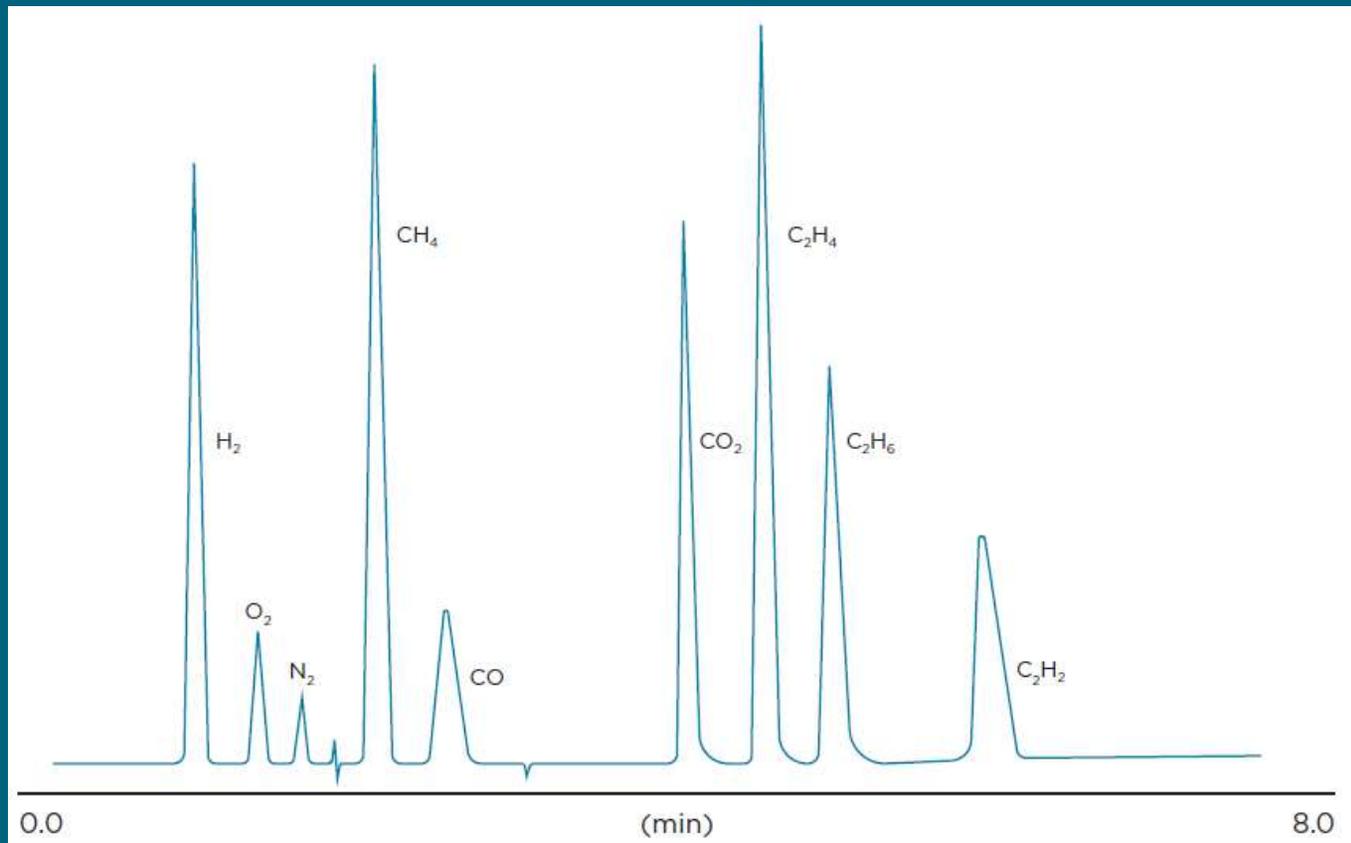
Ref: IEC 60567 3rd ed., 2005

Gas chromatography

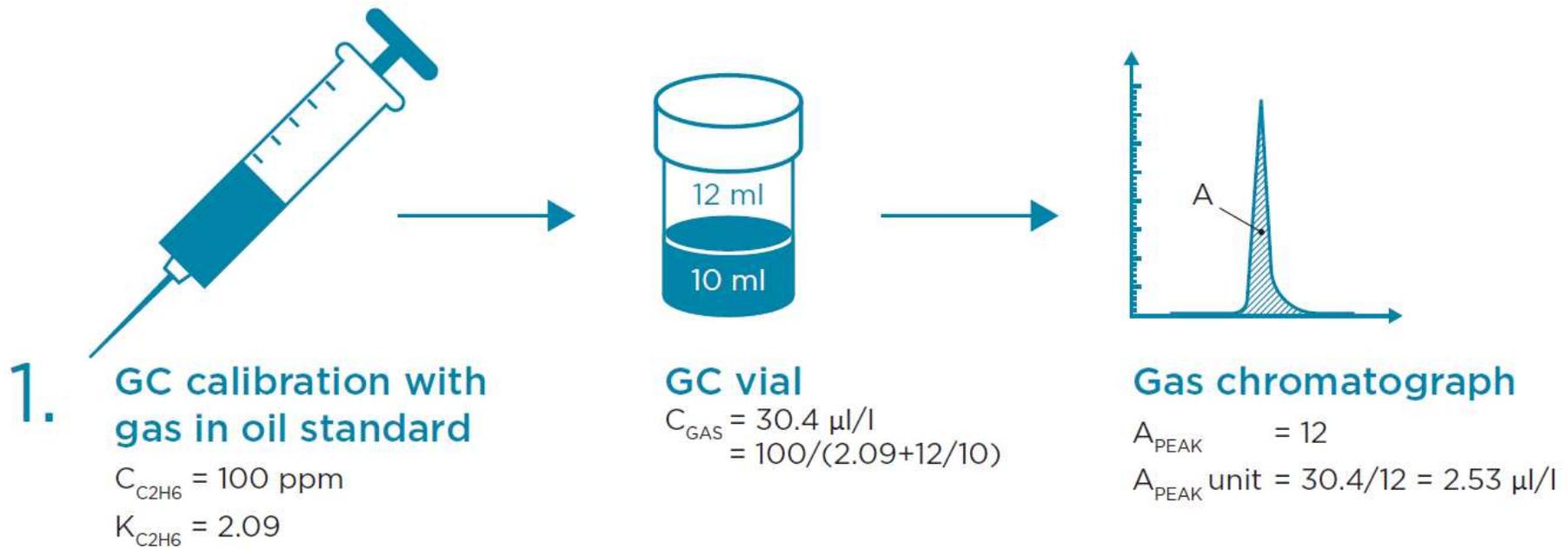
- Calibration with gas-in-oil standard or certified gas mixture.



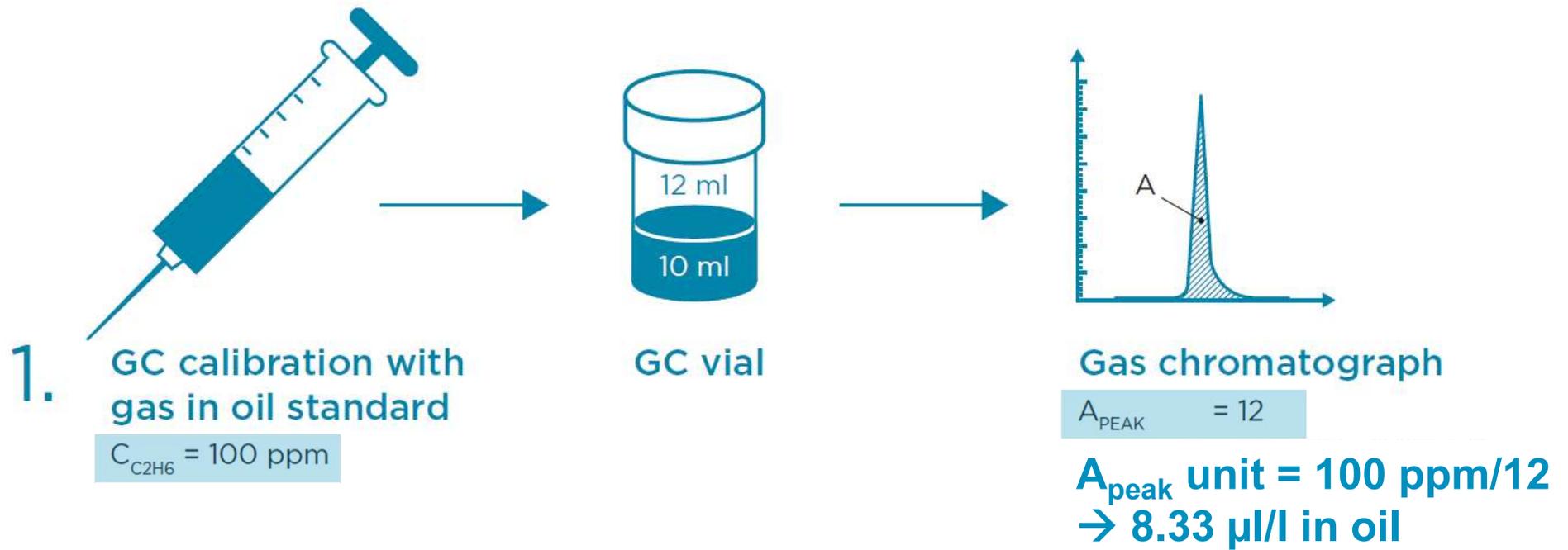
Source: CIGRE TB783



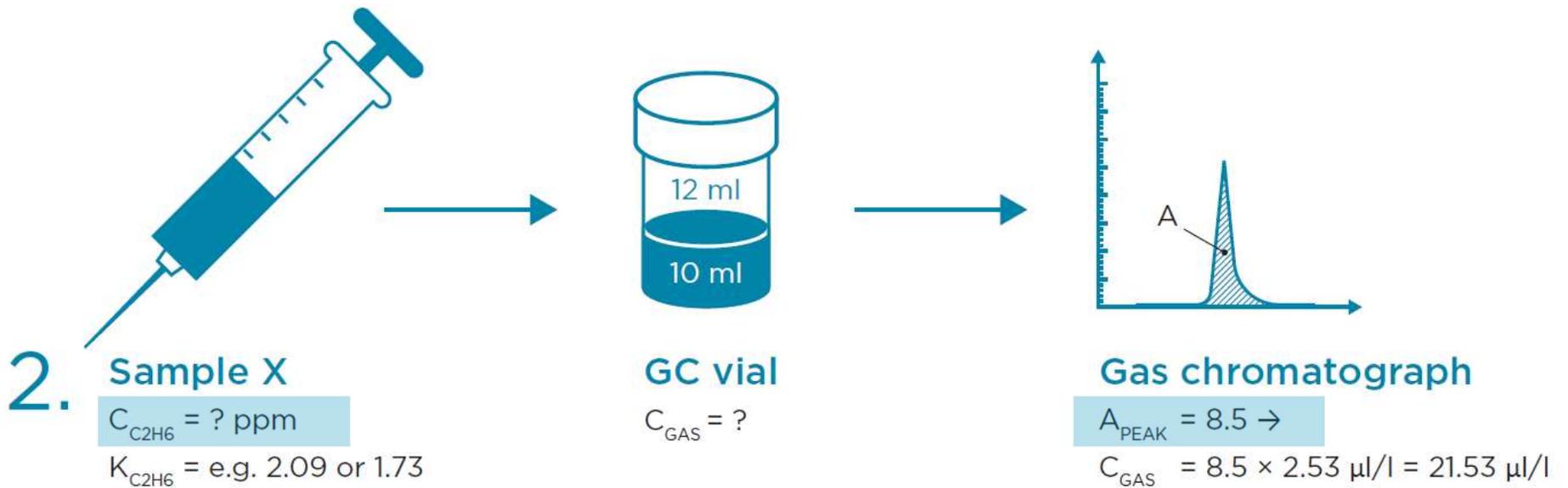
GC Calibration



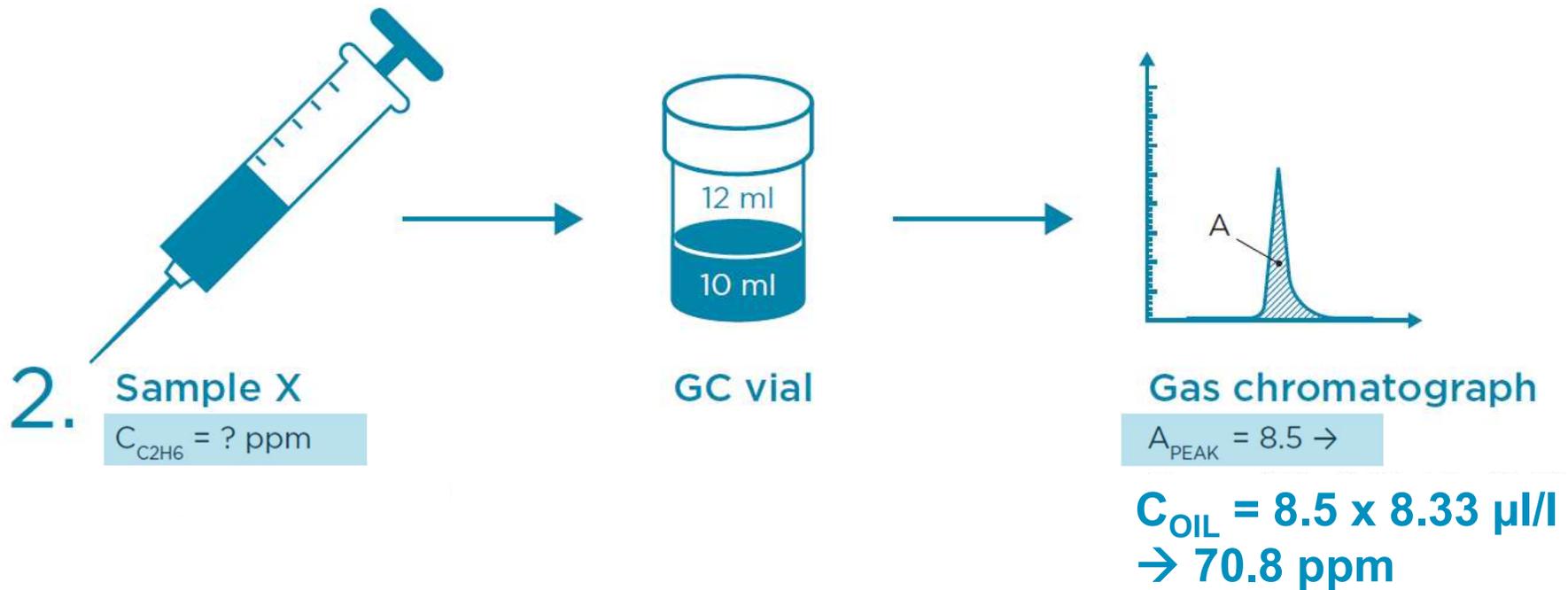
GC Calibration



Oil sample analysis



Oil sample analysis



How to calculate gas in oil concentration?

$$C_{OIL} = C_{GAS} \left(K + \frac{V_{GAS}}{V_{OIL}} \right)$$

- Using the same K as standard (2.09) → $C_{OIL1} = \underline{70.8 \text{ ppm}}$
- Using $K = 1.73$ → $C_{OIL2} = \underline{63.1 \text{ ppm}}$
- 10% difference.

Which one is correct or neither?

- In gas volume calculation IEC 20°C vs ASTM 0°C temperature → ~8% difference in results $V = nRT/p$

? ppm



Uncertainties with different extraction methods

EXTRACTION PROCEDURE	Accuracy in presentage of the nominal value	
	MEDIUM CONCENTRATION	LOW CONCENTRATION
TOEPLER	13	35
PARTIAL DEGASSING	13	30
STRIPPING	18	23
HEADSPACE	18	37
MERCURY-FREE TOEPLER	15 ¹	14 ¹
MERCURY-FREE PARTIAL DEGASSING	11 ¹	
SHAKE TEST	15	44

¹Based on a limited number of analyses.

It is recommended by IEC 60567 that every laboratory determines its own accuracy, meaning in practice its uncertainty.

This information should then be made available for users of the laboratory's services.

Accredited laboratories must have this available as a requirement of their accreditation.

Ref. IEC 60567 ed4-2011

Laboratory intercomparison tests (RRT)

METHOD	AVERAGE ACCURACY OF LABORATORIES (%)		NUMBER OF INACCURATE LABORATORIES, % OF PARTICIPANTS	
	> 100 ppm	< 8 ppm	> 100 ppm	< 8 ppm
Partial degassing	12	18	17	0
Stripping	19	65	60	63
Head space	28	51	75	42
IEC SPECIFICATION	15	30		

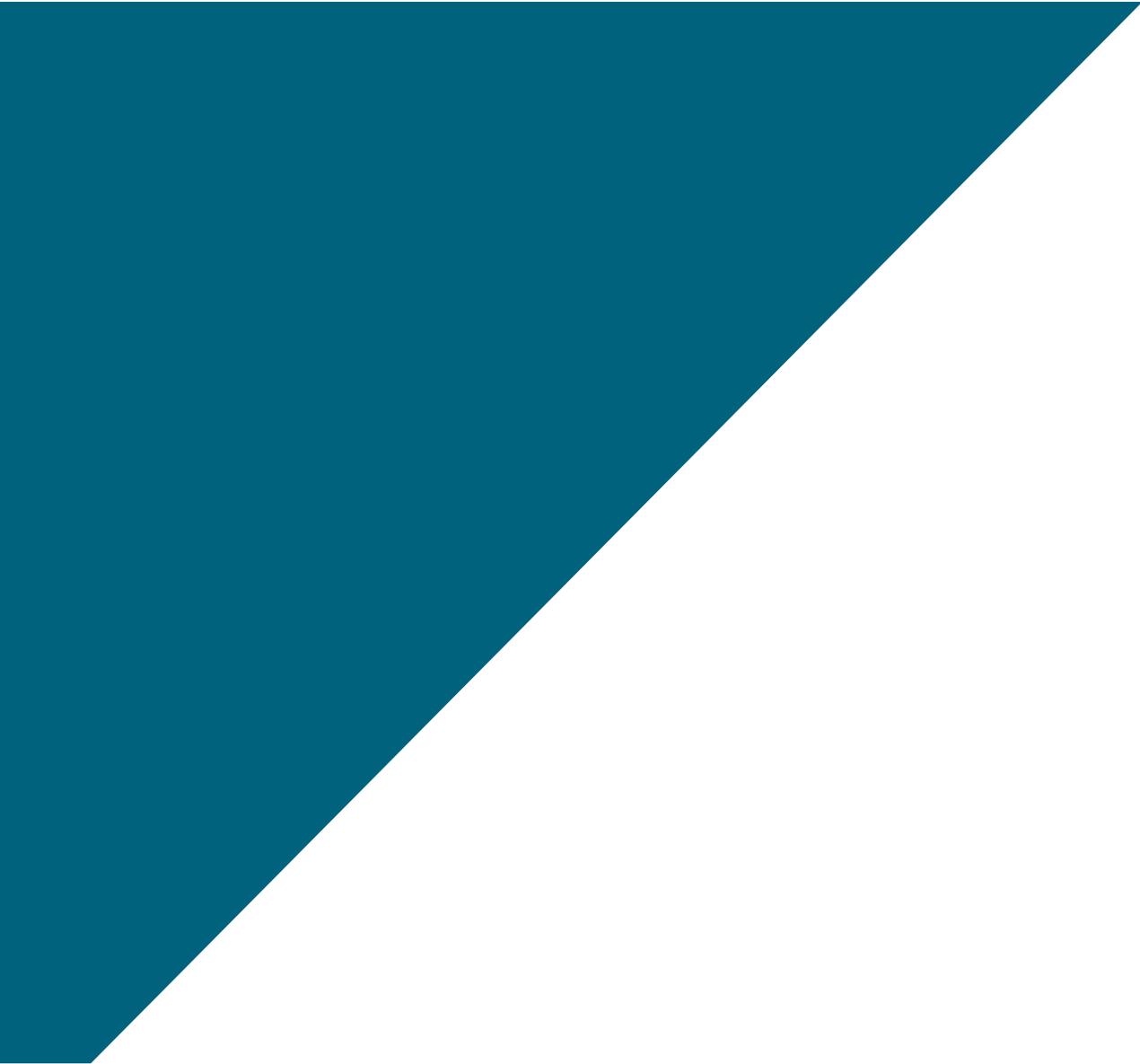
Source CIGRE TB783
(IEC, CIGRE, ASTM, and Institute for Inter-Laboratory Studies)

Uncertainty of an accredited laboratory

	ACCURACY (%) IN LOW CONCENTRATIONS	ACCURACY (%) IN MEDIUM CONCENTRATIONS	ACCURACY (%) IN HIGH CONCENTRATIONS
H ₂	15.6	9.5	5.9
CH ₄	13.9	8.3	6.7
C ₂ H ₄	26.7	10.6	3.8
C ₂ H ₆	26.2	22.3	6.3
C ₂ H ₂	33.6	18.8	8.3
CO	26.5	14.1	8.9
CO ₂	10.7	11.3	11
LAB. AVERAGE	21.9	10.4	
IEC 60567:2011 FOR HS	37	18	

Low concentrations means roughly 10 ppm and lower (CO₂ 100 ppm)

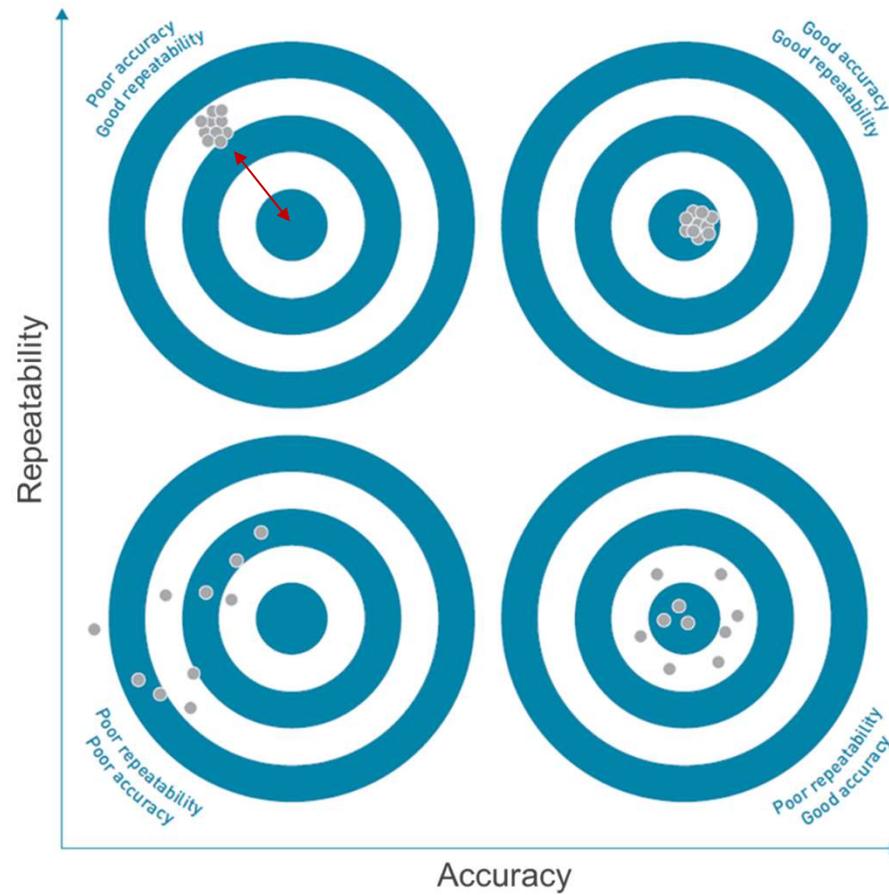
High concentrations roughly 100 ppm level.

A large teal graphic element consisting of a diagonal line from the top-left to the bottom-right, forming a triangle on the left side of the page.

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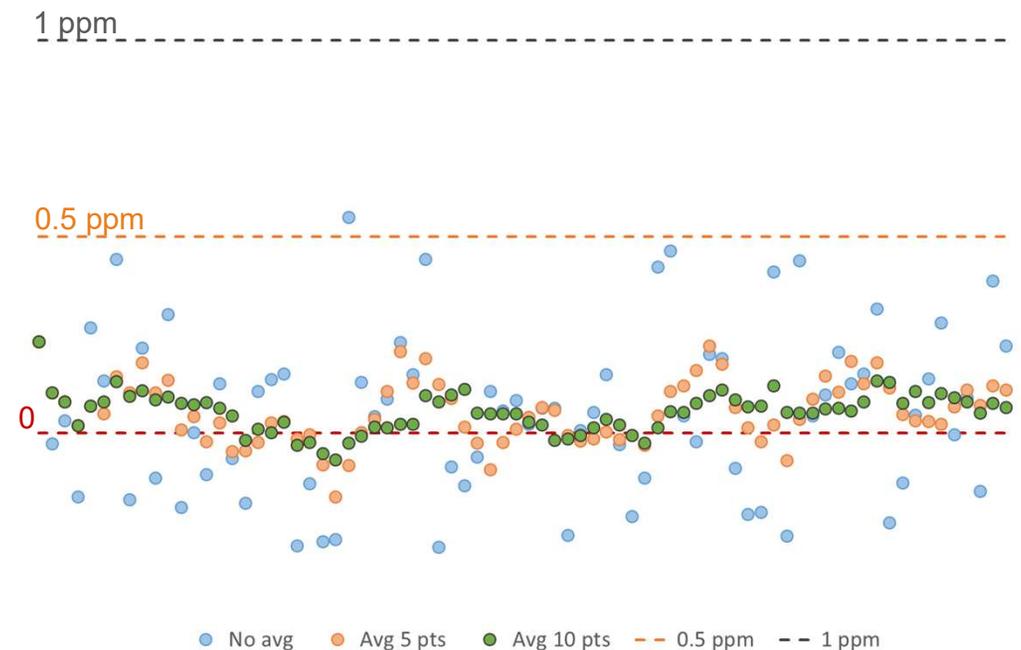
Online DGA monitors

Accuracy and repeatability



Lower detection limit (LDL)

- LDL is the lowest concentration reliably distinguished from zero.
- Relationship between repeatability and LDL.
 - Averaging improves repeatability and decreases LDL.
- LDL specification could be, for example, 2x standard deviation at a 0-ppm gas level.
- Very challenging to create reference samples with very low gas concentration, e.g. <1 ppm
 - almost impossible to test LDL in practice.
 - can be defined theoretically based on the repeatability.



Needed measurement ranges?

90-percentile typical values found in transformers that are operating normally

SOURCE	NUMBER OF DGA	H ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	CO	CO ₂
CIGRE TB771	>300,000	118	85	111	56	5	700	6,300
IEEE C57.104*	>800,000	40-100	20-110	15-150	25-90	2	500-900	3,500-9,000
IEC 60599	NA	50-150	30-130	20-90	60-280	2-20	400-600	3,800-14,000

*Data divided by transformer age and O₂/N₂ ratio

Measurement ranges, how to test?

GAS	GAS-IN-OIL CONCENTRATION, PPM	GAS-IN-GAS CONCENTRATION, PPM (K AT +70°C, IEC 60567)	LEL PPM (IN AIR)
METHANE	20,000	45,455	50,000
ETHANE	20,000	9,569	30,000
ETHYLENE	20,000	13,605	27,000
ACETYLENE	20,000	21,505	25,000
CARBON MONOXIDE	20,000	166,667	125,000
HYDROGEN	20,000	270,270	40,000

CH₄ 50,000 ppm in oil → 113,600 ppm in gas phase. Well above LEL!

Accuracy specification stated on the datasheet

- Most monitors have their accuracy specified at the point of calibration.
 - Calibration certificate?
 - Calibration reference?
- Reported accuracy specifications are not applicable as such for a real transformer in operation.
 - Oil type & age, partition coefficients, extraction type etc?
 - Monitor datasheets missing information on performance in real application.
 - *“what the user can expect in a transformer installation with very old oil at +40°C, five years after monitor installation”*



OPT100 Accuracy spec & typical field performance

Measurement specification

Parameter	Range	Accuracy ^{1) 2)}	Repeatability ²⁾
Methane (CH ₄)	0 ... 10 000 ppm _v	±4 ppm or ±5 % of reading	10 ppm or 5 % of reading
Ethane (C ₂ H ₆)	0 ... 10 000 ppm _v	±10 ppm or ±5 % of reading	10 ppm or 5 % of reading ³⁾
Ethylene (C ₂ H ₄)	0 ... 10 000 ppm _v	±4 ppm or ±5 % of reading	10 ppm or 5 % of reading
Acetylene (C ₂ H ₂)	0 ... 5000 ppm _v	±0.5 ppm or ±5 % of reading	1 ppm or 5 % of reading
Carbon monoxide (CO)	0 ... 10 000 ppm _v	±4 ppm or ±5 % of reading	10 ppm or 5 % of reading
Carbon dioxide (CO ₂)	0 ... 10 000 ppm _v	±4 ppm or ±5 % of reading	10 ppm or 5 % of reading
Hydrogen (H ₂)	0 ... 5000 ppm _v	±15 ppm or ±10 % of reading	15 ppm or 10 % of reading
Moisture ⁴⁾ (H ₂ O)	0 ... 100 ppm _w ⁵⁾	±2 ppm ⁶⁾ or ±10 % of reading	Included in accuracy

- 1) Accuracy specified is the accuracy of the sensors during calibration gas measurements.
 2) Whichever is greater.
 3) Repeatability of ethane measurement is specified with averaging of five measurements.
 4) Measured as relative saturation (%RS).
 5) Upper range limited to saturation.
 6) Calculated ppm value is based on average solubility of mineral oils.

- How is the actual performance on site?
- What is the reference and its uncertainties?
- Not to use term accuracy for field performance, as there's no explicit reference available.

Field performance

Parameter	Typical variance to laboratory DGA ¹⁾
Acetylene (C ₂ H ₂)	±1 ppm or ±10 % of reading
Hydrogen (H ₂)	±15 ppm or ±15 % of reading
Other measured gases	±10 ppm or ±10 % of reading
Moisture (H ₂ O)	±2 ppm or ±10 % of reading

Reality, field performance

Test No	Monitor	Accuracy in %							Average
		H ₂	CH ₄	C ₂ H ₄	C ₂ H ₆	C ₂ H ₂	CO	CO ₂	
1	A	14	11	-	3	-	2	3	6
2	A	-19*	0	-	-4	-	21	0	5
3	B	-25*	-5	19	4	-	-16	0	9
4	C	-35*	-8	-15	-7	-	18	0	10
5	D	-20*	-23	0	23	-	8	-20	15
6	D	0	4	16	31	-	16	0	11
7	E	11	17	42	48	51	45	28	35
8	F	11	-	-	-	-	-	-	11
9	G	12	-	-	-	-	-	-	12
10	H	0	7	25	78	8	14	16	21
11	I	-26	0	3	0	-	10	10	8

Accuracy of on-line gas monitors tested by members of WG D1/A2.47 (CIGRE TB783)

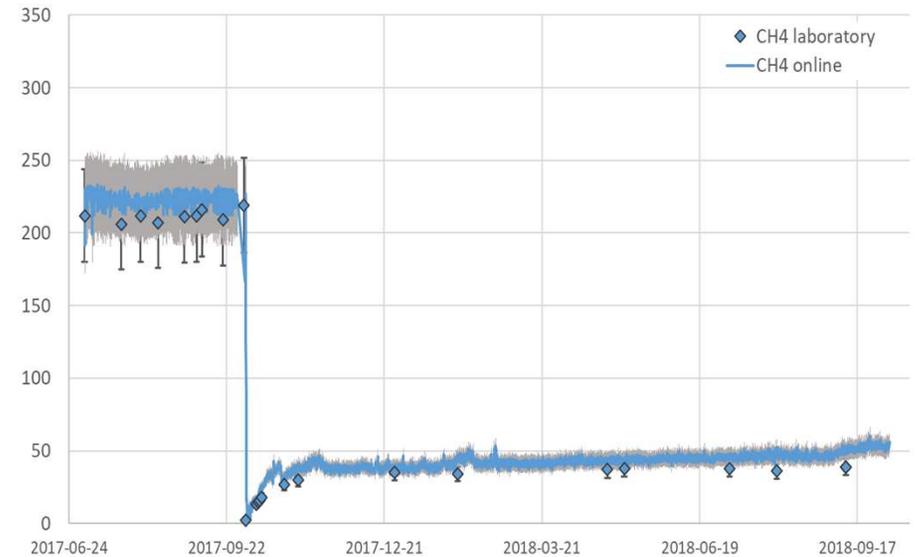
Monitor evaluation, CIGRE method

- No standard available for testing and evaluation of online monitors in the field.
- CIGRE WG D1/A2.47 TB783
“Procedure for evaluating the accuracy of gas monitors and laboratory results”
- Includes also a method to evaluate the performance of the reference laboratory.
- Only a snapshot, but can be utilized also for evaluation of longer term stability of monitors.



Monitor evaluation

- The best way to get a true picture of the performance in operation is to test the monitor.
 - Longer period with a live transformer.
 - Reference oil samples to two laboratories every 4 weeks or so.
- Due to the uncertainties related to DGA - online or offline - one should expect some differences in results even if the samples were ideal.



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