Improved Monitoring of Dissolved Transformer Gases on the Basis of a Natural Internal Standard (NIS)

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SUMMARY

Dissolved Gas Analysis (DGA) is a well-accepted method in the field of transformer diagnostics. Its principles are described by IEC 60567. In practice, this method could give rise to unacceptable differences between results from different laboratories and short cyclic analyses of the same laboratory. It can also result in differences between on-line measurements and laboratory analyses. Basically these differences are influenced by sampling technique, sample transportation and storage, gas extraction and analysis methods. This contribution will present the effect of certain factors that influence the results of DGA analysis and how the DGA accuracy can be checked and improved.
Based on experimental gas-in-oil analysis, different factors that influence oil sample quality and gas analysis are being investigated.
An innovative way to overcome the above mentioned difficulties are to define a Natural Internal Standard (NIS) for transformer oil under saturation condition in an air-breathing transformer. This represents a further development of the external air-in-oil standard defined by IEC 60567. On-line equilibrium gas, for which pressure and nitrogen concentration must be measured accurately, aims at providing direct evidence of this state. Pressure and nitrogen concentration in oil have to be equivalent to those in the atmosphere (NIS criterion). Hence, the technical implementation of the online equilibrium gas ensures that all other gases are in an equilibrium state as well.
Based on Henry and Dalton's law, it has been demonstrated that transformer monitoring techniques meeting the NIS criterion have an average value of C_{N2} = 66,000 ppm ± 5%. This may be regarded as a simplified NIS criterion, which can be generally applied to equilibrium techniques.
The handling of samples using a minimum number of steps is very important for the manual application of equilibrium gas. This differs from the on-line equilibrium gas, in which oil and gas phase must be added to calculate the gas-in-oil concentrations.
If the NIS criterion exists, an accurate composition of the equilibrium gas is available as long as calibrated measuring equipment is used. Solubility coefficients allow all gas-in-oil concentrations to be calculated.
The application of the NIS criterion allows quality-controlled analyses at any time and without any additional cost. If the equipment for equilibrium gas works reproducibly under NIS application, then it is possible to reduce quality control to calibration for re-saturation and hermetic conditions. More reliable diagnostics require not only NIS-based data but also exact information about the gas household. This will lead to less variation in values for evaluation criteria.

KEYWORDS

Oil sampling, gas extraction, oil sample storage, air bubbles in oil, light, temperature, DGA, natural internal standard (NIS), NIS criterion, extraction gas sampler (EGS), TGM, equilibrium state.

1 INTRODUCTION

Throughout the service life of air-breathing power transformers, insulating materials are prone to ageing caused by electrical, mechanical, environmental and thermal stresses. The condition of insulation materials; oil and paper, are considered as a functioning indicator of power transformers, thus an effective evaluations of the insulation provide trustworthy information for an accurate diagnostic. Generally, moisture, acids, sludge and gases dissolved in oil are known as products of ageing [1]. Under conditions of normal transformer functioning, ageing can occur at a slow pace however this process tend to accelerate harmfully due to electrical and thermal faults. The transformer oil undergoes chemical reactions that result in generation of soluble gases of hydrocarbon composition. Thus, concentration and gas rate generation usually are dependent on fault characteristics, such as type and intensity. Fault gases dissolved in oil are known as a mixture of light hydrocarbons such as methane, ethane, ethylene, acetylene, propane and propene along with carbon monoxide, and carbon dioxide, hydrogen, oxygen and nitrogen.

A very useful tool to diagnostic incipient faults in power transformers is the DGA method [1]. This method has become very renowned as an effective and rather simple method that aims at predicting the lifespan of a power transformer. The quality and accuracy of a DGA analysis depend on right performance of the method. The first part of DGA method consists of appropriate oil sampling [3], which implies avoiding external contamination of the sample and air in the sampling container. This will guarantee a representative analysis of the sample. The second part consists of extraction of dissolved gases by means of an appropriate and reliable extraction technique. Third part is for qualitative and quantitative analysis of the extracted gas by gas chromatography or spectroscopy. In the case of analysis done in laboratories, samples taken by authorized personnel are stored while they are sent for DGA analysis. Before laboratory analysis, samples can be exposed to some influencing factors during storage, transportation and handling. However, unwanted errors of oil analysis could be minimized by state-of-art online monitoring techniques of DGA. Continuous oil evaluation can provide insight into gas-increasing rate and fault development, allowing implementation of right and timely maintenance plans. An effective DGA analysis program depends radically on the proper technique of oil sampling [2], sample storage and gas extraction.

There are several degassing techniques useful to extract dissolved gases from oil. For instance, vacuum extraction by Topler pump or non-mercury vacuum pumps, which extract gases by repetitive vacuum extractions. Other popular degassing technique is based on headspace equilibrium. In this case certain oil volume contained into a glass vial is set in contact with an inert gas phase (headspace) under controlled temperature, pressure and agitation conditions. Based on the Henry's law a mole fraction of gas dissolved in oil is directly proportional to the partial pressure of the gas in equilibrium with the liquid surface at a fixed temperature [3]. Thus, the headspace created above the oil surface contains gases dissolved in oil in equilibrium with the liquid phase. Then the concentration of extracted gases can be quantified by gas chromatography analysis. The quality assurance of the gas-in-oil analysis by different extraction methods can be verified by means of external gas-on-oil standards. Round Robin tests that combine extraction and gas chromatography may show deviations up to 44%.

2 INFLUENCE OF STORAGE OF OIL SAMPLES ON DGA

After sampling oil samples are sent for laboratory analysis contained either in syringes or aluminium bottles. These containers should be free from contamination and air tight sealed. During sample transportation, these should remain properly stored in their containers, avoiding external factors that can influence the result of gas-in-oil analysis. Usually sample containers should be fully filled up and kept without air. Thus, adequate sample storing becomes of vital importance to obtain the most accurate gas-in-oil analysis result.

Some experiments were conducted in order to investigate the influence of factors such as air bubbles, daylight or darkness, and temperature on stored oil samples contained into glass syringes.

Oil samples were prepared in 50 ml syringes using mineral oil Nynas Nytro 10 GBN under air-saturated condition. Samples were stored for certain periods under the effect of one of the investigated factors. After the test period, gas-in-oil analysis was conducted by means of portable gas-in-oil

equipment based on photo acoustic spectroscopy, Transport X from Kelman. In this equipment, the oil sample is introduced into a container, in which the sample is steadily agitated and re-circulated at constant temperature in order to establish the equilibrium between headspace gases and oil [4]. Thereafter, concentrations of dissolved gases (CH_4, C_2H_4, C_2H_2, C_2H_6, CO, CO_2, H_2) were determined by a photo acoustic spectrometer. Analysis of gas-in-oil results has demonstrated the quantitative impact of storage factors on the results of DGA. Especially attention was focused on the concentration of hydrogen as a critical component.

2.1 Effect of Air Bubbles

In order to analyze the effect of air contained in the sample container, air bubbles of different volume were introduced into the sample and then stored in darkness for 4 days. Samples were prepared with oil aged at 120 °C for 4 days. Additional samples were stored in darkness without air bubbles in order to use them as a reference for comparison analysis. After obtaining result of gas-in-oil analysis, the values were normalized on the basis of concentrations of reference samples. The Fig. 1 shows a graphical representation of the effect of air bubbles of different volume contained in the sample, on the concentration of H_2, CO and CH_4, which were the components that presented major deviation on their concentrations. Thus, it can be seen these concentrations tend to decrease as the volume of air bubble increases. Especially the concentration of hydrogen is significantly affected by a decrease of approximately 35 % when air volume is more than 1% of the sample volume. The behaviour of these gaseous components can be explained by the low solubility of these gases in oil and diffusion between gas-oil phases in the sample volume. Therefore bigger air bubbles allow larger diffusion of the less soluble components in oil, consequently, there will be lower concentration of dissolved gases in oil.

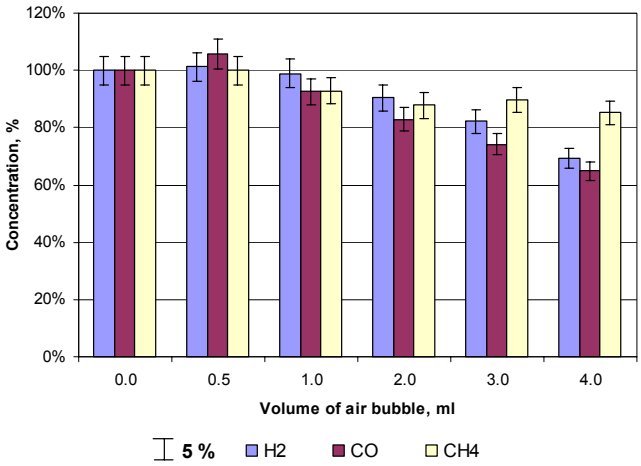

Fig. 1 Influence of air bubbles of different volume on DGA results

Air bubbles in oil samples can occur either during oil sampling or storage, and their effect will result in erroneous DGA results. Hydrogen concentration can decrease up 40%.

2.2 Effect of Light

The influence of light was investigated with samples stored under effect of sunlight or darkness. These tests were done with samples prepared with air-saturated oil of new or aged condition. After 8 storage days, results of gas-in-oil analysis have demonstrated that concentrations of hydrogen and carbon dioxide were the most affected components for both oil conditions; new and aged oil. The Fig. 2 shows a comparative representation of concentrations influenced by sunlight or darkness. The Concentrations were normalized with respect to reference samples stored in dark without air bubbles.

In the case of samples of new oil, the concentration of carbon monoxide (519 ppm) can reduce 12% stored in darkness, while hydrogen concentration does not suffer any alteration since its concentration is less than 5 ppm.

Samples prepared with aged oil were artificially induced to undergo oxidation reactions that lead to generation of gases dissolved in oil. For the reference sample, hydrogen concentration was 72 ppm and carbon dioxide 544 ppm. Thus, it can be seen that under the influence of sunlight the concentration of hydrogen can increase up to 24%, while concentration of carbon dioxide did not presented any change. The further production of hydrogen under the effect sunlight can be assigned to

photochemical reactions that involve decomposition of water molecules generated during ageing [4]. In the case of darkness, hydrogen concentration increases approximately 10% due to further reactions occurring during storage. However, it should be considered that these concentrations could range within the 5% of measurement deviation. Other components did not presented any significant concentration deviation with respect to the reference values.

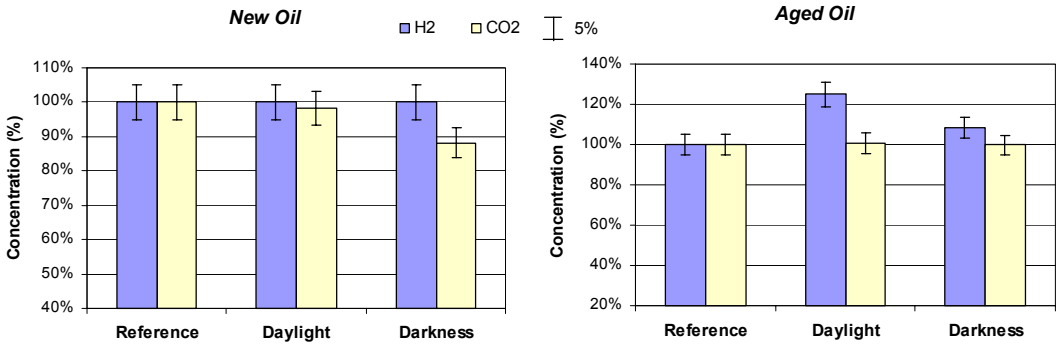

Fig. 2 Influence of sunlight and darkness on concentrations of H_2 and CO_2

2.3 Effect of Temperature

2.3.1 Storage at 60 °C (in darkness without air)

This experiment was done to demonstrate the effect storage at high temperature. Generally, samples should be stored at ambient temperature and in darkness, however during sample transportation to laboratories, it can be exposed to high temperatures.

The Fig. 3 represents the concentration development of carbon dioxide, hydrogen and carbon monoxide within a test period of 192 hours. Thus, it can be seen that at the end of the test period of 192 hours, concentrations remained almost invariable, and therefore storage at relatively high temperature did not cause a significant variation of concentrations.

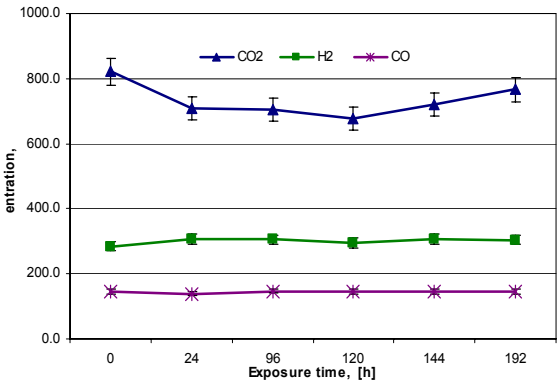

Fig. 3 Influence of temperature on DGA results

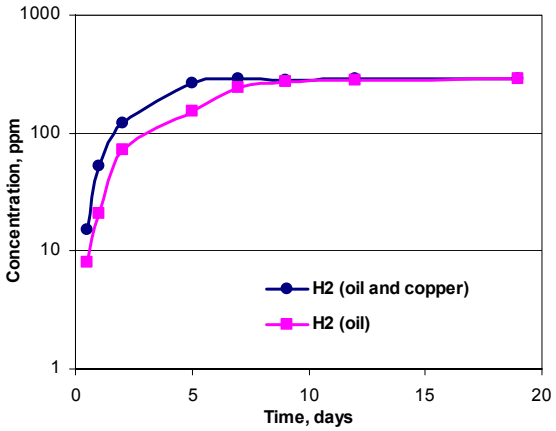

Fig. 4 Stray gassing effect @ 90°C

2.3.2 Stray Gassing

Samples stored at 90°C for about 20 days has demonstrated an unusual gassing behavior [5] that present some mineral transformer oils when they are heated at relatively at low temperatures. This effect is called as stray gassing, and it is accelerated by oil interactions with metallic parts, such as copper. The gassing behavior includes increased production of hydrogen until reaching a plateau (see Fig. 5), and in some cases also methane and ethane. Concentrations of stray gassing oils can be easily mistaken for a fictitious electrical fault, and therefore DGA analysis can lead to wrong interpretation. The experimental investigation has demonstrated that the oil investigated corresponds to stray gassing oil.

3 BASIC PARAMETERS OF THE GAS HOUSEHOLD

3. Two Phase Storage/Extraction Equipment

It is usually not possible to store dissolved gas-in-oil samples in a stable way. A storage temperature that is lower than the sampling temperature, leads to oil volume contraction with gas separation. The result is a lower gas concentration in the oil, especially for the gases with low solubility. The loss is higher in bottles than in syringes. All extraction techniques are affected. A practical solution was developed in form of the **e**xtraction **g**as **s**ampler (EGS) of the GATRON company [6].
The Fig. 5 shows the sampling unit. It is a bottle with a cap in which a vertical filling tube with an inflow/outflow valve and thermometer (a) is integrated. When the sampling process is finished, the filling cap must be exchanged with the end-sealing cap. The result is that the volume of the filling tube is replaced by a free air volume (b). This is a well-defined two-phase system. All necessary parameters are registered for the sampling record. Because it is a closed system, all changes between the two phases during storage can remain unknown. It is only necessary to have the equilibrium state at the moment of sampling for the analysis. The equilibrium state is simply achieved by horizontal shaking over a period of one hour at laboratory temperature. In principle, it is possible to take an oil sample for the common gas extraction after measuring the equilibrium pressure. But this requires an additional gas extraction. The best way is sampling of equilibrium gas for a direct gas chromatographic analysis. This may be done manually or with an auto sampler. The result is the complete determination of both the atmospheric and the fault gas concentrations in the oil. This can be regarded as a further development of the known headspace technique.

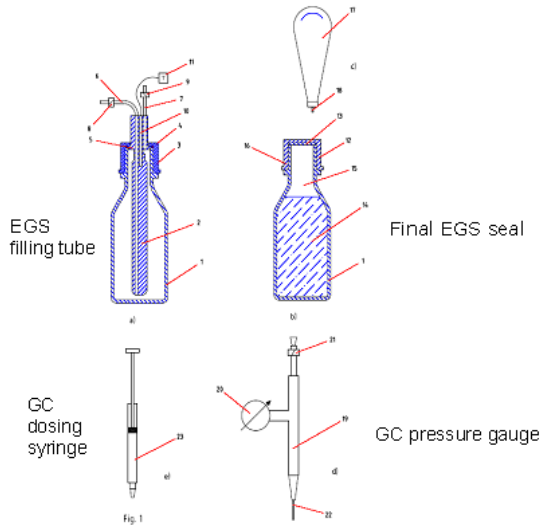

Fig. 5 Extraction gas sampler (EGS)

4 NEW QUALITY CONTROLLED DGA

For on-line techniques, it is necessary to redefine quality control. The user has to know what the true gas-in-oil concentrations are. The best way is to measure them in an integrated process during sampling. A straightforward way to measure and evaluate dissolved gases on-line is shown by the "riser tube experiment" in Fig. 6. In the vertical tube, which is closed on the top, is a natural on-line equilibrium gas. Henry and Daltons' law define its pressure. The solution pressure is proportional to the oil level in the closed tube. There are three typical fixed points of the gas household on the scale of the solution pressure. For practical purposes, it is not accepted to use a tube longer than 10 meters on the transformer.
The technical solution is the transformer gas monitor TGM [7] developed by the GATRON Company. Fig. 7 shows the extraction column of the TGM in a simplified form. Its height is just approximately 50 cm. *The oil flow from the transformer into the tube is free and the oil level constant if a regulated oil pump is used.* Above the oil level, there is a sealed equilibrium gas space. All these three conditions are necessary and controllable with the TGM software. Under such conditions, the solution pressure Σp_i can be measured directly, continuously and faultlessly as the pressure in the equilibrium gas space with the help of a calibrated sensor.
So the solution pressure is used as the basic parameter of the gas household in practical measurements, which means:

a) comparison of the measured pressure with the calculated solution pressure, which is based on a full analysis of all known analytical techniques;

b) calibrated measuring of the composition x_i of the equilibrium gas on-line or manually and use of the real solubility coefficients k_i (T) for calculation of the true gas concentrations in oil c_i. *From this follows that the measured solution pressure is a new quality criterion. It can be used only on-line after TGM installation.*

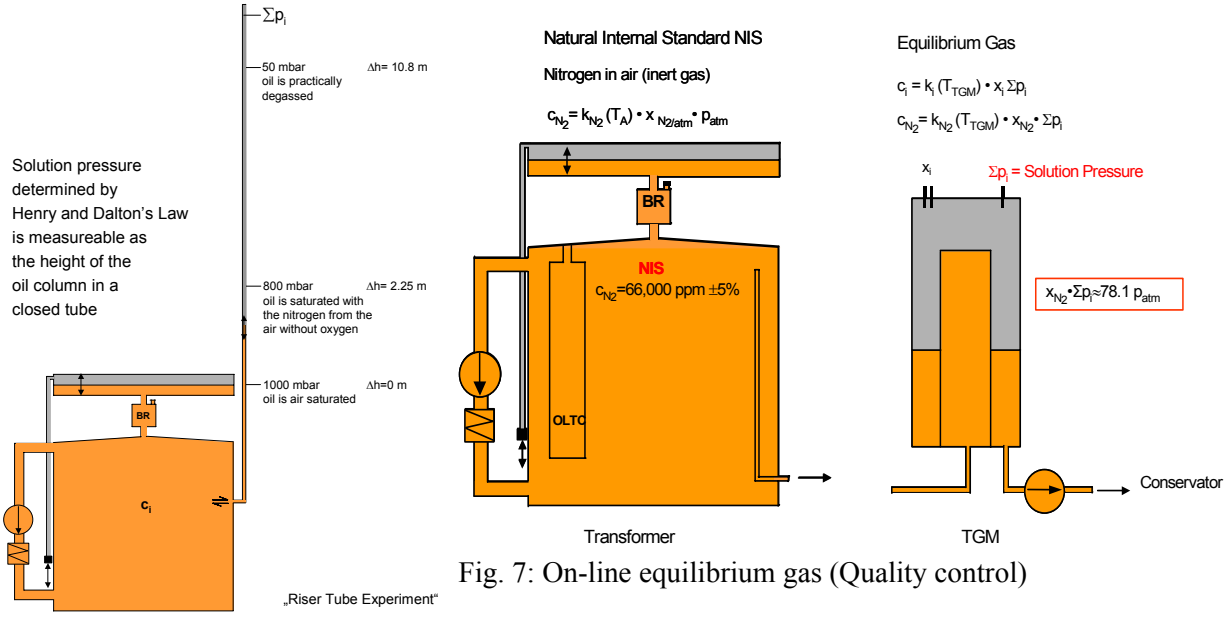

Fig. 7: On-line equilibrium gas (Quality control)

Fig. 6: Basic parameters of gas household solution pressure Σpi

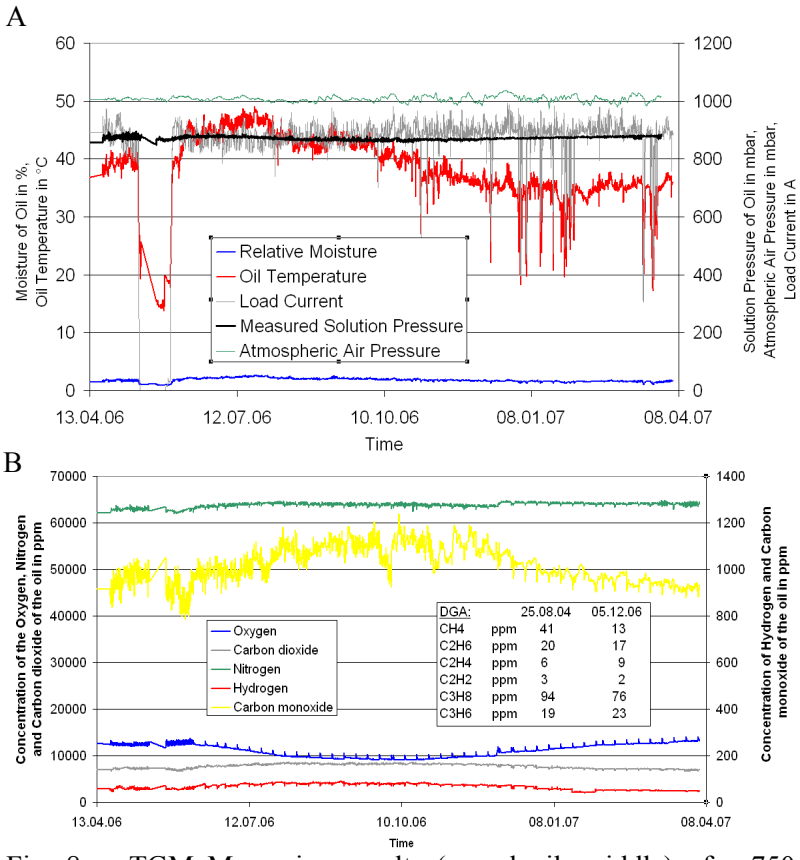

Fig. 8: TGM Measuring results (vessel oil, middle) of a 750 MVA GSU Transformer (open breathing type).

Fig. 8 shows results of the TGM system. Part A depicts the slope of the solution pressure over a period of one year. In difference to the atmospheric pressure the solution pressure is constant. The individual gases measured on-line are shown in Fig. 8 B. The values correspond with a high degree to the values measured by conventional DGA sampling. The enhanced version of the TGM also allows to monitor the sum of hydrocarbons on-line.

Experience from more than 50 air breathing transformers over the last 5 years shows that the nitrogen partial pressure in the equilibrium gas is the same as in the atmospheric air. The equation (a) showed in Fig. 7 can be used as the **n**atural **i**nternal **s**tandard (NIS) for the equilibrium state. For general use, it is necessary to calculate the nitrogen concentration for the average atmospheric pressure

and conservator temperature with the real k_{N2} (T).
The result is the simplified NIS criterion: c_{N2} = 66.000 ppm ± 5% (see Fig. 7). The ± 5% means independence of the height above sea level of the transformer location, of the conservator temperature and of the real k_{N2} (T).

	T 1 (SP middle, 05.02.2007)				T 2 (SP middle, 05.02.2007)			
	Total Extraction Laboratory 3	TGM Display (online)	TGM Gas [1] (manual)	EGS (GATRON)	Total Extraction Laboratory 3	TGM Display (online)	TGM Gas [1] (manual)	EGS (GATRON)
H_2 [ppm]	40	55	59	64	21	25	26	33
O_2 [ppm]	15,800	13,000	12,310	13,434	12,000	5,500	6,370	5,768
N_2 [ppm]	61,200	64,000	63,892	64,774	65,300	64,000	64,707	64,900
CO [ppm]	537	950	1,026	1,004	474	740	826	853
CO_2 [ppm]	3,030	7,500	8,631	7,649	2,080	5,000	5,004	5,287
CH_4 [ppm]	15		11	14	20		19	24
C_2H_6 [ppm]	12		14	17	14		15	22
C_2H_4 [ppm]	11		7	11	10		6	9
C_2H_2 [ppm]	6		1	< 1	<1		< 1	< 1
C_3H_8 [ppm]	20		77	72	27		106	111
C_3H_6 [ppm]	10		19	27	15		35	53
Solution Pressure [mbar]	875	890	890 [2]	920 [3]	900	840	840 [2]	866 [3]

[1] Laboratory 3, [2] from TGM, [3] calculated

Tab. 1: Comparison of different NIS controlled analytical methods with the total extraction

The very important advantage of the simplified NIS criterion is that it applies to all equilibrium methods. It is possible to transfer the equilibrium state of nitrogen to all other individual gases, which are dissolved in the oil. In combination with calibrated analytics and real k_i (T) sufficiently accurate gas concentrations c_i can also be calculated. For methods other than equilibrium methods, the simplified NIS criterion is not sufficient for quality control. The developed EGS method is such a suitable equilibrium method.

Tab. 1 is a comparison of total extraction with two quality controlled equilibrium methods (TGM, EGS). *In stable state of an air-breathing transformer, there are some differences to the total extraction results although the NIS criterion is fulfilled.* The interesting points are:

- Total extraction and manual analysis of the TGM gas by the same laboratory (lab 3) leads to different results;
- The comparison of the TGM gas (manual) and EGS shows that different laboratories and different methods lead to same results analogous to TGM values (on-line).

It can be concluded that the simplified NIS criterion is also a new quality criterion, but valid only for general application to equilibrium methods.
In the case of laboratory analytics, a mixture of samples is typical: stationary state and different degassed oil of air breathing transformers, oil of all types of hermetic transformers and perhaps also oil of nitrogen blanketed transformers. Therefore, it becomes also necessary and also acceptable to use the simplified NIS criterion for the quality control of transformers

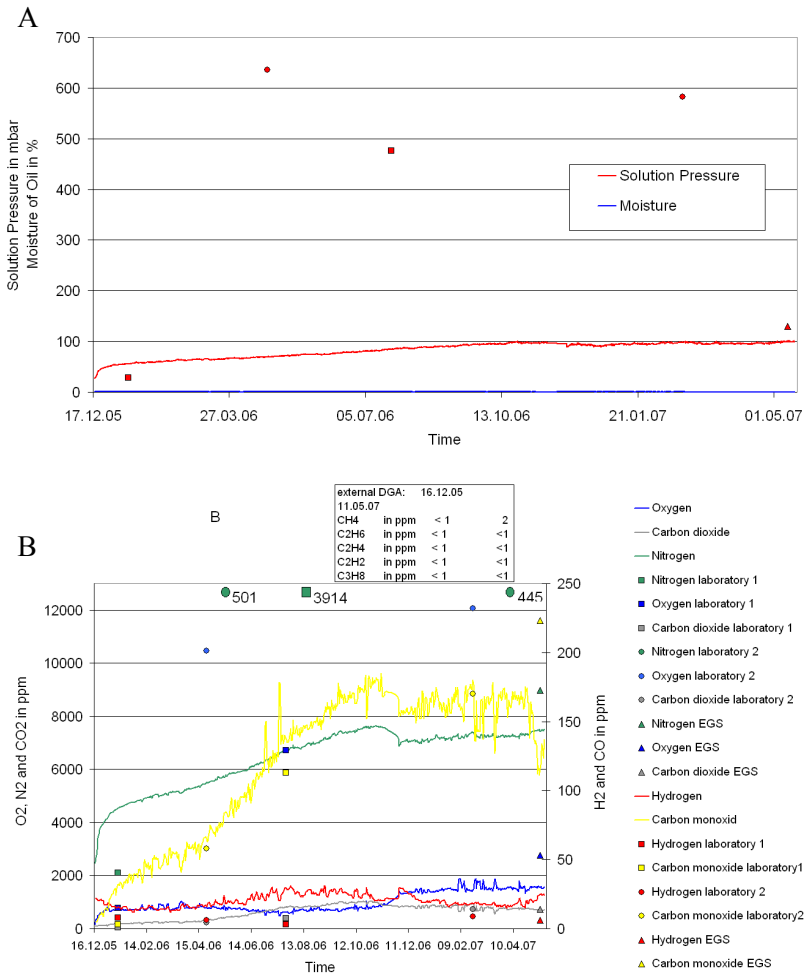

Fig. 9: Comparison of laboratory analysis with the TGM slope of sealed type transformer (date of commissioning 12/05)

other than air breathing ones. It is a big problem to monitor degassed oil transformers with externally controlled laboratory methods. Fig. 9 shows the TGM slopes of the gas parameters. The solution pressure is slowly increased to 100 mbar. The total extraction techniques (labs 1 and 2) show significantly higher values. EGS control is within an acceptable tolerance. In the case of the individual gases, it is the atmospheric gases, which show high concentrations. The reason might be problems with the hermetic condition.

5 CONCLUSIONS

Experimental investigations have demonstrated quantitatively the effect of factors such as air bubbles, daylight or darkness, and temperature on stored oil samples contained into glass syringes. Thus, the concentration of critical components as hydrogen can be significantly affected by these factors. Air volume larger than 1% of oil sample can cause a hydrogen concentration decrease of 35%. Sunlight can lead to further production of hydrogen up to 125%, and storage at temperatures above ambient (up to 90°C) can have a significant effect if the oil presents stray gassing behaviour.
Generally, oil samples stored at room temperature in darkness and contained in sealed containers without air, could guarantee a more accurate DGA.
The simplified natural internal standard (NIS) criterion is a new quality criterion applied for general application of equilibrium methods. The very important advantage of the simplified NIS criterion is that it is possible to transfer the equilibrium state of nitrogen to all other individual gases, which are dissolved in the oil.

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