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Report on Gas Monitors for Oil-Filled Electrical Equipment

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Report on Gas Monitors for Oil-Filled Electrical Equipment

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1 EXECUTIVE SUMMARY

1.1 Introduction

Dissolved gas analysis (DGA) is widely used for detecting faults in insulating fluid-filled, high voltage electrical equipment in service. Still today, DGA is performed mostly by laboratories using standardized methods for the extraction and analysis of gases dissolved in oil. Hydrogen on-line monitors allowing the detection of abnormal gassing in service, continuously or at much more frequent time intervals than with regular laboratory analysis, have also been available for a long time. However, in the past decade, an increasing number of multi-gas on-line monitors have appeared on the market, able to follow the formation of some or all of the other DGA gases and to provide on-line diagnosis. This has raised questions among potential users of these devices, such as:

- which monitors should be used for which applications?
- how to verify that monitor readings are accurate and reliable in service, especially when they do not agree with laboratory results?
- what is the long-term stability of gas monitors?

The purpose of this Report is to try to answer these often asked questions.

1.2 Applications of gas monitors

A dozen gas monitors (from Morgan-Schaffer, GE-Energy, Serveron, Kelman, Energy Support, Gatron, Unisensor and EMH, among others) have been examined. About half of them monitor a sufficient number of fault gases allowing them to provide fault diagnosis in service. The others have gas alarm capabilities only, with only a few gases monitored. A majority of the monitors can be installed on electrical equipment and used for on-line monitoring. Some can be used as portable instruments for on-site analysis of oil samples taken manually. Examples of on-line installations are shown in Figure 1.

On-line monitors are particularly useful for applications where gas formation in electrical equipment must be followed at frequent time intervals (e.g., in strategic or expensive equipment, or where significant faults have already been detected). In the overall cost of a monitor, not only the cost of the instrument has to be considered, but also the costs associated with its installation and operation in service, e.g., for the treatment and interpretation of the large amounts of DGA data generated.

Figure 1: Examples of installation of on-line monitors

1.3 Accuracy of gas monitors

When comparing gas monitor readings to laboratory results, it should be remembered that laboratories may sometimes be quite inaccurate themselves. A method has therefore been developed in this Report to correct laboratory results for bias and repeatability of the sampling/ laboratory analysis process, using prepared samples of gas-in-oil standards as a reference, along the lines of IEC/ CIGRE recommendations.

A round robin test involving 19 laboratories worldwide and the different types of gas monitors has been organized using this method. Samples of oil were taken from the sampling port of the gas monitors and analyzed by the laboratories. The corrected laboratory results were then compared to monitor readings in order to obtain an estimation of monitor accuracies. Accuracy values were determined separately at routine and low gas concentrations (above and below 5 times the normalized detection limits of the monitors, respectively), since accuracies are usually worse at low concentrations. The effect of possible gas loss or contamination during oil sampling has also been taken into consideration. The accuracies of the various types of monitors (A to K) thus evaluated at routine gas concentrations is indicated in Table A.

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

	Monitor	Number of DGA results	Accuracy
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.

Values in Table A in general meet or are sufficiently close to IEC specifications on accuracy (± 15%) to allow reliable diagnosis to be made. The readings of some monitors for hydrogen, however, are not accurate enough, and diagnosis methods which do not use this gas (e.g., the Triangle method) should preferably be used in such cases. Also, some monitor units are more accurate than others of the same brand or model, and their accuracy in service may be verified using the method recommended in this Report. The accuracy of gas monitors at low gas concentrations are relatively similar in general to those observed at routine levels.

Since on-line monitors usually provide more DGA results over the same period of time than laboratories using manual oil sampling, the gassing rates provided by gas monitors are also more reliable, as long as these rates are calculated over proper time intervals

1.4 Stability of gas monitors

No stability problems in service related to the internal design of the monitors tested in this Report have been reported. The long-term stability of the more recent monitors on the market, however, is not known. The readings of some monitors may be affected by some ambient atmospheric conditions.

2 INTRODUCTION

The scope of this Report is to address questions often asked about gas monitors such as:

- What are the gases to monitor, and therefore the gas monitors to use, for different types of applications in service?
- When monitor readings do not agree with laboratory results for the same transformer oil, how to determine who is right?
- How to verify that monitor readings are accurate and reliable in service?
- What is the long-term stability of monitors?

Note: superscripts in this report (from [1] to [33]) refer to members or participants who made specific contributions to the report (unpublished data or concepts). The list of superscripts and corresponding authors can be found in section 14. References in this report (from [1] to [10]) refer to published documents, which are listed in section 13 .
After section 7, laboratories are identified as # a to # s, and gas monitors as # A to # K.

3 GENERAL DESCRIPTION OF GAS MONITORS

A list of commercial gas-in-oil monitors is indicated in Table 1. This list contains the main monitors available at the date of preparation of this report (2007) and is not exhaustive. The approximate prices given for monitors are for 2006 and may vary depending on vendors and countries.

On-line gas monitors are monitors which are installed on a transformer in service and which provide very frequent readings of gas concentrations dissolved in the oil of the transformer, without having to take an oil sample manually. Some on-line gas monitors may be moved from one transformer to the other. Note: only the version of the Gatron monitor which was available and tested during the course of this study is described in the Report. A new version with different analytical capabilities may be available since.

Portable monitors require taking an oil sample from the transformer and analyzing it manually with the portable monitor, either on-site or off-site, without the transportation delays associated with laboratory analysis.

In addition to dissolved gas-in-oil content, some gas monitors provide other information (e.g., moisture content, oil temperature, fault diagnosis), which has not been evaluated in this report.

Table 2 indicates the internal calibration of monitors used by manufacturers in the factory. Table 3 indicates the automatic internal calibration used in some monitors after they have been installed on transformers in service. The approximate life of monitor parts (mechanical and analytical), as indicated by manufacturers, is given in Table 4. Table 5 indicates the detection limits of monitors provided by manufacturers.

4 PRINCIPLES OF GAS EXTRACTION OF GAS MONITORS

In most gas monitors of Table 1, gas extraction is based on the headspace principle and is performed:

- either by direct contact between the oil and a small gas phase above it,
- or through a membrane separating the two phases (membrane of semi permeable PTFE or other polymer),
- at atmospheric pressure, or under a partial vacuum,
- at the temperature of the oil coming from the transformer tank, or at ambient temperature, or at a fixed temperature,
- with equilibrium obtained without agitation, or by bubbling the gas phase through the oil in a closed loop.
- with or without pumping the oil continuously into the monitor.

For all these monitors operating on the headspace principle, a good knowledge of Ostwald or solubility coefficients K is required at all temperatures of gas extraction, in order to calculate gas concentrations in oil C_L (monitor readings) from gas concentrations in the gas phase C_G (actually measured by the monitor). This is particularly true for monitors directly in contact with the large volume of tank oil, or where the oil is continuously pumped into the monitor, since in such cases $C_L = K\ C_{G.}$

Two monitors are based on the vacuum extraction principle.

Table 1: List of commercial gas-in-oil monitors

Company	Model	On-line	Portable	Gases detected	H_2O	Gas Extraction	Detector	North American cost, 2006 US $
Morgan Schaffer	Calisto	x		H_2	x	PTFE	TCD + IC	11,000
Morgan Schaffer	Myrkos		x	7 (not O_2, N_2)		Headspace	TCD	35,000
GE-Energy	Hydran 103B		x	(H_2 + CO)	x	PTFE	FC	9,000
GE-Energy	Hydran M2	x		(H_2 + CO)	x	PTFE	FC	9,000
GE-Energy	Hydran 2010	x		C_2H_2, H_2	x	PTFE	FC	13,000
GE-Energy	TNU	x		7 (not O_2, N_2)	x	Membrane	FTIR + FC	88,000
Serveron	TM8	x		9 (N_2 calculated)	x	Membrane	GC, TCD	33,000
Serveron	TM3	x		3 Triangle gases	x	Membrane	GC, TCD	18,000
Kelman	Transport-X		x	7 (not O_2,N_2)	x	Headspace +stripping	PA/IR +filter + IC	32,000
Kelman	Transfix	x		9 (N_2 calculated)				
Kelman	Mini Trans	x		(H_2+C_2H_2+CO)				
Big Dipper	4810	x		7	x	Headspace	Laser IR	
Unisensor	E 200	x		10 (not O_2, N_2)	x	Vacuum	IR + FC	74,000
Energy Support	Mobile GC	x	x	11		Vacuum	TCD + FID	50,000
Gatron	TGM	x	x	H_2, CO, CO_2, O_2 (N_2 calculated)	x	Headspace	TCD, IR, Press.,Magn.	55,000
EMH	HydroCal	x		H_2, CO		Membrane		
SRI	Mobile GC		x	9		Membrane	TCD + FID	18,000
Buchholz Relay				All		Alarm gases	Gas volume	varies

TCD = Thermal conductivity ; FC = Fuel cell ; IR = Infrared ; GC = Gas chromatograph;
FTIR = Fourier transform infrared ; PA/IR = Photo-acoustic infrared; IC = solid-state sensor;
FID = Flame ionisation; Hydran M2 , 201i and 201T1 in this report refer to different versions of the same monitor.
Serveron TM8 and True Gas also refer to different versions of the same monitor.
The "7" gases mentioned above are: H_2, CH_4, C_2H_4, C_2H_2, C_2H_6, CO and CO_2.. The "9" gases are the "7" gases + O_2 and N_2.. The "10" gases are the "7" gases + C_3H_6, C_3H_8 and C_4H_{10}. The "11" gases are the "7" gases + O_2, N_2, C_3H_6 and C_3H_8. The "3" Triangle gases are CH_4, C_2H_4 and C_2H_2.

Table 2: Internal calibration in the factory

Company	Model	Calibration for gas-in-oil concentration with gas-in-oil standards	Calibration for temperature with gas standards	Lab results	Temperature control	Calibration curves
Morgan Schaffer	Calisto		x	x	x	x
Morgan Schaffer	Myrkos		x	x		x
GE-Energy	Hydran 103B	x		x		
GE-Energy	Hydran M2	x				x
GE-Energy	Hydran 2010	x				x
GE-Energy	TNU	x			x	
Serveron	TM8, TM3	x	x			x
Kelman	Transfix Transport-X Mini-Trans		x*		x (30 °C)	
Unisensor	E 200		x	x	x	x
Energy Support	Mobile GC	x	x	x	x	x
Big Dipper	4810		x			
Gatron	TGM	NIS	x		x	x
EMH	HydroCal	x			x	
SRI	Mobile GC	x	x	x	x	x

NIS = Natural Internal Standard
*No reading adjustment available

Table 3: Internal calibration in service

Company	Model	Automatic calibration for concentration with	
		Gas standards	Baseline every
Morgan Schaffer	Calisto		3 hours
Morgan Schaffer	Myrkos		
GE-Energy	Hydran 103B	Every 6 months	
GE-Energy	Hydran M2		
GE-Energy	Hydran 2010		
GE-Energy	TNU		3 months
Serveron	TM8, TM3	Every 4 days	
Kelman	Transfix		
Unisensor	E 200		Zero point calibration before every measurement
Energy Support	Mobile GC	x	Week-month
Big Dipper	4810		
Gatron	TGM	NIS	
EMH	HydroCal		
SRI	Mobile GC	Every day	

NIS = Natural Internal Standard

Table 4: Life of monitor parts, in years (as indicated by manufacturers)

Company	Model	Mechanical	Detectors	Columns	Vacuum -resistant membrane	Failure warning available	Years on the market
Morgan Schaffer	Calisto	10	10		x	x	30
Morgan Schaffer	Myrkos	10	10	> 10		x	20
GE-Energy	Hydran 103B		10		x	x	25
GE-Energy	Hydran M2		10		x	x	25
GE-Energy	Hydran 2010		10		x	x	5
GE-Energy	TNU	10	5		x	x	10
Serveron	TM8, TM3	15	10	4-10	x	x	5
Kelman	Transfix	10	5			x	5
Unisensor	E 200	10	>5		x	x	
Energy Support	Mobile GC	10	>5	5		x	1
Big Dipper	4810	10	1				2
Gatron	TGM	10	>10			x	2
SRI	Mobile GC						5
Buchholz Relay							60

Table 5: Detection limits, in ppm (as indicated by manufacturers)

Company	Model	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2
Morgan Schaffer	Calisto	5								
Morgan Schaffer	Myrkos	5	1	1	1	1	1	1		
GE-Energy	Hydran M2	25								
GE-Energy	Hydran 2010	25			2					
GE-Energy	TNU	10	1	3	1	20	5	10		
Serveron	TM8	3	5	3	1	5	5	5	30	5000
Serveron	TM3		10	3	1					
Kelman	Transfix	5	1	1	0.5	2	1	10	100	
Kelman	Transport X	5	1	1	0.5	1	1	2		
Unisensor	E 200	5								
Energy Support	Mobile GC	1	0.2	0.1	0.1	0.1	0.2	0.2	30	30
Big Dipper	4810	10							10	
Gatron	TGM	10					100	10	500	
EMH	HydroCal	25					25			

5 MAIN APPLICATIONS OF GAS MONITORS

The main applications of on-line gas monitors are indicated in Table 6. They depend on the number of gases monitored, from 1 to 9 (C_3 hydrocarbons are not taken into account in this Table). See Table 1 for the individual gases monitored by each monitor. Only the monitor versions available during the course of this study are indicated in Table 6. Fault identification, i.e, PD, D1, D2, T1, T2, T3, is according to IEC 60599 [1] or other methods (IEEE Guide, Rogers, Duval Triangle, etc).

Table 6: Main applications of on-line gas monitors

A	Abnormal gassing and fault identification
B	Abnormal gassing
C	Load monitoring with minor faults
D	False gas (air) alarms
E	Actual oxygen consumption

Monitor	Calisto	Hydran M2	EMH	Hydran 2010	Serveron TM3	Gatron	TNU	Uni sensor	Big Dipper	Trans fix	Serveron TM8	Energy Support	Buch holz
Number of gases	1	1	2	2	3	5	7	7	7	8	9	9	
Application													
A				(x)	x		x	x	x	x	x	x	
B	x	x	x	x	x	x	x	x	x	x	x	x	x
C	x	x	x	x	x	x	x	x	x	x	x	x	
D						x				x	x	x	x
E						x				x	x	x	

The Transport-X and SRI portable monitors indicated in Table 1 can be used for applications A, B and C. Portable monitors allow DGA results to be obtained on-site more rapidly without the delays associated with transportation to the laboratory.

A major advantage of on-line monitors, as compared to laboratory analysis and portable gas monitors, is the capability to detect abnormal gassing and faults occurring between manual oil samplings. For regular maintenance with laboratory analysis, manual oil samplings are usually performed every year or 6 months, and up to daily in case of abnormal gassing. With on-line gas monitors, gas analysis is performed much more frequently (e.g., every 4 hours or 10 minutes). Catastrophic gassing occurring without prior warning is detected by the Buchholz gas relay in less than a minute (time for free gases to reach the relay), and by the Sudden Pressure Valve within seconds or fractions of a second [9].

Oil samples for DGA analysis in the laboratory or with portable monitors are taken mostly from the bottom of the tank, because this is easier from there. On-line gas monitors are usually installed higher on the tank or in the top oil. This is for practical reasons, but also because gases formed within the active parts of the transformer are detected earlier in the top oil than in the bottom oil as a result of oil convection. During periods of large gas formation, however, gas compositions in the top oil may be different from those around the fault and in the bottom oil, if partially un-dissolved gas bubbles are still present in the oil. The interpretation of DGA results in transient cases should take into account the non-uniform distribution of gases in oil. When equilibrium is reached, gas concentrations and compositions are the same in the top oil and bottom oil.

Application A requires monitoring fault gases necessary for fault identification (e.g., at least the 3 Triangle gases).
Applications B and C require monitoring at least one fault gas (e.g., H_2).
Applications D and E require monitoring atmospheric gases (mostly, O_2).

The choice of an on-line gas monitor depends on its intended application in service:

1) Monitors for applications A, B and C are particularly useful in:
- strategic transformers, or transformers used under overload conditions (e.g., industrial transformers), where power cannot be interrupted for economic reasons.
- transformers in nuclear power stations, where catastrophic problems may occur in case of power disruptions, and the frequency of oil sampling is already higher (every 6 months), even in healthy transformers [4].
- transformers that have a large economic impact on the facility [20]
- transformers with previous problems, which can be operated only below a certain load to avoid failure [1].
- when local regulations forbid to sample on-line (e.g., in case of a faulty tap-changer or bushing)[2,33].
- for following gas trends, since the variability of gas monitors with time is usually less important than with laboratory results [2, 12].

2) Monitors for application A are preferable when a problem is expected in a transformer, and B and C in the other cases [4]. The accuracy of monitor readings should be sufficient (typically, ±15%), otherwise the uncertainty on diagnosis is too high and the diagnosis may not be reliable [2]. Furthermore, their long-term stability must be good, as the detection of trends plays a decisive role for condition assessment.

3) Monitors for applications D, E are particularly useful in:
- transformers with regular overheating problems.
- free-breathing transformers with frequent gas alarms, to check if these alarms are only due to air bubbles [2].
- sealed transformers, to detect air ingress.
- transformers where oil is continuously degassed (only a few of these are presently in operation).
- also to see if manual oil samples have been contaminated with air (a common laboratory sampling problem) [4].

4) In addition to the basic cost of gas monitors indicated in Table 1, other costs associated with their installation or operation in service should be taken into consideration, e.g., for:
- retrofitting them on the transformers [11, 33]
- communication infrastructure and software modifications for treating the large quantities of DGA data generated [20]
- personnel required for analyzing data and evaluating the condition of monitored transformers [9].
- maintenance and repair on-site or in the factory [9].
- regular verifications of the accuracy of monitor readings [9].
- interpretation of gassing behaviour related to normal operation of the transformers (e.g., load variations) [9].

As a comparison, the cost of analyzing a manual oil sample in the laboratory is between 50 and 300 $, depending on the laboratory and whether or not a diagnosis is provided. This does not include the cost of oil sampling [9].

6 EVALUATING THE ACCURACY OF GAS MONITORS

6.1 Accuracy of gas monitors in the factory and in service

Table 7 indicates the accuracy and reproducibility of gas monitor readings as measured in the factory by manufacturers.

Table 7: Reproducibility and Accuracy measured in the factory by monitor manufacturers, in ± %

Company	Model	Reproducibility			Accuracy		
		H_2	C_n	O_2	H_2	C_n	O_2
Morgan Schaffer	Calisto	2			5		
Morgan Schaffer	Myrkos	2	2		6	6	
GE-Energy	Hydran M2	5			10		
GE-Energy	Hydran 2010	5	5		10	10	
GE-Energy	TNU	5	5		10	10	
Serveron	TM8	1-2	1-2	1	2	2	2
Serveron	TM3		1-2			2	
Kelman	Transfix	2	2	2	5	5	5
Unisensor	E 200	5	1-10		10	5-10	
Energy Support	Mobile GC	2	2	2	5	5	5
Big Dipper	4810	1	1	1	10	10	10
Gatron	TGM	5		5	5		5
EMH	HydroCal				15		

Accuracy, as defined in IEC 60567 [3], is the difference, in %, between the gas concentration values measured by a laboratory or a gas monitor in a prepared sample of oil (a “gas-in-oil standard”) and the values actually introduced in the prepared sample.

Reproducibility is the difference observed when several samples of the same batch of oil are analyzed by a laboratory or a gas monitor over different periods of time [2,3].

The overall accuracy of a gas monitor is the combination of the accuracy on gas extraction and gas analysis, as for laboratory analyses. In the factory, the accuracy of individual gas monitors is mainly evaluated by calibrating with gas-in-oil standards (external or internal), as shown in Table 2. These individual monitors are then installed in transformers in service, where the oil may not be exactly the same as in the factory, and therefore the calibration curves and the monitor readings may be a bit different. The calibration of the devices used for gas extraction in the monitors may also change slightly with time. And finally, the calibrations used in the factory may have systematic biases, as is sometimes the case for laboratories. For all these reasons, it is a good analytical practice to verify the accuracy of gas monitors in service.

Ideally, this should be done using gas-in-oil standards [1]. However, not all monitors have the by-pass valves and piping to do that. Also, this would require large volumes of gas-in-oil standard (between 300ml and 20 litres, including purge, depending on the type of monitor), which cannot presently be prepared or purchased at a reasonable cost (this may change in the future). So, the only alternative presently is to compare monitor readings with laboratory DGA results for an oil sample taken from the monitor.

6.2 Direct comparisons between monitor readings and laboratory results

Some direct comparisons of monitor readings with laboratory results have been published or reported by TF members. Examples are indicated in Table 8. Such comparisons, however, are not reliable because they do not take into account the accuracy of the laboratory and the

repeatability of the oil sampling/ oil analysis process. It is well-known that some laboratories may be quite inaccurate [2].

Table 8: Examples of differences reported between monitor readings and laboratory results, in %

Monitor	Ref.	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	Average
TNU	[7]	2	5	5		50			15
Transport-X	[26]	60	3			18		4	21
	[4]	39	18	15	14	40	15	12	22
	[27]	37	43	115	11	235	21	8	67
	[2]	14	16	2	8	27	33	12	16
	[9]	48	27	15	0	8	18	36	22
	[31]	25	15	23	87	80	16	7	36
	[5]		20	10		25	20	30	21
	[4]	38	8	8	3	7	11	72	21
Serveron									
True Gas	[6]	200*	23	12	43	28	25	21	25
TM8	[13]	34	10	7	18	6			15
Hydran 103B	[10]	37							
	[30]	41							
	[5]	12							
	[29]	11							

*exceeded the maximum levels of the gas monitor

6.3 Comparisons between monitor readings and corrected laborator y results

Laboratory results can be affected by:

- the repeatability of the oil sampling/ laboratory analysis process. This can be evaluated for example by taking several duplicate samples from a transformer and analyzing them in the laboratory. The average laboratory repeatability has been reported during IEC/ CIGRE round robin tests to be around ± 7% at routine gas concentrations [2].

- the accuracy or systematic bias of the laboratory gas extraction/ gas chromatography analysis, because of errors in the calibration curves used and other factors. The average accuracy of laboratories has been reported IEC/ CIGRE round robin tests to be around ± 15% at routine gas levels [8], but this varies widely among laboratories and depending on the gas chosen.

- errors introduced in some cases during oil sampling. For instance, when oxygen content is very low in a transformer in service, it may be very difficult not to contaminate the oil sample with outside atmospheric air (including CO_2) during sampling with syringes or other devices. It has also been mentioned that hydrogen may be lost during oil sampling, but this has not been clearly demonstrated and will be examined on a case-by-case basis in this Report.

A round robin test (RRT) has thus been organized by TF15 to compare monitor readings with laboratory results, after correcting or adjusting them for laboratory accuracy and repeatability. The treatment of RRT results is according to IEC and CIGRE recommendations [3,8], using gas-in-oil standards as a reference rather than the statistical analysis of unknown samples used by other organizations [9].

7 ROUND ROBIN TES T OF TF1 5 FOR E VALUATING MONITOR AC-CURACY IN SERVICE

7.1 Participating laboratories and monitors evaluated

Table 9 indicates the laboratories having participated to the round robin test of TF15 on monitor accuracy.

Table 9: Participating laboratories

Contributing TF member	Laboratory	Country
[16]	ABB	Norway
[4]	ABB	Sweden
[21]	Arizona Public Serv.	USA
[13]	EdF	France
[22,23]	EnBW	Germany
[17]	Eskom	South Africa
[14]	Georgia Power	USA
[10]	Tisza Pharma Vet	Hungary
[9]	IEC	Israel
[15]	Laborelec	Belgium
[12]	National Grid	UK
[18]	PacifiCorp	USA
[8]	Petroleumkemie	Sweden
[2]	Siemens	Germany
[5]	Terna	Italy
[6]	U.Stuttgart	Germany
[11]	VaTech	Austria
[20,25]	Weidmann-ACTI	USA
[19,28]	ZTZ	Ukraine

TF 15 has evaluated the following gas monitors: Hydran M2, Hydran 103B, TNU, True Gas, TM8, Transport-X, Transfix, Myrkos, TGM, Mobile GC, EMH HydroCal, Calisto. See Table 1 for the manufacturers of these monitors.

7.2 Procedure used by laboratories for the RRT

In order to compare monitor readings with laboratory results, participating laboratories were asked [1] to:

- take a reading on one or several of their on-line gas monitors installed on transformers in service.
- take an oil sample from the sampling point of the monitor(s), as representative as possible of the monitor reading, immediately or rapidly after having taken the reading.
- for portable gas monitors, take two samples of oil from a transformer in service. Take a reading of the portable gas monitor, using one of the two oil samples. The other oil sample is for the lab.
- send all the above oil samples to the DGA laboratory.
- when ready for the analysis**,** analyze on the same day and using the same analytical equipment this (these) oil sample(s), and a sample of gas-in-oil standard sent separately to the laboratory. This gas-in-oil sample ("True North") had been prepared by Morgan Shaffer[3] in Montreal.

In order to evaluate the repeatability of the oil sampling/ laboratory process, they were also asked [1] to:

- take at least 4 duplicate samples of oil from one of their transformers.
- send them to the laboratory for analysis.

7.3 Calculations made on monitor readings and laboratory results

All monitor readings and laboratory results were first converted to IEC ppm (at 20ºC, 101.3 kPa), if they had not already been given in these units. Table 10 indicates the units used by different types of gas monitors to express their readings in ppm. The standard pressure used for all monitor readings is standard atmospheric pressure.

Table 10: Units used for monitor readings:

STP (0°C)	IEC (20°C)	25°C	55°C
Hydran TNU Energy Support Calisto	Transport X Transfix	TM8 TM3	EMH

Laboratory results with the gas-in-oil standard were first used to calculate the bias and accuracy of each laboratory, in %.

Laboratory results with the oil samples taken from the gas monitors were then corrected for laboratory bias for each gas, in ppm.

The differences between monitor readings and laboratory values corrected for laboratory bias and accuracy were calculated for each gas and each individual monitor tested, in %. In the case of Hydran monitors, a composite value of corrected laboratory results corresponding to the composite reading of the monitors was used: 100% of H_2 + 18 % of CO + 8 % of C_2H_2 + 1.5 % of C_2H_4. Examples of the calculations made are indicated in Table 11.

Average (overall) values were calculated for each individual monitor unit for all gases. Also, average values for each type of monitor and each gas. Finally, the average repeatability of the oil sampling/ laboratory analysis process, and the uncertainty on the gas-in-oil standard used, were subtracted from these values, to obtain an approximate value of accuracy in service for each gas and each type of gas monitor.

Table 11: Examples of calculations made

Lab # x		H2	CH4	C2H4	C2H2	C2H6	CO	CO2	O2	N2	Overall1
Standard	Prepared STP	102	104	99	97	102	102	130	13302	45269	
	Prepared IEC	109,4	111,6	106,2	104,1	109,4	109,4	139,5	14276,5	48585,4	
	Measured IEC	94,4	106,2	97,6	98,7	97,6	84,7	141,6	15309	52333,2	
	Accuracy %	-13,7	-4,8	-8,0	-5,1	-10,7	-22,5	1,5	7,2	7,7	-9,5
Monitor E	Lab value IEC	54,5	137	854	112,6	146	515	11209	18288		
	Corrected	63,1	143,9	929,1	118,7	163,6	664,9	11039,1	17054,5		
	Reading IEC	65,8	159	1091	112,4	154	403	14700	20842		
	Detection limit	5	1	1	1	2	25	25	500		
	Difference %	4,1	10,4	17,4	-5,3	-5,9	-39,3	33,1	22,2		16,5

Lab # y		H2	CH4	C2H4	C2H2	C2H6	CO	CO2	O2	N2
Standard	Prepared STP	102	104	99	97	102	102	130	13302	45269
	Prepared IEC	109,4	111,6	106,2	104,1	109,4	109,4	139,5	14276,5	48585,4
	Measured IEC	122	115	113	79	105	99	147	14991	54617
	Accuracy %	11,4	3,0	6,3	-24,1	-4,0	-9,5	5,3	5,0	12,4
Monitor A	Lab value IEC	9,9		131			625			
	Corrected	8,8		123,1			691,1			
	Composite	135,1								
	Reading STP	118								
	Reading IEC	126,6								
	Detection limit	25								
	Difference %	-6,2								

8 RESULTS OF THE ROUND ROBIN TEST

8.1 Accurac y of laboratories

Table 12 indicates the differences observed between gas concentration values measured by the laboratories and values actually prepared in the gas-in-oil standards at routine concentration levels. For example, a value of -6% means that the laboratory reported a value of 94 ppm instead of 100 ppm. This includes the potential errors introduced when transferring the sample of gas-in-oil standard to the gas extraction vessel of the laboratory. The gas-in-oil standards contained ~ 100 ppm of each of the fault gases and ~ 6% of air. It has been shown by the manufacturer of these gas-in-oil standards that their gas content is not affected by sampling, transportation and storage over a period of several weeks [3]. Identification of laboratories in Table 12 is by order of reception of results (from # a to # s). The values indicated in Table 12 also represent the accuracies of the participating laboratories at routine concentration levels.

Table 13 indicates the accuracy of two laboratories that required oil standards at low concentration levels (~ 10 ppm of the fault gases).

Table 12: Laboratory accuracies at routine concentration levels (~ 100 ppm of fault gases), in %

Laboratory #	Method	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2	Overall 1	Overall 2
o	HS	-6	-5	+4	+1	+2	-7		-11	-30	4	7
p	HS	-8	-3	-6	-7	-5	-2	-5	-27	-37	5	11
c	HS	-20	-5	+2	-6	-4	+6	-8	-3	-12	7	7
q	HS	-10	-5	-9	-6	-10	-4	-12	-6	-1	8	7
j	HS	-9	-7	-8	-6	-6	-5	+13	+106	+40	8	22
d	T	-18	-3	-10	-12	-16	-5	+2.5	-4	+4	9	8
f	T	-14	-5	-8	-5	-11	-22	+1.5	+7	+8	9	9
e	T	+11	+3	+6	-24	-4	-10	+5	+5	+12	9	9
b	S	-5	+15	+14	+3	+9	+7	-9	+16	+11	9	10
i	HS	-2	0	+5	+13	+18	+3	+27	-37	-38	10	16
n	HS	-26	-11	-10	-7	-15	-11	-3	-5	-34	12	14
r	HS	0	+1	+50	0	-5	-1	+44	-2	-28	14	15
l	MFPD	+22	+15	-1	-3	-2	+16	+37	-39	-7	14	16
h	MFT	-14	-20	-20	-17	-25	-19	+43	-37	-36	23	26
s	HS	-21	-25	-32	-30	-38	-10	-14	-11	-7	24	21
m	HS	-29	-37	-27	-37	-31	+11	-17	-15	-21	27	25
Average 1		**13**	**10**	**13 11**		**13 9**		**15**	**19**	**21**	**12**	**14**
Average 2		-9	-6	-3	-9	-9	-2	+7	-2	-11	-5	-6

HS: Head Space, T: Toepler, S: Stripping, MFPD: Mercury Free Partial Degassing, MFT: Mercury Free Toepler
Overall 1: excluding air; Overall 2: including air (average of absolute values)
Average 1: average of absolute values; Average 2: arithmetic average

Table 13: Laboratory accuracies at low gas concentration levels (~ 10 ppm of fault gases), in %

Laboratory	Method	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2	Overall 1	Overall 2
g	HS	+2	-7	-20	-38	-22	-7	+52	-8	-6	21	18
a	HS	+45	+12	+34	+34	+3	+34	+70	-33	-11	33	31
Average											**27 25**	

Notes: HS = Head Space; Overall 1: excluding air; Overall 2: including air (average of absolute values)

8.2 Definition of routine and low gas concentrations for gas monitors

For the purpose of this RRT, routine and low gas concentrations are based on the "RRT detection limits" of the gas monitors, in order to get comparable results and to be fair with gas monitors with lower [6] or higher detection limits than the others. The RRT detection limits are defined as the true detection limits or the IEC detection limits for routine gas levels in service, whichever is the greater.
The RRT detection limits used are indicated in Table 14.

Table 14: Detection limits of the gas monitors for this RRT, in ppm:

	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2
True detection limits									
Transport X	5	1	1	0.5	1	1	2		
Transfix	5	1	1	0.5	2	1	10	100	
Serveron	3	5	3	1	5	5	5	30	
Gatron	10	1	1	1	1	100	10	500	
Energy Support	1	0.2	0.1	0.1	0.1	0.2	0.2	30	30
TNU	10	1	3	1	20	5	10		
IEC	5	1	1	1	1	25	25	500	2000
RRT detection limits									
Transport X	5	1	1	1	1	25	25		
Transfix	5	1	1	1	2	25	25	500	
Serveron	5	5	3	1	5	25	25	500	
Gatron	10					100	25	500	
Energy Support	5	1	1	1	1	25	25	500	2000
TNU	10	1	3	1	20	25	25		

Routine gas concentrations are defined as > 5 times the RRT detection limits of the gas monitors. Low gas concentrations are defined as between 2 and 5 times the RRT detection limits. Gas concentrations < 2 times the RRT detection limits are not used in the calculation of RRT results.

8.3 Differences betw een monitor r eadings and corrected laborator y results

Tables 15-24 indicate the differences in % observed between monitor readings and laboratory results corrected for laboratory bias. For example, a value of -10% in Tables 15-24 means that the monitor reading was 90 ppm and the corrected laboratory result 100 ppm. Gas monitors are identified as monitors A to K to avoid that RRT results are used to commercially favour one monitor over the others on the basis of accuracy values presented in this Report. Results are separated according to type of monitor (single or multi gas monitors), and to gas concentration level (routine or low).
In Tables 15, 17, 19, 21 and 23 (at routine gas concentrations), blank cells correspond to corrected concentrations measured by the laboratories which have been defined as low concentrations for the gas monitors (see Table 14). In Tables 16, 18, 20, 22 and 24 (at low gas concentrations), blank cells correspond to corrected concentrations measured by the laboratories which have been defined as routine concentrations for the gas monitors. In all Tables 15-24, blank cells may also correspond to corrected concentrations measured by the laboratories which are less than twice the RRT detection limits of the gas monitors.

Tables A1-A6 in Annex A indicate the monitor readings in ppm. The small number of values available for monitors G to K reflect the fact that only a few number of these monitors are in service and available for testing, compared to the much larger number of monitors A, D, E and F in operation worldwide.

Table 15: Differences observed for single gas monitors A and B, in % at routine concentration levels

Monitor	Lab #	Unit #	Differences
A	d	1	-10
	e	1	-6
		2	-21
		3	-30
		5	-32
	g	L1-2	+71
		L2-1	-46
		L3-2	-17
		L1-3	+9
		L2-2	-14
		L3-3	-19
	i		+233
	n		-19
	Average 1		**25**
	Average 2		-11
B	i	3	+2
	k		-10

Notes: Average 1: average of absolute values; Average 2: arithmetic average
Result of lab i for monitor A was excluded from calculations as an outliar.

Table 16: Differences observed for single gas monitors A, B and C, in % at low gas concentration levels

Monitor	Lab #	Unit #	Differences
A	d	2	-80
	e	4	-30
	g	L1-1	+31
	i	2	+4
	Average 1		**37**
B	i	1	+145
		2	-4
C	l	1	+6
		2	-34
		3	-34
		4	+17
		5	-4
	Average 1		**19**

Note: Average 1: average of absolute values

Table 17: Differences observed for multi-gas portable monitor D, in % at routine concentration levels

Monitor D	Lab #	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	Overall 1
2004	i	4	-55	+11	+43		+13	+21	+84	38
		2		-13			-21	+7	+24	16
		3	-60	+9	-3		+3	-9	+22	18
2005	j	1	-64	-30	-13		-11	-24	+24	28
		2		-22	+5		-26	-18	+34	21
		3		-16	-12		-7	-12	+45	18
		4		-17	-16		-10	-10	+52	21
2004	d	2		-19				-18	+19	19
		1	-76	-8	+6	-18	+1	-11	+28	16
2006	b	1		-13	+3		+2	-11	-2	6
		2	-23	-3	-3	-6	-6	-15	-4	9
		3			+14			-13	-3	10
		4			+33			-16	-6	18
	a		-56	+21	+68	+43			+47	47
	n		-54	-19	+14		+4	-8	+20	17
	p		+21	-14	+3	-16			+33	17
	q		+28	-5		-27		-15	+16	18
	Average 1		**49 15**		**17**	**22**	**9**	**14 25**		**20**
	Average 2		-35	-9	+10	-5	-5	-10	+25	-4

Note: Average 1, Overall 1: average of absolute values; Average 2: arithmetic average; Overall 1: excluding air

Table 18: Differences observed for multi-gas portable monitor D, in % at low gas concentration levels

Monitor D	Lab #	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	Overall 1
2004	d	2	-66		+172					118
2006	b	1	-14							14
		3	+27	+43						35
		4	+22	+100			+9			44
2004	i	3				+51				51
	a						-79			79
2005	j	2	-70							70
		4	+8							8
	p						+138	-73		105
	q				+70					70
	Average 1		**34 71**		**121 51**		**75**	**73**		**59**
	Average 2		-15	+71	+121		+22			+50

Note: Average 1, Overall 1: average of absolute values; Average 2: arithmetic average; Overall 1; excluding air

Table 19: Differences observed for multi-gas monitor E, in % at routine concentration levels

Monitor E	Lab #	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	Overall 1
	f		+4	+10	+17	-5	-6	-39	+33	+22	16
	j	1	+243	-6	-1		-1	-2	+35		48
		2		-79	-34		-56	-49	-12		46
	a		+34	-42	+6	+27			+34		29
	l	7		-26	+37			-5	+43		28
		8							+90		90
		9			+23			-9	+54		29
		10	+20		+72				+76		56
		11	+98	-35				-11	+48		48
	n		+26	-34	-16		-14	-34	0		21
	p		-16	+39	-81	-19			+13	+9	34
	Average 1		**71**	**33**	**26 16**		**19 21**		**42**		**40**
	Average 2		+65	-30	+13		-10	-21	+44		+10

Note: Average 1: average of absolute values; Average 2: arithmetic average; Overall 1: excluding air

Table 20: Differences observed for multi-gas monitor E, in % at low gas concentration levels

Monitor E	Lab	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	Overall 1
	a						+30				30
	j	1								-88	
		2	+20								20
	l	7	+116								116
		8		-47				-27			37
		9	-6	-75							40
		10		-4		-27		+4			12
		11			+50						50
	p							-72			72
	Average 1		**47**	**42**	**50 27**		**30 15**				**47**
	Average 2		+43	-24	+50	-27	+30	-32			+7

Note: Average 1, Overall 1: average of absolute values; Average 2: arithmetic average; Overall 1 excluding air

Table 21: Differences observed for multi-gas monitor F, in % at routine concentration levels

Monitor F	Lab	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	Overall 1
2006	a					+65			+40		53
2004	j	3		-20	-37		-27		+21		26
		4		-18	-40			-8	+19		21
	o			-10				-3		-93	7
	r	1							+28	-100	28
		2					-29		+16	-100	23
		3		-18			-41	-20	+25	-100	26
		4		-12			-37		+23	-98	24
		5		-26				-18	+4	-97	16
		6		-12			-3	-5	+48	-86	17
		7	+13	-7	-28		-25	+22	-12	-86	19
	o	1		-8			-17	-2		-82	9
		2	+137	+3	-60		-35	+20		-85	51
		3		-16			-8	-23		-98	16
		4	+9	+11			-3	+8		-91	8
		5	+25	-9	-58		-9	+2		-88	21
		6	-46					-30		-98	38
		7		+2			-11	+4		-96	6
		8						+6		-81	6
		9		-14				-22		-95	18
2006	s	1		-9	-24		-9		+18	-98	15
		2						+1	+20	-99	10
		3							+76	-99	76
	Average 1		**46**	**12**	**41**		**19 12**		**27**	**89**	**23**
	Average 2		+27	-10	-41		-19	-4	+25	-89	-4

Note: Average 1, Overall 1: average of absolute values; Average 2: arithmetic average; Overall 1 excluding air

Table 22: Differences observed for multi-gas monitor F, in % at low gas concentration levels

Monitor F	Lab	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	Overall 1
2006	a		+30		-100						65
2004	j	3						-16		-82	26
		4	+157				-27			-78	92
	o				-35						35
	r	1			-16						16
		2		-40							40
		4						-14			14
		5					-43				43
		6			-51						51
	o	1			+70						70
		6		-27			-25				26
		8	+75	+39			+16				43
		9					-24				24
2006	s	1						+7			7
		2	-100	-37							68
	Average 1		**90 36**		**54**		**27**	**12**		**80**	**43**
	Average 2		-40	-16	-26		-20	-10		-80	-22

Note: Average 1, Overall 1: average of absolute values; Average 2: arithmetic average; Overall 1 excluding air

Table 23: Differences observed for multi-gas monitors G to K, in % at routine concentration levels

Monitor	Lab #	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2	Overall 1	Overall 2
G	c					-46		-9	-21		-7	25	17
	p	2	+7	-14	-1	-1			+25	+4	-8	9	8
	Average 1											17	12
H	c		+47	-13	-19		-14	-3	-18			16	
I	c								-13		0	13	7
J	l		-40					+43					
								+46					
								-7					
								-49					
	Average 1		40					36				38	
K	m		-11					+63	-14			29	

Note: Average 1, Overall 1,2: average of absolute values; Overall 1: excluding air; Overall 2: including air.

Table 24: Differences observed for multi-gas monitors G to I, in % at low gas concentration levels

Monitor	Lab #	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2	Overall 1	Overall 2
G	c			-23	-18					+1		20	14
	p	2					+75	-70				72	
	Average 1											46	
I	c		-20					+33		+18		27	23

Note: Average 1, Overall 1,2: average of absolute values; Overall 1: excluding air; Overall 2: including air.

9 DISCUSSION OF RRT RESULTS

9.1 Accurac y of laboratories

In Table 12, Average 1, Overall 1 (excluding air) and Overall 2 (including air) are the averages of absolute accuracy values, in %. They indicate the average deviations from prepared values (or accuracy) of laboratories for each gas (Average 1) and for the average of all gases (Overall 1 and Overall 2).

Average 2 is the arithmetic average of accuracy values for each gas, in %. It indicates the tendency of laboratories to under- or over-estimate the contents of each gas. It can be seen that laboratories on average tend to measure less than was prepared, but not much (-5 % for all gases). This suggests that gases do not escape from the syringe used for the gas-in-oil standard. If they did, H_2 would escape more than C_2H_2 or C_2H_6, since it diffuses more rapidly, contrary to what is observed. Also, no significant contamination by air is observed (Average 2)

Head Space (HS) was used as the gas extraction method by a majority of laboratories. Some had a good accuracy on average (Overall 1 and 2), others were less accurate. This confirms previous CIGRE studies [8] that all extraction methods can provide accurate results or not, depending on how well or not they are applied.

9.2 Differences betw een monitor r eadings and corrected laborator y values

Tables 15-24 indicate the differences between monitor readings and laboratory values corrected for laboratory bias or accuracy. For example, a value of -10% means that the monitor reading was 90 ppm and the corrected laboratory value 100 ppm.

Average 1, Overall 1 (excluding air) and Overall 2 (including air) are the averages of absolute values for each gas and each monitor. Average 2 is the arithmetic average of values for each gas. It indicates the tendency of gas monitors to under- or over-estimate the content of each gas

The values in Tables 15-24 were examined first on a case by case basis, as mentioned in section 6.3, to evaluate in which cases they may have been affected by oil sampling and in which cases they clearly can be attributed only to the monitor itself.

In Tables 15-16, laboratory results for H_2 tend to be higher than the readings of single-gas monitor A (Average 2). Therefore, the differences observed cannot be attributed to a loss of hydrogen during oil sampling (since this would lead to lower laboratory results), but to the monitor itself.

Tables 17-18 refer to the multi-gas portable monitor D. The effect of oil sampling is the same for portable monitors and laboratories. The differences observed therefore cannot be attributed to oil sampling but to the monitor itself.

In Tables 19-20, the readings of H_2 for the multi-gas monitor E tend to be much higher than laboratory results (Average 2). This might be due in part to hydrogen loss during oil sampling. However, they are much higher than for the multi-gas monitor F in Tables 21-22, so a large part of the difference (in Average 1) for H_2 for monitor E is probably due to the monitor itself, and might be related to the detector used for H_2 (a solid state sensor not very adapted for that purpose).

The readings of monitor E for CO_2 are higher than laboratory results. If they were due contamination by air of the oil sample, they would be lower. The difference (in Average 1) for CO_2 with monitor E is therefore mostly due to the monitor itself.

In Tables 21-22, the readings of H_2 for the multi-gas monitor F tend to be a bit higher than laboratory results (Average 2). This might be due to hydrogen loss during oil sampling, but also to the different solubility coefficients K of oils used in the factory and in service, or to the use of Helium as a carrier gas at the relatively low hydrogen levels monitored (see Table A5 of Annex A).

The readings of monitor F for CO_2 are higher than laboratory results. If they were due to contamination by air of the oil sample, they would be lower. The difference (in Average 1) for CO_2 with monitor F is therefore mostly due to the monitor itself.

The readings of monitor F for oxygen are much lower than laboratory results. This is probably due in a large part to contamination by air during oil sampling, which is almost impossible to avoid at the low oxygen levels monitored (see Table A5).

9.3 Accuracy of gas monitors

The accuracy or bias of laboratories is taken into account in Tables 15-24, but not the repeatability of the oil sampling/ laboratory analysis process. This repeatability is indicated in Tables 25-26 for several laboratories. The repeatability of laboratory l for H_2 and CO (concerning monitor J) was 15% and is not indicated in Table 25 but taken into account in Table 27.

Table 25: Repeatability of the oil sampling/ laboratory analysis process, in ±%, at routine gas concentrations (> 5 ppm)

Laboratory #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2
b	5	9	0		1	1	0	24	1
c	10		1			5	2	22	10
g	18	3				1	1	4	2
i	13		7			11	13	62	38
d	0	0	0.5	5	2	0	0	10	0
n	1	2	1		2	1	0	2	1
Average	8	4	2	5	2	3	3	21	9

Table 26: Repeatability of the oil sampling/ laboratory analysis process, in ±%, at low gas concentrations (< 5 ppm)

Laboratory #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2
c		20		9	14				
g			0	28	28				
i			35		46				
n				1					
Average		20	17	13	29				

This repeatability represents an additional uncertainty on laboratory results, which should be subtracted from the average values of Tables 15-24 for each gas to be fair with the gas monitors. There is also a small uncertainty on the gas-in-oil standard used, of less than ± 2% since it is prepared by weight and is NIST-traceable.

The accuracy values for gas monitors, indicated in Tables 27-28, have been obtained as follows:

- Tables 15-24 provide the differences (in ± %) between monitor readings and laboratory results corrected for laboratory bias, for each monitor and each gas, at routine and low gas concentration levels (“Average 1” values).
- The average repeatability of the oil sampling/laboratory process in Tables 25-26, and the uncertainty on the gas-in-oil standard (±2%), are then subtracted from Average 1 values, for each gas.
- The values thus obtained are used as a reasonable estimate of the accuracy of gas monitors, taking into account all the uncertainties related to laboratory results (laboratory bias, repeatability and gas-in-oil standard)

- For monitors (E, F and H), hydrogen readings tend to be higher than what is found by the laboratory in the oil syringe, so there is a reasonable doubt that some hydrogen may have been lost during sampling (see section 9.2). The values of H_2 for these monitors therefore are indicated in brackets in Tables 27-28 and are not included in the calculations of Overall 1 values. A part of the difference between monitor readings and laboratory results, however, is likely to be due to the monitor itself, for some monitors.
- O_2 and N_2 also are not included in the calculations of Overall 1 values because of possible contamination of the oil by air during sampling the oil from the transformers.

Table 27: Accuracy of gas monitors at routine gas concentrations, as estimated by TF15, in ±%

Monitor	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2	Overall 1
A	15									15
D	39	9	13	15	5	9	20			16
E	(61)	27	22	9	15	16	37			21
F	(38)	6	38		15	7	22	(68)		17
G	0	8	0	16		4	18	(0)	(0)	8
H	(37)	7	15		10	0	13			9
I							8			8
J	30					38				34
K		4				58	9			24

Table 28: Accuracy of gas monitors at low gas concentrations, as estimated by TF15, in ±%

Monitor	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	Overall 1
A	27						27
C	9						9
D	24	49	102	36	44	66	53
E	(37)	20	31	12	0	8	14
F	(80)	14	35		0	6	14
G		1	0		44	63	27
I	10					25	18

Overall 1: excluding air

Values for some individual gases and gas monitors in Tables 27-28 are based on a very small number of DGA results and therefore may not be representative enough. The Overall 1 values, based on a larger number of results, are more representative and are indicated in Tables 29-30 as a function of the type of gas monitor used (on-line or portable, with diagnosis capabilities or only gas alarm capabilities) and with the number of DGA results indicated:

- "Monitors with fault diagnosis capabilities" in Tables 29-30 means: monitors having the capability of identifying faults PD, D1, D2, T1, T2, T3 according to IEC 60599 or IEEE.
- "Number of DGA results" means: number of DGA results used for the calculation of accuracy values. Accuracy values calculated with a small number of DGA results (e.g., < 10) should be used only with caution.

At routine concentration levels, the IEC specification for accuracy is ±15% in order to get a reliable diagnosis [3]. In Table 29 at routine gas concentrations, several gas monitors with fault diagnosis capabilities meet or are close to that requirement, and therefore can be used directly to calculate fault diagnosis on-line. Those which do not meet that requirement are still reasonably accurate and may be used to calculate fault diagnosis on-line, provided a calculation of the uncertainty on the diagnosis is made, using for example the method described in [2]. Gas monitors with an accuracy above ± 30% in Table 30 should avoid calculating fault diagnosis on-line, or do so only after having calculated the uncertainty on the diagnosis.

In Tables 27-28, for monitors where the number of results for H_2 is large enough to be representative and the accuracy of monitor readings for H_2 is >±30%, it may be preferable to use DGA diagnosis methods (e.g., the Triangle) which do not use this gas.

The accuracies of gas monitors in service evaluated by TF15 in Tables 29-30 in general are not as good as the accuracies measured by manufacturers in the factory and indicated in Table 7. A number of possible reasons explaining these differences have been indicated in section 6.1.

For example, the oil used in a transformer monitored in service is seldom the same as the oil used in the factory to calibrate the monitor, and as the oil used in the laboratory to calibrate laboratory results. This may result in differences between monitor readings in the factory, monitor readings in service, and laboratory results using headspace gas extraction. Depending on the chemical type and density of the oils, these differences related to solubility coefficients have been reported as between ±6% according to [10] and ±15% according to [9], and may be sufficient to explain the differences of accuracy observed in the factory and in service.

Among possible other reasons: systematic biases in the calibrations used in the factory and changes of the properties of gas extraction devices (membranes) with time.

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.

Table 30: Accuracy of laboratories and gas monitors in service, in %, as estimated by TF15 at low gas concentration levels

	Monitor	Number of DGA results	Accuracy
Laboratories		14	27
IEC specification			30
Monitors with fault diagnosis capabilities			
On-line	F	29	14
	E	12	14
Portable	D	15	53
	G	5	27
Monitors with gas alarm capabilities only			
On-line	C	5	9
	A	4	27
	I	2	18

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

10 MEASURING GASSING RATES WITH ON-LINE GAS MONITORS

It has been shown [2] that the measurement of gassing rates from laboratory gas concentration values is much more uncertain than the measurement of concentrations themselves. When calculating gassing rates, what should be considered is not the accuracy of gas concentration values but its reproducibility [1], because laboratory bias (accuracy) affects the position (concentration level) of gassing curves but not their slope (change of concentration with time, or rate).

The definition of reproducibility is given in section 6.1. The average reproducibility of laboratories has been evaluated at around ±10% [2]. When using only two consecutive values of gas concentrations, the uncertainty on the subtraction and therefore on the gassing rate may be very high if the difference is small. The larger the number of concentration values used over a period of time, the less uncertain the calculation of gassing rates, with the use of linear regression equations.

In the case of on-line gas monitors, the number of concentration values measured is much higher (typically, six concentration measurements per day) than with laboratory sampling. The reproducibility of measurements is also better for some gas monitors.

The reproducibility of gas monitors can be evaluated by looking at the small fluctuations and width of the baseline when the monitor is installed on a transformer which does not gas, or which gases only very little. It has thus been evaluated as ± 1-2% for the TM8 [2] and the TNU [7], ± 2-4% for the Tranfix [8,2,1,26], ± 4-10% for the TGM [2,24] and ± 5-10% for the Hydran [1,5] (< 5% in the more recent units).

Table 31 [7,1] indicates the number of days necessary to measure a gassing rate with an accuracy of ±15%, for gas monitors with a reproducibility of 2% and 10%, and for a typical laboratory. It can be seen that gas monitors are able to provide accurate values of gassing rates after a much shorter period of time than laboratory results. Table 31 is valid only if the gas monitors and laboratories have been regularly calibrated and maintained. Also, caution should be exercised when looking at gassing rates calculated over short periods of time, as these may be due to normal variations of gassing with operating conditions (e.g., load, ambient temperature) rather than to an actual fault [9].

The variability of gas concentration values with time is also lower with on-line gas monitors than with laboratory results, where inconsistent values (unexplained positive or negative gassing peaks) are often observed over long periods of time, as a result of changes in laboratory personnel or analytical components. These inconsistencies are sometimes difficult to detect and may cause interpretation problems.

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

11 STABILITY OF GAS MONITORS IN SERVICE

Only one case of unexplained differences between Hydran readings and laboratory results as a function of load has been reported to the TF [4], and could not be attributed to an internal stability or design problem of the sensor. In one report [4], 6 out of 6 Hydran monitors failed after 7 years. In another report [5], 44 Hydran monitor units were taken out of service from a total of 209 units installed over a period of 19 years. This corresponds to an average failure rate of ~2% per year, which is similar to the failure rate of transformers themselves. Furthermore, 80% of Hydran failures in the older Hydran units are related to the bursting of membranes when transformer is put under a vacuum. This problem has been solved in more recent units. 300 Hydran monitors 201T1 in operation in 2006-2007 had an average failure rate of ~ 0.5% per year [6]. Some teething problems have been reported [6] with the new Hydran M2 monitors.

Changes in the hydrogen readings of Transport-X monitors after 2 years of use have been reported [9]. Also, the readings of some monitors appear to be affected by extreme atmospheric conditions such as dryness (below 5% of humidity) or high sun exposure[9].

Gas monitors do not otherwise appear to have significant stability problems in service. It is to be noted, however, that several of the new gas monitors on the market have been in operation for only a few years (see Table 4) and that their long-term reliability in service is not known.

12 CONCLUS IONS

1 The accuracy of gas monitors in service has been evaluated by TF15 by comparing monitor readings with laboratory results corrected for laboratory bias, repeatability of the oil sampling/ laboratory analysis process and the uncertainty on the gas-in-oil standards used for evaluating the bias.

2 At routine concentration levels (> 10 ppm for hydrocarbons), most gas monitors tested in this Report meet or are close to the IEC requirement of accuracy on DGA measurements (± 15%), except for hydrogen with some monitors, and therefore can provide fault diagnosis on-line. For those above ± 15%, it is recommended to calculate the uncertainty on the diagnosis provided, using published methods [2]. Gas monitors with accuracy above ±30% should avoid calculating diagnosis, as these would be too unreliable.

3 When comparing monitor readings to gas concentration limits in service (particularly for monitors with only gas alarm capabilities), the accuracy of the monitor reading should be indicated (e.g., 100 ppm H_2 ± 15 ppm).

4 Some monitor units in service are less accurate than others of the same brand or model. When in doubt, the accuracy of these units can be evaluated using the procedure described in Annex B of this Report. Several units can be tested for accuracy at the same time, using the same sample of gas-in-oil standard.

5 The H_2 readings of some gas monitors differ markedly from corrected laboratory values, and their accuracy in service should preferably be verified using the procedure described in Annex B. DGA diagnosis methods which do not use this gas (e.g., the Triangle method) would be preferable in such cases.

6 On-line gas monitors tested in this Report are more reliable than laboratory results for measuring gassing rates and following gassing trends, provided these are calculated over proper time intervals. As compared to laboratory analyses, they also allow to detect faults which might otherwise go unnoticed between regular oil sampling intervals.

7 No stability problems in service related to the internal design of gas monitors tested in this Report have been reported. The long-term stability of the more recent monitors on the market, however, is not known. The readings of some monitors may be affected by some ambient atmospheric conditions.

8 When abnormal gassing is detected, it is recommended to seek confirmation of monitor readings by laboratory analysis and of transformer condition by DGA experts. Catastrophic failures occurring without prior warning within minutes or seconds may only be detected by the Buchholz gas relay or the Sudden Pressure Valve.

9 The overall cost of monitors should include the costs of software and personnel necessary for handling and interpreting the large quantities of data generated by monitors, and also for their maintenance and repair on-site or in the factory.

10 The future development of gas-in-oil standard samples to evaluate the accuracy of gas monitors in service would be desirable, using the same oils as in the transformer where the gas monitors are installed.

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14 CONTRIBUTING AND PARTICIPATING MEMBERS

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APPENDIX A – READINGS IN PPM OF SINGLE GAS MONITORS

Table A1- Readings in ppm of single-gas monitors A and B

Monitor	Lab #	Unit #	Reading
A	d	1	658
		2	22
	e	1	118
		2	150
		3	98
		4	22
		5	81
	g	L1-1	50
		L1-2	279
		L2-1	170
		L3-2	300
		L1-3	160
		L2-2	197
		L3-1	15
		L3-3	320
	i	1	149
		2	73
	n		143
B	i	1	109
		2	73
		3	142
	k		107

Table A2- Readings in ppm of single-gas monitor C

Monitor	Lab #	Unit #	Reading
C	l	1	7
		2	8
		3	7
		4	13
		5	10

Table A3- Readings in ppm of portable, multi-gas monitor D

Monitor D	Lab #	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H6	CO	CO_2
2004	i	4	18	1113	1027	0	731	313	1828
		2	19	7	4	0	4	442	1223
		3	42	174	470	4	300	193	3122
2005	j	1	10	102	61	0	157	440	4292
		2	5	42	8	0	82	140	1512
		3	0	91	58	0	96	94	1464
		4	12	51	40	1	22	225	6169
2004	d	2	5	5	6	0	4	478	2591
		1	167	463	595	189	306	312	7326
2006	b	1	20	177	28	0	56	447	1570
		2	46	150	290	21	56	106	2514
		3	8	5	10	0	3	142	2679
		4	9	7	14	0	4	134	3389
	a		12	13	10	33	1	17	348
	n		29	205	91	0	640	639	6322
	p		132	16	24	73	9	15	628
	q		43	5	8	6	6	229	2568

Table A4- Readings in ppm of multi-gas monitors E

Monitor E	Lab #	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2
	f		66	159	1091	112	154	403	14700	20842
	j	1	95	137	70	0	176	565	4668	127
		2	20	11	5	0	49	88	992	113
	a		37	6	6	29	6	14	319	141
	l	7	24	8	114	0	16	887	15700	
		8	5	1	0	0	3	66	2587	
		9	10	1	11	0	11	245	6822	
		10	34	4	17	1	10	92	2414	
		11	67	5	5	1	9	144	1428	
	n		80	166	67	0	531	459	5274	645
	p		92	26	4	70	0	15	537	36441

Table A5- Readings in ppm of multi-gas monitors F

Monitor F	Lab	Unit #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2
2006	a		35	0	0	48	5	15	391	91
2004	j	3	12	88	42	0	76	90	1246	308
		4	29	51	29	0	18	234	4927	284
	o		1	79	7	0	123	201	2499	417
	r	1	3	573	7	0	5	3	545	29
		2	0	15	2	0	66	10	818	57
		3	6	34	0	0	31	127	2943	136
		4	12	53	1	0	48	79	1493	190
		5	12	46	1	0	14	213	4830	270
		6	24	192	7	0	276	385	6846	670
		7	68	574	204	0	222	1336	18525	694
	o	1	16	268	23	0	418	573	11904	725
		2	65	590	200	0	230	1375	17919	723
		3	18	53	4	1	43	137	3162	125
		4	28	234	1	0	152	594	6978	316
		5	52	132	6	0	91	311	7309	485
		6	21	16	0	0	9	99	1253	66
		7	18	83	0	0	54	314	5350	221
		8	20	33	0	0	12	173	31983	2209
		9	14	51	1	0	16	269	4926	265
2006	s	1	0	44	22	0	67	123	1926	301
		2	0	12	0	0	0	140	1928	49
		3	0	0	0	0	0	17	4200	45

Table A6- Readings in ppm of multi-gas monitors G-K

Monitor	Lab #	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	O_2	N_2
G	c	1	3	3	7	0	160	831	22721	66680
	p	109	15	22	80	6	16	551	32212	68353
H	c	100	52	85	1	276	534	7638		
I	c	14					213	3122	25117	67049
J	l	20					1461			
K	m	13	24	3	1	5	318	4500		

APPENDIX B: P ROCEDURE F OR CO MPARING GAS MONITOR RE AD-INGS WITH LABORATORY RESULTS

-Purchase a sample of gas-in-oil standard from an appropriate vendor, or prepare one according to IEC 60567 or ASTM D3612.
-Take a reading on one or several on-line gas monitors installed on transformers in service.
-Take 4 duplicate samples of oil from the sampling point of the monitor(s), immediately after having taken the reading.
-For portable gas monitors, take 5 duplicate samples of oil from a transformer. Using one of the 5 samples, take a reading of the portable monitor.
-Send all the above samples of oil to the DGA laboratory.
-Analyze all samples on the same day (or over no more than a few days), using the same analytical equipment for all samples.

-Convert all DGA results and monitor readings to the same units (IEC or STP ppm).
-Calculate the bias of the laboratory by comparing its results for the gas-in-oil standard sample to what was actually prepared.
-Correct all other DGA lab results using the bias calculated above.
-Calculate the average values (A) of each set of 4 duplicate samples, in ppm.
-Calculate the repeatability (R) of lab results as the difference between results for the individual 4 samples and average values (A), and express it in %.
-Calculate the difference (D) between gas monitor readings and average values (A), and express it in %.
-The maximum accuracy of the gas monitor as measured by the lab = (D-R-2), in %, where 2% is the uncertainty on the gas-in-oil standard.

For example, if
-Gas-in-oil standard S = 100 ppm, Lab result for S = 90 ppm,
-Lab results for 4 duplicate samples = 250, 230, 210, 240 ppm,
-Lab results corrected for bias = 275, 253, 231, 264 ppm,
-Average value (A) = 256 ppm, Repeatability (R) = 9%,
-Monitor reading = 300 ppm, Difference (D) = +17%
-Maximum accuracy of gas monitor = (17-9-2) = +7%