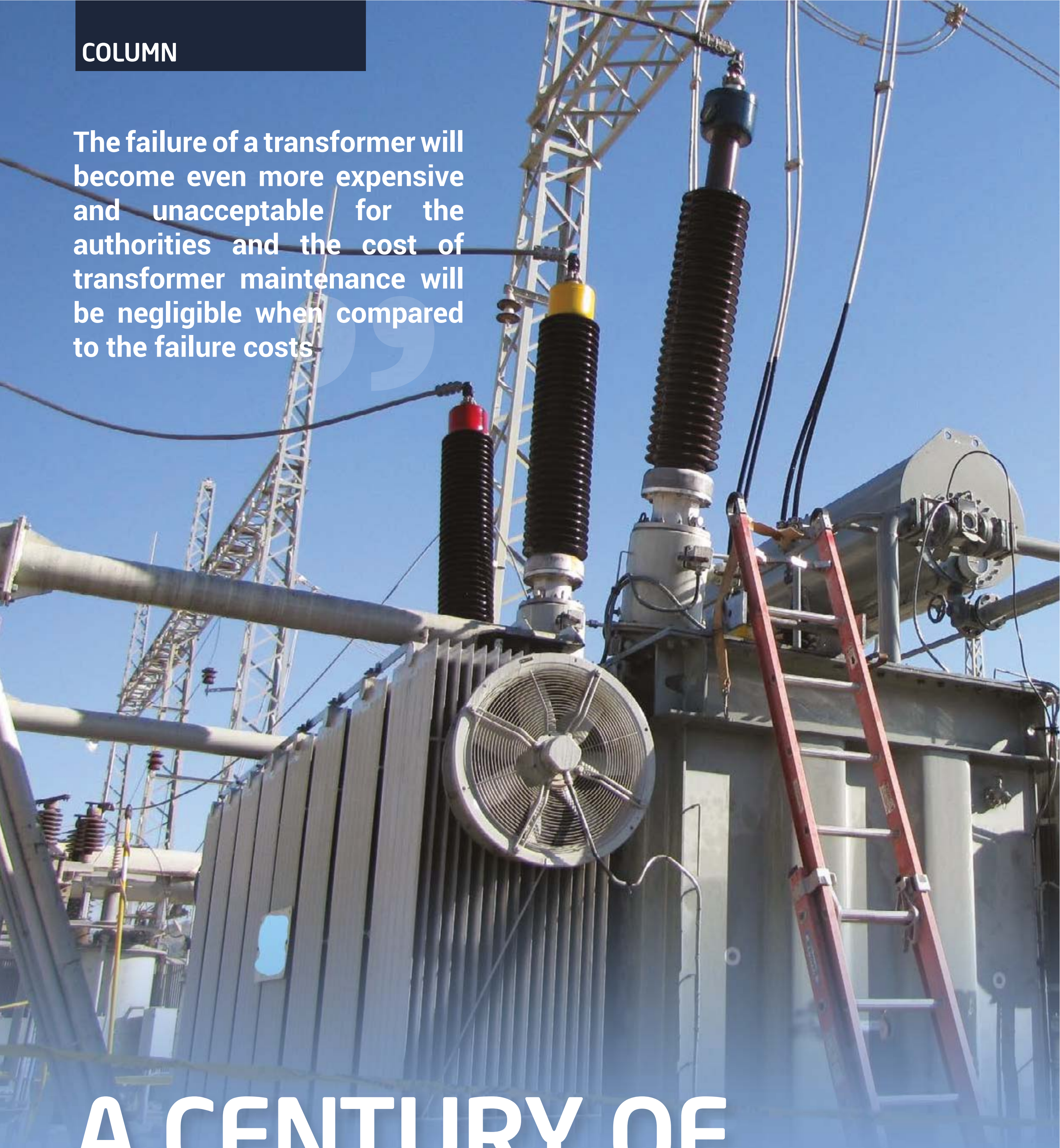


The failure of a transformer will become even more expensive and unacceptable for the authorities and the cost of transformer maintenance will be negligible when compared to the failure costs

A CENTURY OF DISSOLVED GAS ANALYSIS - PART III

Halstead's visual correlation between gas concentrations and temperatures from 1973 is probably the most cited paper for DGA diagnosis, but time showed that it has many restrictions

Introduction

With time, the size of the transformer increased exponentially both in power and voltage. Although huge improvements have been made regarding the magnetic core and the decrease of core losses, a transformer is now producing much more heat due to the design optimization and size reduction. Heat reduces the insulating properties of the insulating matrix, reducing the conducting properties and accelerating all chemical reactions including ageing and corrosion.

The stresses from the insulation materials increase gradually. In the last century, the ratio of oil volume to the transformer power decreased substantially, and concomitant with this trend, the transformer power and voltage increased. This means less cooling and less insulation for each MVA and kV.

The transformer's efficiency increased as well, mainly due to the development of new core material alloys. Also, the thickness of the core plates gives assistance in reducing no-load losses.

Insulation oil history

1919 – Hydrogen appears to be correlated to the disruptive discharge of the insulating oil [1].

1930 - 1960 and until today - According to IEEE approach, the diagnosis of the transformer condition is done by interpreting percentage concentration of combustion gases in the headspace above the oil or in an alarm relay such as Buchholz [2]. 5 % in gas space or 0.5 % in oil have been the pre-failure limits for the last 80 years.

1966 - DGA intuitive diagnosis [3] and basic key gas.

1973 – Thermodynamics approach, Halstead [4]. Probably the most cited paper for DGA diagnosis. Presents a visual correlation between relative gas concentrations and assumed temperatures. Although this model is widely accepted in the industry, time showed that this model has many restrictions. Some of them are described in recent literature [5]. One of the most important understanding should be the understanding that the graph of gasses and temperature is not bidirectional. In most thermal fault cases, gas formation is a sign of high temperatures inside transformers, but temperatures do not always produce gases in real operational transformer. The main cause of these discrepancies is the

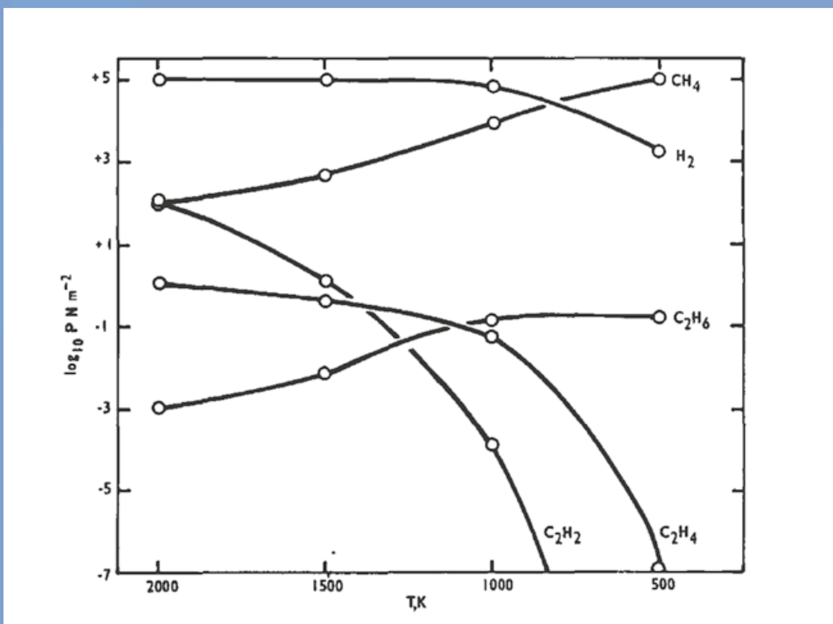


Figure 1. The 1973 theory was developed for a specific oil composition [4]. The oil has hundreds of different molecules in dynamic fluctuating. Each isomer decomposes on a different energy level

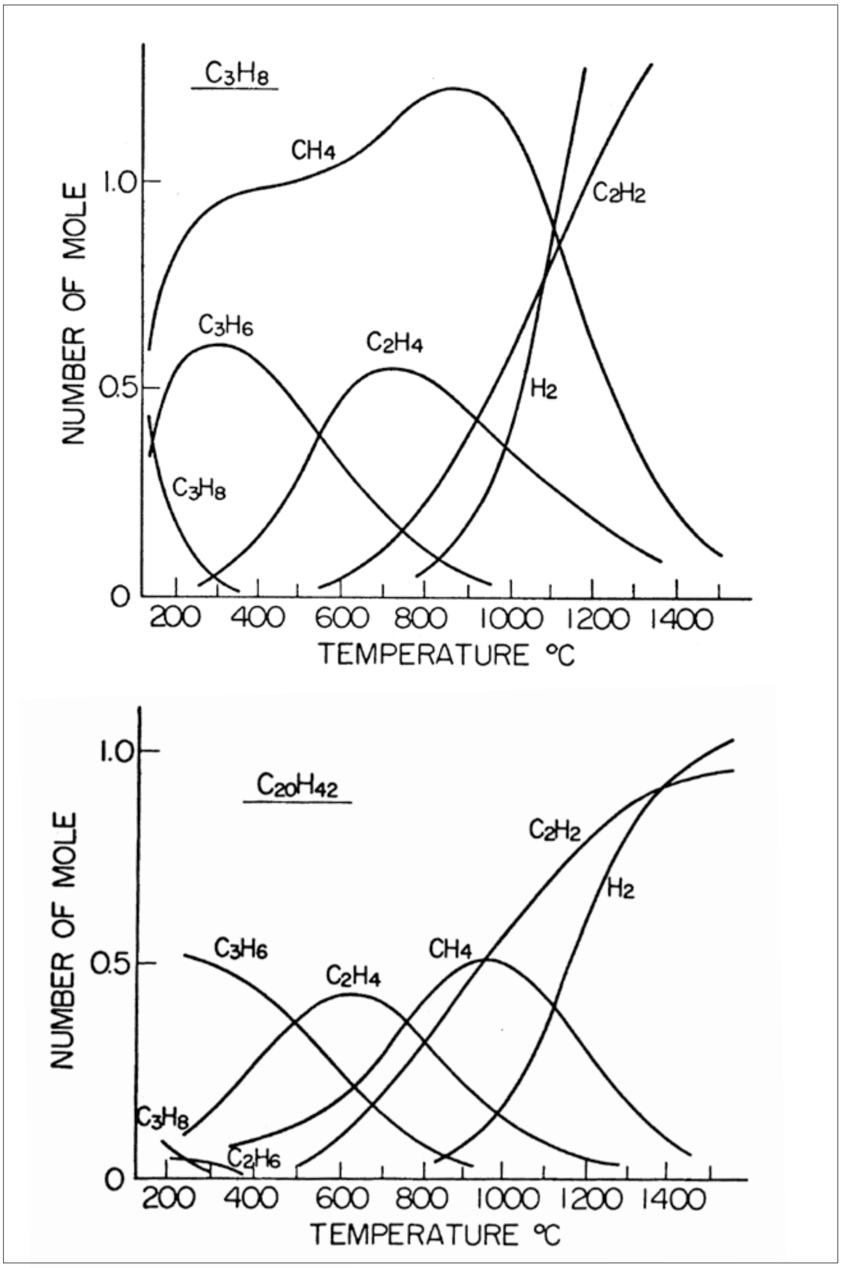


Figure 2. By M. Shirai et al. 1977 [6]. Different oil molecules breakdown in different gases at the same temperature

In most thermal fault cases, gas formation is a sign of high temperatures inside transformers, but temperatures do not always produce gases in real operational transformer

kinetics, activation energies of molecules formation. These phenomena were also observed in several attempts when using chemical indicators tags for the temperature inside the transformers or via fiber optics measurement.

Different oil molecules breakdown in different gases at the same temperature. The unrealistic one-way and unique correlation of gases emerging from oil and temperature or defects that produce them does not correlate with the reality.

1970 -1990 - Different schemes and diagnosis methods such as Laborelec [7], key gas method, nomograph [8], Dörnenburg [9, 10], numerical and graphical methods such as Rogers Ratios, Church, Nomography [11, 12, 8, 13] were developed.

A recommended review of almost all DGA methods can be found in [13] by Mollmann and Pahlavanpour.

1977-1978 - IEC599 and IEEE C57.104.

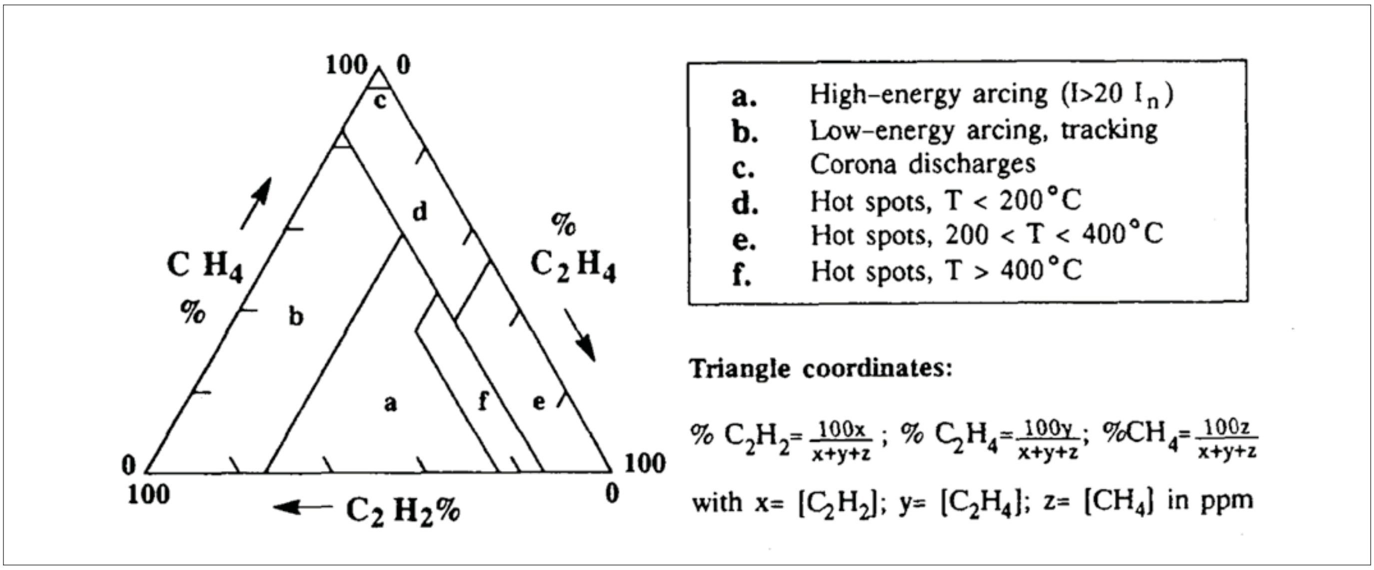


Figure 3. Duval triangles, the first and the best graphical methods for DGA diagnosis

It is the best available data for DGA interpretation processes, filtered by engaging and available experts of the époque. Today and probably then as well, not all experts can influence the content of a standard, but the brainstorm during the meetings can influence the participants.

1974 -1980 and 1980 – 1989 – Basic Duval triangle, Figure 3 [14, 15].

2002 - Additional Duval triangles version for OLTC, low temperature [15, 16] and non-mineral oils in 2008.

2012 - 2014 Duval pentagons, Figure 4 [17] and some similar concepts by Mansour [18].

2017- many papers published on DGA interpretation, a new approach to thermodynamics theories by S.M. Ghoneim [5] and reviews by Shirai et al. [6] and X. Deng at al [19].

2017 – Duval pentagon for different non-mineral liquids [20].

2018 – Different scholars around the world attempt to develop even more sophisticated geometric shapes such as the heptagon for DGA interpretation by O. Gouda, Figure 5 [21].

1985 – computerized algorithms, artificial intelligence, health index including different weighting methods for gases and/or their energies, more advanced algorithms including all chemical and electrical tests were used. AI was presented in 1985 [22] by HSBI at Doble Conference as an improvement to the DGA diagnosis. One of the first commercial software introduced in 1992 was TOA4 made by Delta X which was founded by J. Dukarm [23].

Nemeth et al. [24] developed an ANN based fault diagnosis recently, but the software evaluation showed that the solution is still not sufficient to make an operational decision and it is necessary to consult an expert as well.

2000 – many authors published researches and academic thesis on DGA from a programming point of view. One of the most popular subjects, besides new diagnosis models and algorithms and AI, is to compare the different diagnostic schemes, models and diagnosis [25]. Of course, it is not surprising that there are inconsistencies when comparing success values. For example, the benchmark for all those studies is a classical Duval triangle. In some studies, it reaches 96 % and more, but in other, it reaches lower success rate, especially if it is divided into specific failures. Some authors also observed that in different transformer types, the percentage of diagnostic accuracy is different. Maybe the next step should be a comparison among the studies of accuracy. It would not be surprising if these studies were found to be somehow biased. It is a very well-known fact that statistics results are highly influenced by the study's strategy. In this case, a few unresolved issues can be

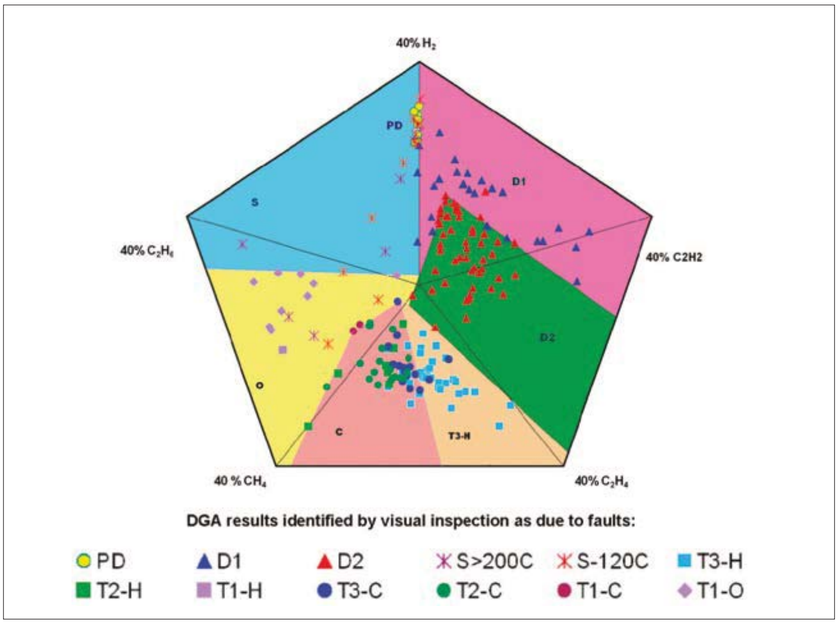


Figure 4. Duval pentagons, 2014 - 2016

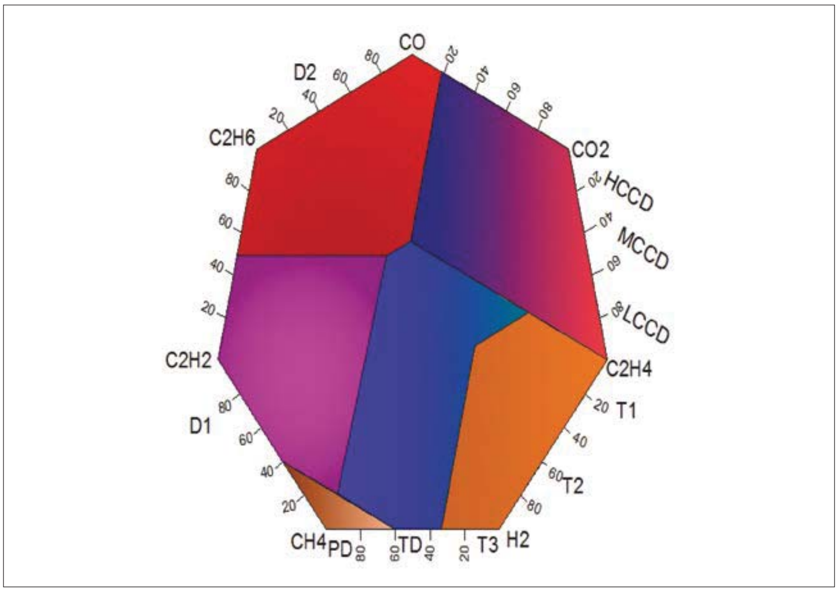


Figure 5. Proposed heptagon graph for DGA interpretation of transformer oil, O. E. Gouda [21]

Hydrogen detectors appeared only due to technological limitation of the 1970s, while probably the most informative behavior is that of oxygen, especially for modern non-breathing transformers

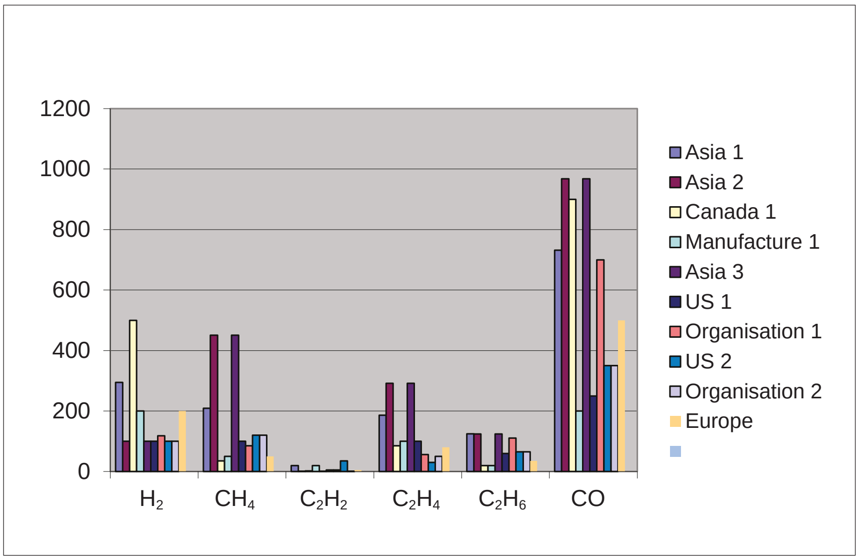


Figure 6. Different limits for DGA used by different organizations

One of the reasons why general software fails to predict incipient failure for the majority of transformers is that there are no straight rules valid for all transformer types, manufacturers, applications, etc.

found, as in the case of ratio methods such as IEC or Roger. The question is whether unresolved interpretation is a normal behavior? The triangles and other geometric and ratio methods shapes do not contain "normal" zones, which have to be achieved by using correct value limits for gas concentrations. By using this, the accuracy of the diagnosis will depend on the user, instead on the diagnostic method. The reason for this is that the limits for normal or alarm values depend on practically endless parameters; some of them are attributed to the technician's skills.

Selecting the proper limits is very tricky as shown in Figure 6.

The solution is to calculate the 90 % or 95 % or 98 % according to the maintenance policy of the transformer owner. If a false alarm is preferred regarding missing failures, then 90 % limit is a preferential choice. Nevertheless, the limits should be calculated according to the transformer's special characteristics. Those characteristics should be very carefully selected by a transformer specialist according to the restrictions and replacement policy. No straight rules valid for all transformer types, manufacturers, applications, etc. can be deduced. This is one of the reasons general software fails to predict incipient failure for the majority of transformers.

Future scenarios for DGA diagnosis

Duval's basic triangle is the most popular diagnosis method. The reason for its popularity can be found in the fact that it was based on the statistical occurrence of a failure in the operating transformers and in the laboratory [5], which means that it covers all possible faulty conditions. Another advantage seems to be that hydrogen is not taken into consideration in this model. In contrary to other opinions, the hydrogen can substantially increase the uncertainty of the diagnosis because it can be created by many issues unrelated to common failures, such as hydrolysis, iron corrosion, core lamination, and much more. If the gas concentration is below the threshold value, the normal state is achieved. The minor uncertainty of this method is probably due to the uncertainty surrounding the cutoff values.

DGA diagnosis will develop and change rapidly with the development of more economical and environmentally friendly materials and approaches. The old methods and diagnostic schemes will continue to disappear and be replaced with the new ones.

These changes are driven by four main trends:

- Development of materials and technologies used by transformer manufacturers impose new models for gas evolution related to the internal and especially insulating materials. Of course, the new technologies will be a few steps ahead of the diagnosis concepts.
- Development of online measurement technologies will provide more data on more tests. Data integration is one of the keys to successful failure presentations.
- Software and hardware for calculating and integrating the data using the similar mode experts use. Although the

Table 1. Different transformer characteristic, different value limits. This one shows a particular fleet of around 300 units with specific operational data

Transformer gas analysis statistics 90 % values										
	TG	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	O_2	N_2
All data	9	175	260	10	170	124	797	6059	2	7
TG < 5.0 data only	4	138	254	3	186	96	600	3043	0	4
N_2+O_2 < 5.0 data only	5	176	313	5	203	107	621	3796	0	4
C_2H_2 < 200 data only	9	144	220	7	137	120	786	5653	2	7
MVA < 50 data only	9	280	342	9	203	125	841	6512	2	7
MVA > 50, < =100 data only	10	126	195	26	88	205	673	4270	2	9
MVA > 100 data only	7	74	172	1	202	107	786	7762	0	5
year < 1990	9	295	209	20	186	125	732	8343	2	7
year > =1990	6	100	451	1	292	124	968	2542	0	6

gap seems to be significant right now, it could be overcome in the future.

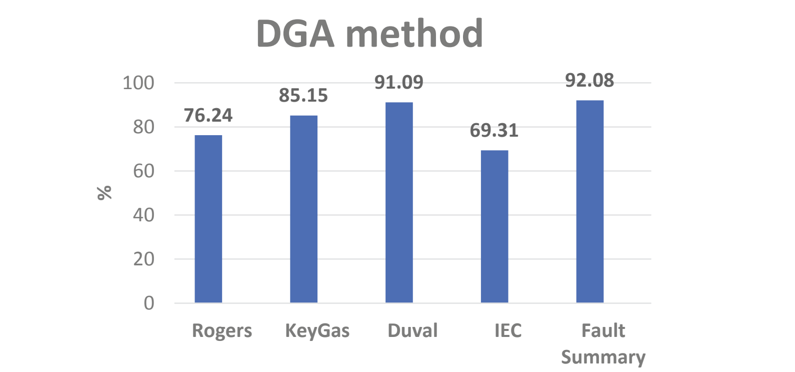
- Availability of DGA diagnosis experts will be reduced for utilities and transformer owners. If the big laboratories disappear, specialist will no longer be available.

Up until now, and probably in the near future, no diagnosis can be 100 % accurate and the efficiency of DGA tests and diagnosis could be questioned. In the future, energy sources will be limited due to global warming, but the needs for electricity will not decrease. These may affect the transformer loading conditions and their redundancy. The failure of a transformer will become even more expensive and a problem for the authorities. The cost of transformer maintenance, treatments, and monitoring will be negligible when compared to the failure costs. This may help in encouraging the professionals to turn to this special and multidisciplinary profession. Some countries already initiated this trend.

Recently, many scholars around the world compared the accuracy of the existing diagnosis methods. Even though the conclusions are non-consistent, the modern methods seem to be more accurate than the older ones. For example, one study attributes 50 % accuracy to the Duval triangle and others attribute 88 % or even 91 %. Who is correct?

Diagnostic method	Number of correct cases						Total accuracy %
	LT	MT	HT	PD	LED	HED	
Proposed pentagon	59	18	41	24	45	78	70%
Duval triangle 1	39	10	48	20	48	59	59%
Duval triangle 1+4	28	13	48	13	48	59	55%
Duval triangle 1+5	55	8	50	13	48	59	61%
IEC 60599	74	23	34	12	29	45	57%

a)



b)

Figure 7a and Figure 7b. No diagnosis is 100 % accurate and there is no consensus regarding the accuracy level among the scholars [26, 27]

Duval's basic triangle is based on the statistical occurrence of a failure in the operating transformers and in the laboratory, which means that it covers all possible faulty conditions

Overall conclusion

The importance of DGA will continue to increase until other measurement technique for the transformer health condition is invented. DGA will be preferred to the electrical test methodology. The mission will remain to improve the accuracy by continuous examination of all the stages, from sampling to diagnosis. The offline and online will continue to compete with their pros and cons, and of course, will continue to provide a lot of materials for debate and exchange of opinion at different forums. As seen in the past, most of the online devices existing today will disappear and will be replaced mostly by the new version of historical measurement methods. Scientists and engineers will try a new approach for the same principles. Also, in laboratory, DGA methods will be modified. As a chemist with 30 years of experience in gas chromatography and other analytical chemical techniques I dare to forecast, that in about 10 years, the classic gas chromatographic techniques will be replaced by more reliable and simpler detection and separation. Probably some kind of spectrometry will be used again for offline and online application, maybe a cheaper version of mass spectral methods or new solid-state detectors will be more efficient, cheaper, and more accurate than GC. The classical extraction methods will be no longer applicable for the new insulating liquids of any type. Also, the portable device will be preferred due to their fast response in emergency situations, but also during normal circumstances. The most reliable, easy to operate, fast, portable instrument for DGA disappeared from the market, and hopefully will be available in the future again. The GC headspace technique cannot survive long in this epoch, because it demands very skilled and highly paid operators, and even they cannot guarantee enough accuracy and reliability. Also, the transformer technology will impose a technology capable of measuring low total gas concentrations with higher repeatability, especially for new oil types such as the biodegradable ones.

One of the main obstacles for a more reliable diagnosis via health indexes or statistical evaluation from a large database is data privacy and security. Sharing data between private organizations and companies is not an option in our days and will probably not be an option in the near future. The data characteristic to the transformer operation is a major factor for energy control infrastructure and, at the same time, it can be unavailable to the transformer manufacturer. Without sharing operational data, the computerized diagnosis will be limited to a relatively small fleet. The quality of the diagnosis is highly depend-

Table 2. Analysis of gas sample taken from nitrogen cylinder in warehouse stock, per cent volume, measurement and identification of gases above the oil by MS [35]

Type of Gas	Analysis by Mass Spectrometer	Combustible Gas Content
Methane	0.1	0.1
Hydrogen	0.1	0.1
Carbon monoxide	0.1	0.1
Argon	0.2	
Carbon dioxide	0.4	
Nitrogen	99.1	
Total	100	
Total combustible gas content*		0.3
*Gas detector reading 0.3 %		

able on the size of the database. If these obstacles are not solved, the importance of a skilled and experienced expert will increase. At this stage of AI development, only experts are capable of learning to deduct and invent one of the best mandatory opportunities to share data and gain experience through active participation within specialized working group such as standardization bodies, CIGRE or specialized and high-level conferences and meetings. For example, the sulfur corrosion issue was discussed and clarified on such meetings and conferences long before it appeared in any diagnose algorithm standards or health index code. Also, today there are such hot topics that are intensely discussed among the experts. They will only appear in computerized algorithms after being thoroughly explained by the experts. Among those, issues relevant to DGA, such as stray gas, gas evolving, material compatibility between new insulation materials, liquids, influence of transformer designs on DGA, and others can be found. For example, carbon monoxide is three times more likely to be found in a new transformer design. The 90 % of CO values in non-free breathing transformers that operate at low to medium high load can be above 900 ppm, without any signs of cellulose degradation. These also appeared recently in the literature [28].

Additional gas such as ethylene [29] and ethane [30], display concentrations different than predicted by thermodynamics theories such as Halstead's [4] and later F. Jakob and J.J. Dukarm's [31]. Shirai et al., developed a more general theory [6] which correlated to more specific hydrocarbon raw material with enthalpy energies connected to the formation of each species. Now, the future studies on these issues have to take into consideration the kinetics of all gas formation. Unlike the old transformer designs, the new design has high load and forced oil flow where the oil does not have enough time for equilibrium, even in high energy conditions. In these cases, the formation of the gas is influenced by time contact of the failure location and a specific oil amount. Also, the gas solubility and dispersion factor of the gas in transformer's internal parts should be taken into consideration. The updated DGA diagnosis has to take in mind other considerations beside the classical one. Of course, the most important activities when it comes to correct assessment and improved diagnosis is to participate at the transformer inspection after DGA evaluation. As is the case with medicine, the DGA technique is an endless study and research process [33]. The DGA experts have to accompany the oil sample taken from sampling during the test in field or laboratory and later on when explaining the meaning of the diagnosis to the client and during later inspection of tested samples. Of course, the software cannot cover this entire value chain, it can only assist experts, but it cannot explain the process or make a decision.

In the future, portable devices will be preferred due to their fast response in emergency situations but also during normal circumstances

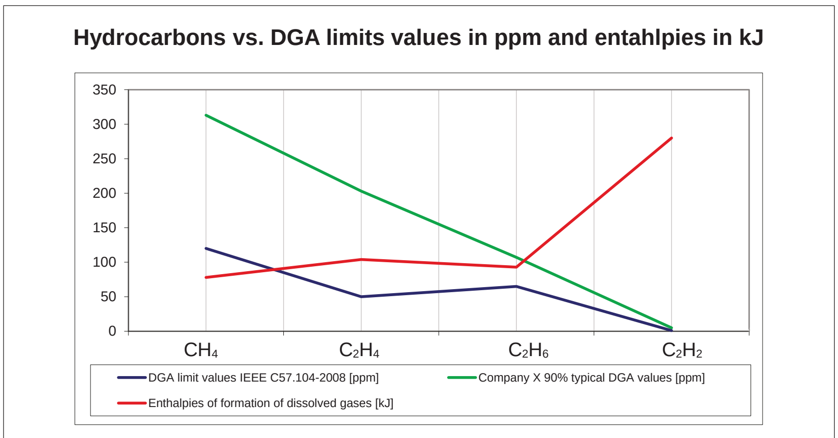


Figure 8. Value limits for DGA in different organization vs. enthalpies of gas formation

When comparing the enthalpies with the value limits for DGA, it is probably logical that, for the gases with the highest enthalpy, the limits will be lower. These are also considered in [34]. Table shows that only acetylene conforms the logic, and that methane, instead of having the highest limit values, has a medium one. All those gases that represent the thermal faults are another evidence that thermodynamic theory is not

100 % correct in real life for transformers in service.

One possible solution to this is to use other materials that have to be attached in the region susceptible to vulnerability inside the transformer and that decompose on certain predefined temperature. An attempt to develop such a material was made by A. Skholnik et al. in 2004 when they tried to integrate such a material in a few transformers in Israel [36] which was patented in 2008. This patent is similar to the ones developed by M. Duval [37] in Canada since it has additional material inside the transformer for measuring the real temperature. In the Canadian patent, the substance is dissolved in oil, so any region inside a transformer can influence it. Israeli patent is composed of several different materials that may indicate not only the temperature, but also the location of the hot spot. Each version has advantages and disadvantages, and one of the most important assumptions that both methods need to confirm is the thermodynamic theory of correlation between the temperature and gases ratio. The theory was, of course, validated in laboratory experiments, but the question, if it is suitable for real operating transformers, should be debated in further published research. Another open question for both approaches is the kinetics issue e.g., if the substance will degrade in time at a much lower temperature instead of instantaneously at the predicted temperature. Those open questions are of course valid for all current internal materials that are used for transformer operation, including the oil and cellulose.

New typical values for DGA concentration are highly influenced by many, declared and undeclared, natural or synthetic additives used to improve the liquid behavior for oil manufacture and oxidation mechanism. The new liquids with new additives are expected to also substantially change the gas solubilities in oil and all type of partition coefficients between the liquid and gas phase, and absorption to new solid insulation.

More and more users find that although there are so many diagnostic methods, no method can provide a real early trigger warning for the abnormal state [38].

Another anomaly that will be probably fixed in the future concerns the online gas detector which will switch from hydrogen to a gas more valuable for transformer condition monitoring such as ethylene, acetylene or carbon oxide. From this historical review, it can be observed that hydrogen detector appears only due to technological limitation of the 1970s. Probably the most informative behavior of a gas dissolved in oil is that of oxygen, especially for the non-breathing modern transformer. Those were observed even in the early days [39] and also recently [40, 41]. Today, the technology for detection of each gas dissolved in oil, as well as a technology for cheap detection of dissolved oxygen, exist [42]. As is the case in other technology fields, the diagnosis field will also experience the prevailing tendency of shifting away from human experts and other simple or conventional version to artificial intelligence. The motivation for this process will, on one hand, be the exponential accumulation for Big Data and on the other the diminution of experienced and skilled experts after overcoming the sharing operational data obstacle.

One of the main obstacles for a more reliable diagnosis via health indexes or statistical evaluation from a large database is data privacy and security

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Author

Marius Grisaru has a M.SC. on Electro-Analytical Chemistry from the Israel Institute of Technology. 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.