



ABSTRACT

Transformer insulation matrix has already co-existed for more than 120 years alongside the transformer itself [1]. During that time, many different tests were developed in an effort to find the best solution to assess the transformer condition and to predict and avoid transformer failure. Even though the dissolved gas analysis was not the first test used and considering it is not an electrical test at all, the analysis has nowadays become the most widely and effectively used diagnostic test for transformers' health status. It is claimed that more than 50 % of incipient problems associated with transformer health can be detected by this single but very complex test. The popularity of the DGA can be attributed to many factors, but the majority of the users will have a hard time understanding the test's nature. Most extraordinary facts concerning DGA is how this chemical par-excellence test became the most important test for this special

kind of magnetic and electrical device. The rivalry between electrical, physical, and chemical tests still exist, but for the last ten years, all transformer owners rely mainly on this test considering it the most important one. And as a chemist with a 30 years experience in chemical tests for insulating oil and especially DGA, I suggest that the apex of DGA as it is performed today is near, and other tests with a more accurate and robust monitoring technique might soon replace it.

Oil immersed transformers have been routine equipment since the end of the 19th century and a correlation between failures and combustion gas apparition has been observed since then. During the last 100 years [2], dissolved gas analysis has become the most important test for assessing liquid-immersed equipment condition and is especially useful in prevention of catastrophic and costly failures. Even though a transformer is an electrical device, the

DGA is a purely chemical test, which combines vast knowledge of different chemistry specialties together with electrical knowledge for diagnostic purposes. Throughout this long epoch, the transformer function, design, and materials remain, at first glance, unchanged but in reality they underwent many changes. Despite the huge funds spent by many companies all around the world, DGA is still an emerging method. This situation will be explained and elaborated, along with an overview of its main pain points, solutions to a better implementation of the method and plausible scenarios for the next generation.

The technique of extracting gases from the insulating materials to evaluate the transformer condition will probably disappear in the future. The transformer conditions have to be considered independently from the continuous alteration of the structure of insulating materials.

DGA has become the most widely and effectively used diagnostic test for transformers' health status

A CENTURY OF DISSOLVED GAS ANALYSIS - PART I

Introduction

Electricity powers the world and is an indispensable product for humanity, almost like water and food. This energy category needs two types of materials which make it feasible - electrical conductors and electrical insulators. In practice, no one can afford to use ideal conductors and insulations matrixes. Accordingly, the industry has to compromise with the best available materials at acceptable prices. Power transformers, like any other electrical device, have to contain these two types of materials. The most advantageous insulation media for most power transformers today is liquid insulation combined with solid insulation for both mechanical and electrical strength. It is well known that increases in temperature of conductive and insulating materials decrease their capabilities to conduct and to isolate the electricity, respectively. Temperature positive feedback deteriorates the properties of both media, conductors and insulators, exponentially. One of

the advantages of using liquid insulating in electrical equipment is having a potential log data of all malfunctions of the transformer or other electrical equipment. In dry and gas insulation these information sources of faulty conditions are practical inexistent or hard to achieve, at least nowadays, but that may change in the future. If the oil reservoir is accessible for sampling, the operational data can be extracted without disturbing the exploitation of the equipment. For limited oil volume devices, obtaining a sample can be more complicated and can impose special restraints. Most liquid-immersed power transformers and other liquid-immersed devices are enabled for obtaining a representative oil sample

in reasonably safe conditions. These oil samples contain around 70 % of operational data [3]. The most important and significant test for evaluating transformer condition is the dissolved gas analysis - DGA. This test contains the greatest amount the operational data. The main benefit of DGA is the unique advantage of being potentially capable of predicting the majority of the failures and evaluating the health state of transformers. Of course, it cannot assist in preventing all of the internal failures. Also, a great percentage of the issues detected inside the transformer are not vital and without the DGA it is plausible that transformer may be able to operate until the planned end of life even if it produces gases. [10]

It is claimed that more than 50 % of incipient problems within a transformer can be detected by this single test - DGA

The sampling is the most critical and important step for DGA reliability

It is very interesting and amazing that after more than 80 years of using DGA as the most important method to diagnose electrical equipment, there is still a significant ongoing debate about the gas formation mechanism, nomenclature, diagnosis etc. as written recently by R. Cox [4] mentioning “mystery” of unusual or stray gassing [5]. The main conclusion transformer users should come at is that the entire chain of DGA from sampling to diagnosis and recommendations depends on their maintenance policy, strategy and investments, as well as on the sensitivity of alarms for unusual cases, even when alarms are not triggered by a software or external service supplier.

It is important to remember that DGA, like any other chemical method proposed to evaluate the condition of an electrical device such as power transformer, was only recently accepted as reliable and ultimate method by electrical engineers. No more than 20

years ago, DGA was considered to be an unusual marginal method that tried to compete with well established and well-known electrical procedures. Although the technical literature in the last 40 years mentions DGA as a valuable method, electrical engineers around the world were very suspicious how those parts per million gases dissolved in oil can predict incipient failure. It probably took a few failed transformers to convince the industry that chemical tools are able to predict electrical faults in electrical devices. DGA has been weirder and more extreme than any other historical oil test, such as breakdown voltage, water, or acidity.

DGA today

Although most of scientific and professional literature as well as marketing materials refer to DGA as a method for interpretation of principal dissolved gases concentrations, the DGA method is much more than ratios,

mathematical algorithm, geometric shapes or even thermodynamics models.

A reliable DGA evaluation must consist of these 4 steps: sampling, extraction of gases, measurement of gases and finally, diagnosis, i.e. assessment of the transformer condition. The importance of the steps starts from low to high tech, e.g. the low-tech procedures are the most important ones.

Sampling

The sampling is the most critical and important step for DGA reliability. Although at first glance it seems to be a trivial process, most of the causes for the uncertainty is related to the sampling quality. The most accurate measurement and the best diagnostics cannot correct inadequate sampling.

Each of those sampling devices has advantages and disadvantages. The transparent glass is easy to clean and to observe oil condition or to notice the appearance of bubbles; however, glass is fragile. From 80’s onward, the hypodermic syringes became the best option. The great advantages of syringes are that they:



Figure 1. Ampule syringe and bottles

In practice, the oil taken from the main tank does not contain homogenous gas concentration, even in the case of forced oil cooling

- Permit to obtain an oil sample that was never exposed to the atmosphere
- Allow oil expansion and contraction without exposing it to any kind of atmosphere
- Are suitable to simply inject or introduce the oil directly without exposing it to any kind of ambient conditions in the majority of the measurement devices for DGA.

Main disadvantages are fragility, limited volume in comparison to previous containers and price especially regarding higher quality ones. The quality is crucial for syringes because it is essential for sealing and resistance to abrupt pressure variations. Another important disadvantage is the relative sophistication of sampling procedures. Only a trained and experienced

technician may obtain qualitative and representative samples.

The syringe size has to conform to the laboratory standards. Some DGA devices use 20 ml, other use 100 or even 200 ml. Recent portable devices are designed for special syringes of 50 ml or unique design of around 100 ml.

In this outsourcing epoch, most of the oil samples are transported by planes to long distances. Syringes are exposed to a variety of different extreme pressures and temperatures during air transport and at airports. In these cases, the chances of quality sealing are compromised. Some companies adopted aluminum bottles for overseas transportation of DGA samples, but some gases are always in danger of escaping due to temperature

and pressure fluctuations in the headspace above the oil and they will be absent later at the measurement. Other potential errors during sampling can be:

Different transformer types can have different valves, so the usage of the correct valve and the valve where the sampling is representative is crucial.

In practice, the oil taken from the main tank does not contain homogenous gas concentration, even in the case of forced oil cooling. That is especially true when there is an active fault that produces gases. In some cases, different technicians obtain oil from different valves and that itself can cause huge errors. Sampling from Buchholz relay of an energized transformer is not recommended for routine sampling due to the possibility of bubbles entering the tank during the sampling through the upper piping.

Of course, checking a positive pressure of oil before taking a sample is a must to avoid harsh or even deadly accidents.

The quantity of flushed oil prior to

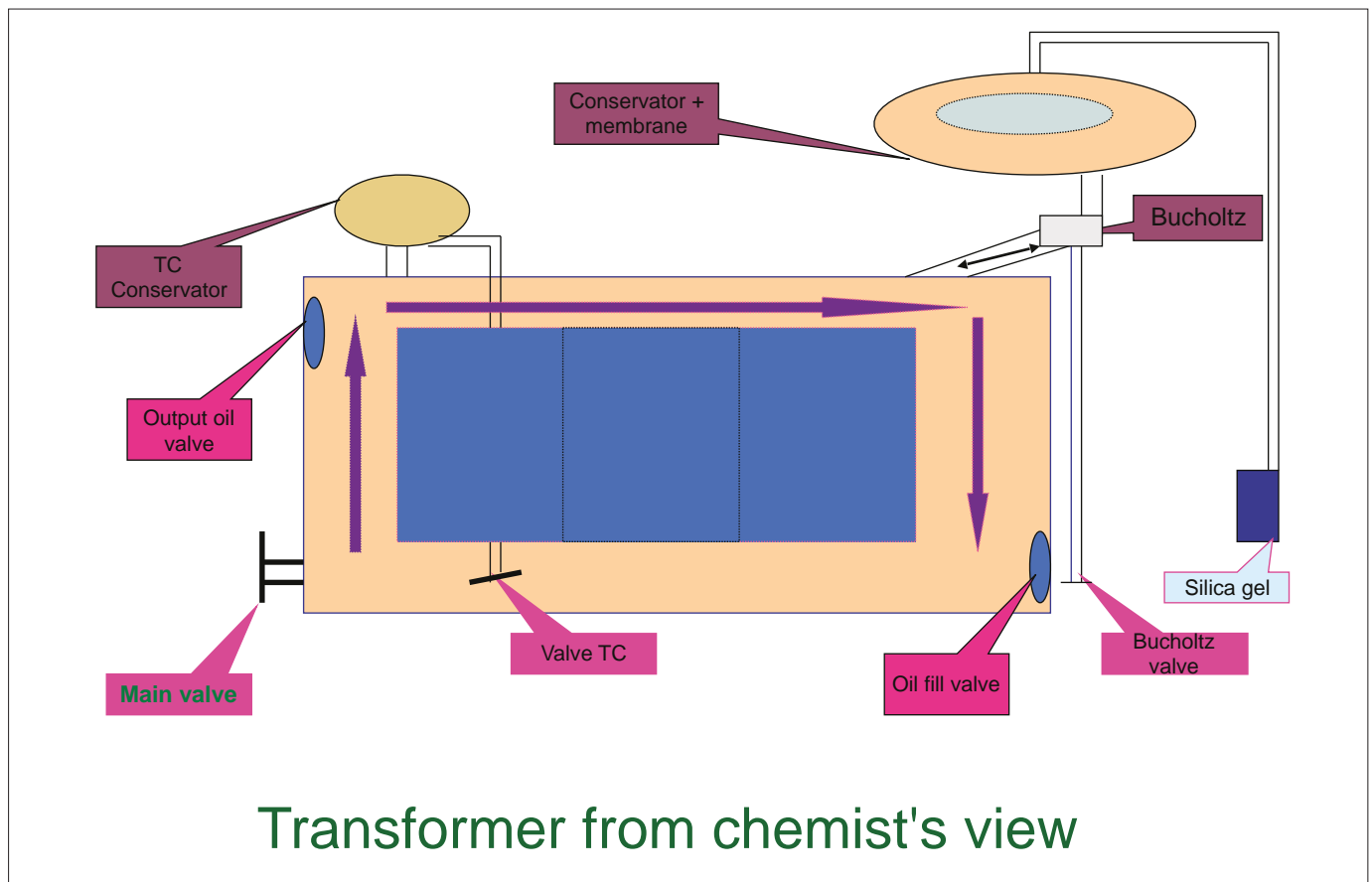


Figure 2. The transformer as a chemical reactor with different sampling valves.

Most extraordinary fact concerning DGA is how this chemical test became the most important test for an electromagnetic device, such as transformer



Figure 3. Sampling from the correct valve improves the accuracy of diagnosis



Figure 4. Sampling through portable humidity device assures homogeneity.

filling the sampling vessel also affects final results. These quantities should be, according to the transformer size, between half a liter and 2 liters. No more and no less. The preferable option for correct oil volume flush before sampling is to take the sample through a relative humidity device. These kinds of devices have a graph that indicates when the bulk oil arrives at the sampling valve. Duplicate sampling is a good practice that allows backup samples in case a bubble appears in one syringe or if the syringe is damaged.

Sampling issue is also problematic for online devices. Those devices can obtain the oil from the main tank through one valve or two valves, one for extracting the oil and the other for injecting it back. Both cases can impose an abnormal situation. In one valve design, the exchange rate of oil is very slow; most of these devices are operating on a temperature gradient as shown in Figure 5. In some models, the oil remains unchecked in the device and the measurement is erroneous. For the second valves option, the oil is flowing through an external pump. This design can increase the device's maintenance needs or, in the worst case, introduce bubbles inside the transformer. One real case was observed in which an online device introduced bubbles through the non-hermetic pump, and the Buchholz relay tripped the transformer. Theoretically, bubbles can induce failures.

Dissolved gas separation and measurement

Today the available methods for extraction and measurement are vacuum extraction, with or without mercury, and headspace. As displayed in Table 1, the striping method is mentioned mainly for historical reasons; almost none of the laboratories implements it nowadays.

The vacuum extraction methods, even the total extraction, is based on efficiency, a factor expressed by different constants. Today, those constants are far different from those calculated 40 years ago. Also, the composition of the oil is altered during the ageing process, and all those factors induce a high uncertainty of the vacuum extractions techniques. The differences between extraction factor in literature and in reality are

Headspace technique is the most popular technique for DGA and probably more than 75 % of offline DGA is performed by this method

presented in [6] and a graph from this paper explains the differences among the tested oil. Those experiments should, of course, be repeated.

Headspace (HS) technique is the most popular technique for DGA and probably more than 75 % of offline DGA is performed by this method. In North America, it is even close to 100 %.

The main advantage of HS gas chromatograph (GC) is high efficiency; it can be operated 24/7 almost without human intervention. The current commercial system is developed by IREQ [7]. If the system seems easy to use in routine, it gets complicated when an effort is made to stabilize it and adapt it to the local need, especially for testing transformer with low gas concentrations from sealed conservator with total gas concentration lower than 3 %.

The accuracy of the Headspace technique is influenced mainly by extraction, and the discrepancy between theories and reality should be checked for each case [8].

The principle of these methods consists of shaking 15 ml of oil volume in 22.5 ml vial for 30 min at 70 °C. The gas obtained in the headspace above the oil is then injected into a sensitive GC pre-calibrated by gas from gas-in-oil standards. The main issue that remains is how to calculate the original gas-in-oil concentration for each of the gases. In theory, the correlation between the oil volume and gas concentration in the gas phase should be linear. But, as shown in Figures 8 and 9, that is not the situation for all gases and all concentrations.

As expected, hydrogen behaves differently than acetylene, Figure 8.

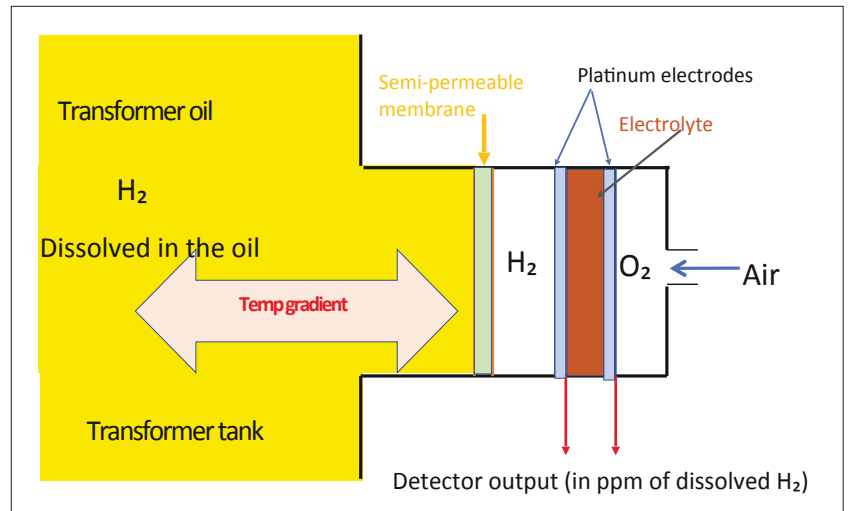


Figure 5. Hydrogen-in-oil detector, continuous monitoring. Sampling bu temp gradient, the "Hydran" based on [9]

Table 1. Comparison of DGA test methods from current IEC and ASTM

DGA method	Calculation	IEC 60567	ASTM D3612	Compatibility & Remarks
Vacuum extraction by partial degassing	Ostwald coefficients gas in oil and gas peaks calibrated by gas in gas	7.3	A	Yes Suitable for factory testing
Stripping extraction method	Efficiency coefficients and gas peaks calibrated by gas in gas	7.4	B	Yes Not suitable for factory test
Multi-cycle vacuum extraction using Toepler pump apparatus	Absolute volume of gases and gas in gas calibration	7.2	No	Best and total method
Headspace method	IEC calibrated by gas in oil standards or partition factor ASTM by calculated partition coefficients and gas peaks calibrated by gas in gas	7.5	C	No Not suitable for factory test

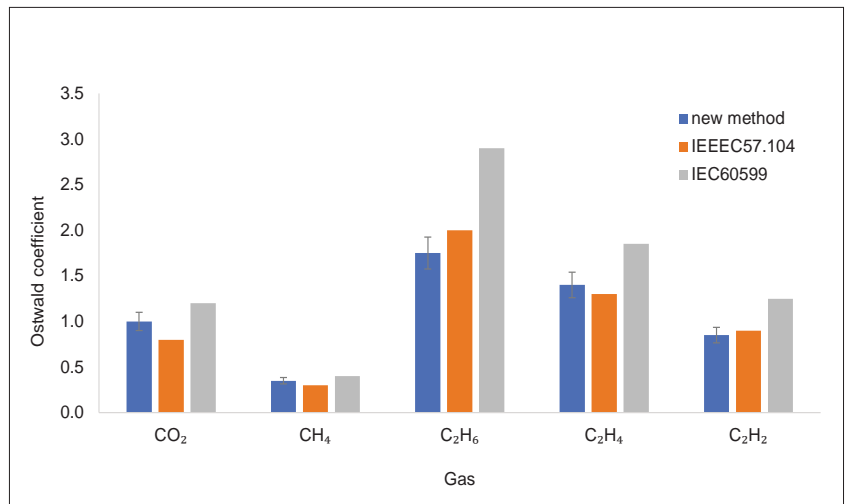


Figure 6. Ostwald coefficients of key gases in the mineral oil Shell Diala S2 ZU-I in comparison with the solubility coefficient values presented in IEEE C57.104 and IEC 60599 based on [6]



Figure 7. Extraction by partially degassing with mercury, high risk-low efficiency

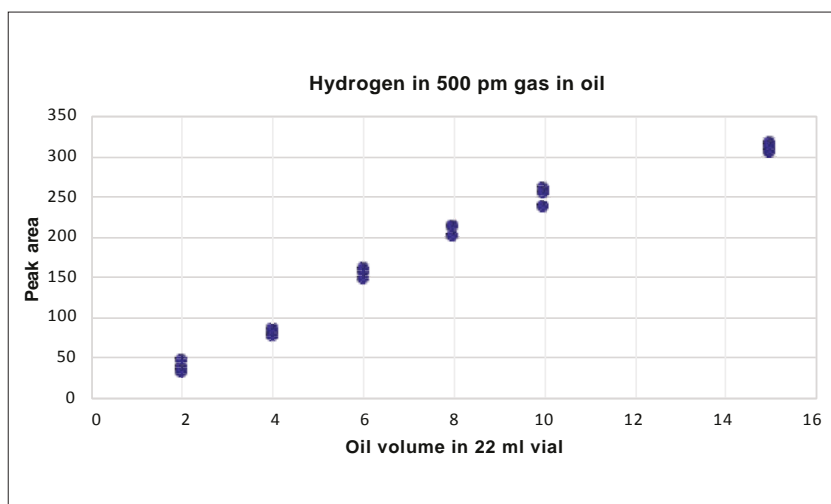
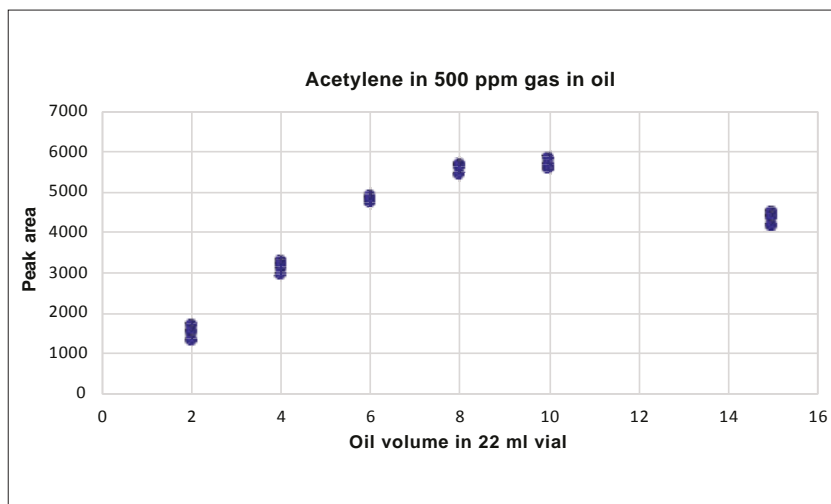


Figure 8. The peak area vs gas-in-oil concentrations for acetylene and hydrogen.

The graphs in Figure 9 show there is a contradiction between three critical factors:

- Importance of very low and very high detection limits, especially for hydrogen and acetylene, in one single run
- For hydrogen, the recommended best oil volume in the 22 ml vial is a maximum of 15 ml.
- For acetylene and ethylene, anything above 10 ml of oil dramatically decreases the yield of extraction.
- The optimal gas extraction is different for different gases, and ranges from 9 ml up to 15 ml. The chosen volume will always be a compromise of sensitivities for each gas.
- The K calculation is based on the assumption that the correlation of reciprocal area and phase ratio is linear. The graphs show that is not the case for the C₂ hydrocarbons when vial contains more than 10 ml of oil. Each gas behaves differently.
- The best solution to these issues is in-house preparation of gas-in-oil standards from 1 ppm to 1000 ppm, using the commonly used oil in each organization.
- Then we need to calculate and sketch the calibration curves for each gas' entire range.
- To determine the lower detection limits for each gas and response factor for different range concentrations.
- Due to imperfection of dissolving gases in the oil and in the pressurize gas phase, it is important to have each of the calibration curves in degassed and air saturated matrices.
- These graphs are obtained by specific GC with a specific condition, involving shaking and pressure. Of course, each operator in each lab can obtain different curves with better or worse linearity. The sensitivity of GC, detection and separation, can allow receiving K in the linear range. But the influence of different oil matrices has to be taken into consideration.

The actual and popular Headspace GC also possess many other disadvantages such as:

- Contamination of the transfer tubing caused by oil vapors leading to fast contamination and destruction
- Very skilled operators needed to fill the vial correctly
- Sensitivity to SF₆

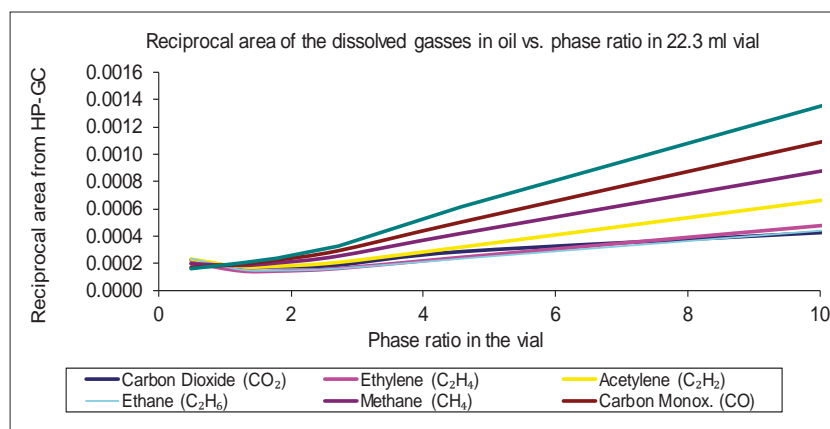
The main benefit of DGA is its unique advantage of being capable of predicting majority of the failures and evaluating the health state of transformers

- Memory effect for contaminated oils especially in the columns or valves or if the previous sample possess unusual gas concentrations
- Need for special safety procedures in the lab for operating the system overnight and over the weekend
- Very costly instruments and very expensive installations and logistics.

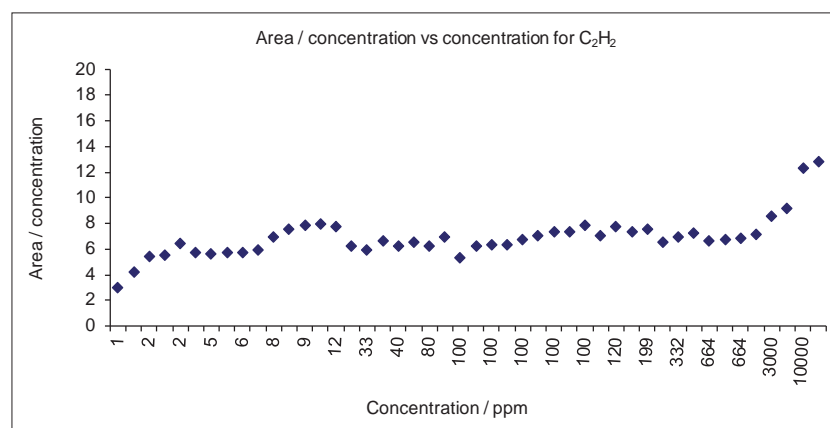
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a)



b)

Figure 9. a) For high volumes and high concentrations, the theories are not applicable for K calculation. b) In theoretical conditions, the line should be totally flat. These behaviors represent the irregularities when using this type of extraction.

Table 2. Comparison of gas concentration calculated by calibration curves with the commercial gas-in-oil standards True-North.

	10 ppm GC-HS	10 ppm MS	100 ppm GC-HS	100 ppm MS	500 ppm GC-HS	500 ppm	500 ppm MS
Hydrogen	12	12	93	98	491	491	12
Carbon dioxide	45	34	147	130	502	531	34
Carbon monoxide	10	10	101	102	534	514	10
Ethylene	11	10	99	101	485	505	10
Ethane	10	10	100	101	488	508	10
Methane	11	10	99	102	501	526	10
Acetylene	11	10	97	100	483	495	10
TDCG	65	62	589	604	2982	3039	62

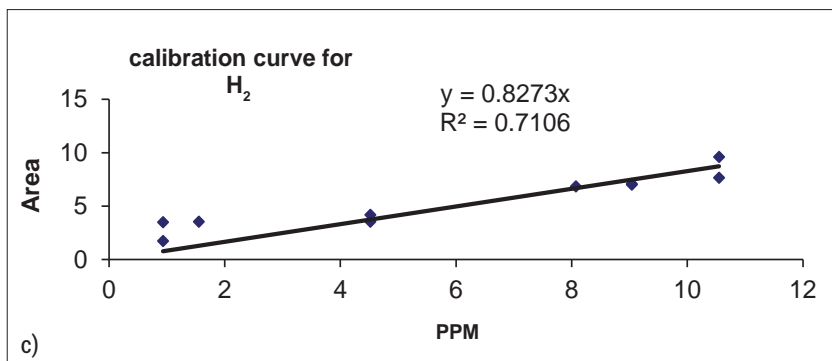
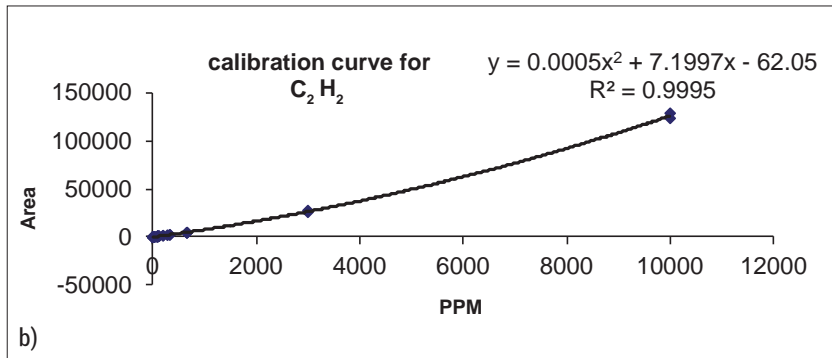
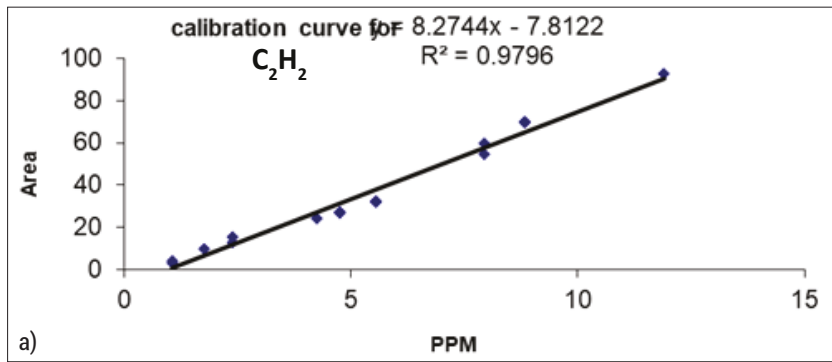


Figure 10. a), b) and c) To meet the accuracy indicated in IEC60567, the only option is to prepare in-house gas-in-oil standards.

Author



Marius Grisar has a M.Sc. on Electro-Analytical Chemistry from the Israel Institute of Technology. He is working as a sub-engineer on electrical equipment control. Marius has almost 30 of intense experience on almost all transformer oil tests chain, from planning, sampling, diagnose, recommendations and treatments mainly in Israel but also in other parts of the world as well. He is responsible for establishing tests strategy and procedures,

and for creating the acceptance criteria for insulating liquids and materials, based on current standardization and field experience.

He trains and educates electrical staff on insulating matrix issues from a chemical point of view. He is an active member of relevant Working Groups of IEC, CIGRE and former member of ASTM.

He is also the author and co-author of many papers, CIGRE brochures and presentations at prestigious international conferences on insulation oil tests, focused on DGA, analytical chemistry of insulating oil and advantageous maintenance policy for oil and new transformers.

After more than 80 years of using DGA to diagnose electrical equipment, there is still a significant ongoing debate about the gas formation mechanism, nomenclature, diagnosis etc.

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