CHEMICAL ENGINEERING TRANSACTIONS

VOL. 118, 2025

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Laura Piazza, Francesco Donsì, Giorgia Spigno, Paolo Ciambelli, Luca di Palma

ISBN 979-12-81206-19-9; **ISSN** 2283-9216

DOI: 10.3303/CET25118068

PCB Contaminated Oils and the Detection of Transformer Aging, according to IEEE STD C57.104-2019

Miguel W. Bernabé[a]*, Lino R. Rodríguez[b], Rosario D. López[c], Margarita J. Egúzquiza[c], Roger O. Lujan[d], Manuel A. León[b]

[a] Industrial Researcher, IEEE-Comité de Industria - Region 9, Lima, Perú.
[b] Universidad Nacional José Faustino Sánchez Carrión, Huacho, Perú.
[c] Universidad César vallejo, Lima, Perú.
[d] Universidad Nacional Mayor de San Marcos, Lima, Perú
ing.mwbernabe@ieee.org

The presence of polychlorinated biphenyls (PCBs) in transformer oils can influence the aging and deterioration process, posing a significant challenge in the electrical industry based on IEEE STD C57.104-2019. The standard provides guidelines for the interpretation of gases generated in transformer oils, specifically the presence of PCBs. An innovative methodology is proposed that integrates the detection of PCBs with the analysis of gases generated in transformer oils. The approach combines advanced gas chromatography and mass spectrometry techniques, along with a predictive analytics model, to improve accuracy in detecting and analyzing transformer aging. Dielectric oil samples from a 1250 kVA transformer were analyzed, obtaining concentrations of PCBs (Aroclor 1242, 1254 and 1260) below 2 ppm, below the permitted limit of 50 mg/kg. The results show that the concentration of methanol is an indicator of aging, ranging from 0.01 to 0.5 ppm, correlated with oil degradation. The predictive model achieved a sensitivity of 96.5% and a specificity of 94.8% in the detection of incipient faults, surpassing traditional methods such as the Dornenburg and Rogers rules (sensitivity: 85-90%). This study presents an innovative solution with significant implications for the scientific community and industry, improving the accuracy of PCB detection.

1. Introduction

The presence of polychlorinated biphenyls (PCBs) in transformer oils poses a significant environmental challenge due to their toxicity (UNEP Chemicals, 2024); (Lundgaard et al., 2004). These compounds, known for their dielectric properties, have been the subject of intense scientific research (Bjarne and Egaas, n.d.); (Moganti and Ercal, 1995), due to its resistance to degradation and potential toxicity (ATSDR, 2024) (Gilbert et al., 2010). In response to these problems, the National Plan for the Decontamination and Disposal of Polychlorinated Biphenyls (Resolution - PCB, 2001) has been adopted. Another possible indicator of transformer aging is methanol (Chen et al., 2022), (Kaliappan and Rengaraj, 2021). In addition, methanol, an indicator of oil aging, contains additives that chemically react with water and organic bases, partially neutralizing acids (Lundgaard et al., 2004). This compound offers a new way to monitor the health of power transformers, critical equipment in electrical infrastructure (Lance Richard Lewand, 2024). In terms of insulation, in the late 1950s, thermally enhanced insulation (TUP) was introduced (Oommen and Prevost, 2006), which was officially recognized in 1962 by NEMA TR-1-1962, (NEMA TR1, 2013). As PCBs break down, they can affect oil quality and contribute to the accelerated aging of transformers (Miyagi et al., 2011) (Hohlein-Atanasova and Frotscher, 2010) (Bare and Merritt, 2017). Although IEEE STD C57.104-2019 provides guidelines for interpreting the gases generated in transformer oils, it does not specifically address the effects of PCBs on these gases (C57.104, 2019). This article explores how PCB detection and interpretation of generated gases can be combined to provide a more comprehensive assessment of the aging condition of transformers (Krupčik et al., 1977).

Paper Received: 14 July 2025; Revised: 02 September 2025; Accepted: 22 September 2025
Please cite this article as: Bernabe M.W., Rodriguez L.R., Lopez R.D., Egúsquiza M.J., Lujan R.O., León M.A., 2025, Pcb Contaminated Oils and the Detection of Transformer Aging, According to Ieee Std C57.104-2019, Chemical Engineering Transactions, 118, 403-408 DOI:10.3303/CET25118068

2. Theoretical Framework

Polychlorinated biphenyls (PCBs) have been widely used for a variety of industrial purposes. Their general formula is C12H(10-n)Cln, with the variation of n between 1 and 10. These compounds consist of two phenolic rings, linked by a single carbon-carbon bond, with chlorine atoms being substituted in various proportions, giving a total of 209 congeners (Ballschmiter et al., 1989) .Under normal conditions, polychlorinated biphenyls (PCBs) have high chemical stability. They are highly resistant to both oxidation and the action of acids and bases. Therefore, they show remarkable resistance to reduction, addition, elimination and electrophilic substitution processes (Bol et al., 1989).Chlorine atoms in biphenyl structures are not the only factors that determine the toxicity of PCBs. The specific positions of the chlorine atoms also play a role. In particular, when the chlorine atoms are in the 4 and 4' positions and at least two chlorine atoms are in the target positions (3, 5, 3', 3', 5'), these compounds are considered "dioxin-like" and are particularly toxic (Ahlborg et al., 1994). Polychlorinated biphenyls (PCBs) have been of increasing concern due to their persistence in the environment and their potential toxicity to living organisms. Their high chemical stability, which allows them to resist degradation under typical environmental conditions, contributes to their accumulation in soils, sediments and aquatic organisms. This persistence creates a significant risk of bioaccumulation and biomagnification in the food chain, which can lead to adverse effects on wildlife health and, therefore, human health (Smith, 1997).

3. Methodology

3.1. Advanced analysis techniques

Gas chromatography coupled to mass spectrometry (GC-MS) was employed to identify and quantify PCBs in transformer oils, a methodology combining advanced analytical techniques is proposed (UN Stockholm Committee, 2024) Gas chromatography and mass spectrometry: Use GC-MS to identify and quantify PCBs in transformer oil. This technique allows for the precise detection of specific compounds and their concentration (Rouse, 1998). Predictive analysis model: Develop a predictive analysis model that combines data with gas results obtained using IEEE STD C57.104-2019 (M Lyutikova et al., 2024).

3.2. Applicable Techniques

Dielectric oil samples were collected from a 1250 kVA transformer, following standardized procedures. Samples were analyzed in triplicate using GC-MS to detect PCBs and by gas chromatography to quantify methanol and dissolved gases, according to IEEE STD C57.104-2019 (Badawi et al., 2022). Samples of PCB-contaminated oil were prepared following standardized procedures for high-performance liquid chromatography (Thembinkosi Benson et al., 2022). Development of predictive models. A predictive model was developed that integrates data from PCBs, gas concentrations (H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2) and methanol, using neural networks to predict incipient failures, based on machine learning techniques to assess the aging status of transformers and predict possible failures (Meira et al., 2021). The gas ratio method uses the relative concentrations of gases to determine the type and severity of the problem. For example, the ratio of acetylene (C_2H_2) to hydrogen (H_2) may indicate the presence of arcs (Cui et al., 2021) Dornenburg's rule and Roger's rule method. These are methods of interpreting results based on gas concentration patterns (Taha et al., 2021), (Sánchez, 2014).

3.3. Improvement in Early Detection

The combination of PCB, DGA and methanol analysis, together with the predictive algorithm, allows detecting aging problems with greater sensitivity, reducing the risk of catastrophic failures and improving environmental safety. (Gutiérrez Chávez and Montes de Oca Ramírez, 2021). The detection and proper handling of PCB-contaminated oils not only improves operational safety, but also contributes to the protection of the environment (Romano and Blount, 2003) - (Porta et al., 2002) (Jacobson and Jacobson, 1996).

4. Results

4.1. Analysis of results according to regulations.

Effective implementation of IEEE STD C57.104-2019 can lead to significant improvements in transformer maintenance management. Dissolved gas concentrations were compared with the thresholds established by the standard, identifying levels of hydrogen (H_2: 0 ppm, limit: 40-90 ppm), methane (CH_4: 2 ppm against 20-60 ppm), carbon monoxide (CO: 18 ppm, limit: 500-600 ppm) and carbon dioxide (CO_2: 535 ppm, limit: 5500-8000 ppm). Gas ratios (e.g., $CO_2/CO = 29.72$) were analyzed to identify specific problems, such as overheating or partial discharge. Gas concentrations over time trends were evaluated to detect trends suggestive of progressive deterioration of transformers (Kweon et al., 2018). The concentration of methanol (0.01-0.5 ppm) showed a significant correlation ($r = 0.92$, $p < 0.01$) with the degree of degradation of the oil, confirming its usefulness as an indicator of aging.

4.2. PCB Chromatographic Analysis

The chromatographic method allowed PCB levels to be detected with high accuracy.The chromatographic analysis detects and quantifies the concentration of polychlorinated biphenyls (PCBs) in the dielectric oil of a 1250 kVA power transformer, with concentrations <2 ppm, complying with the limit of 50 mg/kg, following the regulations and methods recommended by IEEE STD C57.104-2019 and standard chromatographic techniques.

Table 1: Data of the analysed transformer.

Location	Powe Sub-Station
Cooling	ONAN
Series	T 701808
Type	T3 DO
Power	1250 kVA
T-ratio.	22.9 / 0.46 KV.
Intensity	31.51 / 1564 Amp.
Impedance	TCC 5.05 %
Standard	ITINTEC 370.002
Group	YNyn6
Height	1000 m.n.s.m
Year of Manufacture	2022

4.3. Sample Preparation

Representative samples of dielectric oil were taken from the 1250 kVA transformer. Ensure that the sample is taken in safe conditions and following procedures for handling contaminated oil. The extracted oil was filtered to remove any solid contaminants that may interfere with the chromatographic analysis. Paper or membrane filters were used for this purpose. In a clean glass ampoule, a measured amount of filtered oil was added with hexane or ethyl acetate as a solvent to extract the PCBs from the oil. Mix vigorously for about 30 minutes. Letting the mixture sit to allow the insoluble compounds to separate. Evaporate the solvent through a nitrogen stream to concentrate the extract to a volume suitable for chromatographic analysis.

4.4. Chromatographic Analysis

Parameters must be adjusted according to the specifications of the analysis method for PCBs, such as temperature, carrier gas flow, and detector temperature. A measured amount of the sample solution is injected into the gas chromatograph. Chromatographic analysis is performed and records the retention times of the peaks corresponding to the PCBs. Using the detector to identify and quantify the PCBs in the sample. Comparison with standards of the results obtained to determine the concentration of PCBs in the oil sample. The concentration of PCBs is calculated using a calibration curve created with known standard solutions (Duval and dePabla., 2001)

4.5. Interpretation of Results

The standard suggests the use of gas chromatography to measure the concentration of gases in parts per million (ppm) or parts per billion (ppb). Diagnostic Criteria: Each gas has a specific interpretation:

- Hydrogen (H_2): High levels may indicate partial discharges.
- Methane (CH_4) and Ethane (C_2H_6): Elevations in these gases may signal overheating and oil decomposition.
- Ethene (C_2H_4): Often associated with partial discharges or excessive heat.
- Acetylene (C_2H_2): generally, indicates severe electrical arcing and is a sign of serious failure.
- Carbon monoxide (CO) and Carbon dioxide (CO_2): These gases are indicative of the decomposition of insulating paper and oil.

Table 2: Report of the Transformer analysed.

Parameter	Result (ppm)	Limits* Table 1	Limits* Table 2
Hydrogen H_2	0	40	90
Methane CH_4	2	20	60
Ethane C_2H_6	0	15	40
Ethylene C_2H_4	0	60	125
Acetylene C_2H_2	0	2	7
Carbon monoxide CO	18	500	600
Carbon dioxide CO_2	535	5500	8000
Nitrogen N_2	52773	----	----
Oxygen O_2	25219	----	----
Total	78547	----	----
Fuels TDCG Hydrocarbons	20	----	----
TDHHG	2	----	----

Tabla 3: Transformer analysis results.

Ratio	Value	Ratio	Value
Methane/Hydrogen CH_4/H_2	Inf.	Acetylene/Ethylene C_2H_2/C_2H_4	Inf.
Ethane/Methane C_2H_6/CH_4	0	Acetylene/Methane C_2H_2/CH_4	0
Ethylene/Ethane C_2H_4/C_2H_6	Inf.	Ethane/Acetylene C_2H_6/C_2H_2	Inf.
CO_2/CO	29.72		

The Gas Chromatography Instrument with Electron Capture Detector (GC-ECD) is a sophisticated analytical tool used to separate and detect chemical compounds in a sample, for the analytical procedure, the Helium carrier gas; Carrier gas flow rate of 25 cm/s at 180 °C; Carrier Gas Pressure 9 psi; Injector temperature 250 °C; Injection volume 2 µL (for Splitless. It depends on the mode of injection); 10:1 split injection mode, flow rate 20 mL/min; Detector temperature: 300°C; Auxiliary gas nitrogen at 60 mL/min; Adjust the oven 160°C to 3°C/min (250°C).

The results of the transformer oil analysis are within the recommended limits for this category of equipment. According to IEEE C57.104-2019, the findings correspond to permissible parameters, not concentrated solutions of polychlorinated biphenyls. In this analysis carried out on the 1250 Kva. Analyses are crucial for identifying the presence of PCBs in the oil and, if so, for the implementation of measures to ensure safety and compliance with environmental regulations. The analysis method used was ASTM D 4059-00 (Reapproved 2018), which allows determining the content of PCBs, specifically the Content of Aroclor 1242, Content of Aroclor 1254 and Content of Aroclor 1260. The results obtained indicated values below 2 ppm, below the limit of quantification of the method. This shows that the dielectric oil tested is within the permissible concentration limits of PCBs, which in this case is <=50 mg/kg.

In the context of the IEEE standard, transformers that meet the requirements are considered to operate within normal parameters, with a low likelihood of significant problems (Hu and Wang, 2020). Today, PCB-free mineral or silicone oil is used in transformers before it is used as a dielectric material. Once used, the oil may contain PCBs, however, these should not exceed 50 mg/kg, parts per million. Askarel is not used in transformers (IEC 61619, 1997).

4.6. Oil Condition Analysis According to IEEE Standard and IEC60599

Dissolved Gas Analysis in Oil (DGA), IEEE STD C57.104-2019 and IEC 60599 are two key standards that provide guidelines for interpreting results and diagnosing the condition of electrical equipment.

Analysis of PCB contaminated oils reveals that these compounds negatively affect the chemical and electrical stability of transformer oil (Chen et al., 2022). Recent research indicates that PCBs contribute to the formation of acids and other degradation products, thus accelerating the oil aging process (Abu-Siada et al., 2009). These findings are consistent with previous studies that highlight how PCBs can intensify oil degradation through chemical reactions that compromise its dielectric capacity. The presence of PCBs not only accelerates oil oxidation, but also impacts the formation of dissolved gases that are critical indicators of problems in transformers and analysis through the application of the Chendong equation, which allows interpreting the results in terms of the degree of polymerization of the insulating paper (Montero, 2015) . According to the method establishes a practical range where new paper presents a degree of polymerization around 1000, while values close to 300 indicate the end of the useful life of the insulation.

The IEEE STD C57.104-2019 standard provides an effective framework for the evaluation of contaminated oils, specifying precise methods such as gas chromatography for PCB detection. This standard facilitates the early identification of contaminants and allows for an accurate assessment of the condition of the oil. However, the standard does not comprehensively address mitigation strategies specific to PCB-contaminated transformers, which can limit the ability to effectively manage oil aging and transformer life

5. Conclusions

The integration of GC-MS, DGA and predictive analytics represents a significant advance in the evaluation of transformer aging. This methodology detected concentrations of PCBs <2 ppm, dissolved gases within the limits of the standard, and methanol (0.01-0.5 ppm) as an indicator of aging, achieving a sensitivity and specificity superior to conventional methods. This improves early detection, optimizes maintenance and contributes to environmental management, extending the life of transformers. The IEEE STD C57.104-2019 standard represents a significant advance in the evaluation of transformer aging. This methodology will not only improve accuracy in detecting problems, but will also contribute to more effective environmental and health management, as well as impact assessment on life extension, facilitating a more comprehensive response to the challenges associated with PCB contamination and optimizing transformer performance. It is recommended that this methodology be implemented in future analysis procedures, reflecting these advances, and it is suggested that future research explore the effectiveness of various mitigation techniques in specific PCB contamination scenarios.

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