



IEEE Guide for the Use of Gas-in-Fluid Analysis for Paper and Laminated Paper-Polypropylene Insulated Cable Systems

STANDARDS

IEEE Power and Energy Society

Developed by the
Insulated Conductors Committee

IEEE Std 1406™-2020
(Revision of IEEE Std 1406™-1998)



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Approved 8 January 2020

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

Keywords: aging, cable diagnostic, DGA, dissolved gas analysis, fluid-filled cable, gas analysis, gas-filled cable, IEEE 1406™, liquid filled cable, pipe-type, remaining life, self-contained, transmission cable

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Introduction

This introduction is not part of IEEE Std 1406-2020, IEEE Guide for the Use of Gas-in-Fluid Analysis for Paper and Laminated Paper-Polypropylene Insulated Cable Systems.

This guide is intended for the engineering specialist interested in the evaluation and maintenance of fluid-filled cable systems. This includes high-pressure fluid-filled (HPFF) and high-pressure gas-filled (HPGF) pipe-type cables, as well as self-contained fluid-filled (SCFF) cables operating at low, medium, or high pressure. The pressurizing medium can be either a dielectric liquid or gas. The primary focus of this document is on testing of liquid-filled systems, with less emphasis on gas-filled systems, since HPGF cables constitute a significantly smaller amount of the total circuit miles of pipe-type cable systems. However, where applicable, the document will identify tests and analyses that can be used on gas-filled systems.

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 gases that are present in solution using a gas chromatograph. The results can provide clues as to the amount of thermo-electric aging that the cable system has experienced and how this aging may be progressing in time. DGA can also identify where there may be problems in the system, especially in the vicinity of cable accessories such as splices and terminations.

The technology parallels the application of DGA to transformers as described in IEEE Std C57.104™. Following a historical background discussion, the fundamentals of gas generation in dielectric papers and fluids is presented as the basis for the technology. Guidance is provided so that the user can relate the 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. 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 are also covered. Procedures are discussed that can be used to lower the dissolved gas content when system operation may be jeopardized. Additionally, a data-reporting format is suggested to aid utilities to trend the condition of their cable system.

The first meeting of ICC Working Group 5–28 “Guide for DGA for HPFF Cables,” chaired by J.S. Engelhardt, was held in April 1982. This ultimately led to the publication of IEEE Std 1406™-1998 “Trial Guide to the Use of Gas-In-Fluid Analysis for Electric Power Cable Systems” in 1998. The re-affirmation requirement for the 1998 document along with the need to better represent the current state-of-the-art led to the formation of ICC C05W “Guide for the use of Gas-in-Fluid Analysis for Electric Power Cable Systems”. The ICC C05W working group first met in Fall 2011 and undertook the revision of the original 1998 guide.

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IEEE Guide ~~for to~~ the Use of Gas-in-Fluid Analysis for Paper and Laminated Paper-Polypropylene Insulated ~~Electric Power~~ Cable Systems

1. Overview

1.1 Scope

The scope of this guide is to furnish an a-basie understanding of the conditions that generate gases in paper and laminated paper-polypropylene insulated fluid-filled cable systems; ~~to establish a recommended universal method for sampling, of data collection, analysis; and retention, to suggest guidelines for the evaluation of samples,~~ and to identify possible remedial actions ~~recommend methods~~ for ~~treatment of~~ systems with high dissolved gas-in-fluid content.

1.2 Purpose

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

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ASTM D88, Test method for Saybolt viscosity.¹

¹ASTM publications are available from the American Society for Testing and Materials (<http://www.astm.org/>), ~~100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA.~~

[ASTM D445, Test method for kinematic viscosity of transparent and opaque liquids \(and calculation of dynamic viscosity\).](#)

[ASTM D664, Test method for acid number of petroleum products by potentiometric titration.](#)

[ASTM D831/D831M, Test method for gas content of cable and capacitor oils.](#)

[ASTM D877, Test method for dielectric breakdown voltage of insulating liquids using disk electrodes.](#)

[ASTM D878, Test method for inorganic chlorides and sulfates in insulating oils.](#)

[ASTM D923, Practices for sampling electrical insulating liquids.](#)

[ASTM D924, Test method for dissipation factor \(or power factor\) and relative permittivity \(dielectric constant\) of electrical insulating liquids.](#)

[ASTM D974, Test method for acid and base number by color-indicator titration.](#)

[ASTM D1500, Test method for ASTM color of petroleum products \(ASTM color scale\).](#)

[ASTM D1533, Test method for water in insulating liquids by coulometric Karl Fischer titration.](#)

[ASTM D1563 Withdrawn 1985, Method of test for peroxide number of mineral insulating oils.](#)

[ASTM D1827 Withdrawn 2009, Test method for gas content \(Nonacidic\) of insulating liquids by displacement with carbon dioxide.](#)

[ASTM D2161, Practice for conversion of kinematic viscosity to Saybolt universal viscosity or to Saybolt furol viscosity.](#)

[ASTM D2298 Withdrawn 1987, Method of test for stability of insulating oils under electrical stress \(Merrell Test\).](#)

[ASTM D2300, Test method for gassing of electrical insulating liquids under electrical stress and ionization \(modified Pirelli method\).](#)

[ASTM D2522, Test method for chlorine content of polybutenes used for electrical insulation.](#)

~~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 D2945, Withdrawn 2011, Test method for gas content of insulating oils.](#)

~~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 oils by gas chromatography.

IEEE Std C57.104TM-1991, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.^{2,3}

3. Definitions, acronyms, and abbreviations

3.1 Definitions

[For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.](#)⁴

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⁴[IEEE Standards Dictionary Online](#) is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

dissolved gas: ~~Implies~~ A gas that ~~the gas~~ is dissolved in the dielectric liquid fluid. In solution, these gases lose all semblance of gaseous matter. There are no gas bubbles in the liquid 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 liquid at normal operating pressures fluid.

dispersed gas: Gases that may be generated during the operation of a HPGF cable system, which are dispersed within the dielectric gas.

dissolved gas content: The amount of gas dissolved in a liquid ~~the fluid~~ expressed as a percent of, or in $\mu\text{L/L}$, or parts per-million (ppm) relative to, the volume of the liquid 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~~.

saturation: The amount of a particular gas that can be dissolved in a liquid 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 liquid fluid samples in the laboratory lab.

gas-in-fluid analysis or dissolved gas analysis (DGA): A means and method to determine the level of gaseous by-products associated with the thermo-electric decomposition of the insulation system and the dielectric fluid.

3.2 Acronyms and abbreviations

DGA dissolved gas analysis

DP degree of polymerization

HPFF high-pressure fluid-filled

HPGF	high-pressure gas-filled
PAS	photo acoustic spectroscopy
PFT	perfluorocarbon tracer
PPM	parts per million = $\mu\text{L/L}$
SCFF	self-contained fluid-filled
STP	standard temperature and pressure
TCG	total amount of combustible gases
TMB	thermal-mechanical bending
TMM	thermo-mechanical movement

4. Gases used in this guide

The gases that are the subject of this guide are listed in [Table 1](#) and [Table 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. [Table 1](#) and [Table 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	Molecular weight	Density (g/L)
Nitrogen	N ₂	28	1.250 7
Oxygen	O ₂	32	1.428 9
Carbon dioxide	CO ₂	44	1.976 8

(New)

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

(Deleted)

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

Type of gas	Symbol	Molecular weight	Density (g/L)
Carbon monoxide	CO	28	1.250 1
Hydrogen	H ₂	2	0.089 8
Methane	CH ₄	16	0.716 7
Ethane	C ₂ H ₆	30	1.356 7
Ethylene	C ₂ H ₄	28	1.264 4
Acetylene	C ₂ H ₂	26	1.170 8

(New)

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

(Deleted)

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 have historically been the principal method of delivering electric energy to the major urban centers of North America and around the world. The reliable operation of these circuits is critical to ~~society-in-general-and-to~~ utilities since they generally serve large loads, and since ~~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 is enhanced through ~~requires thorough~~ knowledge of a circuit's condition. With the age of existing HPFF, HPGF, ~~pipe~~ and SCFF cables approaching or ~~and in some cases~~ exceeding their design life expectancy of 40 years, there is a need to develop or refine ~~for~~ methods that can help determine ~~or establish~~ the condition of these cable systems. The methods can ~~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, and be reliable.

Some methods ~~As direct observation~~ of determining the cable's condition require ~~is basically impossible without~~ de-energizing the circuit and removing cable for laboratory lab evaluation. Less intrusive, alternate methods of monitoring the ~~present~~ condition and detecting possible degradation of cable insulation are needed. Gas-in-fluid analysis is an ~~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 or displaced shielding and insulating tapes caused by thermal-mechanical bending (TMB) or thermo-mechanical movement (TMM) activity, movement of ~~loose~~ skid wires, excessive pulling forces, or damage prior to or during installation.
- Electrical stress concentrations in the dielectric sufficient to generate partial discharges of low intensity at operating voltage.
- Extreme electrical stress causing intense partial discharges in the dielectric system.

Gas-in-fluid analysis, referred to as dissolved gas-in-oil analysis (DGA), provides a method to observe ~~facilitates the observation of~~ the by-products in ~~of this degradation through its environment,~~ the pressurized dielectric ~~insulating and pressurizing~~ fluid. With periodic DGA sampling, 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 concentrations ~~concentration~~, and their rates of production can provide insight into the condition of the cable dielectric and the cable shielding system. DGA, 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 system's ~~cable's~~ internal components and early detection of potential problems. Supplemental information including dielectric electrical breakdown strength, dissipation factor (power factor), moisture content, and physical appearance can further aid in the evaluation process. Since sampling (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. It is also important to note that the generation of gas is a consequence of some electrical or electro-chemical activity. The concentration of the gases build with increased activity, which can eventually lead to a cable system failure.

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 shield wires to the pipe, overheated or burned shield leads due to induced currents or fault currents, and [displaced or improperly grounded splice or terminal stress cone shields](#). These problems also produce distinctive gases, especially acetylene, [which signals](#) ~~that signal~~ the need for internal maintenance.

[It is important to note that the sampling and analysis is usually undertaken at a cable accessory. While this will likely give an indication of condition issues at the accessory, it may or may not represent the overall cable condition.](#)

5.2 Historical use [of DGA and interpretation](#) 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 [prevent](#) ~~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, fiberboard, and insulating fluids. Gas concentrations are selectively characteristic of the incipient faults or [distresses](#) ~~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 [application of](#) DGA.

In 1977, the General Electric Company published a bulletin summarizing the application of DGA to transformers ([see \[B15\] Lyke, \[B13\]³](#)).⁵ The following discussion presents much of the information found in that bulletin.

³ ⁵The numbers in brackets correspond to those of the bibliography in [Annex A Clause 14](#).

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.

Table 3 correlates the gases and gas ratios likely to be found as a result of various problems, reproduced from Table 2 of [B15] Lyke, [B-13].⁶

Table 3—Typical transformer problems and related dissolved gases

Occurrence	Typical gasses evolved
Corona	H_2 , CH_4 , some C_2H_6 Ratio $CH_4/H_2 > 0.1$
Overheated metal @ 200 °C @ 400 °C @ 600 °C	H_2 , CH_4 , C_2H_6 , C_2H_4 Ratio $C_2H_4/C_2H_6 = 0.4$ Ratio $C_2H_4/C_2H_6 = 1$ Ratio $C_2H_4/C_2H_6 = 1.5-2.0$
Arcing and sparking (visible/light)	C_2H_2 + others. Acetylene is almost always a sign of arcing.
Faults, degradation, involving cellulose (impregnated paper)	CO , CO_2 , and H_2O . Ratio CO/CO_2 increases with temperature.

⁶Table 3 reprinted with permission from GE, "A Power Transformer Dissolved Gas Analysis," © 1977.

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 CO₂; this ratio is, therefore, a dependable analytical tool for estimating the maximum exposure temperature of cellulose-based materials.

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 [since the early 1970s](#) ~~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. [The source from where DGA samples are drawn, such as from fluid reservoirs, have to be taken into consideration while interpreting the results. Furthermore, considerations have to be applied when assessing the DGA interpretation to the type of joints and accessories as the ratio of oil to paper in these different accessories vary.](#) 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 ([see \[B14 Lawson, et al., \[B-12\]\]](#)) 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 [dissipation factor](#) (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 [HPFF 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, [as](#) discussed more fully in Clause 8. Fluid samples have been taken according to ASTM [D923](#)⁷~~D3613-92~~⁴ using a syringe, stainless steel 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.

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

⁷ ⁴Information on references can be found in Clause 2.

- The joint was on a 230 kV circuit and the utility had monitored high levels of hydrogen ~~(5000 to -10 000~~ [μL/L \(ppm\)](#) in that joint for some time. When the H₂ level reached 22 000 [μL/L \(ppm\)](#), 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 [Total Combustible Gases \(TCG\)](#). The acetylene level was 70 ~~to -105~~ [μL/L \(ppm\)](#), where the normal level ~~should be is~~ below 5 [μL/L \(ppm\)](#). The TCG level was 5500 ~~to -6300~~ [μL/L \(ppm\)](#), versus a normal range of 400 ~~to -800~~ [μL/L \(ppm\)](#). 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.
- [The utility required the manufacturer to undertake DGA measurements following one year in-service of a newly commissioned 230 kV SCFF cable system, and required that the acetylene concentration be less than 1 μL/L \(ppm\). After one year in-service, oil samples were drawn from the 230 kV SCFF cable termination and the concentrations were reported to be about 4 μL/L \(ppm\), which violated the utility's requirements. The utility then decided to ask the manufacturer to dis-assemble the "suspect" termination and ascertain the cause of such increased concentrations. The results revealed that within the condenser style paper cone there were missing layers of the grading aluminum sheet, which resulted in non-linear stress distribution, resulting in arcing, tracking, decomposition of the paper and oil, and gas generation, which explained the observed increased concentration of acetylene. The ability to decide on the condition of the asset based on gas concentrations will rely heavily on the type of the accessory and design. In this case, the very presence of acetylene \(albeit at low concentration\) showed significant arcing damage in the termination that if left unattended could have led to a catastrophic termination failure.](#)

Caution should be used when attempting to generalize the results of these cases. There have been some cases where joints have been disassembled without finding evidence of any serious anomalies. A monitoring program of periodic DGA tests along with flushing of dielectric fluid and X-raying of joints is a wise practice to follow prior to any decision to take apart a joint. Prudent engineering judgment should ~~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 contains ~~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 non-hydrocarbon 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 fluid ~~gas~~ sample. The chemical processes that may be involved are briefly discussed in 6.1.1 through 6.1.4 ~~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 ([B2]), (Clark, [B4]) F. M. Clark noted that “[t]hese chemical changes not only produce increased dissipation 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 ([B16] Murphy, [B14]) and 1962 ([B17] Murphy, [B-15]). In 1964, L. C. Flowers extracted moisture evolution rates from Murphy’s data (Flowers, [B6]). In 1977, W. G. Lawson et al., [7] presented gas evolution rates specific to the thermal degradation of impregnated unimpregnated cable papers ([B14] 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 ([B10] Head, [B8]).

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

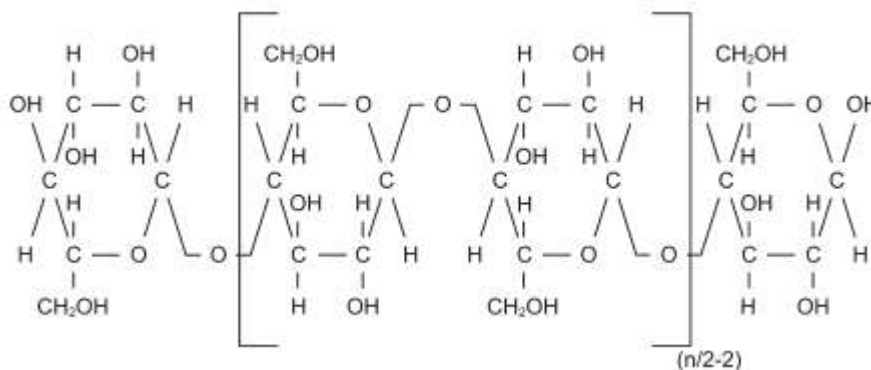


Figure 1—Basic molecular structure of α alpha-cellulose

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% ~~α~~ ~~alpha~~-cellulose. Papers with the higher percentage of α -cellulose 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 $\mu\text{L/L}$ (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 the degree of polymerization (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. ~~These,~~ ~~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.

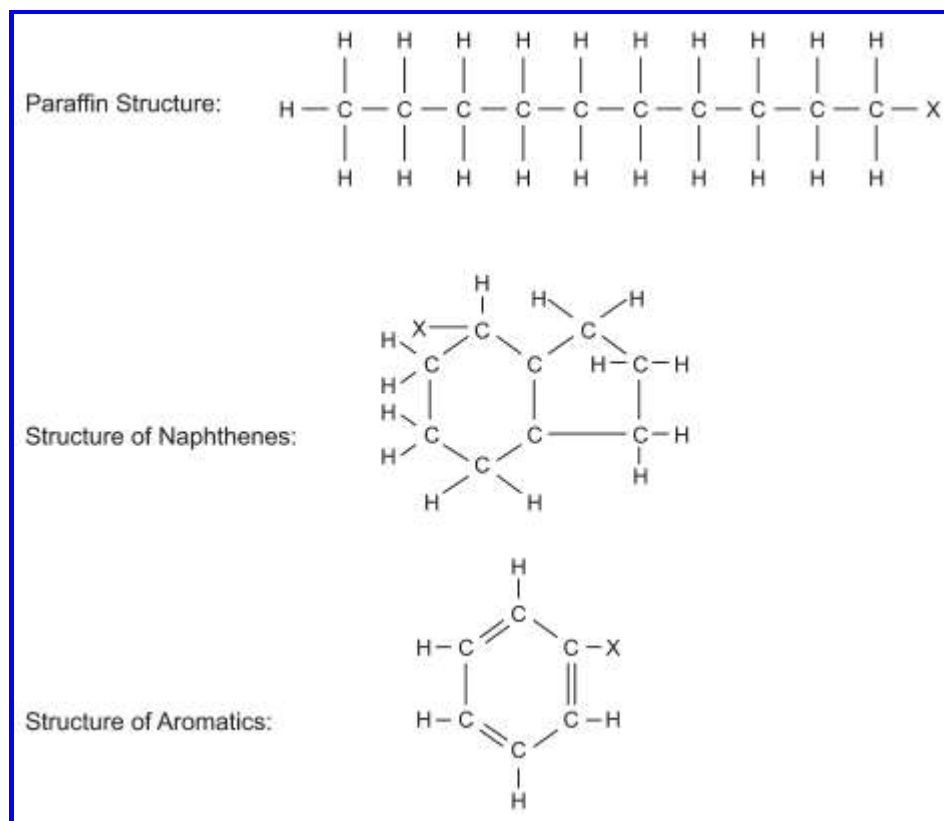
6.1.2 Effects ~~Effect~~ of electrical stress on the decomposition of cellulose

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. ([B10] ~~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, possibly due to dielectric heating.

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 ([\[B1\]](#) ~~Bartnikas and Srivastava, [B3]~~). "X" represents a possible point of connection between components.



[\(New\)](#)

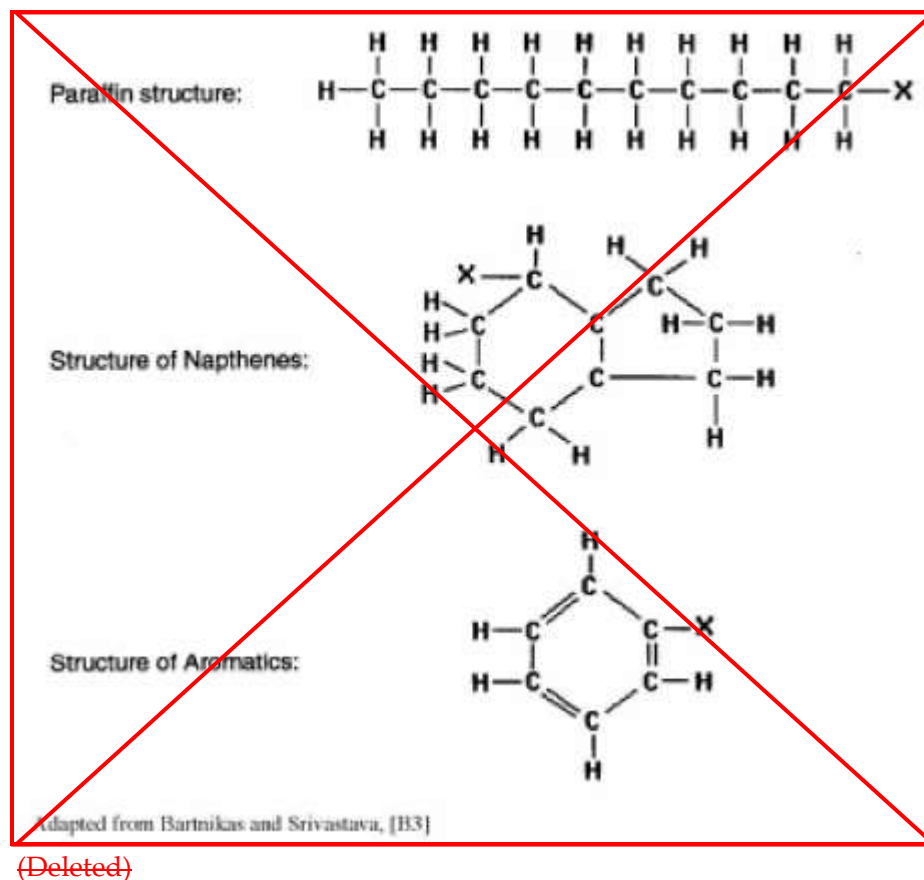


Figure 2—Chemical structure of mineral oil components [\(Adapted from Bartnikas and Srivastava \[B1\]\)](#)

Polybutenes, synthesized from butene gas by catalytic polymerization, were first used in the 1930s to thicken mineral oil impregnants for use in gas-filled cables. In the late 1950s they began to be used as cable impregnants, and in the 1960s as pipe-filling fluids. Polybutenes were known for very low losses and excellent oxidation resistance. The chemical structure of polybutene, considered to be a partially unsaturated hydrocarbon because of the double carbon bond at the end of the molecular chain, is shown in Figure 3.

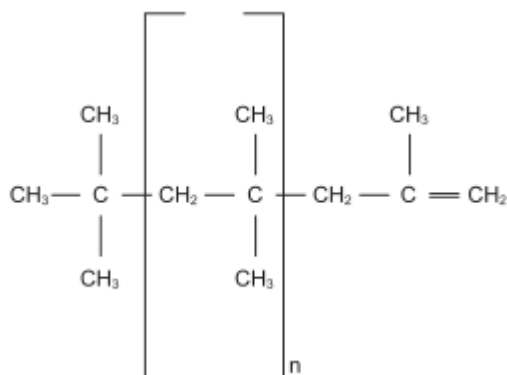
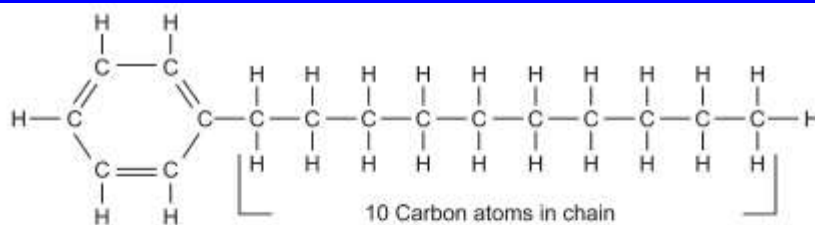


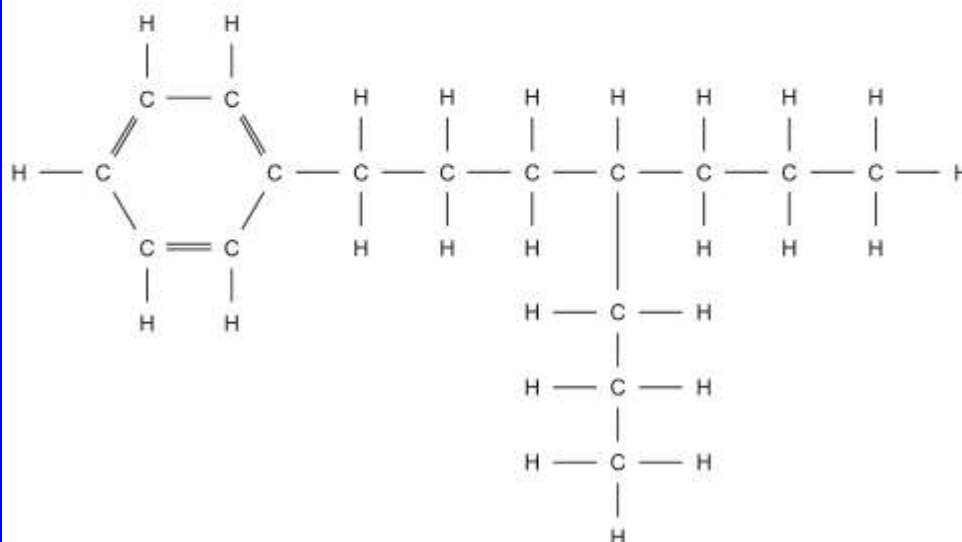
Figure 3—Chemical structure of polybutene

Alkylbenzenes are synthetic compounds that are made by the alkylation of an aromatic substrate with alkyl halides. Two versions are used as dielectric fluids: one has a linear chain structure emanating from the aromatic ring and is designated as “soft,” while the other has a branched chain structure and is known as “hard.” The soft material is classified as a biodegradable material. The chemical structures of these two compounds are shown in Figure 4.



Structure of a Linear Alkylbenzene, "Decylbenzene"

Ten Carbon atoms in a chain



Structure of a Branched Alkylbenzene, "Decylbenzene"

[\(New\)](#)