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ANALYSIS OF THE DIAGNOSTIC CRITERIA USED TO DEFECT TYPE RECOGNITION BASED ON THE RESULTS OF ANALYSIS OF GASES DISSOLVED IN OIL

Dissolved gas analysis is one of the most used and common diagnostic methods for high voltage oil-filled equipment. According to existing methods for interpreting the results of dissolved oil gas analysis, defect types are recognised using different diagnostic criteria. Using different methods to recognize the type of defect may result in different diagnoses. There are a sufficient number of publications on the comparative analysis of methods for the results interpretation of dissolved gas analysis. Most of them do not cover more than 4 methods at a time, and only a small number of publications deal with more methods. Some methods remain unreported, therefore an analysis of diagnostic criteria used in various standards and methods to identify types of defects by the dissolved gas analysis is given. The national standards of Ukraine and the Russian Federation, international methods, as well as a number of author's methods and standards are considered. All considered methods can be divided by the type of diagnosis, by the diagnostic criterion used and by the number of recognizable defects. According to the type of diagnosis, the considered methods can be divided into two groups – analytical and graphical methods. In the considered methods the following diagnostic criteria are used – values of gas concentrations or the gas pair ratios or gas percentage content. Most of the analysed methods allow identification of 6–7 most characteristic types of defects. The highest number of recognizable defects is 13–14, and the lowest only 3–4. Only a few methods make it possible to diagnose defect-free condition and/or damage of solid insulation as well as to recognize combined defects. The results show significant differences in the criteria and norms used by different standards and author's methods to determine the type of defect, which can lead to different diagnoses for the same data.

Keywords: defect, dissolved gas analysis (DGA), gas pair ratios, gas percentage, Doernenburg method, Rogers method, Duval methods, ETRA method, Nomogram method.

О. С. КУЛИК

АНАЛІЗ ДІАГНОСТИЧНИХ КРИТЕРІЇВ, ЩО ВИКОРИСТОВУЮТЬСЯ ДЛЯ РОЗПІЗНАВАННЯ ТИПІВ ДЕФЕКТІВ ЗА РЕЗУЛЬТАТАМИ АНАЛІЗУ РОЗЧИНЕНИХ У МАСЛІ ГАЗІВ

Аналіз розчинених в маслі газів є одним з найбільш використовуваних і поширених методів діагностики високовольтного маслонаповненого обладнання. Згідно з існуючими методами з інтерпретації результатів аналізу розчинених в маслі газів розпізнавання типів дефектів проводиться з використанням різних діагностичних критеріїв. Використання різних методів при розпізнаванні типу дефекту може привести до постановки різних діагнозів. Питанню порівняльного аналізу методів інтерпретації результатів аналізу розчинених в маслі газів присвячено достатню кількість публікацій. У більшості з них розглядається не більше 4 методів відразу і лише в невеликій кількості публікацій розглядається більша кількість методів. Деякі методи залишаються неосвітленими, тому наведено аналіз діагностичних критеріїв, що використовуються в різних стандартах і методиках, для розпізнавання типів дефектів за результатами аналізу розчинених в маслі газів. Розглянуто національні стандарти України та Російської Федерації, міжнародні методики, а також ряд авторських методик і стандартів. Всі розглянуті методи можна розділити за типом діагностування, за використовуваним діагностичним критерієм і за кількістю розпізнаваних дефектів. За типом діагностування розглянуті методи можна розділити на дві групи – аналітичні та графічні методи. У розглянутих методах використовуються наступні діагностичні критерії – або значення концентрацій газів, або відношення пар газів, або відсотковий вміст газів. Більшість з аналізованих методів дозволяє розпізнати 6–7 найбільш характерних типів дефектів. Найбільше число розпізнаваних дефектів становить 13–14, а найменше всього лише 3–4. Лише деякі методи дозволяють діагностувати бездефектний стан і/або пошкодження твердої ізоляції, а також розпізнавати комбіновані дефекти. Результати свідчать про істотні відмінності в критеріях і нормах, що використовуються різними стандартами і авторськими методиками для визначення типу дефекту, що може привести до постановки різних діагнозів стосовно одних і тих же даних.

Ключові слова: дефект, аналіз розчинених в маслі газів (АРГ), відношення пар газів, відсотковий вміст газів, метод Дорненбурга, метод Роджерса, методики Дюваля, метод ETRA, метод номограм.

А. С. КУЛИК

АНАЛИЗ ДИАГНОСТИЧЕСКИХ КРИТЕРИЕВ, ИСПОЛЬЗУЕМЫХ ДЛЯ РАСПОЗНАВАНИЯ ТИПОВ ДЕФЕКТОВ ПО РЕЗУЛЬТАТАМ АНАЛИЗА РАСТВОРЕННЫХ В МАСЛЕ ГАЗОВ

Анализ растворенных в масле газов является одним из наиболее используемых и распространенных методов диагностики высоковольтного маслонаполненного оборудования. Согласно существующим методам по интерпретации результатов анализа растворенных в масле газов распознавание типов дефектов производится с использованием разных диагностических критериев. Использование разных методов при распознавании типа дефекта может привести к постановке различных диагнозов. Вопросу сравнительного анализа методов интерпретации результатов анализа растворенных в масле газов посвящено достаточное количество публикаций. В большинстве из них рассматривается не больше 4 методов сразу и лишь в небольшом количестве публикаций рассматривается большее количество методов. Некоторые методы остаются неосвещенными, поэтому приведен анализ диагностических критериев, используемых в различных стандартах и методиках, для распознавания типов дефектов по результатам анализа растворенных в масле газов. Рассмотрены национальные стандарты Украины и Российской Федерации, международные методики, а также ряд авторских методик и стандартов. Все рассмотренные методы можно разделить по типу диагностирования, по используемому диагностическому критерию и по количеству распознаваемых дефектов. По типу диагностирования рассмотренные методы можно разделить на две группы – аналитические и графические методы. В рассмотренных методах используются следующие диагностические критерии – или значения концентраций газов, или отношения пар газов, или процентное содержание газов. Большинство из анализируемых методов позволяет распознать 6–7 наиболее характерных типов дефектов. Наибольшее число распознаваемых дефектов составляет 13–14, а наименьшее всего лишь 3–4. Лишь некоторые методы позволяют диагностировать бездефектное состояние и/или повреждение твердой изоляции, а также распознавать комбинированные дефекты. Результаты свидетельствуют о существенных различиях в критериях и нормах, используемых разными стандартами и авторскими методиками для определения типа дефекта, что может привести к постановке различных диагнозов применительно к одним и тем же данным.

Ключевые слова: дефект, анализ растворенных в масле газов (АРГ), отношения пар газов, процентое содержание газов, метод Дорненбурга, метод Роджерса, методики Дюваля, метод ETRA, метод номограмм.

Introduction. One of the most urgent scientific and technical tasks of practical importance is the detection and recognition of defects in high-voltage equipment, especially at an early stage of their development. Dissolved gas analysis (DGA) is one of the most used and widespread diagnostic methods. It relies on the fact that the development of a defect of thermal or electrical nature causes destruction of insulation, which is accompanied by emission of gases.

According to existing methods for interpreting DGA results, defect type recognition is performed using different diagnostic criteria. Obviously, the use of different methods in defect type recognition can lead to different diagnoses. Therefore, there is an objective need to analyse the existing methods for interpreting DGA results.

Publications review. A fair number of publications are devoted to the issue of comparative analysis of methods for interpreting DGA results. However, most of them do not consider more than 4 methods at a time. And only in a small number of publications more methods are considered. In [1] only graphical methods of defect type recognition are analysed. In [2] the accuracy of transformer defect type identification methods is analyzed. In [3 and 4] an analysis of electrical defect recognition is presented. In [5 and 6] the recognition of combined defects is considered. In [5] recognition of low-temperature overheating with electric discharges of different intensity is considered, and in [6] recognition of combined defects in low- and medium-temperature range is considered. In [7] the results of a comparative analysis of the reliability of defect type recognition based on the analysis of dissolved gases in oil for more than 1500 high-voltage transformers with defects of different types are presented. In spite of a considerable number of publications, in which recognition methods are discussed, some recognition methods remain unreported, which is the reason for writing this article.

Research purpose. This article analyses the diagnostic criteria used in various standards and methods to recognise types of defects based on dissolved gas analysis.

The core material of the study. Consider the most well known recognition methods.

SOU-N EE 46.501:2006 method (Ukraine) [8]. This method is the official document governing the implementation of the DGA in the Ukrainian electrical power industry. It was officially registered in 2006 and was developed by V. V. Sokolov, V. N. Berezhnyy and other prominent experts in this field. This method recommends the use of both gas ratios and graphical methods (method of graphical images, also known as Nomogram method) to identify the type of defect based on the DGA results. In addition to these methods, the Duval triangle and ETRA square are recommended for defect type recognition.

Each type of defect produces a characteristic gas composition. The concentration ratios of the individual pairs of these gases have definite values for the different defect types, which makes it possible to use these ratios to determine the type of major defect. All defect type determination schemes for individual gas ratios can be applied to all types of equipment. It is recommended that diagnostic schemes that are based on gas ratios (tabular and graphical) be used with acceptable validity if the concentrations of the individual gases comprising the ratios (or at least one of them in µl/l) exceed the following values: $H_2 = 50$, $CH_4 = 15$, $C_2H_4 = 15$, $C_2H_6 = 15$, $C_2H_2 = 3$, $CO = 200$, $CO_2 = 1000$ (1 µl/l = 0.0001 % vol.). Identification of the defect type using the three main gas ratios – C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 – is tabulated in Table 1.

Table 1 – Identification of the defect type using three basic gas ratios

Defect type	**Defect code**	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
Normal oil ageing	Not a defect	NS	0.1–1	< 0.2
Partial discharges	PD	NS	< 0.1	< 0.2
Low energy discharge	D1	> 1	0.1–0.5	> 1
High energy discharge	D2	> 1	0.1–1	> 2
Discharges on the surface and in the insulation layer (creeping discharge)		< 1	0.3–0.5	> 5
Thermal defect with temperature 150–300 °C	T1	NS	> 1	< 1
Thermal defect with temperature 300–700 °C	T2	NS	> 1	1–4
Thermal defect with temperature over 700 °C	T3	< 0.2	> 1	> 4
NS = non-significant ratio. Not considered for this type of defect.				

ANSI/IEEE Std C57.104–2019 standard [9]. In this method, the emphasis emphasis is on defect detection. For this purpose, it is proposed to focus on 4 levels of dissolved gas concentration limits, % vol. The method introduces a new diagnostic parameter, total dissolved combustible gases (TDCG), that is, the sum of all gases other than CO_2. It should be noted that this parameter plays a major role in identifying the defective condition, while CO_2 gas is practically not used in the analysis.

With regard to the nature of defects, this method proposes to use the Rogers Ratio and Duval Triangle 1 to identify the type of defect. In addition, an annex of this standard provides additional identification methods, in particular the Dornenburg and Key Gas methods, as well as Duval Triangles 4 and 5 and Duval Pentagons 1 and 2. An important part of the method is to take account of changes in gas concentration over time.

Dornenburg Ratios method [10]. The Dornenburg Ratios method uses the following gas ratios: CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4 and C_2H_6/C_2H_2. The technique makes it possible to identify three main defects in oil-filled equipment: thermal decomposition, corona (low intensity PD) and arcing (high intensity PD). The concentrations obtained are compared with the limit values given in Table 2. However, this method does not sufficiently distinguish between defects, but allows the use of gases from the gas relay.

Table 2 – Interpretation of DGA results using the Dornenburg Ratios method

Suggested fault diagnosis	CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_6/C_2H_2
Thermal decomposition	> 1	< 0.75	< 0.3	> 0.4
Corona (low intensity PD)	< 0.1	—	< 0.3	> 0.4
Arcing (high intensity PD)	> 0.1 < 1	> 0.75	> 0.3	< 0.4

CEGB/Rogers Ratios method [11]. In 1978, English specialist R. Rogers (CEGB, England) proposed a technique to determine the nature of the defect in a transformer, which is known in the electricity industry as the Rogers Ratios. This method is used by utilities in England and Wales. It is based on the ratio of unsaturated to saturated hydrocarbons in the oil to its temperature. The increase in hydrogen content as a function of increasing temperature is also taken into account. If the concentration of gases exceeds the limit values, the presence of defects in the transformer is suspected.

Four gas ratios are used to determine the type of defect according to the Rogers Ratios method: CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4. The gases are arranged in ascending order of insulation decomposition temperature. Depending on the value of the gas ratios, they are assigned a code number, which leads to a diagnosis. The diagnostic output is based on a combination of codes, which are assigned depending on the gas ratios and the value (or range of values) of the respective gas concentration ratios. Table 3 shows the final result of adding the two Rogers tables.

MSS method [12]. The authors of this method are R. Müller, H. Schliesing and K. Soldner. It was published in 1977. In this method three types of thermal defects are considered:

1) defect with a temperature below 300 °C;
2) defect in the temperature range 300–1000 °C;
3) defect with a temperature over 1000 °C (introduced additionally).

In addition, a new defect called “thermal defect and partial discharges” is introduced. The gas ratios analysed differ considerably from those used in other techniques. For instance, instead of CH_4/H_2 this method analyses H_2/CH_4, instead of C_2H_6/C_2H_2 it analyses C_2H_2/C_2H_6. In addition, the C_2H_4/C_3H_6 gas ratio is additionally introduced. The relationship between defect type and gas concentration ratios is given in Table 4.

Table 3 – Interpretation of DGA results using the Rogers Ratios method

CH_4/H_2	C_2H_6/CH_4	C_2H_4/C_2H_6	C_2H_2/C_2H_4	Diagnosis
> 0.1 < 1	< 1	< 1	< 0.5	Normal Deterioration
≤ 0.1	< 1	< 1	< 0.5	Partial Discharges
≥ 1	< 1	< 1	< 0.5	Slight Overheating, below 150 °C
≥ 1	≥ 1	< 1	< 0.5	Slight Overheating, 150–200 °C
> 0.1 < 1	≥ 1	< 1	< 0.5	Slight Overheating, 200–300 °C
> 0.1 < 1	< 1	≥ 1 < 3	< 0.5	General Conductor Overheating
≥ 1 < 3	< 1	≥ 1 < 3	< 0.5	Winding Circulating Currents
≥ 1 < 3	< 1	≥ 3	< 0.5	Core and Tank Circulating Currents, overheated joints
> 0.1 < 1	< 1	< 1	≥ 0.5 < 3	Flashover without Power Follow Through
> 0.1 < 1	< 1	> 1	≥ 0.5	Arc with Power Follow Through
> 0.1 < 1	< 1	≥ 3	≥ 3	Continuous Sparking to Floating Potential
≤ 0.1	< 1	< 1	≥ 0.5	Partial Discharge with Tracking

Table 4 – Correlation of defects with gas concentration ratios

Defect type	H_2/CH_4	C_2H_4/C_2H_6	C_2H_2/C_2H_6	C_2H_4/C_3H_6	CO_2/CO
PD	≥ 10	< 0.3	< 0.3	–	≥ 3 < 10
D1	≥ 3 < 10	≥ 1	≥ 3	≥ 1	< 3
D2	≥ 0.3 < 1	≥ 1	≥ 3	≥ 1	< 3
T1	< 1	< 1	< 0.3	≥ 0.3 < 1	≥ 10
Thermal defect in the temperature range 300–1000 °C	< 1	≥ 1	< 0.3	≥ 0.3 < 1	≥ 10
Thermal defect with a temperature over 1000 ºC	< 1	≥ 1	≥ 0.3 < 3	≥ 1	≥ 10
Discharge and thermal defect (DT)	≥ 1 < 3	≥ 1	≥ 0.3 < 3	≥ 0.3 < 1	≥ 10
Thermal defect and PD	≥ 10	≥ 1	< 0.3	≥ 0.3 < 1	≥ 10

Methods used in the Russian Federation [13, 14]. In the Russian Federation, there are currently two official standards governing diagnosis based on DGA results. They are RD 153-34.0-46.302-00 [13] and STO 34.01-23-003-2019 [14]. The last one is developed in 2019 instead of RD 153-34.0-46.302-00, but for equipment of voltage classes from 35 kV to 220 kV inclusively.

Y. M. Lvov, T. E. Kasatkina, E. I. Nesvizhsky and E. M. Beda were at the origin of the development of RD 153-34.0-46.302-00. The date of registration of the first edition was 1989. The last version of this standard was published in 2001.

The following gas ratios are used to determine the defect type: C_2H_2/C_2H_4, CH_4/H_2 and C_2H_6/CH_4. The relationship between defect type and gas concentration ratios is given in Table 5.

Table 5 – Interpretation of DGA results using the RD 153-34.0-46.302-00

Defect type	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
Normal oil ageing	< 0.1	0.1–1	≤ 1
PD with low energy density	< 0.1	< 0.1	≤ 1
PD with high energy density	0.1–3	< 0.1	≤ 1
D1	> 0.1	0.1–1	1–3
D2	0.1–3	0.1–1	≥ 3
Low temperature thermal defect (below 150 °C)	< 0.1	0.1–1	1–3
Thermal defect in the low temperature range (150–300 °C)	< 0.1	≥ 1	< 1
T2	< 0.1	≥ 1	1–3
T3	< 0.1	≥ 1	≥ 3

In STO 34.01-23-003-2019 the criteria used to recognise the type of defect are the same as those regulated in IEC 60599.

In addition to the values of gas ratios, both methods recommend the use of graphical images (nomograms) of defects to recognise the type of defects. In addition, STO 34.01-23-003-2019 also suggests using the author's method of defect type identification. It should be noted that both standards also regulate the values of gas ratios for combined defects (that is overheatings that turn into discharges or discharges that are accompanied by heating or simultaneous development of several defects in the same transformer), which is not observed in other standards and methods. For the detection of combined defects, the following ratios are prescribed: $C_2H_2/C_2H_4 \geq 0{,}1$ and $CH_4/H_2 > 0{,}5$ or $C_2H_2/C_2H_4 < 0{,}1$ and $CH_4/H_2 \leq 0{,}5$.

IEC 60599 standard [15]. This methodology is an international standard developed by the IEC. The first edition of the standard was published in 1978, the second edition was finally formulated in 2007. The latest, third edition of the standard was published in 2015.

The following gas ratios are used for defect type recognition: CH_4/H_2, C_2H_4/C_2H_6 and C_2H_2/C_2H_4. Interpretation of the results is only carried out if the concentration of the gases is above a certain level and the sensitivity of the equipment for analysis is sufficient. As an auxiliary criterion the CO_2/CO gas ratio is used, which indicates the presence of paper ageing. To make the diagnosis more precise two additional gas ratios have been introduced: C_2H_2/H_2 (evaluating the influence of gas penetration from the tap changer into the tank) and O_2/N_2 (indicating oil overheating). The identification of the defect type using this standard is shown in Table 6.

Table 6 – Interpretation of DGA results according to IEC 60599

Defect type	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
PD	NS [a]	< 0.1	< 0.2
D1	> 1	0.1–0.5	> 1
D2	0.6–2.5	0.1–1	> 2
T1	NS [a]	>1. but NS [a]	<1
T2	< 0.1	> 1	1–4
T3	< 0.2 [b]	> 1	> 4

Note 1. In some countries, the ratio C_2H_2/C_2H_6 is used, rather than the ratio CH_4/H_2. Also in some countries, slightly different ratio limits are used.

Note 2. $CH_4/H_2 < 0.2$ for partial discharges in instrument transformers. $CH_4/H_2 < 0.07$ for partial discharges in bushings.

[a] NS = Non-significant whatever the value.

[b] An increasing value of the amount of C_2H_2 may indicate that the hot spot temperature is higher than 1000 °C.

In the annex of this standard, Duval Triangle technique and a graphical representation of gas ratios in two projections (Fig. 1) and in three-dimensional form (Fig. 2) are given. Typical gas concentrations IEC 60599 recommends determining from a database of a particular user. It is calculated as the concentration on the integral distribution curve, which corresponds to 90 % of the analyses for transformers in good working order.

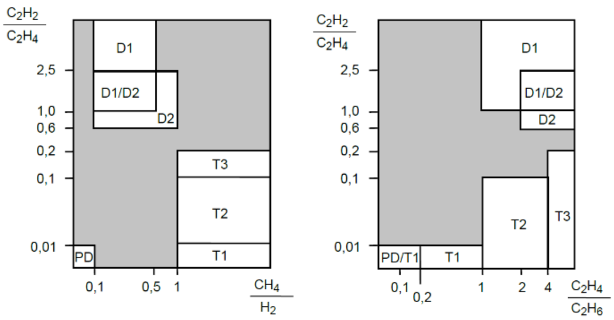


Figure 1 – Two projections of gas ratios based on IEC 60599 recommendations; darkened areas are areas of uncertainty

Duval triangles [16]. This is the first example of a graphical rather than a computationally logical approach to defect identification. The well-known Canadian specialist M. Duval at Hydro-Quebec developed the Duval Triangle in 1974. The method allows the concentrations of three gases (C_2H_2, C_2H_4, CH_4) to plot a point on a graph represented as a triangle (Fig. 3). The triangle area is divided into seven zones. Each zone corresponds to a particular type of defect in the transformer. Seven defect states are considered: PD, D1, D2, DT, T1, T2 and T3. The defect type is determined by the zone to which the point belongs. Somewhat later, M. Duval proposed new versions of the Duval Triangle for equipment filled with mineral oil, for load tap changers of the oil type, equipment filled with nonmineral oils, and for low-temperature faults. In total, there are 7 triangles that are used for different cases. However, Triangle 1 is the most commonly used, and Triangles 4 and 5 are used to clarify the type of defect established with Triangle 1.

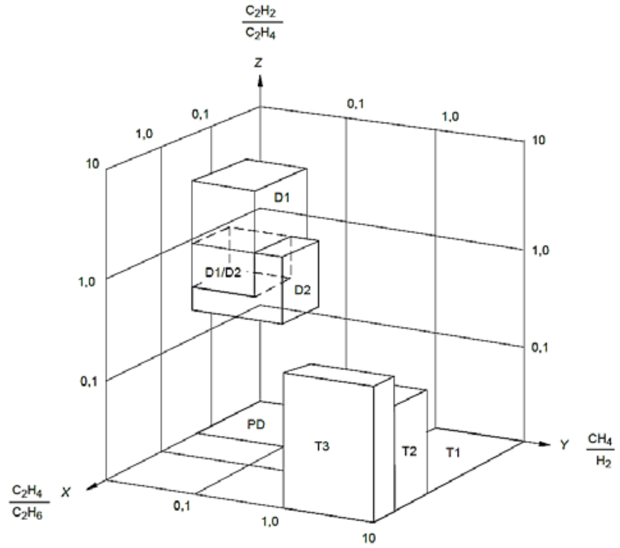


Figure 2 – Dimensional representation of the relationship between defects and gas ratios

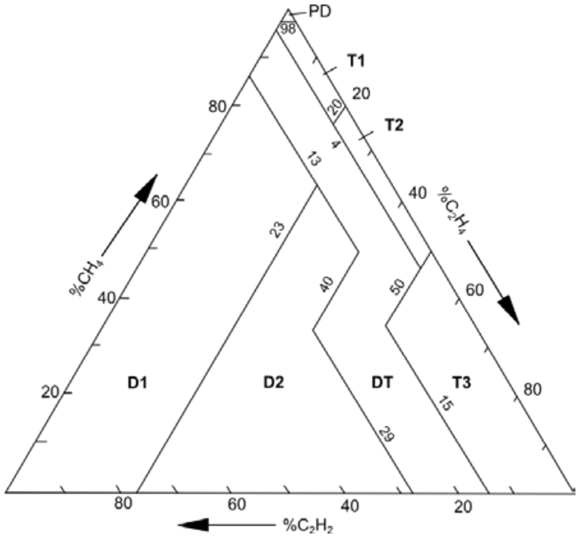


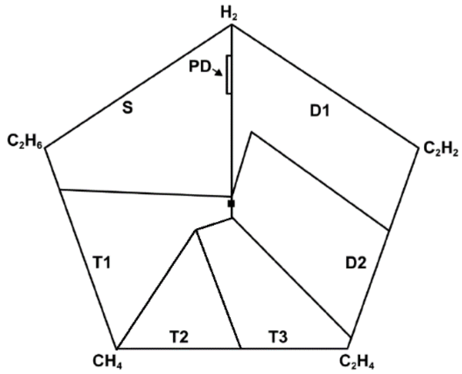
Figure 3 – Duval Triangle 1

In practical use of the Duval Triangle, find the percentage of each gas, plot it on the appropriate side of the triangle and from each point draw three lines parallel to the trailing side, which will intersect at one point. The location of this point will determine the area and the defect to be diagnosed.

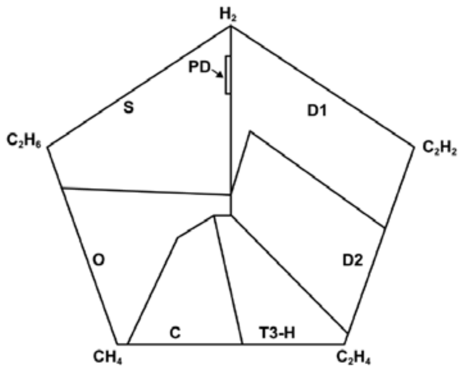
The technique under consideration not only clearly shows the “location” of the defect, but also allows observation of the trajectory of its development, when several DGAs are done after a certain time and the resulting points are sequentially plotted on a triangle. A disadvantage of the Duval triangle is the incomplete use of the diagnostic information obtained from the DGA.

Duval Pentagons [17]. Like the triangle, M. Duval has also developed another additional graphical technique to provide an interpretation of the DGA results in oil-filled transformers – Duval Pentagons (Fig. 4). The relative concentrations of the five dissolved gases (% H_2, % CH_4, % C_2H_6, % C_2H_4 and % C_2H_2) are plotted on each axis in these pentagons. The defect type is identified by calculating the geometric centre of the polygon. Each type of Duval Pentagon can identify seven potential defects.

The Duval Pentagon 1 (Fig. 4 *a*) identifies the 6 “basic” electrical and thermal faults (PD, D1, D2, T1, T2 and T3) considered by IEC 60599, IEEE and Duval Triangle 1. There is also an additional S zone on the pentagon for stray gases of mineral oil. The Duval Pentagon 2 (Fig. 4 *b*) identifies 3 basic electrical defects and 4 more precisely defined, or “advanced”, thermal defects used in Duval Triangles 4 and 5.



a



b

Figure 4 – Duval Pentagons:
a – type I; *b* – type II

A combination of the two existing Duval Pentagons was proposed in [18]. The purpose of this combination is to facilitate automatic damage identification by computer software and, at the same time, to apply all the features of both original pentagons reduced to a single geometry. The result of this combination is shown in Fig. 5.

GATRON method [19]. This method was developed at GATRON GmbH in Germany. It is based on the analysis of seven gases dissolved in transformer oil. Here, in addition to the usual hydrogen, methane, acetylene, ethylene and ethane, propylene (C_3H_6) and propane (C_3H_8) are considered. This approach is used in power transformer monitoring systems in several European countries. As with the Duval Triangle, the interpretation of the chromatographic results is done by geometrically plotting a point on the plane of an equilateral triangle, called a fault gas triangle in this method (Fig. 6).

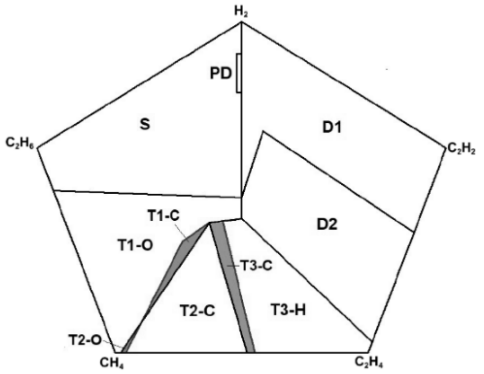


Figure 5 – Combined Duval Pentagon

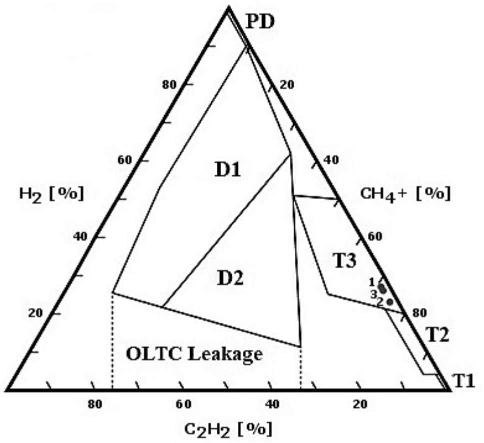


Figure 6 –GATRON Triangle:
• – examples of diagnostic points

Diagnosing only three gases in the Duval technique, as already noted, can in some cases lead to errors in determining the type of defect, since hydrogen and other gases are not considered in the analysis. In the GATRON method the set of gases is very representative, but since it is a question of the sides of a triangle, the following approach is proposed:

- one side of the triangle is assigned to H_2;
- second – to C_2H_2;
- third – to the sum of the gases, which is denoted as CH_4+.

CH_4+ refers to the weighted sum of hydrocarbon gases CH_4, C_2H_4, C_2H_6, C_3H_6, and C_3H_8. It may be measured directly by the sensor during monitoring or it may be obtained by summing the results of a complete chromatographic analysis.

By analogy with the Duval triangle, the sum of H_2, C_2H_2 and CH_4+ is taken as 100 %. Based on the DGA results, the fractions (in percent) of each of the three values are determined and then plotted on the respective sides of the triangle. Lines are then drawn parallel to the side of the triangle, which is lagging (if moving clockwise). All lines, as in the Duval triangle, will intersect at one point. This technique identifies the following types of defects: PD, D1, D2, T1, T2, T3, and, in addition, a previously unexamined defect called "OLTC Leakage".

ETRA method [20]. This methodology was developed by the Electric Technology Research Association and is set out in the Japanese national standard. A 3-level classification system is proposed to identify the presence and extent of internal defects in the transformer under analysis using this method.

- Warning Level 1: While the results of gas-in-oil analysis do not indicate any abnormalities, values are beyond normal levels, and it is judged that some kind of internal change of state has occurred.
- Warning Level 2: The results of gas-in-oil analysis show that signs of abnormality have already appeared in the transformer.
- Trouble Level: The results of gas-in-oil analysis show a progression from Warning Level 2 to a clear internal abnormality in the transformer.

This classification system in the method is presented in the form of a table.

This standard also regulates the use of graphical methods of defect type recognition. The ratios of the three gases C_2H_2, C_2H_4, C_2H_6 are analysed to determine the nature of the defect. In contrast to previous techniques, in this case a rectangle is constructed with irregular scales on its two sides. In the area of the square, the zones corresponding to this or that type of defect are identified. This method proposes the use of 2 similar rectangles – diagnostic chart A and B. They differ in the gas ratios used and the number of defects detected. Chart A is useful for discriminating between overheating and discharge phenomena. Diagnostic chart B is the newly adopted diagnosis method by the ETRA. Discharge domains in chart A are separated into three parts, that is, arc discharge (high energy), discharge (middle energy) and partial discharge (low energy). Fig. 7 shows the diagnostic chart B, better known in Ukraine as the "ETRA square", which is the most convenient way of identifying the type of defect.

If the concentration of C_2H_2 is less than the detection limit, the gas is considered missing. The ratio C_2H_2/C_2H_6 in this case is not calculated, but is conventionally taken as 0.005. In this case, only thermal defects can be diagnosed in the equipment.

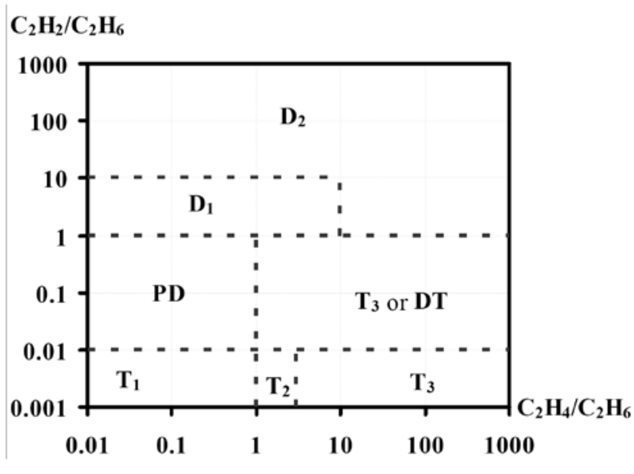


Figure 7 – ETRA square

Key Gas method [9]. The Key Gas method was developed at Doble Laboratories in 1973. The technique is based on determining the percentage of key gas for a given type of defect in high voltage oil-filled electrical equipment. Interpretation of the gaseous decomposition product results is made by simply looking at the facts. For example, a PD in oil is characterised by the release of large quantities of hydrogen and small quantities of other hydrocarbon gases. Thus, for this type of defect the main gas is H_2, and the defect can be identified by a certain percentage of this gas. The main disadvantage of this technique is the limited number of defects that can be identified (Fig. 8).

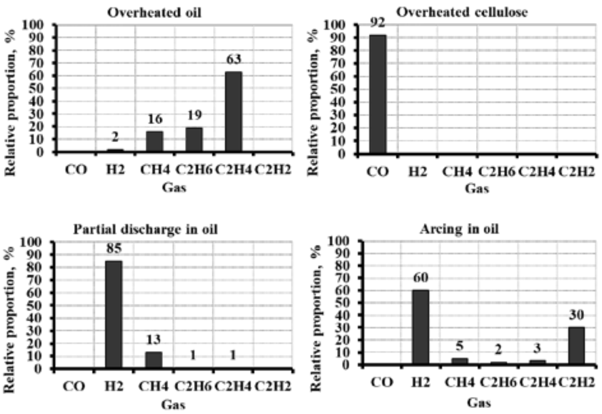
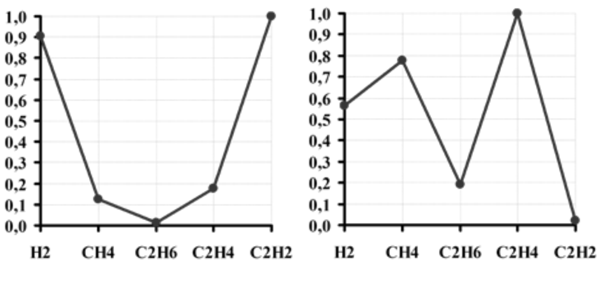


Figure 8 – Defects that are recognised using the Key Gas method

Nomogram method (graphic images of defects) [20, 21]. This technique was proposed by Japanese scientists and has been actively used in Japan since the 1980s under the name of gas pattern. In Ukraine, it is better known as the nomogram method or graphic images of defects. These images are plotted against the concentrations of five gases: H_2, CH_4, C_2H_6, C_2H_4, C_2H_2. The technique was developed based on practical experience comparing actually detected defects with the concentrations of gases derived from DGA. It should be noted that these images are constructed for equipment in which concentrations of some or at least one gas exceed the limit values.

The reference defect images are regulated in [8, 13 and 14]. Fig. 9 shows several nomograms based on DGA results for different defect types. In addition to the regulated images in [22] the results of analysis of graphic images for a wider range of defects are given.



a *b*

Figure 9 – Reference images of defects:
a – arcing; *b* – high temperature overheating

In [23], defect diagrams obtained by digitising the nomograms recommended by the International Energy Commission are given. In addition to hydrocarbon gases and hydrogen, carbon monoxide and carbon dioxide are used. These gases are used to detect damage to the main insulation of transformers.

A comparative analysis of the reliability of defect type recognition performed in [24] showed that one of the significant drawbacks of the method of graphic images is a limited number of reference images, which makes it difficult to recognize many types of defects. The analysis of graphical images constructed based on the results of in-service control of oil gas content in transformers with different types of defects [22] showed that even with the same defect, for equipment of the same type, graphical images can differ significantly both from each other and from the reference images. For this reason, to account for drift in the coordinate values of the graphical images, [25] proposed to use reference areas rather than reference images.

Logarithmic Nomogram method [26]. J. O. Church of the U.S. Bureau of Reclamation developed the Logarithmic Nomograph method. This method is the combination the fault gas ratio concept and the Key Gas threshold value. It was intended to provide both a graphic presentation of fault-gas data and the means to interpret its significance. The Nomograph consists of a series of vertical logarithmic scales representing the concentrations of the individual gases (Fig. 10). Straight lines will be drawn between adjacent scales to connect the points representing the values of the individual concentration. The slopes of these lines are the diagnostic criteria for determining the type of fault. The key at the bottom of the chart between the two axes indicates the fault type for the two axes.

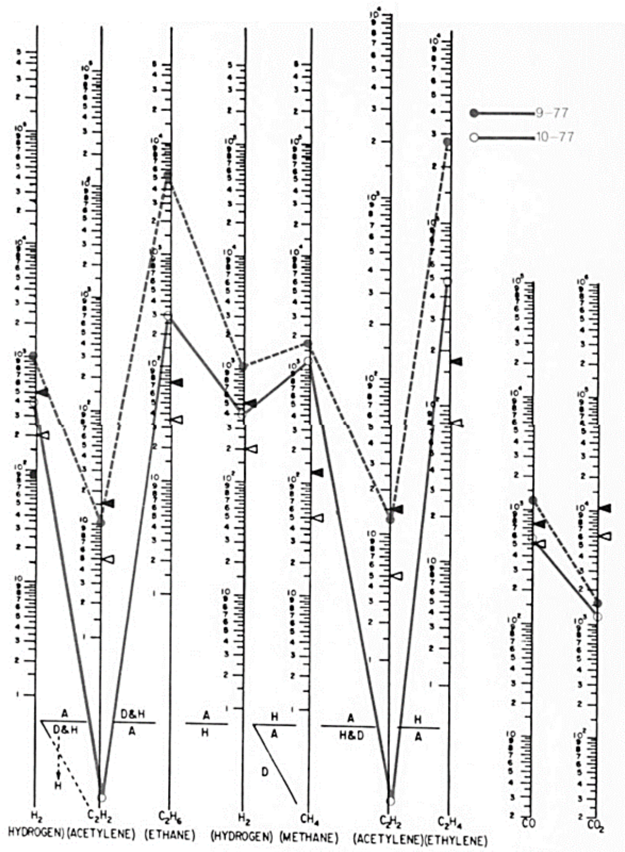


Figure 10 – Logarithmic nomogram

A visual comparison of the slopes of the line segments with the keys given at the bottom of the Nomograph is all that are needed to identify the type of fault (overheating, arcing or partial discharges). Each vertical scale is assigned a threshold value by an arrow. This technique can be applied if at least one of the values exceeds the threshold value. The disadvantage of this technique is the poverty of the diagnostic conclusion, as only three main defects can be identified.

Radar charts method [27]. Serious work on the interpretation of the DGA was carried out by a team of specialists from the Ural Federal University under the leadership of I. V. Davydenko.

At the stage of defect detection they propose to use two levels of values of concentrations of dissolved gases in oil: permissible and the maximum permissible. A study of the factors influencing the concentrations of dissolved gases in oil has led to the following conclusions about the advisability of differentiating permissible and maximum permissible values in the following way:

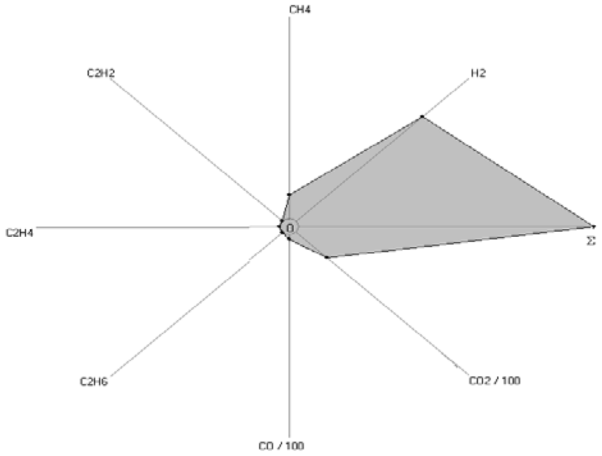
- how the transformer oil is protected (sealed and unsealed);
- by oil grade;
- by service life (up to 3, 3–15, 15–27, 27–37, over 37 years);
- by voltage class (35, 110, 220–500 kV);
- by type of OLTC.

The whole dataset of DGA results was divided into samples according to the influence factors found. An integral distribution function was constructed for each sample to find the permissible and maximum permissible values of gas concentrations.

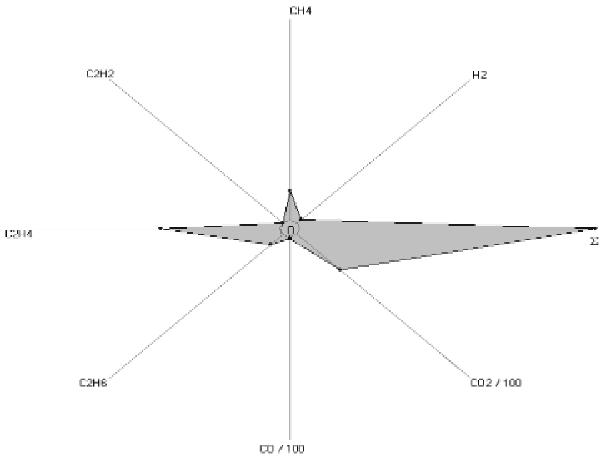
In order to determine the nature of the defect, it is proposed to display the object condition on the basis of DGA results in the form of an eight-blade diagram, where the seven axes show the gas concentrations and the eighth axis shows their sum, calculated according to a certain formula.

An image is preformed on the radar chart, which corresponds to the permissible (maximum permissible) value. The permissible values are selected depending on the design and service life of the equipment mentioned above. All gases received from the DGA are then displayed on the corresponding axises of the diagram. The resulting image of the defective state of the equipment has to be compared with some set of reference images. In order to obtain them, numerous cases of DGA results and subsequent disassembly facts of 35–500 kV transformers were analysed. After examining the collected material, 14 types of reference diagrams reflecting defects of electrical and thermal nature of different manifestation strengths were compiled. Fig. 11 shows a couple of the radar charts for the different types of defects based on the DGA results.

The technique develops a special procedure for comparing the resulting defect image with reference images, which involves scaling the resulting image, calculating measures of proximity and relatedness, and determining the danger coefficient and other characteristics. A special computer software is proposed for this purpose.



a



b

Figure 11 – Radar charts for different defect types based on DGA results:
a – low energy PD, ageing;
b – high-temperature heating, ageing of insulating materials

Heptagon graph [28]. Egyptian researchers proposed the graphical method of the heptagon. The method is based on seven gases produced by the decomposition of oil in defective transformers. In addition to H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2, this method takes into account CO and CO_2 concentrations to assess cellulose insulation degradation. It should be noted that defect type detection in this method is only performed if the concentrations of some or at least one gas exceed the IEEE limit values.

Defect identification is modelled as a graphical representation, which is performed around a visualisation of the gas breakdown zone in the Heptagon coordinate system (Fig. 12). Each zone corresponds to a specific type of transformer defect. Besides the usual defects of electrical (PD, D1, D2) and thermal type (T1, T2, T3) as well as combined defects, this method considers the degree of concentration of cellulose degradation (HCCD is a high; MCCD is a medium; LCCD is a low concentration of cellulose degradation). Each side of the heptagon represents the relative proportions of the concentration of seven gases, which are defined as the percentage of each individual gas to the total concentration of these gases of power transformer, which gives 100 percent (%) of the seven key gases generated from 0 % to 100 % in the clockwise direction for each gas.

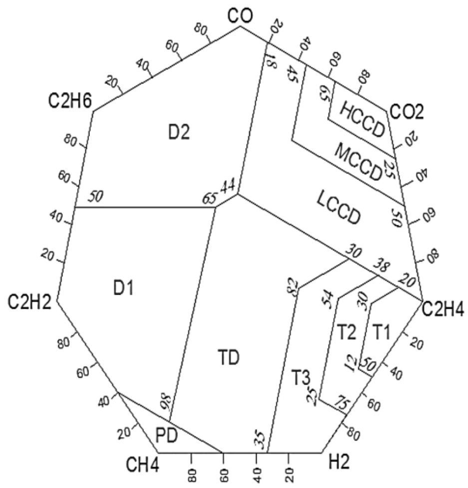


Figure 12 – Boundaries of the Heptagon, which is expressed from 0 to 100 in the clockwise direction

Equilibrium between combustible and non-combustible gases is determine to differentiate between electrical faults and thermal faults for the heptagon coordinates and their relative % are calculated using the certain formulas. The steps to determine the position of DGA points in the heptagon can be summarised as follows.

Step 1: is extracting the gas concentrations.

Step 2: is to cheek the gas concentrations limits (H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO and CO_2) in ppm, it must be in the IEEE normal state before the problem is confirmed.

Step 3: the transformer is considered faulty if at least one of the gas concentrations exceeds the value limits.

Step 4: the relative % of each gas is determined by the formulas.

Step 5: plot the percentage of each gas on the heptagon graph to arrive at the diagnosis; the centre of mass of the percentage concentrations determines the corresponding point for a certain faulty case.

Results review. The above description of DGA interpretation methods, allows classifying the known methods according to the following main attributes:

1. *Diagnosis type.*

All methods considered, according to the type of diagnosis, can be divided into two groups – analytical and graphical methods. The first group includes all methods, in which defect identification is performed by analytical calculations of the required values and their comparison with the values regulated in the standards and methods under consideration. The second group includes methods in which the type of defect is determined graphically rather than by calculation and logic. In addition, methods in this group can be classified according to the method of diagnosed object [1].

2. *Diagnostic criteria to be used.*

Gas concentrations. The use of immediate values of gas concentrations as a diagnostic criterion for interpretation of DGA results occurs only in Radar charts and in the Logarithmic Nomogram method.

Gas pair ratios. The most used diagnostic criterion. Used in all analytical methods. The main disadvantage of methods in which this criterion is used is the possible incomplete use of diagnostic information. In particular, the ETRA technique uses ratios of only two gas pairs, while the minimum number of ratios recommended in [8] is three.

Gas percentage. Used in almost all graphical methods of interpreting DGA results (with the exception of the graphical representation of gas ratios in IEC 60599 and Logarithmic Nomogram method). This criterion can be considered the most practical as it reflects the ratio between the concentrations of all gases in a given sample.

3. Number of recognisable defects.

Most of the analysed methods allow recognition of 6-7 most characteristic defect types. The greatest number of defects are recognised by the graphic images method (13 defects) and the petal diagrams (14 defects). At the same time, the least number of defects are recognized by the Key Gas (4 defects), Dornenburg (3 defects) and Logarithmic Nomogram (3 defects) methods. It is noteworthy that only a few methods (SOU-N EE 46.501:2006, RD 153-34.0-46.302-00, Rogers Ratios method, Radar charts) can diagnose a defect-free condition. In addition, only a few methods can diagnose damage to the equipment's solid insulation, that is, cellulose degradation. These methods include the Heptagon graph, the Key Gas method, and Duval Triangles and Pentagons. Also, not all methods and standards implement the recognition of combined defects. This includes only half of the ones considered. Among the analytical methods, the recognition of combined defects is implemented only in the standards used in the Russian Federation and the MSS methodology. Among graphical methods, recognition of such defects is possible using Duval Triangle, ETRA methos, method of graphic areas, Radar charts and Heptagon graph.

Conclusions. Based on an analysis of known methods for interpreting DGA results, it is found that all methods considered can be divided into:

1. By diagnosis type. All methods considered, according to the type of diagnosis, can be divided into two groups. The first group includes all methods, in which defect identification is performed by analytical calculations of the required values and their comparison with the values regulated in the standards and methods under consideration. The second group includes methods in which the type of defect is determined graphically rather than by calculation and logic.

2. According to the diagnostic criterion used, all the methods considered can be divided into methods that use values of either gas concentrations, gas pair ratios or gas percentages.

3. By the number of recognisable defects. Most of the analysed methods allow recognition of 6–7 most characteristic defect types. The graphical images method and the Radar charts can recognise the greatest number of defects. The Key Gas, Dornenburg and logarithmic nomogram methods recognise the smallest number of defects. Furthermore, only a few methods allow for the diagnosis of defect-free condition and/or solid insulation damage as well as the detection of combined defects.

The results show significant differences in the criteria and norms used by different standards and author's methods to determine the type of defect based on DGA results. Obviously, these differences can lead to different diagnoses for the same data. Thus, it is of practical interest to improve methods for interpreting DGA results.

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