

IEEE Guide to the Use of Gas-In-Fluid Analysis for Electric Power Cable Systems

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Abstract: The application of the analysis of gases dissolved in the fluids of fluid-filled cable systems is discussed with respect to the procedures for sampling, obtaining the dissolved gas data, and analyzing the results.

Keywords: aging, cable diagnostic, fluid-filled cable, gas analysis, remaining life, transmission cable

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Introduction

(This introduction is not part of IEEE Std 1406-1998, IEEE Guide to the Use of Gas-In-Fluid Analysis for Electric Power Cable Systems.)

This guide is intended for the engineering specialist interested in the evaluation and maintenance of fluid-filled cable systems including high-pressure fluid-filled and gas-filled pipe-type cables and self-contained cables operating at low, medium, or high pressure where the pressurizing medium is either a dielectric fluid or gas.

The use of dissolved gas analysis (DGA) began in the 1970s and has become an important tool for those who are responsible for the reliable operation of these cable systems. The technique requires removing a small sample of the pressurizing fluid and analyzing the gasses that are present in solution using a gas chromatograph. The results can provide clues as to the amount of thermal aging that the cable system has experienced and how this aging may be progressing in time, and also whether there may be problems in the system, especially in the vicinity of cable accessories such as splices and terminations that might require de-energization and repair.

The technology parallels the application of DGA to transformers as described in IEEE Std C57.104-1991. Following an historical background discussion, the fundamentals of gas generation in dielectric papers and fluids is presented as the basis for the technology. Sufficient data is presented so that the user can quantify the correlation of DGA data with the conditions that may have caused the gas generation.

Guidelines for the application of DGA and the methods used for sampling, analysis, and interpretation of the results are discussed in detail. Also covered are descriptions of other ancillary tests that can be done on the same samples to provide additional information as to the state of the cable system, and procedures that can be used to lower the discussed gas content when system operation may be jeopardized.

Finally, a reporting format is suggested, and a database that is maintained by ICC Working Group 5-28 is described.

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IEEE Guide to the Use of Gas-In-Fluid Analysis for Electric Power Cable Systems

1. Overview

1.1 Scope

The scope of this guide is to furnish a basic understanding of the conditions that generate gases in fluid-filled cable systems, to establish a universal method of data collection and retention, to suggest guidelines for the evaluation of samples, and to recommend methods for treatment of systems with high gas content.

1.2 Purpose

This guide is intended to provide users of high-pressure fluid-filled (HPFF) pipe cable systems and self-contained fluid-filled (SCFF) cable systems with the basis to establish the use of gas-in-fluid analysis for diagnostic purposes and as an operating maintenance tool.

2. References

The following documents are relevant to the technology of gas-in-fluid analysis:

ASTM D2779-92, Standard Test Method for Estimation of Solubility of Gases in Petroleum Liquids.¹

ASTM D2780-92, Standard Test Method for Solubility of Fixed Gases in Liquids.

ASTM D3612-96, Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography.

ASTM D3613-92, Standard Test Methods of Sampling Electrical Insulating Oils for Gas Analysis and Determination of Water Content.

IEEE Std C57.104-1991, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.²

¹ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

3. Definitions

This clause defines terms used in this guide.

3.1 dissolved gas: Implies that the gas is dissolved in the dielectric fluid. In solution, these gases lose all semblance of gaseous matter. There are no gas bubbles in the fluid under normal circumstances, and there is little tendency for the gases to respond to gravitational forces. Dissolved gases will not accumulate at high points, and they generally do not pose any threat to the dielectric function of the fluid.

3.2 dissolved gas content: The amount of gas dissolved in the fluid expressed as a percent of, or in parts-per-million relative to, the volume of the fluid, where the volume of the gas is defined as that occupied by the gas at a pressure of one atmosphere and temperature of 0 °C. Dissolved gas content can refer to a specific gas, the total amount of all gases, or the total amount of combustible gases (TCG) only.

3.3 saturation: The amount of a particular gas that can be dissolved in a fluid at a given pressure and temperature. The saturation of all gases of interest is linearly proportional to absolute pressure. However, the effect of temperature varies with the specific gas. Some gases exhibit a decrease in saturation with increasing temperature while others tend to increase. The variation with temperature is generally small and can be neglected when evaluating fluid samples in the lab.

4. Gases used in this guide

The gases that are the subject of this guide are listed in Tables 1 and 2 by name and chemical symbol. Throughout this guide they may be referenced by either designation depending on context. While some users include the heavier hydrocarbon gases in their investigations, those listed form the basis of the technology at the time of publication of this guide. These lists may be expanded to include more gases in future revisions of this guide if sufficient data become available. Tables 1 and 2 also include the molecular weight (MW) and density at 0 °C, one atmosphere for each gas.

Table 1—Gases of interest for dissolved gas analysis (noncombustible)

Type of gas	Symbol	MW	Density (g/L)
Nitrogen	N ₂	28	1.2507
Oxygen	O ₂	32	1.4289
Carbon dioxide	CO ₂	44	1.9768

Table 2—Gases of interest for dissolved gas analysis (combustible)

Type of gas	Symbol	MW	Density (g/L)
Carbon monoxide	CO	28	1.2501
Hydrogen	H ₂	2	0.0898
Methane	CH ₄	16	0.7167
Ethane	C ₂ H ₆	30	1.3567
Ethylene	C ₂ H ₄	28	1.2644
Acetylene	C ₂ H ₂	26	1.1708

5. Historical background

5.1 The need for gas-in-fluid analysis

Safety, aesthetics, and the unavailability of lands for rights-of-way have made fluid-filled high-voltage cable circuits the principal method of delivering electric energy to the major urban centers of North America. The reliable operation of these circuits is critical to society in general and to utilities for which they represent a major capital investment. It is important to become aware of potential problems with these cable systems, which may have been overstressed, overheated, contaminated, mechanically damaged, or otherwise operated improperly.

Reliable operation requires thorough knowledge of a circuit's condition. With the age of existing HPFF pipe and SCFF cables approaching and in some cases exceeding their design life expectancy of 40 years, there is a need for methods that can help determine or establish the condition of these cable systems. The methods should identify and discriminate between problems of major and minor consequences, be repeatable, be able to localize a problem, be relatively simple to perform, and be inexpensive.

As direct observation of the cable's condition is basically impossible without de-energizing the circuit and removing cable for lab evaluation, alternate methods of monitoring the present condition and detecting possible degradation of cable insulation are needed. Gas-in-fluid analysis is the best option currently available to assess the condition of the cable's insulation system.

Degradation of the cable system's insulation or components beyond that expected during normal aging may be caused by any of the following:

- Thermal stresses developed at hot spot locations or areas that may have experienced over-temperature for any reason.
- Damaged shielding tapes caused by thermal-mechanical bending (TMB) activity, loose skid wires, excessive pulling forces, or damage prior to installation.
- Electrical stress concentrations sufficient to generate partial discharges of low intensity at operating voltage.
- Extreme electrical stress causing intense partial discharges in the dielectric.

Gas-in-fluid analysis, referred to as dissolved gas analysis (DGA), facilitates the observation of the by-products of this degradation through its environment, the insulating and pressurizing fluid. With periodic DGA, changes in the level of the by-products of cable degradation may be monitored, thus alerting the user to a potential problem with the cable system while providing important clues as to the exact nature of the problem.

DGA is a nondestructive procedure that requires obtaining samples of only the insulating fluid from the cable circuit. It is a precise but relatively simple operation that can be performed on a fluid sample taken from any available access point. As discussed in Clause 6, the types of gases present in the insulating fluid, their concentration, and their rates of production can provide insight into the condition of the cable dielectric and the cable shielding system. When performed in a consistent, systematic way and supplemented by dielectric, water content, and physical appearance tests carried out on the same sample, DGA allows an evaluation of the condition of the cable's internal components and early detection of potential problems. Since access points are normally installed at cable joints and terminations, problems detected can often be localized. Using standard sampling, analysis, and recording procedures, a current result can be compared to previous results to establish trends; and because of its relative simplicity, DGA can be performed on a routine basis with a minimum of service disruption and cost.

In some cases, problems may exist that do not occur within the dielectric but rather are associated with the shielding and grounding system. Such problems may include the sparking of skid wires to the pipe, overheated or burned shield leads due to induced currents or fault currents, and improperly grounded splice or terminal stress cone shields. These problems also produce distinctive gases, especially acetylene, that signal the need for internal maintenance.

5.2 Historical use in transformers

DGA has been used to monitor the condition of transformers since the early 1970s. Experience with transformers prompted the earliest adaptations of DGA as a predictor of inherent problems. Continued work with DGA helped identify the source(s) of degradation and often led to corrective measures to preclude irreparable damage and to avoid the accumulation of the gases themselves, which could cause electrical breakdown.

A number of detectable gases are produced in varying rates and combinations by the effects of thermal and electrical stresses on traditional transformer insulation: cellulose paper, cottons, linens, fiber board, and insulating fluids. Gas concentrations are selectively characteristic of the incipient faults or distress that generate them. Improvements in sampling procedures and rapid evolution of sophisticated gas chromatography equipment coupled with modern computer graphics analysis have advanced DGA to a highly useful scientific methodology. On many occasions, prevention of service disruptions and avoidance of catastrophic failures of expensive transformers have been attributed to astute and timely DGA.

In 1977 the General Electric Company published a bulletin summarizing the application of DGA to transformers (Lyke, [B13]³). The following discussion presents much of the information found in that bulletin.

Gases in varying amounts accumulate in transformers from the following interactions:

- Hydrogen evolved when moisture contamination causes oxidation of iron and steel components.
- Degradation due to high electrical stress and low intensity discharges, usually within the gaseous voids, characterized by large amounts of H_2 together with small amounts of the alkanes methane, ethane, and propane.
- Fluid degradation caused by thermal stresses that develop at hot spots in the metallic components and/or impregnated cellulose components. These are of an intermediate level of energy density and the products of decomposition again include hydrogen and alkanes, but the alkenes, ethylene and propylene, are also present in significant amounts, increasing in volume with increasing temperature.
- The decomposition of cellulose characterized by the generation of carbon monoxide and carbon dioxide with an increase of the ratio of CO to CO_2 indicating an increase in the exposure temperature.

The decomposition gaseous products of cellulose paper, cotton, linens, and pressboards are carbon monoxide, carbon dioxide, water, and hydrogen. For transformers, DGA has evolved into classifications of the gases by relative volume and diagnosis by study of the specific ratios of the gases. The higher the decomposition temperature, the larger is the ratio of CO to CO_2 ; this ratio is, therefore, a dependable analytical tool for estimating the maximum exposure temperature of cellulose-based materials.

Table 3 correlates the gases and gas ratios likely to be found as a result of various problems, reproduced from Table 2 of Lyke, [B13].

³The numbers in brackets correspond to those in the bibliography in Clause 14.

Table 3—Typical transformer problems and related dissolved gases

Occurrence	Typical gases evolved
Corona	H ₂ , CH ₄ , some C ₂ H ₆ Ratio CH ₄ /H ₂ > 0.1
Overheated metal @ 200 °C @ 400 °C @ 600 °C	H ₂ , CH ₄ , C ₂ H ₆ , C ₂ H ₄ Ratio C ₂ H ₄ /C ₂ H ₆ = 0.4 Ratio C ₂ H ₄ /C ₂ H ₆ = 1 Ratio C ₂ H ₄ /C ₂ H ₆ = 1.5–2.0
Arcing and sparking (visible/light)	C ₂ H ₂ + others. Acetylene is almost always a sign of arcing.
Faults, degradation, involving cellulose (impregnated paper)	CO, CO ₂ , and H ₂ O. Ratio CO/CO ₂ increases with temperature.

5.3 Historical application to HPFF and SCFF cable systems

The DGA technology has intrigued manufacturers and users of HPFF pipe and SCFF cable systems for many years. However, the realization that cable systems are configured and operate very much differently than transformers has dictated a cautious approach to the interpretation of DGA results. No universally accepted guidelines existed for analyzing the test results, and such data could not be relied on to provide sufficient information on the condition of a system to justify the expense for any corrective action, except for a few cases involving significant amounts of acetylene at terminations.

The first suggestion that DGA be used as a diagnostic tool was made by Lawson, Simmons, and Gale in a 1976 presentation (Lawson, et al., [B12]) that showed data on the gases produced during the thermal decomposition of cable papers in dry nitrogen.

In 1977, a New England utility performed DGA on 13 fluid samples taken from all accessible locations of a 26-year-old 6.8 km 120 kV HPFF pipe cable circuit. The circuit had performed exceptionally well with no problems since it was first energized. The fluid samples were taken because of the importance of the circuit and the concern that it was getting old. The intent was to try to learn something about the condition of the cables to avoid the serious consequence resulting from a failure and extended outage of the feeder.

Other utilities also began this same type of testing on old HPFF pipe and SCFF circuits with the same thought of trying to use the dielectric fluid as an indicator to help determine the condition of these early cable installations. Without guidelines for the interpretation of the results, these tests were always done in conjunction with other dielectric fluid tests including power factor, dielectric strength, moisture content, and color. This trend continued into the 1980s when a suggestion was made to start an Insulated Conductors Committee (ICC) project to study the gases evolved in pipe cable fluids. A new project, 5-28, was formed and the scope of the project was broadened to include both HPFF pipe and SCFF cable systems.

The first meeting was held at the April 1982 ICC meeting with an attendance of 40 members and guests. This high attendance at the inaugural meeting provided ample proof of the high level of interest in this subject. The attendance has continued to be high at all subsequent meetings with much participation and discussion of data by many involved in the cable industry.

5.4 Methodology and refinements for special cases

Several utilities have used DGA on HPFF pipe cable circuits for many years. The methodology consists of obtaining fluid samples at sampling valves on cable joints in manholes, at cable terminations, and in pumping plants, discussed more fully in Clause 8. Fluid samples have been taken according to ASTM D3613-92⁴ using a syringe, stainless steel

⁴Information on references can be found in Clause 2.

bottle, tin can with flexible sides, or even a glass Mason jar. These samples were obtained on a periodic basis and analyzed according to the methods described in Clause 9. DGA gave the user the ability to confirm the presence and possibly classify the severity of the precursor conditions of an incipient fault.

Two anecdotal cases are presented here to show the value of DGA used by utilities to detect potential failures. Both of these cases involve HPFF cable systems: one in a joint and the other in a termination.

- The joint was on a 230 kV circuit and the utility had monitored high levels of hydrogen (5000–10 000 ppm) in that joint for some time. When the H_2 level reached 22 000 ppm, the circuit was de-energized and the joint disassembled. Examination of the splice revealed significant TMB damage, including carbonized tapes on one phase. A 9.15 m portion of this phase was replaced and the line put back in service.
- At a 345 kV HPFF-to-SF₆ termination, DGA showed high levels of acetylene and TCG. The acetylene level was 70–105 ppm where the normal level is below 5 ppm. The TCG level was 5500–6300 ppm versus a normal range of 400–800 ppm. Disassembly of the termination revealed internal arcing between the termination body and the cable stress cone shielding. The stress cone shielding insulation was rebuilt, and the line was re-energized.

Caution should be used when attempting to generalize the results of these cases. Prudent engineering judgment must be used to determine when a circuit should be de-energized and a joint or termination disassembled for examination and possible repair. The level at which the gas composition, concentration, or rates of generation would indicate component examination is discussed in Clause 11.

6. Fundamentals of gas generation in cellulose and dielectric fluids

6.1 Mechanisms of gas generation

Gases found in solution in cable fluids can be generated by several mechanisms. In general, the gases that are indicative of various aging mechanisms are the result of chemical changes in the major components of the system, the paper insulation, and the dielectric fluids used to impregnate the paper and maintain operating pressure. Chemical changes can be caused by high temperature thermal decomposition, electrical stress, ionization, and chemical reactions. Gases formed by such activity should contain only those elements present in the basic structure of the dielectric materials. Thus, cellulose can contribute only carbon, hydrogen and oxygen, and hydrocarbon-based dielectric fluids will provide only carbon and hydrogen, though both of these materials are likely to contain small amounts of nonhydrocarbon contaminants. Other gases are often present, the most common being nitrogen which is used to blanket fluid storage tanks of HPFF cable systems. Others are the result of contamination, either of the system or of the gas sample. The chemical processes that may be involved are briefly discussed below.

6.1.1 Thermal decomposition of cellulose

The thermal decomposition of cellulose-based dielectrics at temperatures of approximately 100 °C has been recognized for some time. In a 1935 article (Clark, [B4]) F. M. Clark noted that “[t]hese chemical changes not only produce increased power factor but are accompanied by gas formation with subsequent decrease in dielectric strength.” E. J. Murphy published articles on the thermal decomposition of cellulose in 1943 (Murphy, [B14]) and 1962 (Murphy, [B15]). In 1964 L. C. Flowers extracted moisture evolution rates from Murphy’s data (Flowers, [B6]). In 1977 W. G. Lawson et al, presented gas evolution rates specific to the thermal degradation of unimpregnated cable papers (Lawson, et al., [B12]), and in 1982 that work was supplemented by J. G. Head et al., working with impregnated papers exposed to simultaneous thermal and electrical stress (Head, [B8]).

The purest form of cellulose is a polysaccharide known as alpha-cellulose, which contains only carbon, hydrogen, and oxygen atoms in the ratio of C₆H₁₀O₅. The basic structure of the long alpha-cellulose chain is shown in Figure 1.

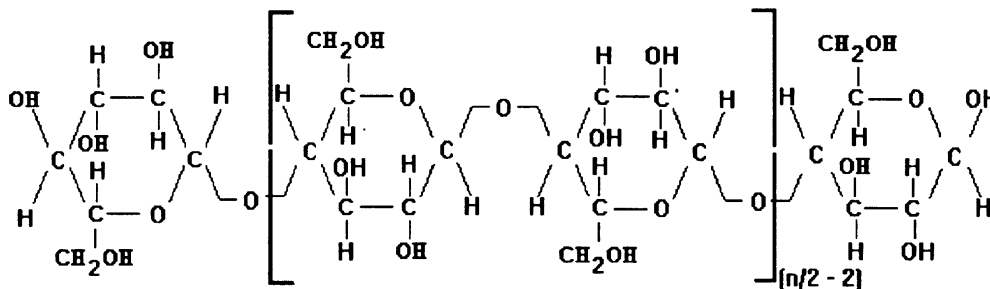


Figure 1—Basic molecular structure of alpha-cellulose

The “n” parameter denotes the length of the chain and will be roughly 1000 for typical cable papers as they leave the cable factory. This parameter is also known as the degree of polymerization (DP)

Kraft paper will contain from 40% to 80% alpha-cellulose. Papers with the higher percentage are used for extra-high voltage (EHV) applications requiring very low dielectric loss. The remaining material in Kraft paper will be variations of the cellulose chain structure known as the hemicelluloses, small amounts of lignin, an aromatic polymer binder present in the wood source, and traces of inorganic salts and other contaminants.

Cellulose is extremely hygroscopic; it readily absorbs free water and also contains chemically bound (adsorbed) water as part of its chain structure. The drying of cable paper to remove as much absorbed water as possible can be considered the first stage of its thermal aging history. Cable vacuum drying temperatures can reach 130 °C at which point the residual free water content will be less than 100 ppm and small amounts of adsorbed water will start to be removed. Fortunately this exposure is limited to a few days at most and the paper will suffer only a small reduction in DP.

Long-term aging in the 100 °C to 160 °C range results in the loss of hydrogen and hydroxyl side groups and the gradual decomposition of the cellulose chain at the end of the glucose units, which are nonreversible chemical reactions. When carbon atoms are freed they tend to form CO₂ first and then CO, which requires slightly more energy. Hydrogen, water, and small amounts of methane will be liberated. As might be expected, the presence of free oxygen will accelerate the decomposition processes and reduce the ratio of CO to CO₂ for a given aging temperature.

6.1.2 Effect of electrical stress on the decomposition of cellulose

The effect of electrical stress on the decomposition of cellulose is not well defined by specific mechanisms. One might expect that thermal decomposition reactions will be accelerated by electrical stress, which could provide additional energy to break the chemical bonds in the cellulose chain. However, data presented by Head et al. (Head, et al., [B8]) show clearly that the generation of CO₂ and CO in fluid-impregnated paper is not affected by the presence of electrical stress below the detectable ionization level, even though the generation of hydrogen and the hydrocarbon gases is accelerated with electrical stress. If discharge activity is present, the CO₂ and CO rates will increase; but it is not clear whether the stress contributes to the decomposition or simply acts to increase the local temperature.

6.1.3 Thermal degradation of dielectric fluids

Dielectric fluids are generally considered to be thermally stable over the complete range of operating temperatures applicable to fluid-filled cables. Thermal degradation processes do not become significant until the fluid is exposed to temperatures of approximately 150 °C.

Three types of dielectric fluids are found in cable systems. The oldest are mineral oils, which are highly refined fluids distilled from natural crudes; and the origin of the mineral oils determines the nature of the resulting fluid. The molecular structure of mineral oils consists of three chemical species: paraffins, naphthenes, and aromatics. The structures of these three components are shown in Figure 2 (Bartnikas and Srivastava, [B3]). “X” represents a possible point of connection between components.