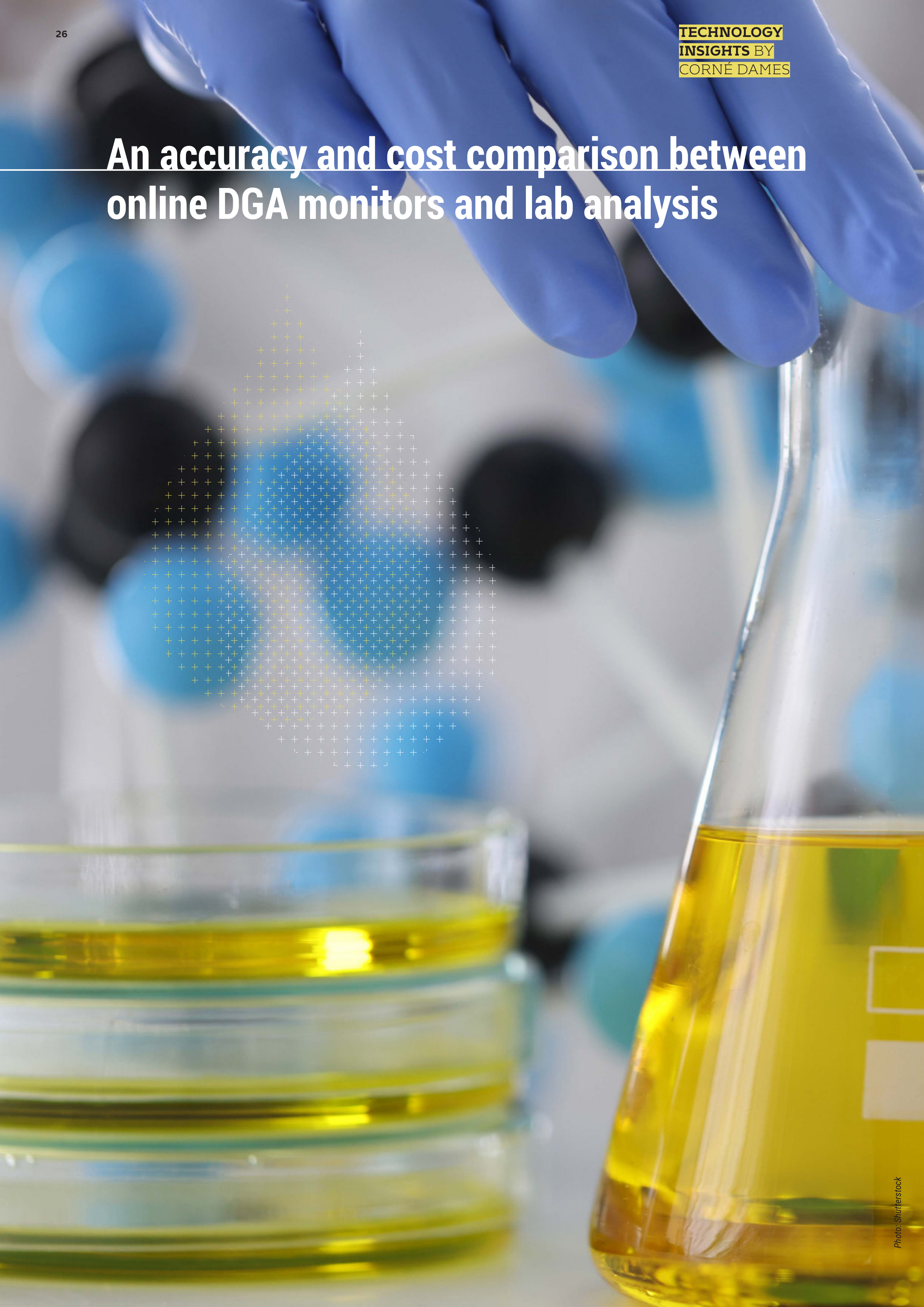
CORNÉ DAMES

An accuracy and cost comparison between online DGA monitors and lab analysis



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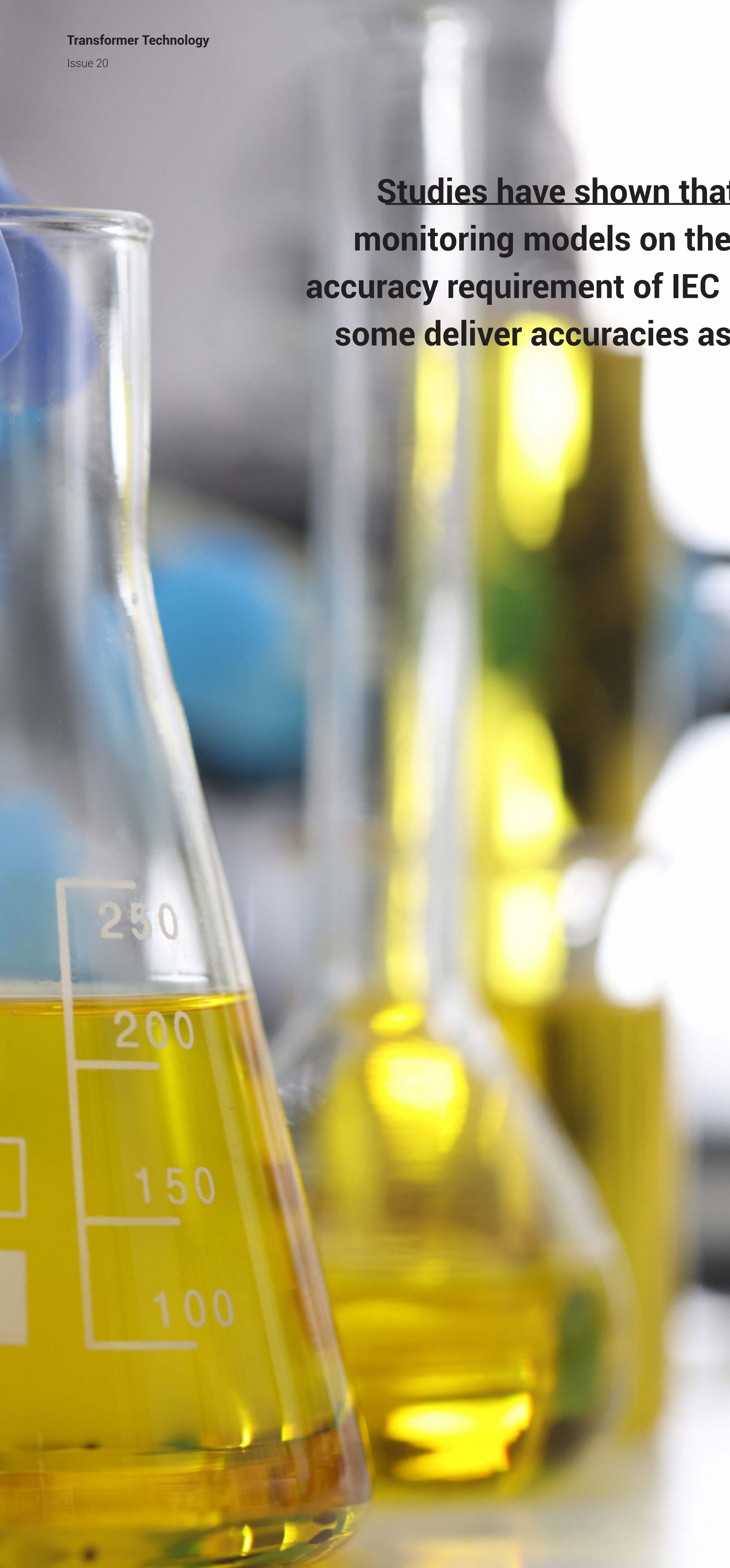
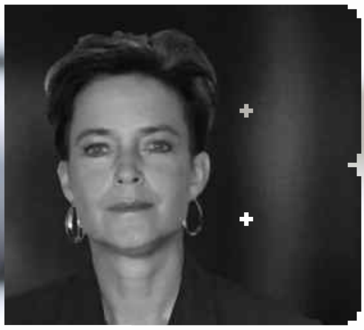


Studies have shown that most online gas monitoring models on the market meet the accuracy requirement of IEC (<15%). However, some deliver accuracies as bad as just 50%.



Corné Dames is the Managing Director of Independent Transformer Consultants, always striving to keep on top of new developments and research. She has expertise as Laboratory Manager in the analysis of transformer oils and as diagnostician identifying problem areas in transformers, as well as profiling of transformers according to available results thus empowering the customer to take preventative steps in maintenance. Corné has vast practical and theoretical knowledge on reliability maintenance programs. Coming from a strong chemical background she has insight in all the chemical processes that are part of the transformer system. Coupled with technical insight, her knowledge and experience help customers optimize their reliability maintenance and electrical asset lifetime.

TECHNOLOGY INSIGHTS BY
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Transformers are some of the most critical and cost-intensive components in the electrical power system. Their operation condition needs to be closely monitored to ensure safe operation, extend their lifetime and reduce maintenance costs.

DGA (Dissolved Gas Analysis) is a well-known and widely used technique to monitor the operating condition of transformers, which also serves as a tool to identify many electrical and thermal fault conditions in transformers and might indicate the severity of the fault.

Recently, natural ester fluids (vegetable oils) have been used increasingly in distribution transformers to substitute mineral oil. Consequently, the established DGA interpretation methods for mineral oil filled transformers have been revised to apply to these alternative fluids. Research has identified that the fault gases generated by natural esters are similar to those generated in mineral oil under various fault conditions. However, the generation rate of dissolved gases in natural ester is slightly lower than in mineral oil, and natural ester remains remarkably stable under medium-temperature thermal faults. Ethane is generated in natural ester if it is exposed to oxygen under normal operating temperatures (<140°C); and under thermal faults, up to 600°C, ethane and carbon oxides account for more than 70% of fault gas generation [1]. **The key gases generated** under Partial Discharge (PD) and sparking faults are hydrogen and acetylene in both mineral oils and natural ester. Under PD faults, the total volume of fault gases was more than 50 times higher in natural ester than in the mineral oil. This is due to the higher rate of PD occurrence. The total volume of fault gases per unit of fault energy is similar for the two liquids [2].

Close to end of life, the laboratory analysis does not meet all the requirements, as the transformer needs to be monitored constantly to ensure safe operation. Thus, more frequent inspections, including DGA monitoring, should be carried out to diagnose faults and implement maintenance plans promptly.

Previously, DGA was performed mainly by periodically sampling liquids from power transformers and analyzing the dissolved gas components in laboratories, using standardized methods for the extraction and analysis. Close to end of life, the laboratory analysis does not meet all the requirements, as the unit needs to be monitored constantly to ensure safe operation. Today, many transformers are approaching the end of life, and thus more frequent inspections, including DGA monitoring, should be carried out to diagnose faults and implement maintenance plans promptly. Another fact to consider is the sampling procedure, handling, and storage; many variables can influence the representativeness of the oil sample compared to the bulk of oil in the transformer. Extreme care should be taken during oil sampling to ensure that the sample retrieved and tested accurately represents the bulk of oil in the transformer.

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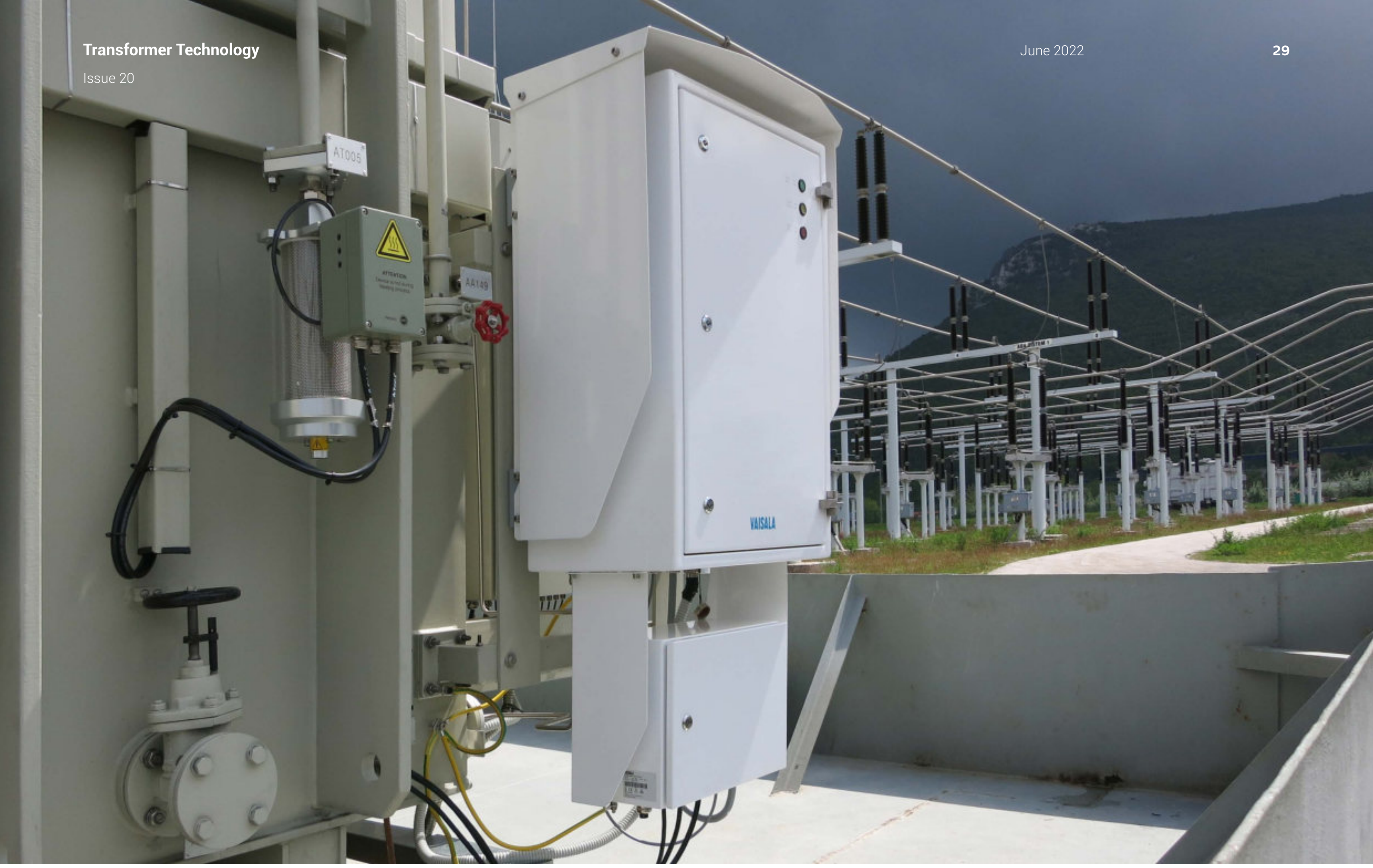
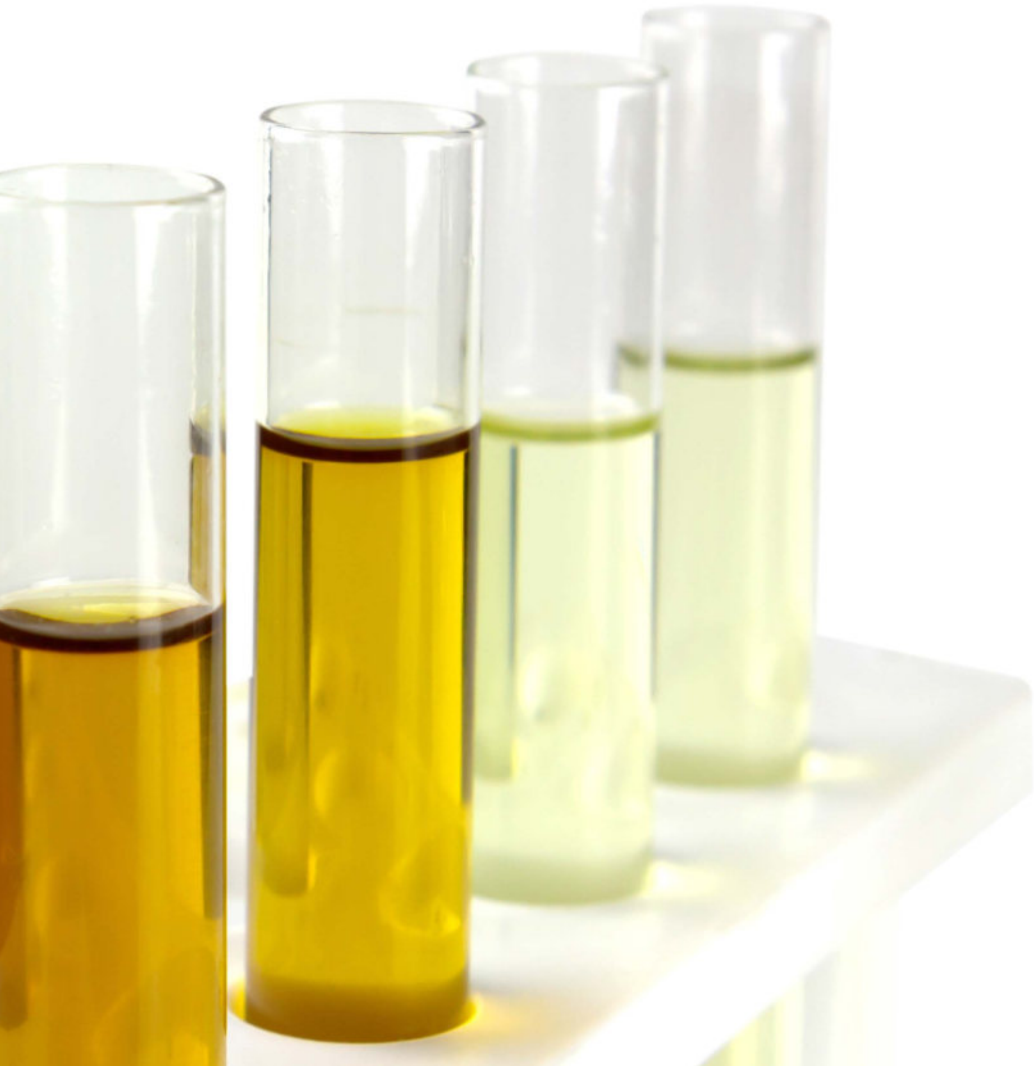


Online DGA monitor installed on a transformer (Photo courtesy of VAISALA)



Over the last decade, numerous online multi-gas monitors have become available and are used to continuously monitor the condition of transformers [3]. Online monitors allow the ongoing monitoring of gases in transformers in service, but this needs to be done in combination and comparison to laboratory results. The monitors are pretty robust with an expected cost-effective lifetime. However, it is unknown if the monitor reading is accurate compared to laboratory readings. Even though a unit is fitted with an online monitor, it is still recommended to send a routine sample to the analytical laboratory. The accuracy and reliability of the online monitors need to be determined to ensure accurate fault identification. As natural esters are being used more every year as dielectric fluid in transformers, the application and interpretation of online monitors need to be adjusted for normal and fault identification parameters in all dielectric fluids currently available in the industry. When using headspace gas extraction methods, the gas solubility coefficients should be carefully determined for application to natural esters. A credible comparison between online monitor results and laboratory analysis is required.

Types of online gas monitors available

Table 1 presents an overview of general online gas monitors that are currently available on the market. In all monitors, the partition coefficient is used. Partition coefficient is temperature-dependent, and this is something that the manufacturer sets so it should be of no concern to the customer. The partition coefficient is also dependent on other factors like the type and age of the oil. Manufacturers do not always compensate for this, leading to incorrect data and inaccurate interpretation of faults.

Monitors using infrared type technology are still to be examined by the Maintenance Team MT25 and IEC Technical Committee TC10 and proposed as an Appendix to IEC 60567, currently only containing guidelines for GC detectors [5].

Only multimeters of type M7 and M9 were found to provide the complete DGA diagnosis online and indicate the requirement for immediate action.

Extraction Method	Gas Measurement Technology	Advantages	Limitations
Membrane, Vacuum	Gas chromatography	Very similar to standardized techniques (IEC, ASTM); Separation of signals to avoid interferences; Automated recalibration with on-board calibration gas	Carrier gas (helium) and calibration gas need to be replaced every 2-4 years Depending on the models, GC columns must be replaced every 3 to 5 years, and there is a potential for carrier gas to leak into the transformer Requires management of compressed gas cylinders
Membrane, Vacuum, Direct headspace	Infra-red (direct absorption or photo-acoustic)	No consumable gases No compressed gas cylinders	Other sensors required to measure H_2, O_2, N_2 Some models are sensitive to contamination by oil vapors, leading to inaccuracy over time and the need for recalibration In some models, accuracy is degraded by interfering compounds present in the oil and/or the ambient air
Membrane, Direct contact with oil	Thermal conductivity cell	No consumable gases	H_2 and CO only
	Electrochemical cell		Composite gas signal
	Metal-oxide sensors		H_2 and CO only, limited accuracy
	Metal film sensors		H_2 only

Table 1. General types of online gas monitors available on the market [5]

Possible faults that different types of online gas monitors can identify

Tables 2 and 3 illustrate the faults that can be detected by various online gas monitors.

As a point of interest, it should be noted that several of these monitors can measure moisture in oil, but this will not be discussed in this article.

The next question is which monitor to use for your transformer; the guidelines compiled by CIGRE TB 409 are set out in table 4.

The cost and benefits of various types of DGA monitoring

The cost and benefit analysis is based on a population of 2,000 large power transformers, having a failure rate of 0.3% per year. This is a commonly observed phenomenon across many networks worldwide [8], which means that **six failures per year on the main tank** (not on any accessories like the on-load tap-changers or bushings) require repairs or replacement. This includes catastrophic failure with fire or explosion in 0.04% of the cases [8] (0.8 such failures per year).

The calculations were based on the following considerations:

- The average cost of these six transformers is $6 million each. Their total cost is $36 million/year.
- The average cost is $6 million for replacing each of them; $2 million for repairs ($4 million/year on average); the cost in the case of a catastrophic failure, including collateral damage, lost revenues and penalties, would be around $30 million (30x0.8 = $24 million/year).
- Laboratory DGA can help avoid approximately two failures due to slow developing faults (2x4 = $8 million/year), while the cost of

	Fault or stress	Definition
Basic fault types	T3	Thermal T>700°C
	T2	Thermal 300<T<700°C
	T1	Thermal <300°C
	PD	Partial Discharges of the corona type
	D1	Discharges of low energy
	D2	Discharges of high energy
Sub-type faults (PD is also part of this group)	S	Stray Gassing of Oil <200°C
	O	Overheating <250°C
	C	Possible carbonization of paper >300°C
	T3-H	T3 in oil only

Table 2. Definition of the types and sub-types of faults or stresses identifiable by DGA [6]

DGA analysis on all transformers, including oil sampling, is around $1million/year. Avoided costs (8-1) = $7 million/year.

- Monitors M1, M1* or M2 were installed on 2,000 transformers. The cost of each is $10,000$ amortized over ten years (cost = $2 million/year). Two additional failures can be avoided due to medium developing faults ((2x4)-2 = $6 million/year), in conjunction with laboratory DGA ($7 million/year). Avoided cost: (7+6) = $13 million/year.
- Monitors M3 to M9 are installed on critical units and severely gassing units (between 30 and 50 transformers) at the cost of $50,000 each on average, amortized over 10 years (cost <$1 million/year).

Application	Type of monitor	Gases measured	Faults possible to identify	Faults not possible to identify
Fault diagnostic	M8/ (M9)	H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2, (N_2)	All ten faults in Table 2, at an early stage	None
	M6/(M7)	H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, (CO_2)		Faults in the paper very often are not detected correctly with CO only with M6, M5, and M2
	M5	H_2, CH_4, C_2H_4, C_2H_2, CO	The six basic faults only	The five sub-types of faults
	M3	CH_4, C_2H_4, C_2H_2		
Fault detection	M2	H_2, CO	None of the ten faults can be identified	May not detect faults D1 and D2 in their early stages, only in their late, sometimes catastrophic stages.
	M1	H_2		
	M1*	Composite reading of H_2 and other gases		

Table 3. Faults possible to identify in transformers with online gas monitors [7]

Type of Monitor	Gases	Transformers
M7/M8/M9	H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2, (O_2), (N_2)	All Transformers, including critical ones (GSU, nuclear) and those already gassing abnormally, require immediate action
M6	H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO	Critical and gassing transformers that do not require immediate action (oil sample required to confirm paper involvement)
M5	H_2, CH_4, C_2H_4, C_2H_2, CO	
M3	CH_4, C_2H_4, C_2H_2	
M2	H_2, CO	Not critical transformers and not already gassing transformers (oil sample required)
M1	H_2	
M1*	Composite reading of H_2 and other gases	

Table 4. Monitors suitable for different types of transformers [5]

Over time, they can help avoid three additional failures due to medium to fast developing faults (3x4)-1=$11 million/year in conjunction with laboratory DGA ($7 million/year) and 0.8 catastrophic failure ($24 million/year). Avoided costs (7+11) = 18(+24) million/year

Avoided costs include the cost for the monitors, but not for their installation, maintenance and communications, which depend very much on the type and brand of the monitor and should be evaluated with monitor manufacturers and then deduced from the avoided costs. The data presented here is from 2019, when CIGRE compiled the report [5].

It is recommended that all laboratories follow the new ISO 17025 and 17024 requirements.

Evaluation of the accuracy of online monitors

The accuracy of monitors evaluated by WG D1/A2.47 is presented in Table 6. The lower the absolute accuracy values, as stated in Table 5, the more accurate the monitor for this specific gas type. Minus values (-) mean the value is below the detection limits of the laboratory, or no values have been reported. Negative values in columns 3 to 9 mean lower values than expected. Positive values mean the values are higher than expected. Values in column 10 are the average values in columns three to nine, expressed in absolute values.

The values for the Test No.1 (monitor A) are the average values obtained from two reference laboratories (Elektropomyar-Elektryka and Laborelec).

During the Tests No.2 to 5, four different monitors were installed on a test loop of oil attached to a transformer during the year. The tests shown in Table 5 were taken at the end of the test period. Hydrogen readings from these four monitors, marked with an asterisk (*) were significantly lower than expected, by 19-35% compared to corrected laboratory results. The WG investigated the possible reasons for these unexpected low readings and identified the commercial gas-in-oil standard sample used as a possible problem. This could lead to the laboratory not properly correcting their equipment to ensure accurate readings. This was ruled out, as the oil standards were received within a week from the actual testing and were accurate. It was established that helium from the online monitor leaked into the oil sample sent to the analytical laboratory for testing. The standard analytical laboratory equipment uses argon gas as a carrier gas and not helium. The equipment then reads helium as hydrogen gas. Once the proper set-up was made and helium and hydrogen gases could be separated in the GC column, it was possible to identify the problem. The monitors displayed the correct readings. The laboratory readings were contaminated by the helium carrier gas, leading to a false reading of hydrogen.

Gas leakage and air ingression that may occur during sample transportation and measurement delay might be the main reason for deviations between online and lab analysis. The sealing efficiency of individual sample syringes is crucial to preserving the sample.

Conclusion

A study done in 2008 by CIGRE TF15 and WG47 showed that most models on the market meet the accuracy requirement of IEC (<15%). However, some do not. They deliver accuracies as bad as just 50%.
It should be stated that the customer should be familiar with the maintenance requirements for each type of monitor and the added cost for the carrier gas and columns where applicable. If the maintenance requirements are not met, accuracy won't be acceptable. Users should also be aware of the measurement performance under actual operating conditions. How will the surrounding environment and operating conditions impact the monitor's reliability, lifetime and accuracy? Would a monitor require site-specific offsets, or is it designed to provide readings of absolute accuracy? These distinctions are critical in choosing a unit that will work for you.

During investigations done by WG D1/A2.47, only multimeters of type M7 and M9 were found to provide the complete DGA diagnosis online and indicate the requirement for immediate action. The single gas type monitors, M1 and M2, will only indicate an abnormal formation of the gases monitored.

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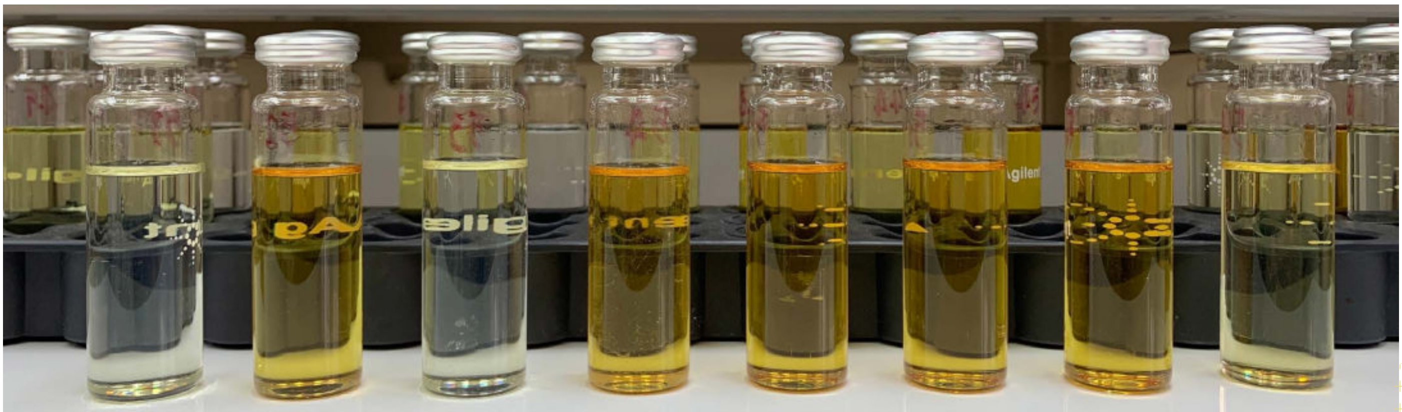
		Accuracy in %							
Test No.	Monitor	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2	Average
1	A	13	11	-	3	-	2	3	6
2	A	-19*	0	-	-4	-	21	0	5
3	B	-25*	-5	19	4	-	-16	0	9
4	C	-35*	-8	-15	-7	-	18	0	10
5	D	-20*	-23	0	23	-	8	-20	15
6	D	0	4	16	31	-	16	0	11
7	E	11	17	42	48	51	45	28	35
8	F	11	-	-	-	-	-	-	11
9	G	12	-	-	-	-	-	-	12
10	H	0	7	25	78	8	14	16	21
11	I	-26	0	3	0	-	10	10	8

Table 5. Accuracy of online gas monitors tested by members of CIGRE WG D1/A2.47



An oil sample should be taken and sent to the laboratory for diagnostics if this scenario arises.

Another issue in the industry is the inaccurate DGA results provided by some laboratories and the lack of high-quality oil sampling practices by some companies. It is recommended that all laboratories follow the new ISO 17025 and 17024 requirements. Gas leakage and air ingression might occur during sample transportation and measurement delay. This might be the main reason for deviations between online and lab analysis. The sealing efficiency of individual sample syringes is crucial to preserving the sample. Liquid samples collected from in-service transformers should be sent to the laboratory for analysis as soon as possible. A shorter delay period can provide more accurate results.

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