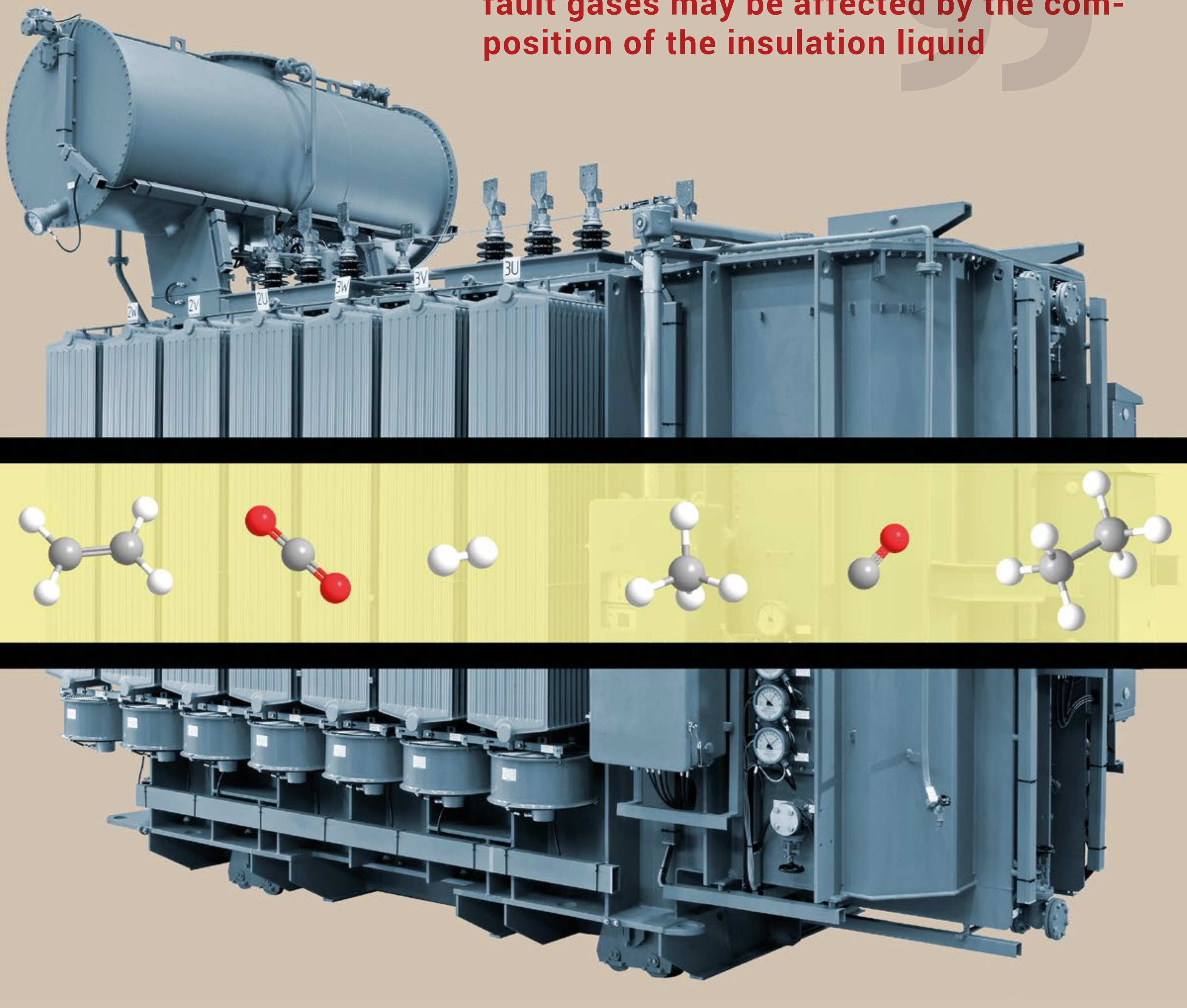
> **In case of thermal or electrical stress, the transformer´s tendency to generate fault gases may be affected by the composition of the insulation liquid**



ABSTRACT

Dissolved gas analysis is a common technique in the supervision and maintenance of transformers. It can give hints on defects and faults in oil-immersed transformers by determining and quantifying the gases arising due to the thermal or electrical stress. Different algorithms for the assessment of transformers, which utilize data obtained from dissolved gas analysis, have been published so far. However, only few investigations exist that deal with the influence of the oil´s composition on the oil´s tendency of releasing gases. This research study presents a comparison of three commercially available transformer oils of different composition regarding that aspect. The results indicate that the oil mainly consisting of paraffinic hydrocarbons shows a different gassing pattern compared to naphthenic oils when it is exposed to thermal stress. Some explanations for this phenomenon are given in the report as well.

KEYWORDS

dissolved gas analysis, thermal stress, transformer oil, fault gases

Bernd CHRISTIAN, Armin GLÄSER

Transformer oil fault gases under thermal stress at 160 °C – Part I

1. Introduction

Oil-immersed power transformers in service can exhibit several defects and faults. Partial discharges, discharges of high energy, arcing, thermal incidents like hotspots, overheating and insufficient cooling are examples of such defects and faults. If a transformer suffers from thermal or electrical stress, gases resulting from oil decomposition and paper degradation will be formed. The most important representatives of those gases in mineral oils are: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), propane (C_3H_8), propylene (C_3H_6), carbon monoxide (CO) and carbon dioxide (CO_2). Hence, the gases listed above can be considered as indicators for defects and faults in transformers; sometimes they are denoted as fault gases [1]. An important technique for determination of fault gases in transformer oils is the so-called Dissolved Gas Analysis (DGA). For many decades now, DGA has been used as a helpful diagnostic tool for detection and evaluation of defects and faults in transformers [2]. The equipment for performing DGA consists of an extraction device coupled with gas chromatography. Several techniques for extraction of dissolved gases from oil are available: (1) multi-cycle vacuum extraction (e.g. Toepler pump), (2) single-cycle vacuum extraction (partial degassing), (3) stripping, and (4) headspace extraction [3]. The gas chromatograph should be equipped with two packed or porous layer open tubular (PLOT) columns containing stationary phases of different polarities. Moreover, the usage of a Thermal Conductivity Detector (TCD) and a Flame Ionization Detector (FID) enables selective detection of all relevant gases. The sensitivity in detecting the gases CO and CO_2 can be improved by means of a methanizer fitted at the inlet to the Flame Ionization Detector. The two carbon oxides (CO and CO_2) are converted to CH_4, a gas which can be registered at a lower limit of detection by FID [3].

The concentrations of dissolved gases, normally measured in µl gas/l oil or parts per million (ppm), obtained by DGA, depend on the character of defects or faults emerging in transformers [4]. Above all, a variety of interpretation schemes has been suggested in order to derive an accurate diagnosis for transformers from raw measurement data. These interpretation schemes are based on empirical assumptions and practical knowledge gathered by experts worldwide [4]. The common interpretation schemes are: Doernenburg Ratio Method [5], Key Gas Method [6], Duval Triangle and Pentagon Method [7, 8, 9, 10], Rogers Ratio Method [11] and the IEC Method [2]. Additionally, various artificial intelligence systems, including fuzzy logic and artificial neural networks, have been developed since the 1990s [12, 13, 14] to enable a more efficient diagnosis on transformers. Table 1 gives an overview of typical faults in transformers and their predominant, significant gases [6].

> **A naphthenic mineral oil with and without inhibitor, and a paraffinic gas-to-liquid oil with inhibitor were tested using an open experimental set-up**

Table 1. Significant gases for the four general fault types in transformers [6]

	Fault type			
Gas	**Overheated oil**	**Overheated cellulose**	**Corona in oil**	**Arcing in oil**
C_2H_4	+			
C_2H_2				+
C_2H_6	+			
CH_4	(+)		+	
CO		+		
H_2			+	+

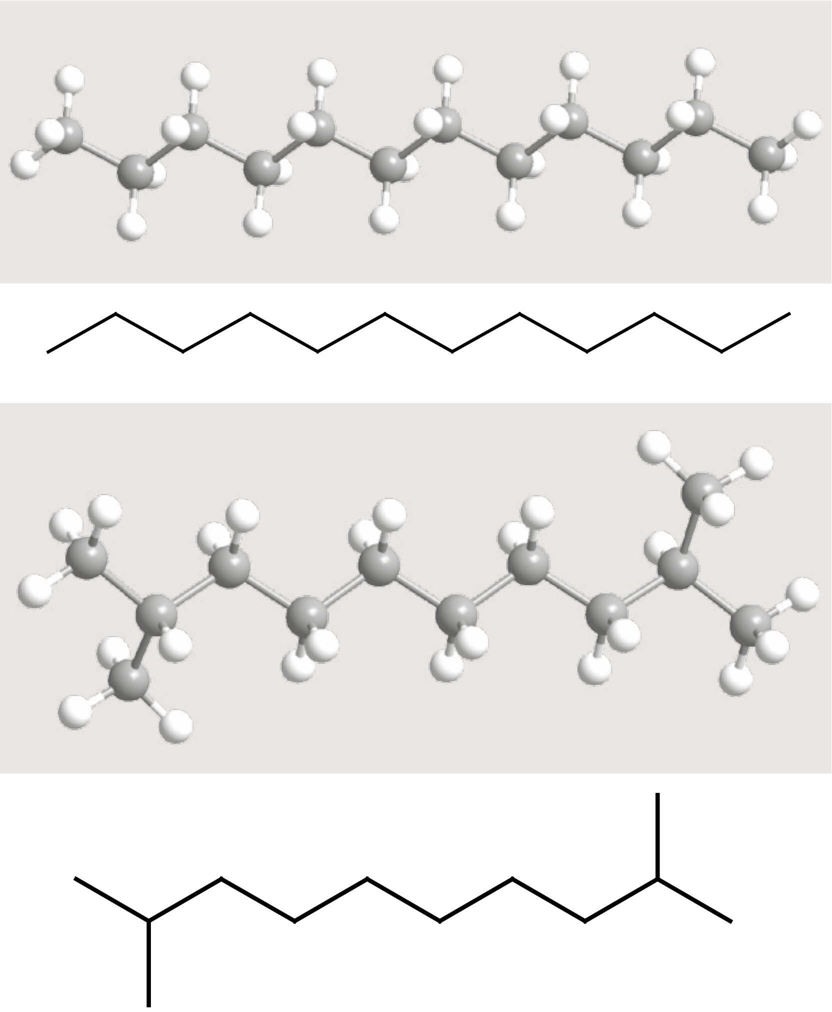


Figure 1. Examples of paraffinic and isoparaffinic hydrocarbons: n-Dodecane (top) and iso-dodecane (bottom)

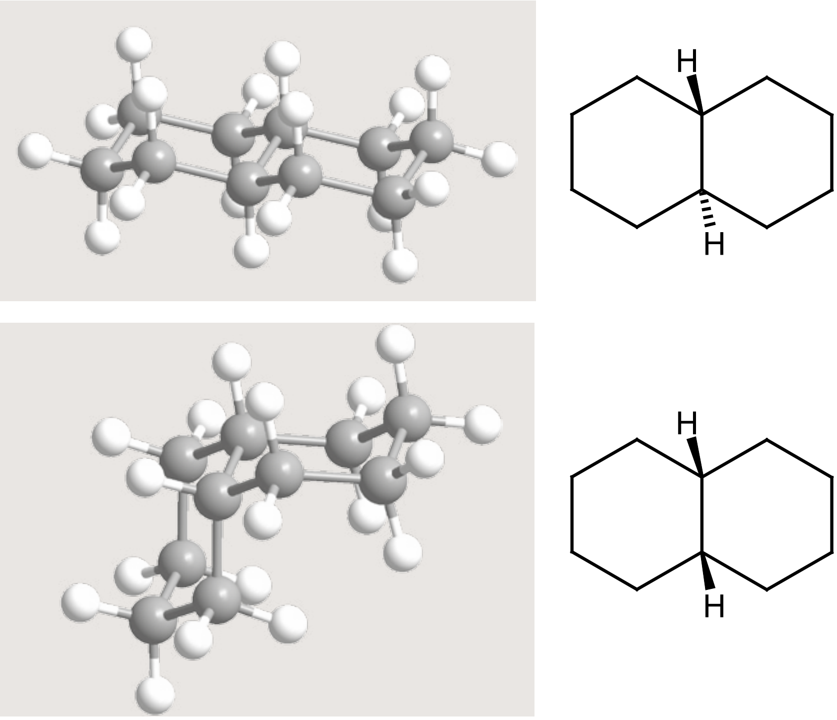


Figure 2. The two isomers of decalin as examples of naphthenic hydrocarbons: trans-Decalin (top) and cis-decalin (bottom)

> **Test oils were heated from 25 °C to reach a maximum of 160 °C; this temperature was maintained for 100 h before the oil was cooled down to 25 °C**

Nevertheless, the transformer´s tendency to generate fault gases, in case of thermal or electrical stress, may be affected by the composition of the insulation liquid as well. Transformer oils based on mineral oils normally consist of paraffines (n-alkanes), isoparaffines (isoalkanes), naphthenes (cycloalkanes) and aromates. Paraffinic hydrocarbons, Fig. 1, provide inferior solubility of polar components (e.g. water and oxidation products) and high viscosity, whereas naphthenic hydrocarbons, Figs. 2 and 3, have advantageous low temperature properties due to their low viscosity and a better solubility of polar components. Aromates, Fig. 4, normally consist of six-membered rings with alternating double bonds and therefore, their physical and chemical properties are different [15]. Additionally, some supplemental, inhibitive anti-oxidative substances (inhibitors) can be added to transformer oils to protect them against oxidative degradation [15].

2. Open experimental set-up

In this article, we present several key experiments in which three different transformer oils were subjected to a heating program with a well-defined temperature profile, followed by an investigation of the fault gases evolved during the heating period. An open experimental set-up (a) was used, which enabled the exchange of matter and energy with the environment, Fig. 5. With the open experimental set-up (a), three different transformer oils were tested, whereas a comprehensive investigation was expanded to four different oils with a closed experimental set-up (b). The results received by experiments with a closed experimental set-up (b) will be published later on.

The experiments were performed by usage of a temperature calibrator (TP M 225 S-U, SIKA Dr. Siebert und Kühn GmbH & Co. KG, D-34260 Kaufungen, Germany): A volume of 450 ml transformer oil destined for examination was poured in the heating cell of the temperature calibrator and the heating cell was closed with a reinforced plastic screw plug which contained five holes (diameter 15 mm) and a drill hole (diameter 3 mm). Within the first sequence of attempts using the open experimental set-up (a), see Fig. 5, the five holes with diameter 15 mm were closed with silicone stoppers, whereas the small drill hole (diameter 3 mm) was left open to enable an interchange of gases with the surrounding atmosphere. The silicone stoppers had been tested for their gassing behavior in advance, by heating them without oil at 160 °C (100 h), not showing any gassing. Therefore, a possible contamination by the silicone stoppers could be excluded. Within this experimental sequence, the test oils were heated from 25 °C at a gradient of 5 °C/min to reach a maximum of 160 °C. This maximum was maintained for 100 h before the oil was cooled down to 25 °C at 2 °C/min. The temperature of 160 °C is on the upper limit of a phenomenon, which is called "stray gassing" [16]. Furthermore, the temperature of 160 °C could be maintained with high precision by the temperature calibrator. In addition, 160 °C is a "common" maximum temperature in the windings of a transformer, according to the authors´ knowledge. During the entire heating period, the oils were not stirred. Test samples from the sampling liquid were taken just before the start and after the termination of the heating program and cooling down in case of the experimental sequence with the open set-up (a). Subsequently, DGAs were performed in triplicate on the liquid samples by means of a calibrated multi-cycle vacuum extractor coupled with a gas chromatograph (TOGA GC version 2, equipped with vacuum extractor and automatic sampling system, Energy Support GmbH, D-41468 Neuss,

> **The temperature of 160 °C is a common maximum temperature in the windings of a transformer and is on the upper limit of a phenomenon called "stray gassing"**

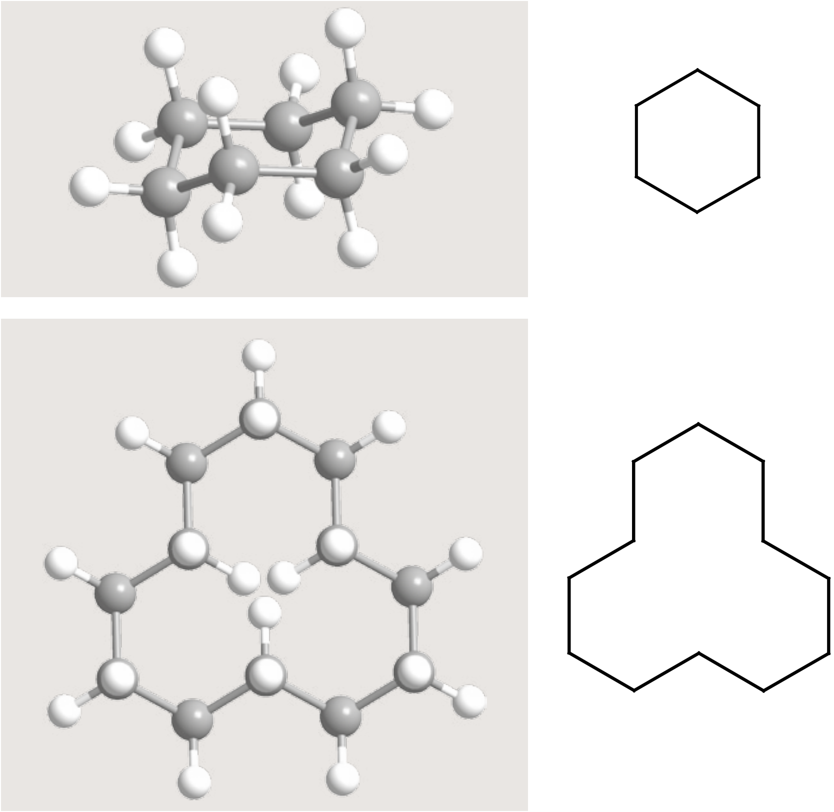


Figure 3. Another two examples of naphthenic hydrocarbons: cyclohexane (top) and cyclododecane (bottom)

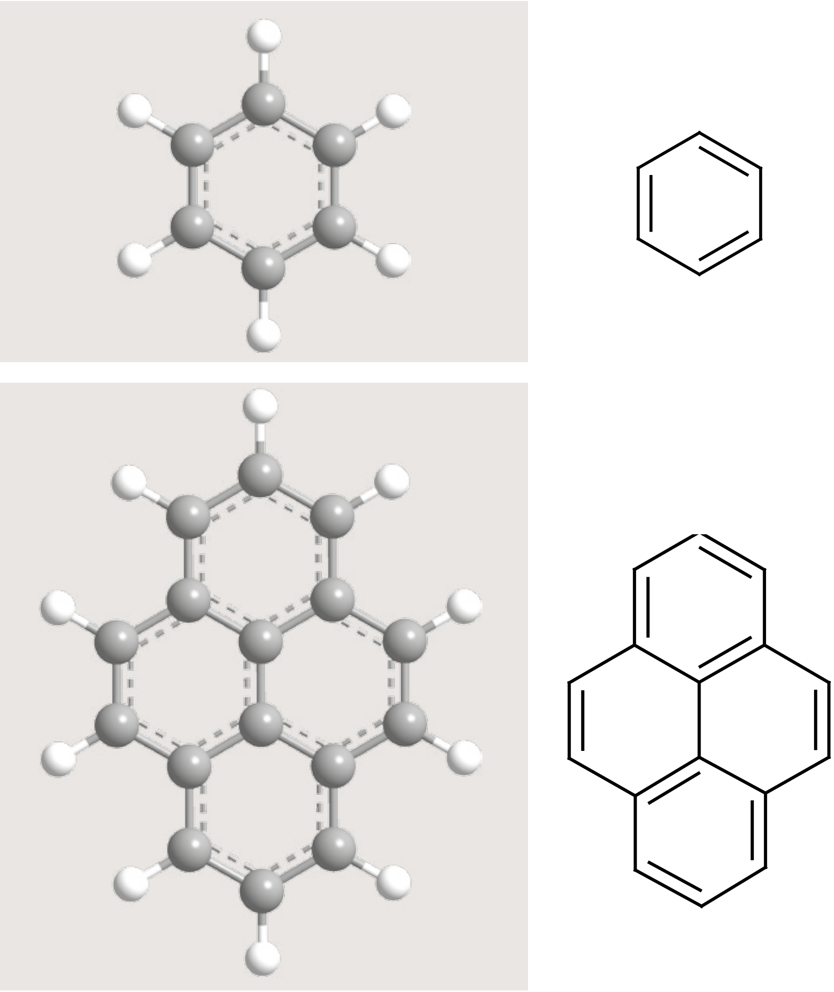


Figure 4. Two representatives of aromatic hydrocarbons: benzene (top) and pyrene (bottom)

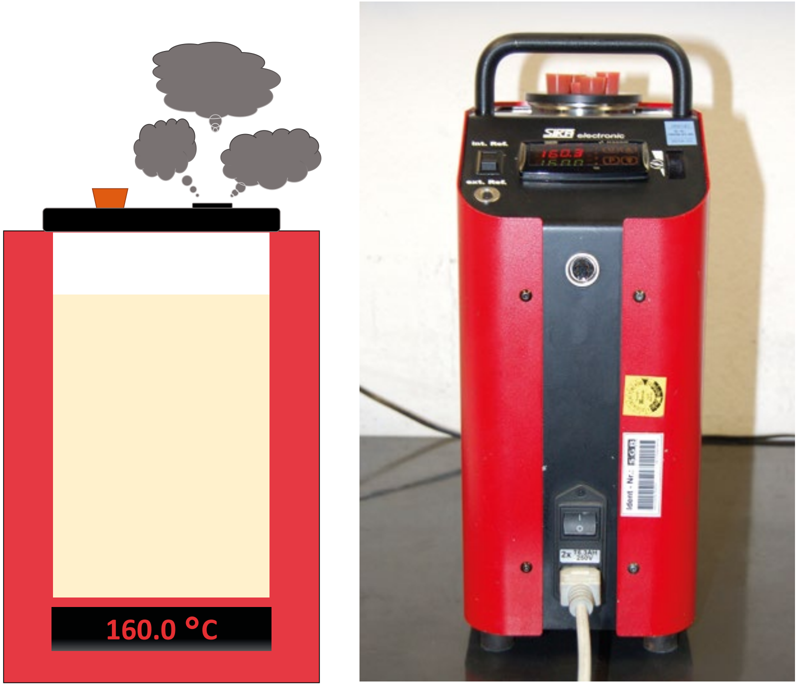


Figure 5. Schematic diagram and photograph of the open experimental set-up (a) with exchange of matter and energy

After the heating period, the gases showing highest concentrations in all three transformer oils were CO_2 and CO

Germany). The new transformer oils examined in this study are commercially available and they were used directly after degassing (p <0.5 mbar; T=50-60 °C; Type AP 60 H Super, Wilhelm Hedrich, Vakuumanlagen GmbH & Co. KG, D-35630 Ehringshausen-Katzenfurt, Germany) and cooling down to the ambient temperature in an airtight aluminum bottle. A degassing unit enables the reduction of gas content in oil from 10 vol-% to 0.05 vol-% in one cycle by heating and vacuum treatment. In addition, a degassing unit reduces the oil´s moisture up to 2 µg/g oil (2 ppm) as well. Extra treatments or addition of supplementary anti-oxidative substances were not performed on the oils. A naphthenic mineral oil without inhibitor (NA-UI: naphthenic uninhibited), an inhibited naphthenic mineral oil (NA-Ia: naphthenic inhibited) and a mainly paraffinic Gas-to-Liquid (GtL)-oil with inhibitor (PA-I: paraffinic inhibited) were chosen for the experiments. The acronyms NA-UI, NA-Ia and PA-I do not imply a general representativeness of the oils for all naphthenic and paraffinic oils on the market; they were simply used for a more facile readability. According

Table 2. Composition and properties of the transformer oils used for testing the trend of generating fault gases during thermal stress with open experimental set-up (a)

	NA-UI	NA-Ia	PA-I
Aromatic hydrocarbons [%][1]	5	7	2
Paraffinic hydrocarbons [%]	49	47	75
Naphthenic Hydrocarbons [%]	46	46	23
Inhibitor [%][2]	--	0.31	0.21
Color[3]	0.5	0.5	0.5
Breakdown voltage [kV][3]	75	75	88.1
Dielectric Dissipation Factor[3]	0.0020	0.0010	0.0010
Neutralization value [mg KOH/g][3]	0.01	0.01	0.01
Water content [mg/kg][3]	2	4	2
Interfacial tension [mN/m][3]	45.3	45.3	45.3
Sediment and sludge [%][3]	<0.02	<0.02	<0.02
Particles[3]	-/13/10	-/12/9	-/13/9
Boiling point [°C][4]	>280	>232	>280

[1] acc. to [17]; [2] acc. to [18]; [3] acc. to [19] and references therein; [4] acc. to the manufacturer´s technical and safety data sheets

Table 3. DGAs and characteristic figures indicating the degradation of oils NA-UI, NA-Ia and PA-I before and after heating (100 h; 160 °C) with open experimental set-up (a)

	NA-UI		**NA-Ia**		**PA-I**	
Gas[1]	before heating	after 100 h at 160 °C	before heating	after 100 h at 160 °C	before heating	after 100 h at 160 °C
CO_2	30.5	2997.7	43.6	3493.3	65.7	1073.7
C_2H_4	n.d.	36.0	n.d.	46.9	n.d.	17.3
C_2H_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
C_2H_6	n.d.	177.0	n.d.	101.2	n.d.	1.4
CH_4	n.d.	283.0	n.d.	513.7	n.d.	7.7
CO	0.1	1864.7	0.2	1973.7	0.2	331.0
C_3H_6	n.d.	186.0	n.d.	104.8	n.d.	32.7
C_3H_8	n.d.	361.3	n.d.	111.0	n.d.	1.3
H_2	n.d.	10.4	n.d.	24.3	n.d.	33.7
O_2	1116.0	6832.0	1030.7	6357.7	4068.3	10774.7
N_2	3261.7	90484.3	3251.7	92421.0	7528.7	37660.7
Inhibitor [%][2]	--	--	0.31	0.23	0.21	0.14
Color[3]	0.5	7.5	0.5	7.5	0.5	1.5
Neutralization value [mg KOH/g][3]	0.01	0.120	0.01	0.120	0.01	0.080
Interfacial tension [mN/m][3]	45.3	23.4	45.3	23.6	45.3	29.8
Sediment and sludge [%][3]	<0.02	0.0240	<0.02	<0.02	<0.02	<0.02
Recovery [%][4]	100.0	93.3	100.0	84.4	100.0	93.3

[1] The concentrations of gases are given in [µl gas/l oil]; n.d. = not detected; [2] acc. to [18]; [3] acc. to [19] and references therein; [4] ratio between volumes (oil) after and before the heating period calculated in percentage

to the manufacturers, the naphthenic oils are based on mineral oils, whereas the paraffinic oil is synthesized from natural gas and oxygen via syngas (CO and H_2) in a Fischer-Tropsch reaction, followed by a catalytic hydrocracking process. For that reason, this paraffinic oil is denoted as "Gas-to-Liquid – (GtL)"-oil by its manufacturer. The selected oils are widespread in transformers all over the world and they are regularly purchased by transformer manufacturers from oil suppliers.

3. Results

At the beginning of our experiments, we did not expect that a significant, notable difference in the oils´ trend of generating fault gases after heating would occur. Amazingly, significant concentrations of the fault gases CO_2, C_2H_4, C_2H_6, CH_4, CO, C_3H_6, C_3H_8 and H_2 were detected after a heating period of 100 h at 160 °C when oils NA-UI, NA-Ia and PA-I were tested with the open experimental set-up (a). The fault gas C_2H_2 was not detected or only detected in traces. The representatives registered with the highest concentrations were carbon dioxide (CO_2) and carbon monoxide (CO) in all three transformer oils. Moreover, the naphthenic mineral oils NA-UI and NA-Ia formed high amounts of the fault gases methane (CH_4), ethane (C_2H_6), propane (C_3H_8), ethylene (C_2H_4) and propylene (C_3H_6), respectively. On the other hand, the mainly paraffinic (GtL)-oil PA-I showed only low quantities of hydrocarbon gases after the heating period, but significantly more hydrogen was detected compared to the naphthenic mineral oils. The exact composition of each transformer oil used with open experimental set-up (a) is listed in Table 2. An overview with the complete

The oil PA-I formed the lowest concentration of fault gases, except for hydrogen

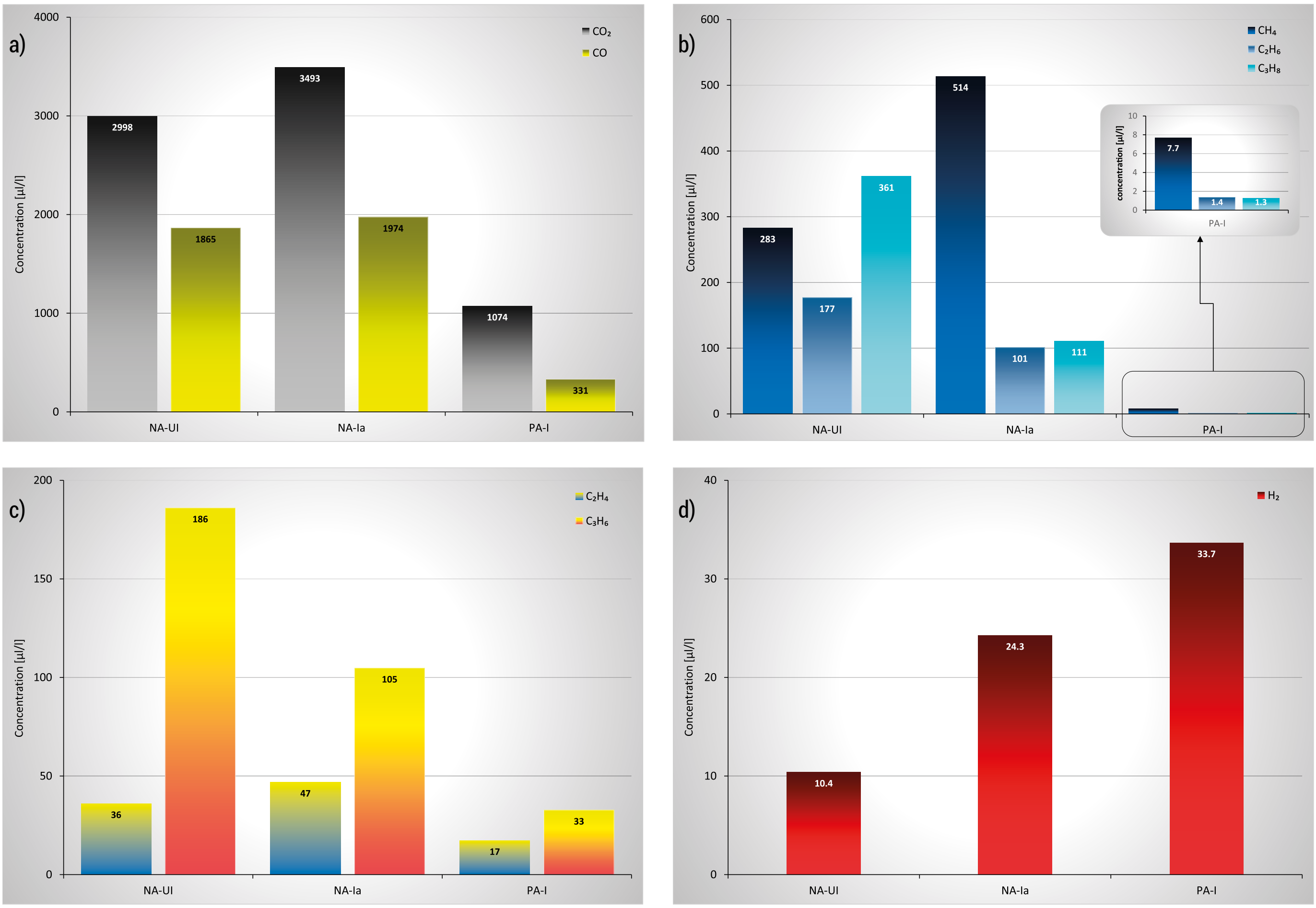


Figure 6. Concentrations of fault gases in oils NA-UI, NA-Ia and PA-I after heating (100 h; 160 °C) with open experimental set-up (a): (a) carbon dioxide CO_2 and carbon monoxide CO; (b) methane CH_4, ethane C_2H_6 and propane C_3H_8; (c) ethylene C_2H_4 and propylene C_3H_6; (d) hydrogen H_2

DGA results received from the experiments with experimental set-up (a) is depicted in Table 3 (top).

Additional parameters as indicators for the state of decomposition were measured from the transformer oils after heating. The uninhibited oil NA-UI showed the highest content of sludge and the lowest interfacial tension, whereas the color and the neutralization number were equal for oils NA-UI and NA-Ia. Nevertheless, the parameters, determined after heating the transformer oils, reveal a higher degradation of the oils NA-UI and NA-Ia compared to oil PA-I, since oil PA-I showed the best values in all measurements. Obviously, the persistence of the oil PA-I is the best of the three oils involved in the experiments. Interestingly, the recovery, as ratio between the volume (oil) after and volume (oil) before the entire heating period, calculated in percentage, was the lowest for oil NA-Ia with 84 %, compared to the other oils with more than 93 %. Probably, the oil NA-Ia contains more components of higher volatility than oils NA-UI and PA-I; an assumption which seems to be sensible since the boiling point for oil NA-Ia is the lowest for all three oils (see Table 2). Characteristic figures indicating the degree of the oils´ degradation after heating with the open experimental set-up (a) can be taken from Table 3 (bottom).

To illustrate, the charts in Figure 6 (a-d) present the concentrations of fault gases received in the experiments with open experimental set-up (a).

4. Discussion

As a consequence of the experiments and results described above, the following aspects can be drawn. Considering the behavior of naphthenic mineral oils with (NA-Ia) and without inhibitor (NA-UI) in open experimental set-up (a), it seems that the presence of inhibitor suppresses the generation of the fault gases C_2H_6, C_3H_6 and C_3H_8, whereas the formation of the fault gases CO_2, C_2H_4, CH_4, CO and H_2 is favored by an inhibitor when a transformer oil is exposed to thermal stress. The characteristic figures determined for each oil after the heating experiments show only marginal differences in case of the naphthenic mineral oils, with the exception of the parameters sludge and recovery, see Table 3 (bottom). Still, some more detailed experiments with a highly sophisticated and extremely sensitive equipment are necessary to investigate the role of inhibitors in the processes of generating fault gases and degradation of transformer oils during thermal stress in an open system. In addition, the oil containing the highest percentage of paraffinic hydrocarbons and accordingly the lowest percentage of naphthenic and aromatic hydrocarbons (PA-I) formed the smallest concentration of fault gases, except for hydrogen, compared to the mainly naphthenic mineral oils involved. After those astonishing results received with the open experimental set-up (a), showing unexpected, differing fault gas patterns, the authors decided to use a more sophisticated, closed experimental set-up, which enables the exchange of energy, but not of matter with the environment (experimental set-up (b)). In addition, another inhibited, naphthenic mineral oil (NA-Ib degassed and air saturated) was included in the experiments. The results of those experiments will be presented in a continuing article in this journal.

> **The presence of inhibitor seemingly suppresses the generation of the fault gases C_2H_6, C_3H_6 and C_3H_8 and favors the formation of CO_2, C_2H_4, CH_4, CO and H_2**

Acknowledgment

The authors thank the Bundesministerium für Wirtschaft und Energie (Germany) for financial support, the Wiener Netze, Prüfanstalt für Isolieröle, Chemisches Labor (Vienna – Austria) for infrared analyses and Analysen Service GmbH (Leipzig – Germany) for oil analyses.

Bibliography

[1] Y. Leblanc, R. Gilbert, M. Duval and J. Hubert, Static headspace gas chromatographic determination of fault gases dissolved in transformer insulating oils, *Journal of Chromatography A* 1993; 633: 185-193

[2] International Electrotechnical Commission, International Standard IEC 60599:1999 + A1:2007, Mineral oil-impregnated electrical equipment in service – Guide to the interpretation of dissolved and free gases analysis, Edition 2, 1999 consolidated with amendment 1, 2007

[3] International Electrotechnical Commission, International Standard IEC 60567:2011, Oil-filled electrical equipment – Sampling of gases and analysis of free and dissolved gases – Guidance, Edition 4.0, 2011

[4] H.-C. Sun, Y.-C. Huang and C.-M. Huang, A review of dissolved gas analysis in power transformers, *Energy Procedia* 2012; 14: 1220-1225

[5] E. Doernenburg and W. Strittmater, Monitoring oil cooling transformers by gas analysis, *Brown Boveri Review* 1974; 61: 238-274

[6] Institute of Electrical and Electronics Engineers, IEEE Standard C57.104-2008, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers, 2008

[7] M. Duval, Fault gases formed in oil-filled breathing EHV power transformers; The interpretation of gas analysis data; IEEE transactions on power apparatus and systems 1974, conference paper C74, 476-478

[8] M. Duval, Dissolved gas analysis: It can save your transformer, *IEEE Electrical Insulation Magazine* 1989; 5: 22-27

[9] M. Duval, The Duval triangle for load tap changers, non-mineral oils and low temperature faults in transformers, *IEEE Electrical Insulation Magazine* 2008; 24: 22-29

[10] M. Duval and L. Lamarre, The Duval pentagon – a new complementary tool for the interpretation of dissolved gas analysis in transformers, *IEEE Electrical Insulation Magazine* 2014; 30: 9-12

[11] R. R. Rogers. IEEE and IEC Codes to interpret incipient faults in transformers, using gas in oil analysis. *IEEE Transactions on Electrical Insulation* 1978; 13: 349-354

[12] J. L. Guardado, J. L. Naredo, P. Moreno and C. R. Fuerte, A comparative study of neural network efficiency in power transformers diagnosis using dissolved gas analysis, *IEEE Transactions on Power Delivery* 2001; 16: 643-647

[13] V. Miranda and A. R. G. Castro. Improving the IEC table for transformer failure diagnosis with knowledge extraction from neural networks. *IEEE Transactions on Power Delivery* 2005; 20: 2509-2516

[14] J. P. Lee, D. J. Lee, S. S. Kim, P. S. Ji and J. Y. Lim, Dissolved gas analysis of power transformer using fuzzy clustering and radial basis function neural network, *Journal of Electrical Engineering & Technology* 2007; 2: 157-164

[15] Nynäs Naphthenics AB, *Base Oil Handbook*, Stockholm, 2001

[16] International Electrotechnical Commission, International Standard IEC 60599:2015, Mineral oil-filled electrical equipment in service – Guide on the interpretation of dissolved and free gases analysis, Edition 3.0, 2015

[17] International Electrotechnical Commission, *International Standard IEC 60590:1977*, Determination of the aromatic hydrocarbon content of new mineral insulating oils, Edition 1977

[18] International Electrotechnical Commission, *International Standard IEC 60666:2010*, Detection and determination of specified additives in mineral insulating oils, Edition 2010

[19] International Electrotechnical Commission, *International Standard IEC 60422:2013*, Mineral insulating oils in electrical equipment – Supervision and maintenance guidance, Edition 2013

Authors

Bernd Christian studied Chemistry at the University of Tübingen, where he received a diploma and a PhD (Dr. rer. nat. – majoring in organic chemistry). After one year as a postdoctoral fellow in Prof. Dr. Ernst Bayer´s group, he joined the Institute of Nutrition (University of Jena) where he completed his Habilitation thesis in food chemistry (Dr. rer. nat. habil.). In 2009, Bernd entered the Labor für Umweltanalytik LUA (Schwerin) for a short time. A year later, he started to work on transformers with Siemens TLM (Nuremberg). Since 2013, he has been responsible for all types of oil analyses in the laboratory of Starkstrom-Gerätebau GmbH Regensburg.

Armin Gläser is a graduate engineer in product engineering, working as a project manager in a smaller company. Previously, he worked as a business development manager at Messko, Germany, focusing on protection, sensor and automation products for power transformers. Prior to this job, he served in different positions in the electrical industry, e.g. as a leading project manager for power transformer repairs at Siemens Nuremberg.