Dissolved Gas Analysis (DGA) for Fluid Filled Terminations of Extruded Transmission Cables

TR-114197

Final Report, December 1999

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REPORT SUMMARY

Extruded transmission cable systems constitute approximately 15% of the underground transmission cables in the United States, and the use of such cables is steadily growing. The failure rate of the accessories of these cables is higher than the corresponding rate for high-pressure fluid-filled (HPFF) cable terminations. Most failures occur in terminations within the first few years of operation. This report describes the equipment and procedure required to sample fluid from extruded cable terminations for assessing the condition of these vital components through Dissolved Gas Analysis (DGA).

Background

As a result of considerable EPRI research dating back to 1983, DGA technology has proved an effective diagnostic tool for monitoring the condition of HPFF cables and their accessories. However, an increasing percentage of the underground transmission cables in service in the United States are extruded transmission cables. Utility experience indicates that most failures in extruded transmission cable systems occur in terminations within the first few years of operation. Poor workmanship during installation is deemed to be the most common cause of these failures. The vast majority of such terminations utilize a dielectric fluid. The growing acceptance of DGA by HPFF cable users prompted this project so that EPRI's DGA research can be extended to extruded cable terminations that require a dielectric fluid for operation.

Objectives

To develop a technique for extracting fluid samples from extruded transmission cable terminations for DGA; to determine which are the key diagnostic gases for the condition of such terminations; to relate gas concentrations to events occurring within the termination.

Approach

Drawing on extensive previous DGA experience, the investigators divided the project into several tasks. The first task was to interact with termination manufacturers to categorize various designs for fluid sampling. The second task related to the measurement of solubility of several gases needed for accurate DGA in silicone and polybutene fluids primarily utilized in such terminations. In the third task, investigators addressed gas generation under laboratory conditions using several electric field arrangements to identify key diagnostic gases and relate them to electrical activity. In Task 4, investigators adapted EPRI Disposable Oil Sampling System (EDOSS) to draw fluid samples for DGA in conjunction with a micro pump and a flexible plastic tubing. In Tasks 5 and 6, investigators conducted DGA testing for terminations of different manufacturers that had been subjected to load cycling and qualification tests at several laboratories in North America. Tested terminations included sound and deliberately flawed terminations. Based on these data analyses and their overall DGA experience, the investigators proposed guidelines for sampling and DGA interpretation.

Results

This project has resulted in a viable procedure utilizing a micro pump to take fluid samples from extruded transmission cable terminations. The vast majority of such terminations contain a dielectric fluid, which is both viscous and limited in quantity. The developed system provides the analysis of 16 gases based on a 5-cc sample. The research identified four key diagnostic gases.

EPRI Perspective

Drawing on previous EPRI work on DGA of HPFF cables, this work extends DGA to extruded transmission cable terminations, most of which utilize a dielectric fluid. Recognizing that the failure rate of extruded transmission cable terminations is higher than that of HPFF cable terminations, EPRI is addressing the development of various diagnostic tools necessary for both post-installation and in-service testing of extruded cable systems. This project seeks to provide a highly cost-effective and easy-to-apply tool to assess the condition of such terminations through DGA that has already proven successful for HPFF cable systems.

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Keywords

Underground Transmission
Dissolved Gas Analysis
Diagnostics
Extruded Cable Systems

INTRODUCTION

There are approximately 8,000 extruded cable terminations operating in the 69 kV through 138 kV range in the United States, the number of 230 kV extruded terminations being under 50. The failure rate of extruded cable terminations is about 3 to 4 times the failure rate of pipe-type and self-contained cable terminations. Statistics show that most failures in extruded cable systems occur in terminations within the first few years of operation. Poor workmanship during installation is deemed to be the most common cause for these failures. While many diagnostic approaches e.g. a wide variety of partial discharge methods and ultrasonic sensors etc. are being addressed, there is no reliably demonstrated diagnostic tool to monitor the condition of extruded cable terminations.

The vast majority of extruded cable terminations at transmission voltage levels presently requires a dielectric fluid for its operation. This fluid, which is either silicone or polybutene, is exposed to electrical and thermal stresses. The degree to which the termination fluid is exposed to such stresses depends on many factors such as design, quality of workmanship during installation, operating conditions, and materials. This situation evidently holds for other fluid-filled equipment such as fluid-filled taped cable systems and transformers, where dissolved gas analysis (DGA) has gained wide acceptance. It follows that extruded cable terminations offer a good opportunity for DGA application.

Based on the extensive laboratory and field knowledge gained during EPRI [i] [ii] [iii] [iv] [v] [vi] [vii] sponsored DGA since 1983 at Detroit Edison, a program was structured to extend DGA to extruded cable terminations. The fundamental objective of this project was to determine the viability of DGA as a diagnostic tool to assess the condition of such terminations in service. To accomplish this goal, it was essential to develop an-easy-to-use technique for extracting fluid samples from these

[i] Singh, N., Morel, O., Butucel, B. and Rochon, M., "Development of an Oil Deterioration Test Method to Monitor the Condition of High-Pressure Fluid-Filled Paper Cable", EPRI Final Report, EL-7488-L, Research Project 7895-1, November 1991

[ii] Singh, N., Morel, O. and Multani, S. "Behavior of Paper-Polypropylene-Paper Laminate Under Thermal and Electrical Stresses, EPRI Final Report, TR-111321, September (1998)

[iii] Singh, N., Morel, O., Singh, S.K., and Cooper, J.H. "Transmission Cable Life Evaluation and Management", EPRI Final Report, TR-111712, December 1998

[iv] Singh, N., and Morel, O. "Dissolved Gas Analysis (DGA) by EPRI Disposable Oil Sampling System (EDOSS)", EPRI Final Report, TR-111322, September (1998)

[v] "Accurate Gas Analysis Reveals Damaged Cable Section." Innovators with EPRI Technology, IN-101579, October (1992)

[vi] "Dissolved Gas Analysis ensures Continued Operation of 115-kV High-Pressure Fluid-Filled Cable System." Innovators with EPRI Technology, IN-101579, August (1993)

[vii] " Dissolved Gas Analysis for Underground Cables Saves PG&E from Expensive Power Outage." Innovators with EPRI Technology, IN-103491, September (1994)

terminations and relate the concentrations of key gases to the dielectric condition of the termination.

The vast majority of U.S. terminations at 69 kV through 138 kV has been supplied by two domestic manufacturers, namely, G & W and Joslyn. Foreign manufacturers such as Kabeldon, Alcatel, NKF Group, Fujikura and Pirelli have also supplied over 750 terminations, often as a turnkey project. However, it was possible only to cover the first four manufacturers in this project.

The design of Joslyn, G&W, Alcatel and Kabeldon was studied and categorized with focus on fluid sampling and gas analysis. While the basic design of Alcatel and Kabeldon is essentially the same, the design of Joslyn and G&W is significantly different from each other as well as from the European designs.

All manufacturers provide a small opening through which the fluid can be accessed. G&W and Alcatel always provide bottom valves. The Joslyn design rules out the provision of a bottom port as the fluid does not reach the termination bottom. Kabeldon design does not provide a bottom port, however, it can be easily provided if requested by the customer.

Unlike fluid-filled taped cable terminations, extruded cable terminations contain limited volumes (about 2 to 15 gallons) of high viscosity fluids under atmospheric pressure or slightly higher. This renders the sampling operation difficult. A sampling system appropriate for such terminations, which can only spare a small amount of fluid, was developed. It is based on the EDOSS (EPRI Disposable Oil Sampling System) method that requires only about 5 cc of fluid for DGA. The traditional methods necessitate 50 to 100 cc of fluid. In the sampling operation, the EDOSS technique utilizes a reversible flow micro pressurization pump and a flexible plastic tubing. The unused fluid can be restored to the termination through reverse flow action. The method has been successfully employed both in laboratory and field evaluations of many extruded cable terminations of several manufactures.

Solubility of various gases in silicone and polybutene fluids was determined, as it is required for accurate DGA by EDOSS approach. The potential of gas analysis in the headspace or condition assessment was addressed. This relatively simple approach seems to hold potential.

It has been reported in previous EPRI[i ii] work involving laboratory investigations for high pressure fluid filled cables that several characteristic gases are generated during pre-breakdown and breakdown processes in hydrocarbon fluids. It was essential to understand this behavior in silicone and polybutene fluids employed in extruded cable terminations so that key gases and their concentrations can be identified. Accordingly, gas generation was studied under pre-breakdown and breakdown conditions utilizing point-to-plane and multipoint-to-pane electrode arrangements. Partial discharges were followed by a spectrum analyzer. Based on these studies, the key gases were identified and related to various levels of discharge activity ranging from onset to breakdown. The identified key gases were: acetylene, ethylene, hydrogen and propylene. The work on termination filling fluids was carried out in several electrode arrangements to relate its outcome to real-life conditions.

Various terminations that have been subjected to load cycling tests at manufacturers' laboratories were sampled for DGA, including Detroit Edison's laboratory. In addition, six terminations

were sampled at NEETRAC, where both deliberately flawed and normal terminations were included to develop diagnostic tools for condition assessment. DGA was also performed on several 345 kV extruded cable terminations undergoing long-term qualification testing at Hydro Quebec laboratories. This sampling also included some 345 kV terminations that had already experienced electrical problems toward the end of testing, providing valuable DGA data.

The gases attributed to the extruded cable insulation, as opposed to the termination fluid, were identified. Relatively large concentrations of methane and butanes evolve from the cable insulation. These gases are the result of the chemical crosslinking and other cable manufacturing processes and should be distinguished from the gases evolving from the fluid. Limited field sampling was performed on in-service 138 kV terminations.

As a result of DGA conducted under a wide variety of conditions such as fluid behavior under electrical stress in simple electrode configurations; load-cycled terminations in the laboratory; deliberately flawed terminations; terminations that had experienced electrical problems in qualification testing; field sampling; and extensive knowledge gathered during EPRI sponsored work dating back to 1983, the limits of key gases and the frequency of DGA testing are discussed. Recommendations for additional fieldwork involving DGA on the filling fluid and gas analysis in the headspace are made.

ABSTRACT

The project covers the extension of Dissolved Gas Analysis (DGA) technology, which is being increasingly applied to all liquid-filled electrical equipment employed at 69 kV and above, to monitor the condition of extruded cable terminations at such voltages. The failure rate of extruded cable terminations high. The objectives of this project were to: (a) develop a technique for extracting fluid samples from extruded cable terminations employed in U. S. utilities; (b) determine the key gases that can assess the condition of operating terminations and relate their concentration to any undesirable events occurring within the termination.

These objectives were accomplished through both laboratory and field investigations. Unlike pipe-type and self-contained cable terminations, most extruded terminations contain a relatively small amount of a highly viscous dielectric fluid, rendering the sampling process difficult, all the more in severe winter conditions. The EDOSS (EPRI Disposable Oil Sampling System) method for DGA was adapted in conjunction with a micro pressurization pump and a flexible plastic tubing. The various commercially available terminations were studied and categorized from the standpoint of sampling and gas generation. Solubility of various gases needed for accurate DGA was determined in termination filling fluids.

Gas generation was studied under laboratory conditions utilizing geometric electric field configurations to identify key diagnostic gases. Thermal studies on cable insulation revealed the gases predominantly evolving from the cable insulation. Several terminations were sampled after undergoing extensive load cycling at the laboratories of termination suppliers in North America, including Detroit Edison's laboratories. In addition, terminations being tested at NEETRAC to develop reliable diagnostic tools for extruded cable accessories were sampled. While the emphasis was on DGA of the termination fluid, the potential of gas analysis in the headspace, which offers a simple alternative, was also addressed.

Based on a wide variety of laboratory testing, including DGA of extruded terminations that had experienced failure in long-term laboratory testing along with limited field sampling, the type, distribution and concentration of key gases were identified. The gas limits for key dissolved gases are proposed with the frequency of DGA testing.

ACKNOWLEDGMENTS

The valuable contributions of Dr. Nezar H. Ahmed and Gerald E. McDonnell of Detroit Edison are deeply appreciated. In addition, the contributions of two graduate students from Michigan Technological University, David Chua and Richard Lewanu, are gratefully acknowledged.

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INTERACTION WITH TERMINATION MANUFACTURERS

The vast majority of extruded cable terminations currently employed in the United States at 69 kV and above are fluid-filled. The majority of such terminations have been supplied by G&W Electric Specialty Company, Blue Island, Illinois and Joslyn Manufacturing Company, Chicago, Illinois. Since the early 1980s, several foreign extruded termination manufacturers such as Alcatel, Kabeldon, Pirelli, NKF Group, Holland and Fujikura, Japan have also supplied a slowly growing proportion of such terminations. With the general exception of Kabeldon and Alcatel, the rest of foreign terminations often supplied as a part of the cable system of the same manufacturer. The objective of this chapter is to discuss various design aspects of key termination types being used in the U. S. as it relates to fluid sampling for DGA. To accomplish this objective, visits were made to G&W, Joslyn as well as Alcatel Canada Wire. Telephone discussions were held with primarily Kabeldon, who has been one of major overseas suppliers. It is worthwhile to mention that all of these manufacturers had occasionally applied DGA to their terminations undergoing developmental testing in the laboratory, however, they encountered a certain degree of difficulty in the sampling process.

While the basic design is essentially the same, each manufacturer offers different features. All 69 through 138 kV designs are non-capacitor graded types with stress-control components. The G&W design at 220 kV incorporates grading capacitors. The filling fluid in all cases consists of a medium to high viscosity silicone or polybutene fluid. The volume of filling fluid varies markedly with different designs. With the exception of G&W, all terminations have a headspace to allow for thermal expansion and compression of the fluid. In the case of G&W, closed cell sponges are utilized to eliminate the headspace and provide volume compensation.

The G&W design incorporates a bottom valve. Detailed information on the basic domestic and foreign designs is given below:

Alcatel Canada Wire

Design

The design of 115 kV through 138 kV extruded cable terminations includes a push-on stress relief cone installed tightly around the cable insulation and cable insulation shield, Figure 1-1. The stress cone has a semiconducting deflector vulcanized to a matrix of silicone rubber. Since the stress cone itself has a diameter slightly smaller than the cable insulation, a tight interference-fit fit is achieved. This assures no movement of the stress cone and eliminates the gap between the silicone rubber and the cable insulation. The empty termination volume is filled with a high viscosity silicone fluid (10,000 cSt @ 25°C). This fluid is added to the termination after field assembly through a port located under the corona shield. For maintenance and field inspection

purposes, the filling fluid can be drained out of the termination through a bottom port (drainage plug, Figure 1-1) located over the mounting plate.

The design of this termination provides enough room for the filling fluid to undergo convective circulation that helps the mixing of gaseous components. However, the filling fluid is not in direct contact with the interface region between the stress cone and the cable insulation due to the tight fit of the stress cone. During installation, silicone grease is smeared over the cable insulation to facilitate slippage of the stress cone. The same grease facilitates the installation of the bottom-sealing gasket.

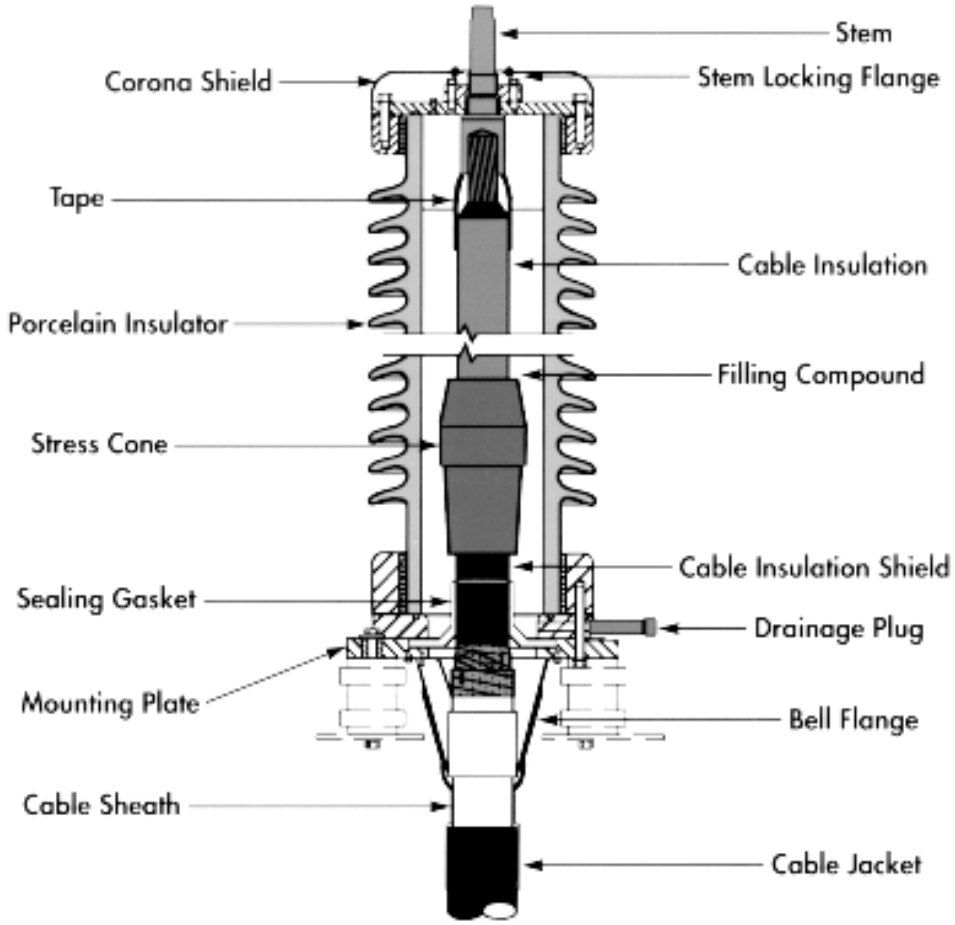


Figure 1-1
Alcatel extruded cable termination

Fluid Sampling

This design allows fluid sampling from both the top and bottom port. Access to the fluid can be gained either through the top filling port located under the corona shield or through bottom draining port located over the mounting plate. The cable has to be de-energized in both cases. The top filling port is large enough to allow a 1/4" or 3/8" OD plastic tubing to be slipped into the termination cavity to a point below fluid level. With a positive displacement pump

the termination cavity to a point below fluid level. With a positive displacement pump connected to the outer end of the plastic tubing, filling fluid can be extracted by suction. The details along with the appropriate EPRI method named EDOSS (EPRI Disposable Oil Sampling System) are given in Chapter 4.

Significance of DGA in this Termination

Since the filling fluid is free to move inside the termination by convection forces, gases evolved in the higher stress regions are allowed to distribute within the filling fluid and headspace region. Because of the tight fit between the stress cone and the cable insulation, it may appear that the gases produced at the interface between the cable and the stress cone do not easily move out to the filling fluid. Nevertheless, since time is an important factor in the gas diffusion processes, meaningful condition assessment could be made based on the detection of only minute amount of key gases through the sensitive gas detectors utilized in gas chromatographs. It should be added that highly sensitive gas detectors, now available, would further improve gas detection capability.

G&W Electric Co.

Design

The design of G&W terminations for extruded cables of a lose-fit stress control assembly that is factory installed and field mounted by a slip-on process, Figure 1-2. A removable cable guide, having the same diameter as the cable insulation, is installed during factory assembly in place of the cable to seal the termination during transit. In the field, the cable guide is pushed out of the termination assembly with the cable, resulting in a fairly simple installation. With this design the stress control unit does not come in close contact with the cable insulation; the filling fluid fills this gap. The filling fluid utilized by G&W consists of a medium viscosity polybutene. The stress control assembly is composed of several pieces and occupies a fairly large proportion of the internal termination volume.

This design does not have a headspace; volume compensation sponges are added to account for the thermal expansion and contraction of the fluid. The termination is filled with the filling fluid at the factory to a small positive pressure. In the field, fluid can be extracted or added to the termination through a bottom port located just above the mounting bracket. Although fluid is free to move between the cable and the stress control assembly, the tight space available inside the termination could severely limit fluid mixing by natural convection.

Fluid Sampling

Fluid sampling can be carried out through the bottom port located over the mounting bracket of the termination. The volume compensating sponges create a small positive pressure sufficient to allow a small amount of fluid out for sampling. Since the fluid is fairly viscous, a positive displacement pump is still needed to force the fluid through the EDOSS sampling vial.

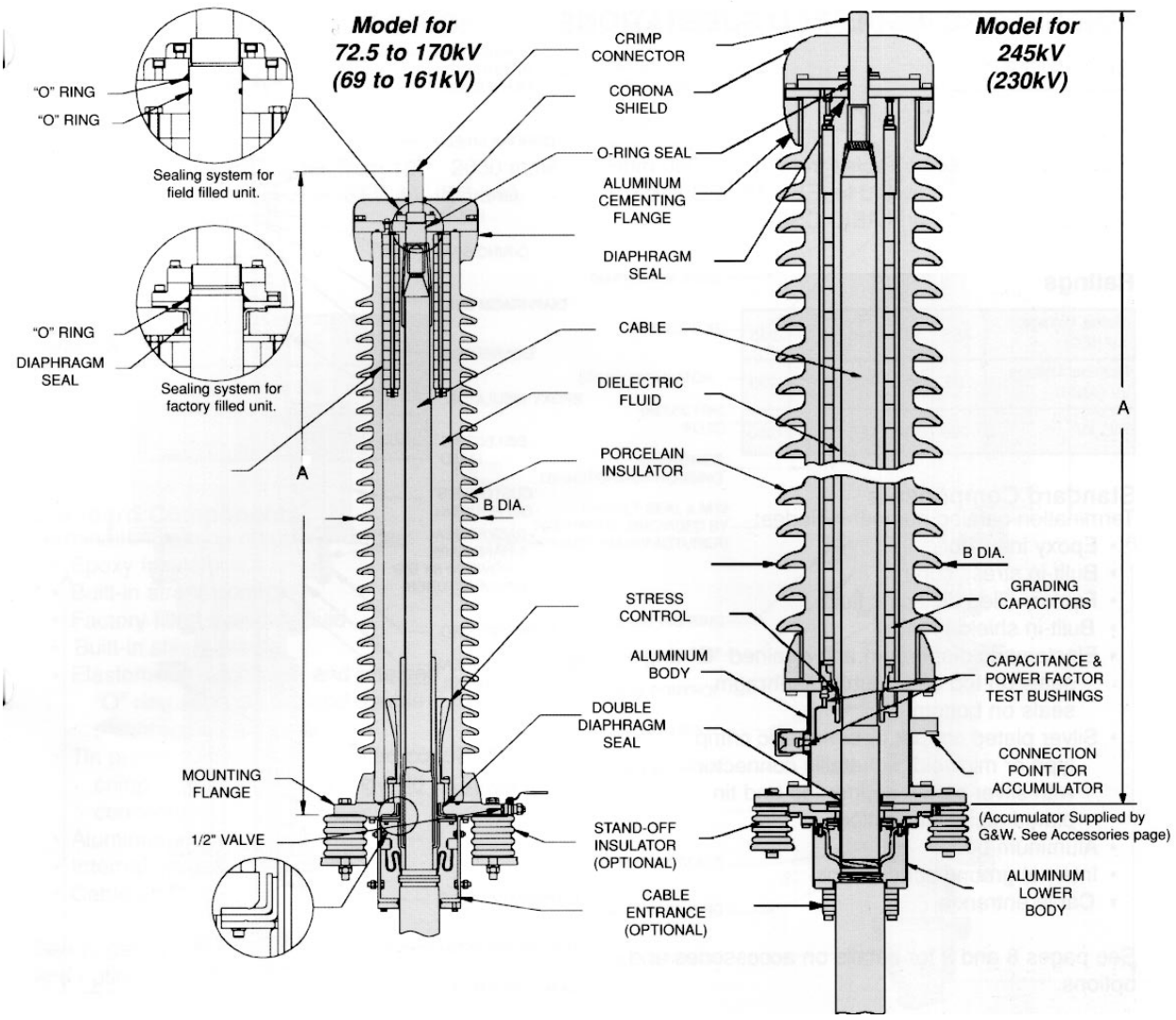


Figure 1-2
G&W Slip-on type termination for extruded cables

Significance of DGA in this Termination

In this design, fluid is allowed in the gap between the cable insulation and the stress control assembly. This allows fluid to reside in areas of high electrical stress and, therefore, gas can be generated in the fluid in case of strong ionization activity associated with an event taking place in the cable. This gas could be easily sampled through the bottom port of the termination.

Kabeldon

Design

The design of extruded cable terminations by Kabeldon is fairly open and similar to that of Alcatel's termination. Although the same design is utilized for 80 kV to 170 kV, some

differences seem to exist for higher voltages, namely 245 kV and 420 kV. In general, the stress cone made of EPDM rubber is held in place by an aluminum flange, which is supported at the bottom flange of the termination, Figure 1-3.

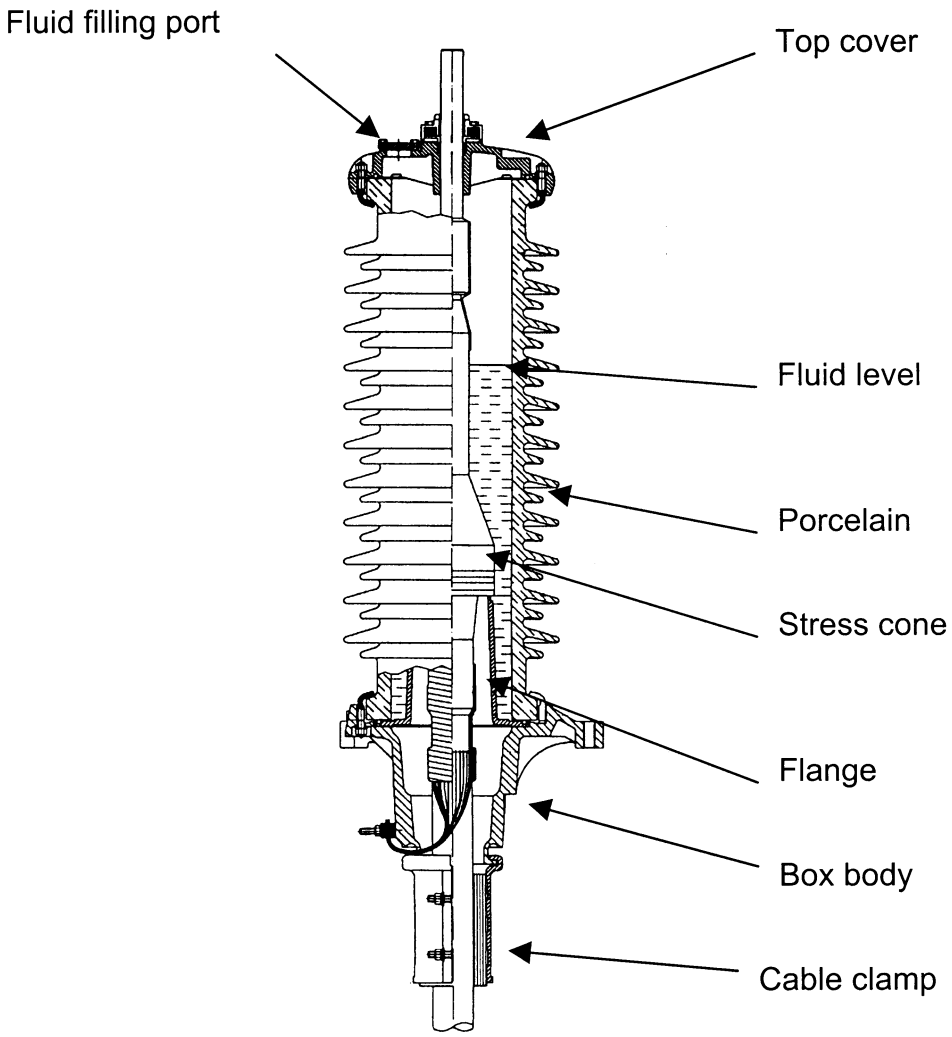


Figure 1-3
Kabeldon extruded cable termination

Fluid Sampling

The large internal volume of the termination is filled with polybutene fluid. There is sufficient space to allow for natural convective mixing of the fluid. Although no drainage plug is provided in the bottom part of the termination, there is a large opening at the top over the corona shield. A flexible tube could be easily introduced to reach the filling fluid that can be extracted by suction from a positive displacement pump.

Significance of DGA in this Termination

The apparently open structure of the termination design assures good fluid mixing, facilitating the distribution of generated gases throughout the fluid and headspace. The fluid can be readily extracted from the flange under the corona shield.

Joslyn Mfg. & Supply Co.

Design

The extruded cable termination manufactured by Joslyn offers a relatively small volume of free fluid, compared to other designs. A major portion of the internal volume of the termination is filled with molded-epoxy inserts (insulator tubes). The stress cone, made by vulcanizing a semiconductive elastomer in silicone rubber matrix, is maintained under compressive stresses transmitted from a spring loaded arrange-ment at the top of the termination by the rigid insulator tubes, refer to Figure 1-4.

A high viscosity silicone fluid fills all the gaps formed between the insulator tubes, porcelain housing and cable insulation. Some excess fluid is left on top of the last insulator tube. The free fluid cannot be readily accessed through the top of the termination due to the presence of the spring-loaded compression device. No bottom port is possible in this termination.

Fluid Sampling

The design of this termination does not include filling or draining ports. Accordingly, to sample this termination one has to insert a flexible termination after removing the top flange, and utilizing a positive displacement pump along with the EPRI sampling and analysis system.

Significance of DGA in this Termination

The stress cone in this termination is closely fitted against the cable insulation and embedded in a silicone rubber piece, Figure 1-4. Gases generated in this area are not free to move, except by slow molecular diffusion. Once gases are evolved from the stress cone device, migration to the top end of the termination takes place through the channels provided between insulator tubes and porcelain housing and cable insulation.

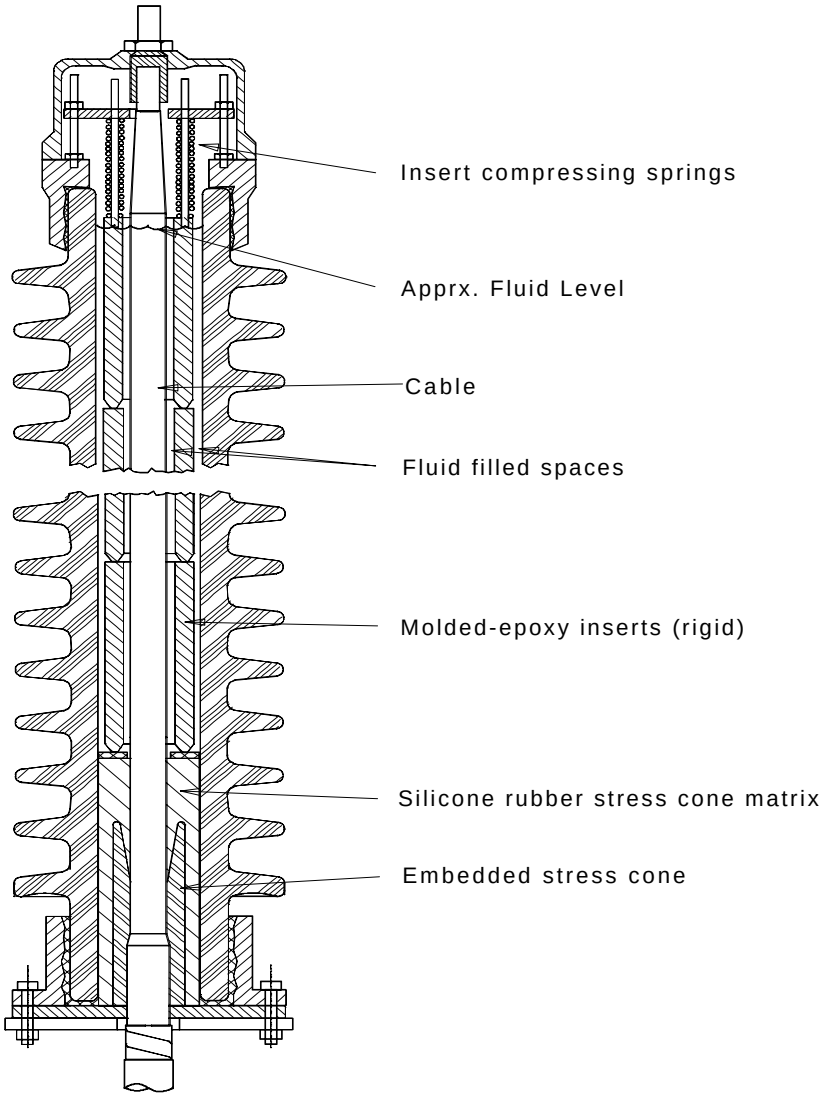


Figure 1-4
Joslyn extruded cable termination

Conclusions

The filling fluid of all transmission extruded cable terminations can be sampled, whether or not there is a port at the bottom. The EDOSS method appears to be the most viable for this purpose. The high viscosity of the filling fluid and lack of pressure requires a flexible plastic tubing in conjunction with a positive displacement pump for both top and bottom sampling.

While G&W and Alcatel designs always have bottom ports, Joslyn and Kabeldon terminations incorporate only a top port. According to Kabeldon, a bottom valve can be provided, if requested by the customer. The Joslyn termination design rules out the provision of a bottom port as the fluid does reach the termination bottom.

2
SOLUBILITY OF GASES IN TERMINATION FLUIDS

Approach

Dissolved gas analysis techniques utilizing a static headspace approach require gas solubility values to establish the final concentration of the remaining gas in the original sample. The solubility data are needed at the same temperature as utilized during sample analysis. The EDOSS procedure employs a sample equilibration temperature of 60°C. Accordingly, 60°C solubility was determined for a high and low viscosity silicone fluid as well as a high viscosity polybutene. Solubility was determined by an approach described in an earlier EPRI report TR-111322, 1998. Stated briefly, during static headspace analysis, the concentration of a gas in the fluid phase is in equilibrium with its partial pressure in the gas phase. The gas concentration in the original sample must be determined from the following a mass balance:

$$C_L^o V_L = C_L V_L + C_G V_G \qquad \text{(eq. 2-1)}$$

Where C^o_L is the gas concentration of component *i* in the original sample; V_L, the volume of the fluid sample introduced in the sampling vial; C_L, the equilibrium concentration of *i* in the liquid phase, V_G, the headspace volume and C_G , the equilibrium concentration of component *i* in the gas phase. By substituting in equation 2-1, C_L for $S_i p_i$ (Henry's Law), where S_i is the solubility and p_i the partial pressure of component *i*, and C_G for p_i/RT, (ideal gas law), the gas concentration of the original sample (C^o_L) becomes:

$$C_L^o = \frac{p_i}{RT}\left[\frac{V_G}{V_L} + S_i RT\right] \qquad \text{(eq. 2-2)}$$

The partial pressure of *i* in the headspace (p_i) is measured by gas chromatography. The solubility values for each gas (S_i) must be determined for each fluid. A calibration procedure, detailed in the aforementioned EPRI report, was developed to determine the solubilities S_i. By rearranging equation 5-2 as an expression of $1/p_i$ and the ratio (V_{vial}/V_L), as follows:

$$\frac{1}{p_i} = \frac{1}{RTC_L^o}\left[\frac{C_{vial}}{V_L}\right] + \frac{1}{C_L^o}\left[S_i - \frac{1}{RT}\right] \qquad \text{(eq. 2-3)}$$

This equation represents a straight line of slope m = $1/[RTC^o_L]$ and intercept n=$1/C^o_L[S_i - 1/RT]$. Data to solve equation 2-3 was obtained by filling vials with different volumes of a solution containing all gases of interest. The actual gas concentration of this solution is not required.

From the partial pressure of each component in the vials, measured by gas chromatography, a linear regression of $1/\underline{p}_i$ against V_{vial}/V_L is used to determine the slope (m) and the intercept (n). The solubility for each component is thus calculated from:

$$S_i = \frac{1}{mRT}\left[n + \frac{1}{mRT}\right] \qquad \text{(eq. 2-4)}$$

This approach is limited to gases with solubilities larger than $1/RT$. Fortunately, this holds true for most dissolved gases of interest, with the exception of hydrogen. A list of gas solubilities in a number of different fluids found in extruded cable terminations is given in the Table 2-1.

The solubility values in this table are given in terms of moles of gas per cc of oil per atm of gas. Assuming NPT (normal pressure and temperature) conditions, that is, one atm pressure and 25°C temperature, solubility values can be expressed in cc of gas per cc of oil/atm multiplied by 2.447×10^{4} or into ppm/atm multiplied by 2.447×10^{10}.

Conclusions

- Solubility values are required for accurate determination of dissolved gases in fluids.
- For highly non-polar fluids such as Silicone 561 and polybutene DCL 500, solubility values are more strongly dependent on the nature of the gas than the nature of the fluid.
- In headspace gas analysis, corrections are required for gases with solubilities over 5×10^{-5} mol/cc/atm (or over 1 cc of gas per cc of oil/atm), otherwise too much gas is left unaccounted for in the liquid phase. Accordingly, if the volume of a sample is 10 times smaller than the volume of the vial, the analysis error is in the order of 10% without solubility corrections. The analysis error increases rapidly for gases of higher solubility, reaching errors in the order of 100% for gases with solubilities over or 4×10^{-4} mol/cc/atm (or 10 cc/cc/atm)

Table 2-1
Gas Solubilities for Termination Fluids at 60°C

	Silicone		Polybutene
	Low Visc. (mol/cc/atm)[1]	High Visc. (mol/cc/atm)	High Visc. (mol/cc/atm)
Methane	3.1E-05	3.5E-05	5.8E-05
Ethane	8.0E-05	2.2E-04	3.9E-04
Ethylene	6.3E-05	1.6E-04	1.4E-04
Propane	2.1E-04	5.7E-04	1.3E-04
Propylene	1.7E-04	4.1E-04	3.0E-04
Acetylene	4.3E-05	1.0E-04	3.5E-05
Isobutane	3.7E-04	1.0E-03	3.5E-04
n-Butane	4.7E-04	1.1E-03	3.1E-04
t-2-Butylene	4.1E-04	9.9E-04	3.5E-04
1-Butylene	4.3E-04	1.0E-03	3.4E-04
Isobutylene	4.1E-04	1.0E-03	4.6E-04
Hydrogen	5.1E-06	5.1E-06	5.1E-06
Oxygen	3.0E-06	3.0E-06	3.0E-06
Nitrogen	4.8E-06	4.8E-06	4.8E-06
C. Monoxide	1.0E-05	1.0E-05	7.0E-05
C. Dioxide	5.0E-05	5.0E-05	3.0E-05

[1] To convert to ppm/atm (@ NPT)[2] multiply mol/cc/atm by 2.447×10^{10}

[2] NPT stands for normal pressure and temperature, 1 atm and 25°C

3
CHARACTERIZATION OF DISSOLVED GASES IN TERMINATIONS

Gas generation by partial discharges and breakdown in silicone and high viscosity polybutene fluids were carried out with two different electrode configurations. First, a point-to-plane electrode was utilized to generate gases under partial discharge activity. The partial discharge inception voltage was determined as a function of gap width and electrical stress. A high voltage dc power supply was employed to avoid RF noise interference associated with ac voltage. In a second part of this work, a multipoint-to-plane electrode configuration was used to generate gases under partial discharges. An ac power supply and a spectrum analyzer were utilized to monitor partial discharge activity as a function of electrical stress during the gas generation study. With the multipoint-to-plane configuration, it was possible to extend the period of time a fluid could be exposed to partial discharges before reaching breakdown.

Point-to-Plane Geometry

Partial discharge intensity and breakdown voltage as a function of gap distance between electrodes was determined. The test cell utilized for determination of gas evolution after partial discharges and breakdown activities as a function of gap distance is shown in Figure 3-1. The test cell was built with two 4.5 inches OD CF (knife-edge) flanges and a 5-inch long double-ended SS/Pyrex glass-metal adapter. A 15 kV feed-through bushing was installed in one end of the cell, while a variable length feed-through assembly was installed in the opposite end. A point-to-plane electrode configuration was utilized in this part of the work. The point was installed on the HV feed-through electrode, while the plate was installed on the variable length feed-through. The plate was attached on a miniature standoff insulator. A lead connected to the base of the plate was run through the flange, utilizing miniature insulated feed-through bushing. This line allowed access to the signal imposed on the plate electrode.

A Hipotronics® high voltage dc source capable of supplying up to 75 kV was used. The dc source was connected to the test cell according to the schematic shown in Figure 3-2. The antenna of a Hagenuk® partial discharge detector was placed in the ground path of the test cell. This allowed the detection of partial discharge activity generated between the two electrodes inside the cell. The entire setup was installed inside a Faraday cage to minimize the amount of electromagnetic interference.

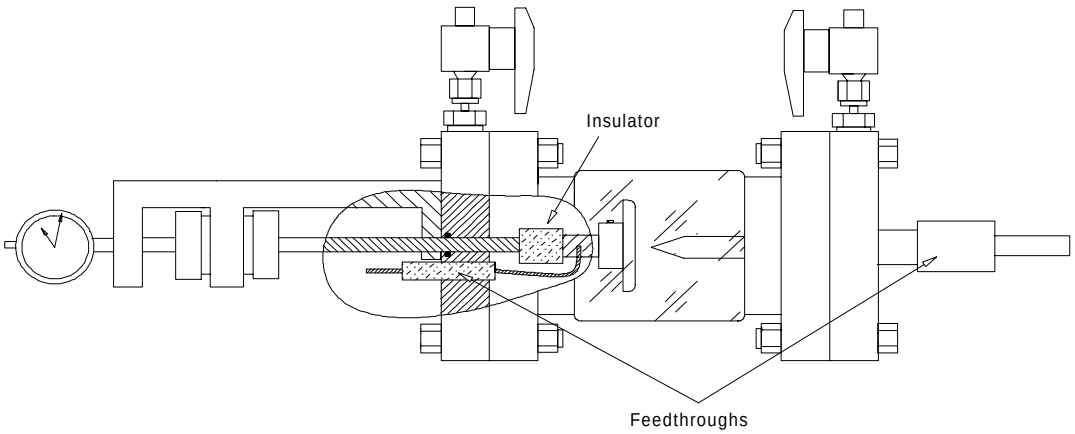


Figure 3-1
Test Cell for the Measurement of gases after Partial Discharge and Breakdown of Dielectric Fluids

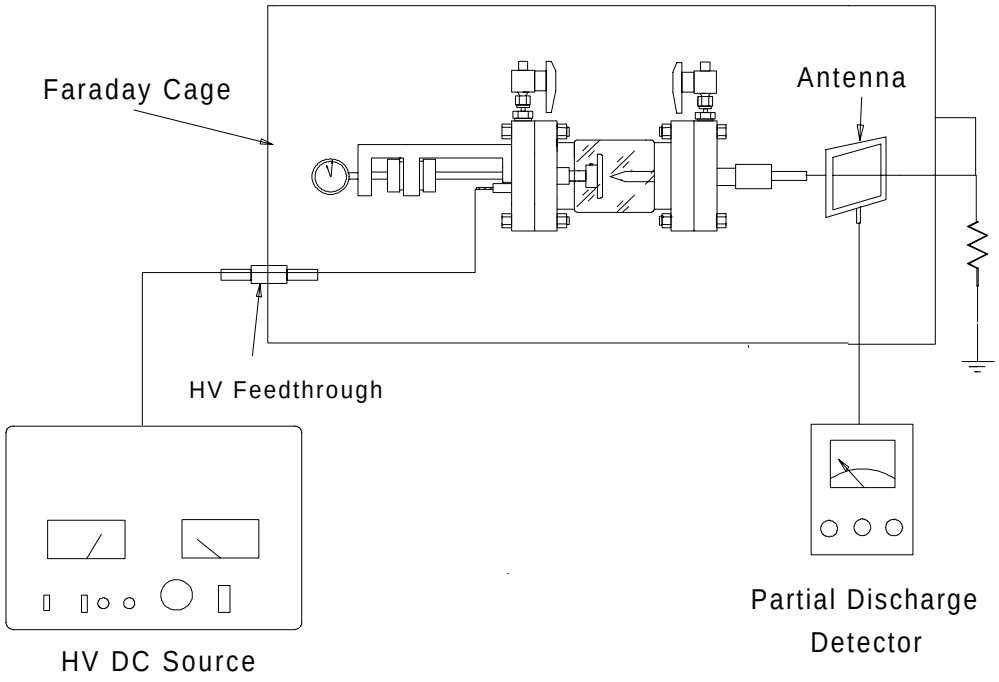


Figure 3-2
Schematic diagram for partial discharge detection

A 100 Ω wire-wound resistor was placed in series with the low voltage electrode and ground to limit the current in case of breakdown. Stainless steel point electrodes and brass plane electrodes were initially utilized. Both the brass and point electrodes were carefully polished with 600-mesh aluminum oxide powder. However, the rapid pitting of the soft brass plane caused

excessive variation of the breakdown voltage. Therefore, a stainless plane electrode replaced the brass plane electrode. Before each test, the plane electrode was polished to a mirror finish with sandpaper and aluminum oxide powder.

A low viscosity silicone fluid was utilized in this part of the work. It is felt that the high viscosity fluid will behave the same way as the low viscosity fluid from a gas generation standpoint. Before filling the test cell, the silicone fluid was carefully degassed, dried under vacuum and filtered utilizing a especial fluid treatment unit. Degassed fluid was delivered into the evacuated test cell. The cell was completely filled with silicone fluid. A 50-cc syringe was installed on one of the cell flanges and was utilized to compensate changes in fluid volume due to variations in room temperature.

Results

The region between PD onset and breakdown was determined as a function of gap distance for a point-to-plane electrode in silicone fluid. The results are shown in Table 3-1 and Figure 3-3.

Table 3-1
Stress Region between Continuous Partial Discharge and Breakdown for a Silicone Fluid as a Function of Gap Distance at Atmospheric Pressure

Gap distance (mils)	Continuous PD (kV)	Breakdown (kV)
10	-7.0	-7.0
20	-12.5	-13.5
30	-15.6	-16.3
40	-18.5	-24.6
50	-20.0	-26.5
60	-20.7	-28.5

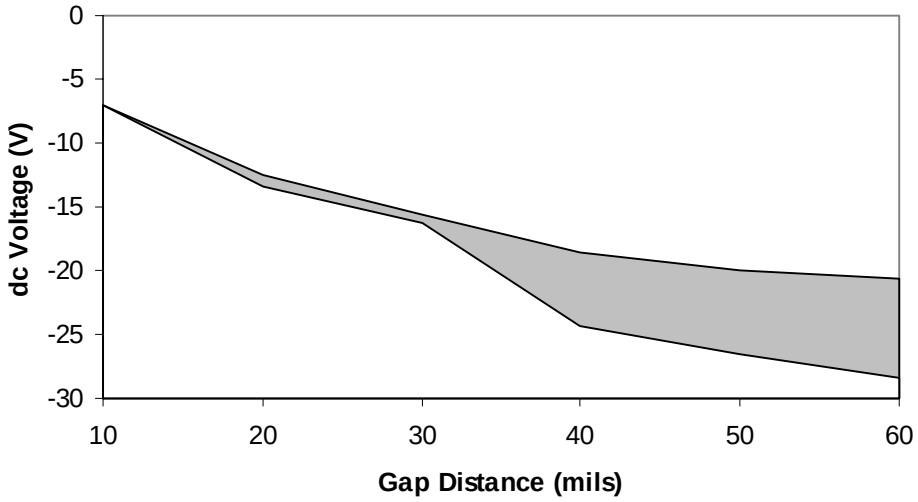


Figure 3-3
Partial discharge region for a point-to-plane configuration

The results shown in Table 3-3 were obtained with stainless steel electrodes. The test cell was filled with silicone fluid and allowed to stand for 5 minutes before voltage was applied. The first observation was measured with a gap distance of 50 mils. The voltage was raised very slowly until continuos PD activity was indicated by the Hagenuk® detector. The voltage was raised in 1 kV steps with 1-minute interval between steps, until -10 kV level was reached. After -10 kV, the voltage was raised in 500 V steps every 2-minute intervals, until the first PD pulses were detected. The first PD activity was observed at -20 kV for the initial gap of 50 mils. With the point of continuous PD established, the voltage was raised in 500 V steps in 2-minute intervals, until breakdown occurred. With the 50-mil gap, breakdown was observed at -26.5 kV. With a 10-mil gap in the point-to-plane electrode configuration, breakdown occurred as soon as PD was first detected.

The objective of this experiment was to determine the zone at which sustained PD activity could be maintained for a period long enough to lead to the accumulation of a measurable amount of gas. This zone is represented graphically in Figure 3-3 by the area between the two lines. At gaps smaller than 30 mils, the separation between continuous PD and breakdown was not sufficient, and it was difficult to maintain constant PD activity without breakdown. However, at increasing gaps, the region at which PD can be sustained before breakdown increases rapidly. A gap of 60 mils was selected in this work since its gives the largest separation between continuous PD and breakdown. It seems clear that larger gap distances would result over a wider PD region, however, the higher voltage needed for PD inception was limited by the rated voltage on the feedthrough bushings. Bushings for a higher voltage rating would have required a larger test cell, which would have resulted in an increased gas dilution effect.

Gases after Electrical Discharge

Gases were generated under PD and breakdown conditions. Typical gas distribution after breakdown of silicone and polybutene fluids is shown in Table 3-2. As shown in this table, there is no striking difference in gas yields after breakdown between silicone and polybutene fluids. Perhaps the only marked difference is presented by the presence of carbon monoxide and carbon dioxide in silicone fluids as well as the smaller acetylene yield compared to the polybutene fluid.

Compared to the polybutene fluid, the yields of ethylene and propylene are somewhat smaller in the silicone fluid. Although no propane was observed after breakdown of silicone fluids, the ethylene to ethane ratio was very large in both cases. Essentially the same yield of acetylene is expected for both high and low viscosity silicone fluids. The observed smaller yield in the high viscosity silicone compared to the low viscosity silicon fluid cannot be explained.

Gas Evolution under Partial Discharges (PD) in a DC Field

Studies of gas evolution from a low viscosity silicone were performed under constant partial discharge intensity as a function of time, and under constant time as a function of PD intensity. The results are given in Tables 3-3 through 3-5. In these tables, only the gases that showed an increase in concentration during the test are shown. Hydrogen was not detected for lack of sensitivity. Traditional detection systems cannot detect less than about 20 ppm of hydrogen, however, hydrocarbons can be detected down to 0.1 ppm.

Despite the natural data dispersion, it was determined that gases such as methane, ethylene, acetylene and propylene are always generated when partial discharges are present. The severity of the partial discharge and extent of the application correlates with the increase of some of these gases.

In silicone fluids, the generation of methane is attributed to cleavage of the methylene groups from the main –Si-O-Si- backbone with abstraction of hydrogen from neighboring groups. However, formation of acetylene, ethylene and propylene must follow considerably more complex mechanisms involving numerous molecular rearrangements. It is expected that hydrocarbon fluids should show a more rapid increase of acetylene than methane.

Table 3-2
Comparison of Gas Distribution after Breakdown of Low and High Viscosity Silicone Fluids and a Polybutene Fluid

	Silicone		Polybutene
Percent Gas Composition	**Low Visc.**	**High Visc.**	**Medium Visc.**
Hydrogen	63.7	72.7	40.6
Carbon Monoxide	12.1	14.8	ND
Carbon Dioxide	1.0	1.5	ND
Methane	7.2	8.6	11.7
Ethane	0.2	0.1	2.0
Ethylene	0.9	0.7	10.7
Acetylene	14.8	1.6	25.5
Propane	0.0	0.0	0.7
Propylene	0.1	0.02	5.6
Isobutylene	0.0	0.0	3.2
Total	*100.0*	*100.0*	*100.0*

Table 3-3
Gas Evolution from Silicone After 48 Hours at Increasing Level of Stress

Applied Stress (kV/mil)	Carbon Monoxide (ppm)	Methane (ppm)	Ethylene (ppm)	Acetylene (ppm)	Propylene (ppm)	Hydrogen (ppm)
0.333	ND	ND	ND	ND	ND	ND
0.367	ND	3.85	0.25	0.15	0.30	ND
0.400	0.30	5.10	ND	0.75	ND	ND
0.433	ND	6.47	0.53	4.80	0.30	ND

Table 3-4
Gas Evolution from Silicone as a Function of Stress Duration for a Constant

Time (hours)	Carbon Monoxide (ppm)	Methane (ppm)	Ethylene (ppm)	Acetylene (ppm)	Propylene (ppm)	Hydrogen (ppm)
24	0.13	6.33	0.33	ND	0.87	ND
48	ND	ND	ND	ND	ND	ND
96	ND	2.00	0.15	0.15	0.20	ND

Table 3-5
Gas Evolution from Silicone as a Function of Stress Duration for a Constant

Time (hours)	Carbon Monoxide (ppm)	Methane (ppm)	Ethylene (ppm)	Acetylene (ppm)	Propylene (ppm)	Hydrogen (ppm)
24	ND	ND	ND	ND	ND	ND
48	ND	3.85	0.25	0.15	ND	ND
96	0.23	5.43	0.37	0.13	6.70	ND

Multi-point-to-Plane Electrode in an AC Field

Experimental

In this part of the work, a different electrode configuration was utilized to increase the amount of time over which partial discharges can be sustained before fluid breakdown. The electrode design consisting of a multiple point-to-plane configuration is shown in Figure 3-4. Two fluids were investigated with the test cell, polybutene and silicone.

Details of the approach, equipment and procedures employed in partial discharge (PD) measurements are given elsewhere in a paper by Detroit Edison[viii]. Partial discharge measurements under time and frequency domains were made to monitor the ionization activity generated in the experimental cell. Frequency domain testing was conducted utilizing a spectrum analyzer capable of performing both full-span and zero-span modes. In the full-span mode, the frequency range can be adjusted to examine the signal in narrow and wide-frequency bands. The zero-span mode was used to examine single-frequency pulses in time domain. The sweep time of the zero-span can be selected to study one or more cycles of the operating voltage.

[viii] Ahmed, N., Morel, O. and Srinivas, N. "Partial Discharge Measurement in Transmission-Class cable Terminations", IEEE T&D Conference, pp. 227, New Orleans, April (1999)

Noise rejection was accomplished by studying the signal captured during the full-span mode. A small current transformer (CT) connected to the ground lead of the test cell was utilized for signal pick-up. The signal of the CT was amplified with a pre-amplifier and then fed to the signal analyzer

An initial run was made with each fluid to determine the onset of PD. The voltage output of the ac power supply was increased in small increments while PD activity was being monitored. The voltage level, where the first indications of steady PD activity were observed, was recorded. Subsequently, the PD equipment was disconnected and the ac power supply output increased in small increments beyond PD inception, until breakdown for the given gap was established. After determination of the breakdown level, PD equipment was reconnected and PD measurements made at 2 kV below breakdown and at other intermediate levels between onset and breakdown. The test cell was cleaned and filled with freshly degassed fluid every time fluid breakdown occurred in the cell.

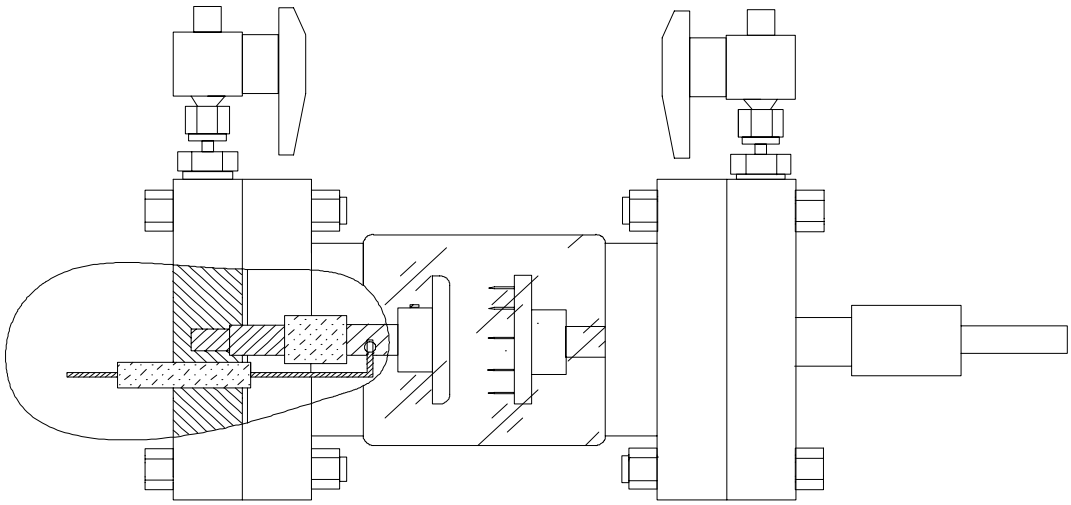


Figure 3-4
Schematic diagram for a test cell fitted with a multipoint-to-plane isolated electrode

Full-span data resulting from measurements on polybutene are presented in Figures 3-5 and 3-6, while data on silicone are presented in Figures 3-8. Partial discharge activity in polybutene fluid is shown in Figure 5 at four levels of stress for a fixed gap. Top left corresponds to PD onset at 15 kV; top right to intermediate level of 17 kV; bottom left to intermediate level of 19 kV; and bottom right to 22 kV, 2 kV before breakdown. Notice the sharp increase of signal level over the steady laboratory noise background in the range from 20 to 60 MHz (each division corresponds to 8 MHz). Also note that the range of the y-axis is increased as the field stress increases. Noise background contains interference from broadcasting stations, forced ventilation equipment and other non-identified sources.

A detail view of a full-scan at 22 kV and respective zero-scan for the same voltage level is given in Figure 3-6. The zero-scan showing four 60 Hz wave cycles indicates repeating PD activity near the crest of the positive and negative cycles.

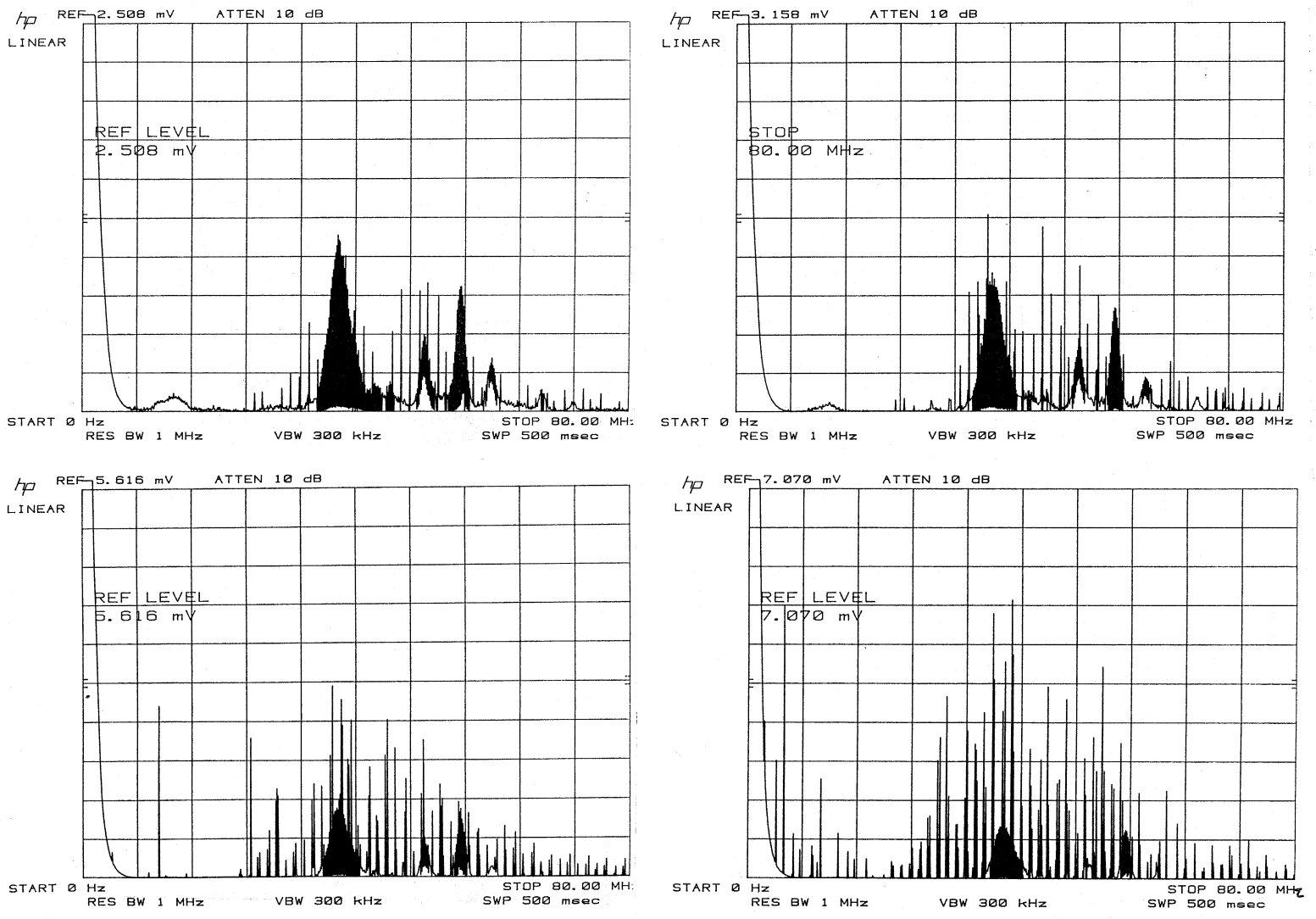
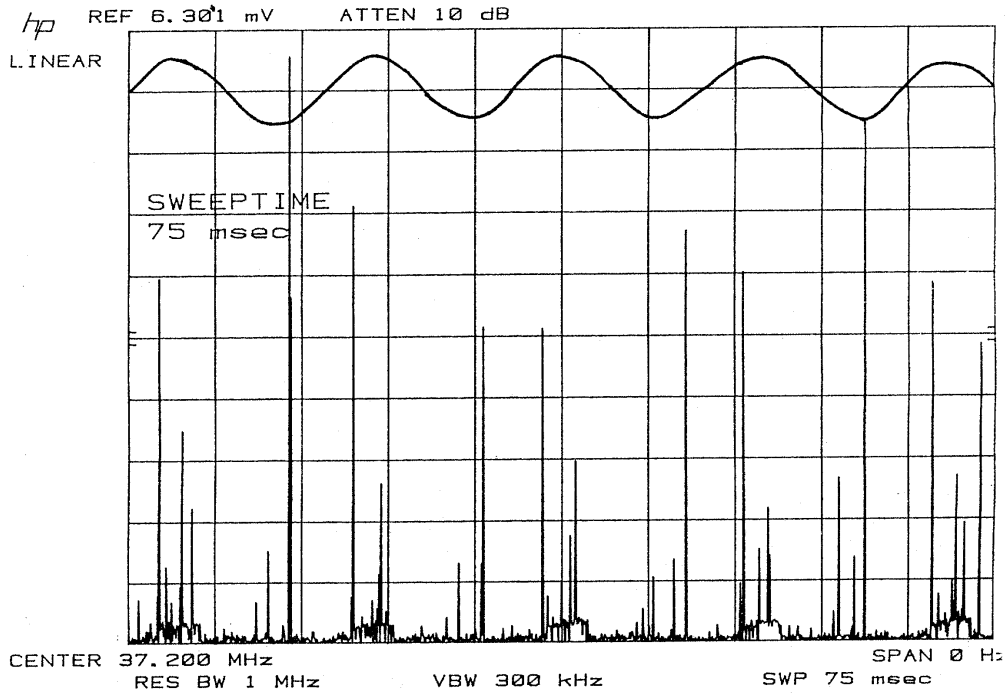


Figure 3-5
Full-screen partial discharge (PD) activity in polybutene. Top left 15 kV (PD onset), top right 19 kV, bottom left 21 kV and bottom right 22 kV (near fluid breakdown).



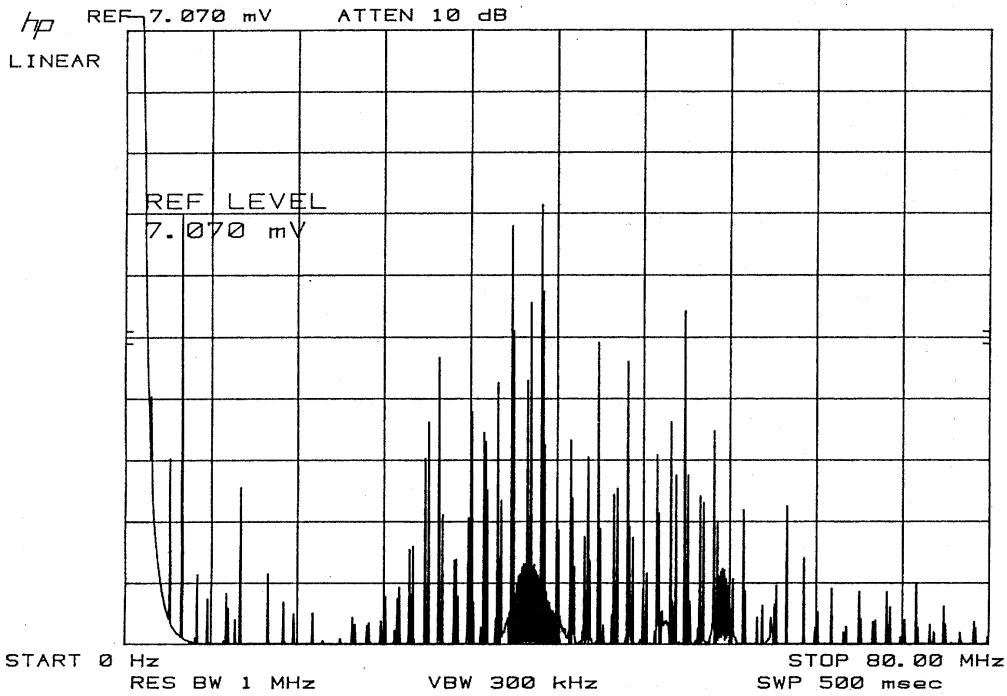


Figure 3-6
Comparison of full-scan and zero-scan for PD activity developed at 22 kV in polybutene fluid

The results of gas generation after application of the PD, corresponding to Figures 3-5 and 3-6, for a polybutene are shown in Table 3-6. The gas concentrations indicated in this table correspond to the gas concentration after the test, corrected by the gas concentration before the test. The number in parenthesis indicates the gases that showed a slight decrease in concentration during the test. The magnitude of the gas concentrations involved was so small that the natural dispersion of the gas analysis can cause these small fluctuations. Gases showing decreasing trends cannot be considered key gases. The concentration of a key gas must show a sustained increase throughout the test. This characteristic was observed for gases such as acetylene, hydrogen and, to some extent, ethylene. Propylene should probably be considered as a key gas, although its increase under low intensity PD is not always observed.

Table 3-6
Gas Evolution from Polybutene After Applied Stresses

	12 kV		14 kV	15 kV		16 kV	18 kV	19 kV	20 kV	22 kV
Gas Conc. (ppm)	**48 (Hours)**	**120 (Hours)**	**48 (Hours)**	**48 (Hours)**	**72 (Hours)**	**48 (Hours)**	**48 (Hours)**	**24 (Hours)**	**48 (Hours)**	**48 (Hours)**
Methane	(0.7)	(0.5)	1.0	(0.1)	0.2	0.0	1.8	(1.6)	4.8	42.9
Ethane	26.9	(0.3)	(5.0)	0.2	(1.6)	(7.6)	0.7	(6.1)	1.3	3.2
Ethylene	0.0	(0.2)	(0.6)	(0.4)	(0.2)	(1.1)	1.2	(0.1)	7.6	54.8
Acetylene	0.3	0.4	0.4	0.8	1.1	0.0	6.8	4.9	71	313
Propane	(0.7)	2.7	(10.0)	(2.4)	(1.1)	(16.8)	0.6	(12.4)	0.0	1.4
Propylene	0.0	0.5	(0.6)	0.2	0.8	(1.1)	0.4	(0.7)	1.0	6.9
Isobutane	0.4	(0.2)	(0.7)	0.3	10.1	(1.3)	1.1	(1.0)	2.0	2.8
n-Butane	(1.2)	(0.2)	(7.3)	(2.7)	(17.2)	(12.6)	3.4	(8.2)	(0.9)	(2.6)
t-2-Butane	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1-Butene	1.3	0.1	(2.6)	(0.1)	(0.0)	(5.1)	0.8	(3.3)	1.6	0.7
Isobutylene	(2.1)	(0.8)	(26.7)	(6.6)	(7.0)	(47.0)	(1.2)	(31.2)	0.3	(3.2)
Hydrogen	0.0	0.0	33.6	47.3	10.2	56.7	13.8	20.1	264.9	992.1
C. Monoxide	11.3	4.0	(11.4)	21.6	4.6	(11.4)	13.5	(11.4)	7.7	16.0
C. Dioxide	253.3	170.1	68.2	9.2	198.0	166.6	268.4	(0.5)	227.9	454.1

In the case of the work performed with polybutene, onset of PD was observed by the appearance of a small amount of acetylene at 12 kV. Hydrogen was not observed at this point, probably due to the fact that our sensitivity to acetylene is more than 100 times than that of hydrogen. At the same time, the onset of PD as measured by the spectrum analyzer was set at about 15 kV in a laboratory environment. This indicates that dissolved gas analysis could have a slightly better detection limit compared to partial discharges. The better sensitivity of dissolved gas analysis derives from the fact that this is an accumulative approach where minute amounts of gases generated accumulate until their concentration reach measurable levels. Partial discharge detection equipment operates on a differential approach, which is based on the detection of very small signals on an actual time basis. In addition, electronic measuring devices face the difficulty to discern the actual signal from the usually noisy backgrounds.

In the case of partial discharges in silicone fluids, the onset of PD was detected at the same stress level by DGA and the spectrum analyzer. This stems from the fact that the yield of acetylene is lower in silicone fluids than in hydrocarbon based fluids, while the yield of hydrogen is considerably larger. Unfortunately, the lack of appropriate hydrogen sensitivity reduces the chances of detecting PD in silicone fluids at a level lower than the spectrum analyzer. However, better chemical instrumentation than was used in this investigation is now available.

A plot of gas concentration as a function of applied stress after 48 hours is shown in Figure 3-7 for the polybutene fluid. In this plot, a clear increase in the concentration of acetylene, hydrogen and ethylene can be observed from PD inception to field stresses approaching fluid breakdown.

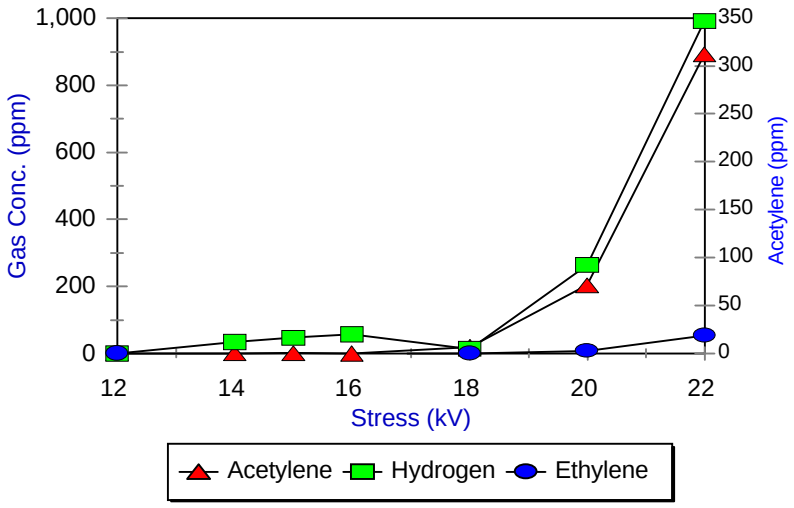


Figure 3-7
Gas evolution in polybutene by partial discharges as a function of electrical stress after 48 hours of exposure

Partial discharge activity applied on a silicone fluid is shown in Figure 3-8. The voltage levels, at which the data represented in this figure were taken, correspond to: top left PD onset at 12 kV; bottom left, intermediate point at 15 kV; and top right 18 kV. A zero-span representation is shown for the measurement at 18 kV in the bottom right plot of the same figure. Three wave cycles are represented in this plot with PD activity appearing near the peak at the negative and positive going cycles.

The results of gas accumulation after exposure of silicone fluid to PD activity described in the previous figures are shown in Table 3-7. Only hydrogen was observed in the case of silicone fluid at the onset of PD. Acetylene was only observed after a more intense field was applied to the test cell, Table 3-7.

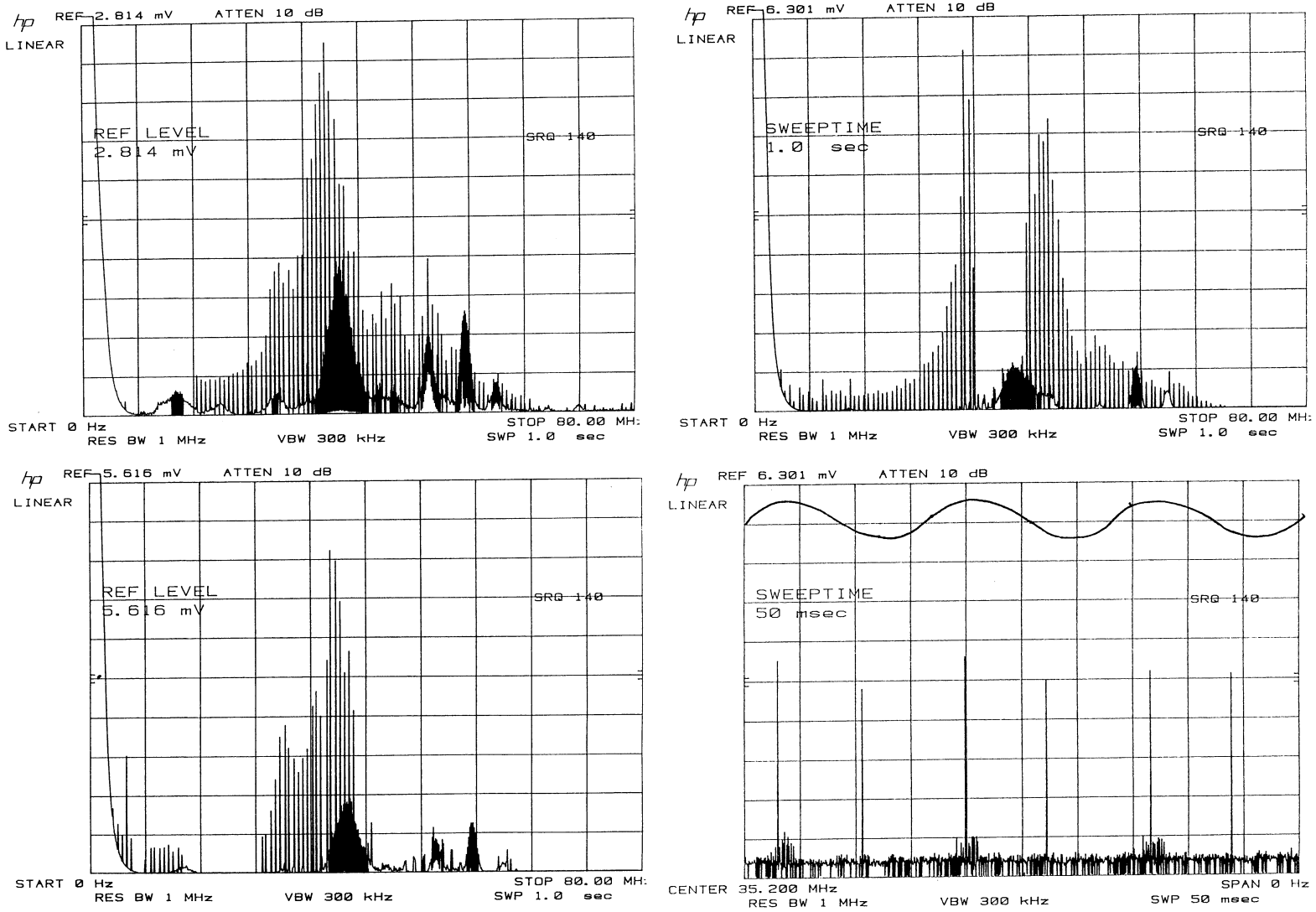


Figure 3-8
Full-scan and zero-scan representation of PD activity in silicone. Top left, 12 kV (PD onset), bottom left 15 kV, top right 18 kV and bottom right zero-scan at 18 kV.

Table 3-7
Gas Evolution for Silicone after Applied Stress

	12 kV	15 kV		18 kV		
Gas Conc. (ppm)	48 (Hours)	96 (Hours)	120 (Hours)	48 (Hours)	72 (Hours)	120 (Hours
Methane	0.0	0.0	0.0	0.0	0.0	0.0
Ethane	0.0	0.0	0.0	0.0	0.0	0.0
Ethylene	0.0	0.0	0.0	0.0	0.0	0.0
Acetylene	0.0	3.2	1.8	0.3	1.2	1.5
Propane	0.0	0.0	0.0	0.0	0.0	0.0
Propylene	0.0	0.0	0.0	0.0	0.0	0.0
Isobutane	0.0	0.0	0.0	0.0	0.0	0.0
n-Butane	0.0	0.0	0.0	0.0	0.0	0.0
t-2-Butane	0.0	0.0	0.0	0.0	0.0	0.0
1-Butene	0.0	0.0	0.0	0.0	0.0	0.0
Isobutylene	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen	34.3	16.3	14.2	53.3	11.5	8.5
C. Monoxide	0.0	0.0	0.0	0.0	0.0	0.0
C. Dioxide	(207)	142	29	(149)	583	110

Acetylene showed an increasing trend both with increasing PD activity, and also with increase of exposure time at constant stress level. Large amounts of hydrogen were always observed at varying levels of electrical stress and time exposure. However, contrary to the direct correlation observed for acetylene and field stress, hydrogen shows a decreasing trend with increasing acetylene concentration. Under PD activity, the highest level of hydrogen was observed at the lowest concentration of acetylene.

Conclusions

- Breakdown of silicone and polybutene fluids generates essentially the same gases, with the exception of carbon oxides and isobutylene. Whereas carbon oxides are related to breakdown of silicone fluids, isobutylene is related to breakdown of polybutene fluids.
- The appearance of large amounts of hydrogen and lesser amounts of acetylene, methane, ethylene and propylene is common to both type of fluids
- The generation of large amounts of hydrogen and acetylene together with lesser amounts of methane, ethylene and propylene were characteristic of breakdown of the two fluids. The yield of these gases was strongly dependent on the intensity and exposure of electrical stress.

- Exposure of a silicone fluid to partial discharges also results in the evolution of large amounts of hydrogen and acetylene. In some experiments, methane, ethylene and propylene were also observed after exposure to partial discharges.
- Although the distribution of gases varies slightly between polybutene based and silicone based fluids, the same key gases (hydrogen, acetylene, ethylene, propylene) can be monitored to assess the condition of extruded cable terminations.
- Due to the high sensitivity by which acetylene can be detected by chemical means, the onset for partial discharge activity in a polybutene fluid can be observed at stresses lower than those through utilization of PD detection equipment.

4
DEVELOPMENT OF FLUID SAMPLING TECHNIQUES AND EQUIPMENT

Unlike high pressure fluid-filled (HPFF) and self-contained fluid-filled (SCFF) terminations, extruded cable terminations contain medium to high viscosity fluids, silicone or polybutene. Moreover, there is hardly any hydrostatic pressure. Accordingly, such terminations cannot be sampled directly. The head pressure of this relatively thick fluid does not allow sample collection by typical devices such as syringes or steel cylinders, particularly at 69 kV-138 kV levels. However, this situation can be overcome by means of a micro pressurization system. This pump would suck the fluid out of the terminations and force the fluid into the collection vessel. It should be noted that the amount of available fluid in extruded terminations is relatively limited, ranging from about 2 gallons to 15 gallons. This renders the application of the ASTM 3612 DGA method with its typical 100 cc syringe impractical.

The EDOSS (EPRI Disposable Oil Sampling System) method that requires an exceedingly small quantity (5 cc) of fluid offers the most viable solution. Coupled with a narrow flexible plastic tube (1/8 in. to 3/8 in.OD) and a micro pressurization pump, the EDOSS method can be well adapted for the sampling of extruded cables.

After a careful review of available micro pumps, a reciprocating valveless pump (Model QC 210, Fluid Metering Inc., Oyster Bay, New York) was selected and tested both in the laboratory and field, Figure 4-1. The delivery flow rate of the pump can be adjusted from 0 to 100%. The direction of the fluid flow can also be reversed. This self-priming pump can generate sufficient vacuum at the inlet port to siphon fluid exceeding 10 feet below the pump inlet. The only difficulty encountered with this pump was the speed of the piston stroke. Although the length of the piston stroke can be adjusted to modify the delivery flow rate, the reciprocating speed of the piston is fixed. When pumping high viscosity fluids (3000 SUS or more) with a fast moving piston, a very high pressure was generated at the piston head, even at the lowest delivery setting. The rapid pressure build-up on the piston caused the motor belt drive to slip. This problem was overcome by modifying the diameter of the pulleys. The adequate motor pulley to pump pulley diameter ratio was found to be 2.9 to 1.0. The operation of this pump is illustrated in Figure 4-1.

This approach is also very useful for SCFF (self-contained fluid-filled) cables operating at low pressures (7 – 10 psi). All the DGA work, involving point-plane geometry and various types of terminations in the laboratory and field, was conducted by the EDOSS approach in conjunction with the micro pressurization pump and flexible tubing.

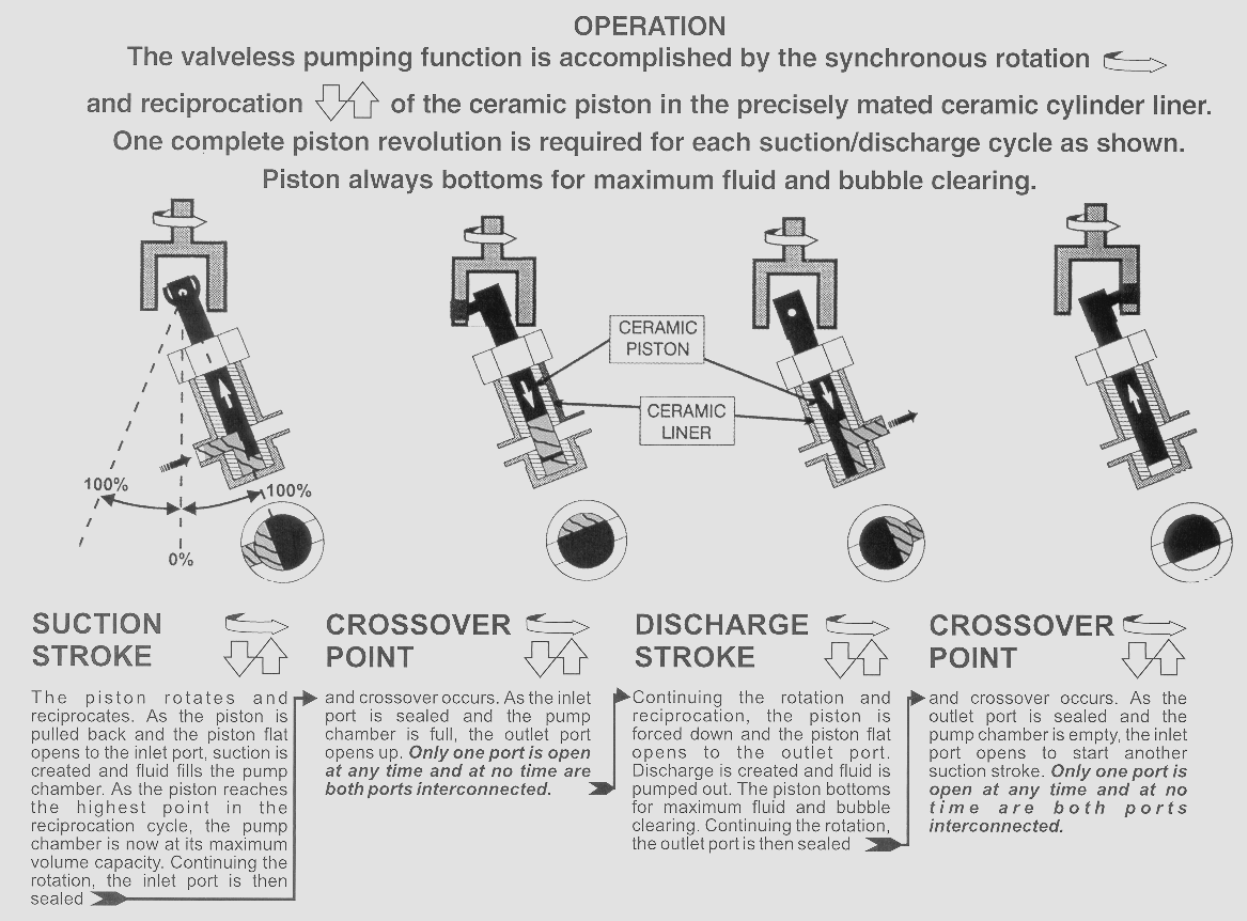


Figure 4-1
Reciprocating valveless positive displacement pump with variable flow delivery

The setup for DGA sampling by the EDOSS method together with the plastic tubing (1/4 in. OD), inserted from the top port of an extruded termination and the micro pressurization pump, is shown in Figure 4-2. While one end of this tubing is carefully inserted into the termination housing (or connected to the bottom valve), the other end is connected to the intake side of the pump. The EDOSS system is connected to the outlet side of the pump, as shown in Figure 4-2.

Since the flow direction in this pump is reversible, both inlet and outlet ports are interchangeable. The free end of the 1/4 " OD flexible tubing should be gently inserted as far as possible between the cable insulation and the internal spacers or between the spacers and the inside wall of the ceramic housing for the case of a Joslyn termination. In some cases, it was possible to reach the top end of the stress cone for the Joslyn design. Compared to the Joslyn design, Kabeldon and Alcatel designs have enough space for the insertion of the flexible tubing.

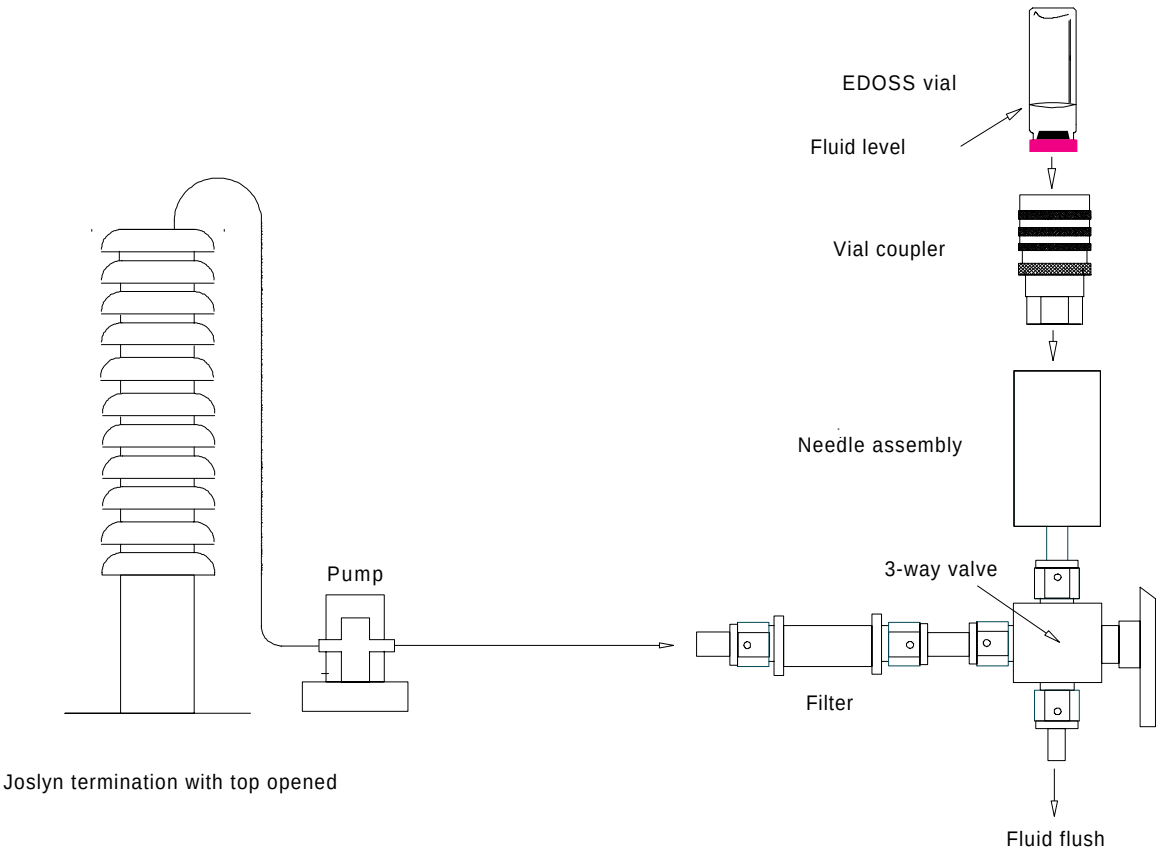


Figure 4-2
Sampling fluid from a Joslyn extruded cable termination with EDOSS

Once the plastic tubing is installed, the fluid can be brought to the pump by the suction of the piston and then forced through the hollow needle into the EDOSS vial. After the necessary samples are taken, the pump flow can be reversed and the excess fluid pushed back into the termination, thus conserving the limited amount of termination fluid. It is noteworthy that the low sample volume requirement (5 cc) together with the ability to place the unused fluid back into the termination makes the EDOSS system the only available option to sample extruded cable terminations, which inherently contain a small volume of dielectric fluid.

Conclusions

A fluid sampling system appropriate for extruded cable terminations that can spare only a small amount of fluid has been developed and successfully applied both in the laboratory and field. It is based on the EDOSS method and utilizes a reversible flow micro pressurization pump and flexible plastic tubing (1/8 in. to 3/8 in. OD). This arrangement can sample the termination filling fluid from both the top and/or bottom ports. The unused fluid can be placed back into the termination through the reverse flow action of the pump.

5
DGA DATA ON EXTRUDED CABLE TERMINATIONS

Field Sampling

Samples from five 138 kV Joslyn terminations from an in-service circuit were taken for dissolved gas analysis. The results are shown in Table 5-1. While three terminations were sampled at the south end of the cable, only two could be sampled from the north end since the third one had recently failed. One end of a ¼ in. OD plastic tubing was kept free while the other end was connected to the EDOSS sampling system through the micro pump, as discussed in Chapter 4. The entire sampling system was brought close to the terminations with a boom truck. After removing the aerial connections, the top flange was removed from the termination. The free end of the ¼" OD tubing was then pushed down the gap between the cable insulation and the spacers. The width of the fluid gap between the cable, spacers and housing varied slightly but it was relatively easy to slide the tube a few feet down the termination. The tube can be flattened slightly, if needed, to facilitate the passage to reach further down toward the stress cone region. Gas concentration does not seem to vary significantly along the length of the termination, however, it is advisable to reach as close to the stress cone as possible. One person performed this relatively simple sampling operation.

The data shown in this table indicates that, besides oxygen and nitrogen, the major components are methane, propane, iso- and n-butane, isobutylene and carbon dioxide. Except for isobutylene, very small amounts of other unsaturated gases (ethylene and propylene) were observed in all these terminations. The absence of acetylene and the presence of a trace of hydrogen, ethylene and propylene indicate that these terminations have not experienced any unusual electrical activity and are operating satisfactorily.

Saturated hydrocarbons (methane, ethane, propane and butanes) and isobutylene (unsaturated) are largely attributed to the solid insulation. This has been demonstrated by headspace analysis of pieces of cable insulation that was heated in a sealed vial to identify and quantify the evolved gases. The presence of a large number of chemicals are associated with peroxide crosslinking reactions, antioxidants and processing agents. The results of this analysis are shown in Tables 5-2 and 5-3. The major permanent gases found in the insulation are methane, isobutane, n-butane and isobutylene. It should be pointed out that the relatively new and unused (cable (dry cure, 1992) had significantly less methane than the old and used cable (steam cure, 1973), but a comparable amount of butanes.

The results in Table 5-1 show a large amount of methane in termination Phase B (South end) and extremely limited in the corresponding termination (North end). This is also true for both terminations at Phase C. It is hard to explain this large difference for the relatively short cable (0.4 miles). This may be due to the fact that methane has escaped from the insulation and the

initial amount of methane may vary along length of the cable, depending on cable processing and materials. After manufacturing, the cable is often degassed to reduce volatile products resulting from the chemical crosslinking process. It can, therefore, be concluded that extruded cable termination fluids are bound to indicate a variable amount of methane and large concentrations of butanes and isobutylene.

Table 5-1
Field DGA Data for a 138 kV Extruded Cable Termination by EDOSS

	South Termination			North Termination	
Gases	**Phase A**	**Phase B**	**Phase C**	**Phase B**	**Phase C**
Methane	11,737	219,309	12,617	223	372
Ethane	36	23	37	27	40
Ethylene	3.3	5.3	3.6	5.2	4.0
Acetylene	0	0	0	0	0
Propane	211	137	227	158	238
Propylene	7	6	8	5	10
Isobutane	1,283	768	1,301	884	1,345
n-Butane	864	544	951	763	1,017
t-2-Butene	24	11	23	14	26
1-Butene	236	115	232	165	241
Isobutylene	2,275	844	1,534	1,142	1,518
Hydrogen	13	18	17	32	25
C. Monoxide	405	209	232	342	686
C. Dioxide	7,546	11,709	8,646	4,837	6,609
Oxygen	13,054	13,736	14,549	69,617	17,533
Nitrogen	106,824	162,206	105,649	969,300	186,879

Table 5-2
Semiquantitative Analysis of Vapors Contained in a sample of New XLPE

Component	Amount
Methylene chloride	Large
Hexene/Butenes	Low
Hexene, hexane, pentane	Low
1,1,1 trichloro ethane	Large
Cyclohexane	Very large
1,1,2 trichloroethane	Low
Methyl cyclohexane	Low
Toluene	Low
Octane	Low
Alpha methyl styrene	Large
Acetophenone (characteristic odor)	Low
Methyl styrene	Very low
Other hydrocarbons of higher molecular weight	Very large

Table 5-3
Quantitative Analysis of Gases in XLPE Cable Insulation

	Cable #1 (New)		Cable #2 (Used)	
Gas	**Concentration (ppm per g of insulation)**	**Volume Percent**	**Concentration (ppm per g of insulation)**	**Volume Percent**
Methane	0.52	2.60	1.37	18.97
Ethane	0.39	1.95	0.12	1.65
Ethylene	0.05	0.24	0.13	1.74
Propane	0.41	2.05	0.09	1.23
Propylene	0.02	0.09	0.08	1.11
Isobutane	3.24	16.22	2.33	32.28
n-Butane-	1.31	6.55	0.75	10.38
Isobutylene	14.05	70.30	2.36	32.65
Total	19.99	100	7.23	100.00

It should be noted that unsaturated hydrocarbons such as ethylene, propylene and acetylene together with hydrogen, are the key diagnostic gases for extruded cable terminations and they will not evolve from the cable insulation.

DGA Data on Extruded Cable Terminations after Laboratory Load Cycle Test

A set of two 138 kV Joslyn terminations were sampled after a 30-day load cycling test at 133 kV, which is about 1.7 the rated voltage for the terminations. The daily thermal cycle consisted of 12 hours of heating the conductor to 100°C, followed by 12 hours cooling to room temperature. Impulse withstand test of about 600 kV was performed at the end of load cycling test. The terminations were sampled at the end of the impulse test.

The DGA results for the fluid and the termination headpace analysis are given in Table 5-4. In addition to sampling the termination fluid, as soon as the termination flange was slightly opened, a sample of the headspace was taken with a glass syringe and a long needle. The results from the headspace sample are shown on the first column of Table 5-4.

Table 5-4
Laboratory DGA Data for a 138 kV Extruded Cable Termination at Various Locations Within the Termination after Load Cycling Test. Sampling points according to Figure 5-1

	North Termination					South Termination	
Gases (ppm)	Headspace	Fluid Surface	Inner-Bottom	Outer-Bottom	Inner-Middle	Inner-Middle	Outer-Middle
Methane	9,867	13,470	12,118	8,112	15,593	9,874	10,284
Ethane	173	901	814	568	931	690	746
Ethylene	2	6	6	7	7	7	5
Acetylene	0	0	0	0	0	0	0
Propane	21	316	295	216	325	261	279
Propylene	1	20	18	15	20	16	17
Isobutane	16	443	428	327	458	383	406
n-Butane	12	482	481	342	506	385	404
t-2-Butylene	0	20	22	11	21	0	22
1-Butene	7	251	249	166	264	166	156
Isobutylene	55	1,938	1,897	1,371	2,023	2,110	2,295
Hydrogen	206	8	24	25	45	10	12
C. Monoxide	1,563	154	180	160	259	250	290
C. Dioxide	3,616	5,228	6,377	3,089	4,726	2,580	2,513

The filling fluid was sampled at different locations along the length of the terminations, as indicated in Figure 5-1. No differences in gas distribution were observed as the location of the sampling was varied. The concentrations of hydrogen and carbon monoxide are higher in the gas phase than the fluid phase due to their low solubility. The opposite situation holds or all other gases, which have higher solubilities.

The gas distribution obtained from the filling fluid removed from these terminations suggests that the load-cycled terminations are operating satisfactorily. Acetylene was not detected at all and the levels of ethylene and propylene are low, with the exception of isobutylene, which is likely to have originated from the cable insulation, as mentioned earlier. Hydrogen concentration is low in all samples, indicating a relatively low ionization activity.

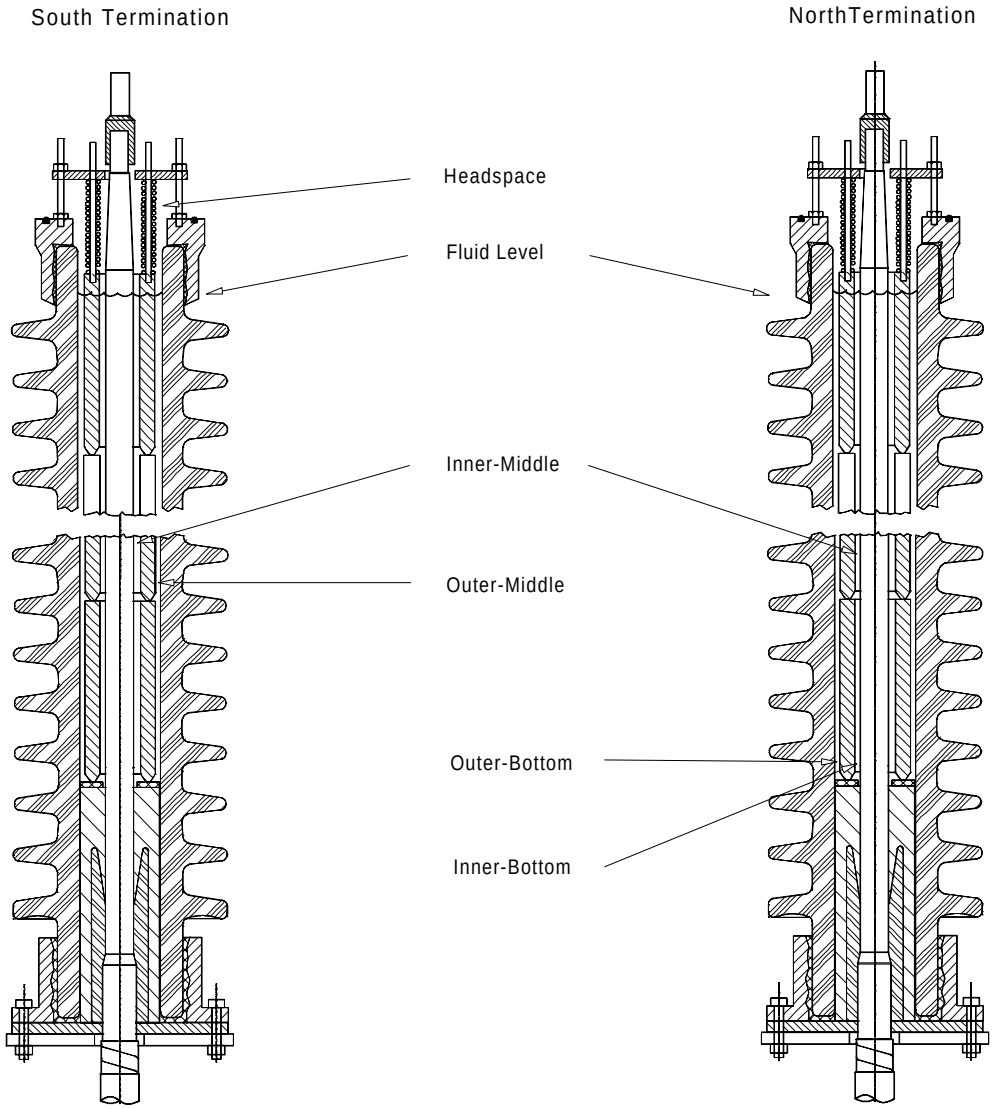


Figure 5-1
Sampling locations for a Joslyn 138 kV extruded cable termination by EDOSS

The concentration of all gases in the headspace is in equilibrium with their counterparts in the fluid. Accordingly, the measurement of headspace gas concentrations might be sufficient for condition assessment. Furthermore, hydrogen and carbon monoxide, which are key diagnostic gases, concentrate in the headspace, making possible their detection at much lower concentrations in the fluid. It is difficult to measure low concentrations of hydrogen (below 20 ppm) and the ability to determine large amounts of hydrogen in the headspace offers an easier alternative. It should be added that the transformer industry, which has been relying on DGA of oil for decades, is now recognizing the importance of headspace gases in nitrogen-blanketed transformers. It is evident that headspace measurements are exceedingly simpler than their liquid counterpart. Moreover, headspace analysis in the field can be more accurately performed in the field compared to the corresponding analysis in the liquid phase, all the more with newly available portable gas chromatographs.

Headspace analysis of extruded cable terminations, which are being increasingly installed at 69 to 220 kV levels in the U.S., should be pursued as a follow-on project. This will also offer a ready opportunity to augment the DGA databank on extruded cable terminations, which is presently limited.

DGA Sampling of 138 kV Terminations at G&W Facility

DGA samples were taken from one 138 kV G&W termination, and the results are given in Table 5-5. This termination was understood to have undergone extensive load-cycling tests. The G&W design does not have a headspace, as discussed in Chapter 1. The sample was taken from the available valve at the bottom of the termination. A high viscosity polybutene is always used in G&W terminations. The gas distribution in Table 5-5 shows the presence of ethylene, propylene, hydrogen but no acetylene. The concentration of methane is lower than that found in other terminations, and this is attributed to the cable insulation. The absence of acetylene suggests the lack any unusual ionization activity. The higher concentration of hydrogen is probably the result of several factors such as differing test conditions, electrical activity and termination design.

Sampling of 138 kV Alcatel Terminations Undergoing Test at Ontario-Hydro Laboratory

Fluid samples were taken from two 138 kV Alcatel terminations undergoing long term testing at Ontario-Hydro Laboratories. The DGA results are shown in Table 5-6. A relatively large concentration of methane is observed in the fluid samples. The samples show small amounts of ethylene, propylene and hydrogen but no acetylene. Again, the gas distribution in this termination indicates low level ionization with no unusual electrical stresses.

Table 5-5
DGA Results on Samples taken from a G&W 138 kV Extruded Cable Termination after Test by the Manufacturer, Chicago, April 1995

Gases/Location	Sample #1	Sample #2	Average
Methane	659	667	663
Ethane	27.4	26.9	27
Ethylene	5.3	5.0	5.1
Acetylene	0.0	0.0	0.0
Propane	13.6	12.9	13
Propylene	10.3	9.8	10
Isobutane	24.2	24.0	24
n-Butane	18.4	18.5	18
t 2-Butylene	6.5	4.7	5.6
1-Butene	8.2	9.2	8.7
Isobutylene	387	387	387
Hydrogen	226	224	225
Carbon Monoxide	427	459	443
Carbon Dioxide	2,298	2,610	2,454
Oxygen	0	31,212	
Nitrogen	55,864	169,617	

Table 5-6
DGA Results onSamples taken from 138 kV Alcatel Extruded Cable Terminations under Test at Ontario Hydro, May 1995

	138 kV Alcatel	
Sample	North	South
Methane	2,088	3,840
Ethane	20	30
Ethylene	2.0	2.8
Acetylene	0.0	0.0
Propane	8.3	10
Propylene	2.1	2
Isobutane	15	21
n-Butane	24	26
t-2-Butylene	2.2	2.5
1-Butylene	51	57
Isobutylene	151	187
Hydrogen	56	60
C. Monoxide	24	38
C. Dioxide	278	276
Oxygen	59,618	59,754
Nitrogen	112,324	113,985

DGA of 345 kV Extruded Cable Terminations Undergoing Long -Term Testing at Hydro-Quebec Laboratories

Four fluid samples in glass syringes were received from Hydro Quebec for DGA by Detroit Edison for analysis. The first two samples were taken on June 3, 1996, followed by two taken on September 23, 1996. The DGA results are shown in Table 5-7. The fluid samples taken on June 3, indicate that the associated terminations are operating satisfactorily because of the absence of acetylene and low concentration of the other key gases.

The two samples taken on September 23, 1996 show a exceedingly large concentration of ethylene and the presence of acetylene. This indicates serious problem with the termination, involving arcing in the fluid and probably tracking over the stress cone components.

No hydrogen was detected due to the fact that the samples were taken in glass syringes, and there was an appreciable interval of time before the samples were received and analyzed at Detroit Edison.

Table 5-7
DGA on 345 kV Extruded Cable Terminations Undergoing Qualification Tests at Hydro-Quebec Laboratories

345 kV Extruded cable Terminations				
Sample	**Outdoor #2 (June 1996)**	**SF_6 (June 1996)**	**#1 (Sep. 1996)**	**#4 (Sep. 1996)**
Methane	**1,873**	6,498	**9,633**	**9,690**
Ethane	**21**	66	**35**	**34**
Ethylene	**1.1**	2.9	**914**	**934**
Acetylene	**0.0**	0.0	**3.9**	**1.5**
Propane	**4.4**	12	**7.6**	**7.9**
Propylene	**1.1**	2.1	**2.0**	**1.8**
Isobutane	**6.7**	20	**3.7**	**5.8**
n-Butane	**7.6**	19	**5.4**	**6.0**
t-2-Butylene	**0.0**	0.0	**0.0**	**0.5**
1-Butylene	**2.5**	6.5	**7.1**	**7.1**
Isobutylene	**35**	105	**78**	**81**
Hydrogen	**134**	88	**0**	**0**
C. Monoxide	**19**	57	**23**	**10**
C. Dioxide	**144**	513	**280**	**369**
Oxygen	**5,452**	38,796	**34,452**	**35,462**
Nitrogen	**60,286**	421,939	**94,759**	**237,893**

DGA of 138 kV Extruded Cable Splice Undergoing Test at Joslyn

This splice design basically represents two 138 kV connected extruded cable terminations. A series of samples were taken from this 138 kV test splice at the end of load cycling tests at Joslyn. The results of these samples are shown in Table 5-8. The results from these samples show small amounts of hydrogen but complete lack of unsaturated hydrocarbons (acetylene, ethylene and propylene). This situation indicates the lack of unusual electrical stresses in the termination, which is in agreement with the very low level of PD activity observed by Joslyn.

Table 5-8
DGA on a 138 kV Extruded Cable Splice at the End of Load Cycling Test at Joslyn Laboratories, January 1998

138 kV Extruded Cable Splice Test			
Samples	**#1**	#2	**#3**
Methane	**625**	726	**939**
Ethane	**3.8**	6.3	**5.3**
Ethylene	**0.0**	0.0	**0.0**
Acetylene	**0.0**	0.0	**0.0**
Propane	**5.6**	3.5	**7.8**
Propylene	**0.0**	0.0	**0.0**
Isobutane	**1.1**	3.3	**4.6**
n-Butane	**1.4**	0.0	**4.2**
t-2-Butylene	**0.0**	0.0	**0.0**
1-Butylene	**0.0**	0.0	**3.1**
Isobutylene	**16**	23	**23**
Hydrogen	**87**	82	**81**
C. Monoxide	**129**	142	**158**
C. Dioxide	**755**	715	**744**
Nitrogen	**106,900**	106,300	**106,900**

Conclusions

Based on several terminations of different designs tested for DGA and headspace gas analysis, the following conclusions are made for Chapter 5.

- Dissolved gas analysis holds potential for condition assessment of extruded cable terminations. This method offers an easy-to-apply and inexpensive tool toward this end.
- Relatively large amounts of methane and butanes originate from the cable insulation. These gases result from cable manufacturing processes, primarily chemical crosslinking and heat treatment commonly employed to reduce volatile compounds.
- Essentially the same key gases, namely, acetylene, hydrogen, ethylene and propylene, are generated from silicone and polybutene fluids when exposed to electrical stresses. It should

be stressed that these gases, particularly acetylene and hydrogen, do not at all evolve from the cable insulation. The contribution of the remaining key gases (ethylene and propylene) from the cable insulation is too minute to affect the overall results in any way.

- The increase in the yield of hydrogen and unsaturated hydrocarbons such as ethylene, propylene and acetylene is indicative of ionization activity. The presence of acetylene shows severe ionization activity involving arcing in the free filling fluid or at the high stress interfaces and/or tracking in the stress cone region. The relationship of acetylene to arcing in fluids employed in HPFF and SCFF cables has been observed and well documented in several EPRI reports involving both laboratory and field data.
- It is possible that in terminations with an air-blanket (headspace), samples of the headspace might be sufficient to detect the presence of abnormal electrical activity. However, further fieldwork is required to properly demonstrate the viability of the headspace measurement approach, which is inherently simple to apply in the field. Likewise, additional fieldwork on fluid DGA is required to realize its promise for extruded cable termination condition assessment.

6

CONDITION ASSESSMENT OF 138 KV EXTRUDED CABLE TERMINATIONS UNDER TEST AT NEETRAC THROUGH DISSOLVED-GAS ANALYSIS

Approach

Fluid sampling and analysis by the EDOSS method was performed to determine the condition of six extruded 138 kV terminations under test at NEETRAC, Atlanta, Georgia. This method was preferred over the previous EPOSS method because it requires a very small amount (5 cc to 6 cc) of the dielectric fluid and can handle high viscosity fluid samples with the help of a micro pump, Chapter 4. Thus, it is appropriate for extruded cable terminations that can spare only a limited volume of their dielectric fluids, unlike pipe-type cable terminations. Considering high fluid viscosity and low fluid volumes involved in extruded cable terminations, EDOSS appears as the only viable option to perform extruded termination DGA, as discussed in Chapter 4.

The basic principle of DGA lies in the fact that certain hydrocarbon gases along with hydrogen and carbon oxides are generated from dielectric fluids that are exposed to electrical and thermal stresses in fluid-filled equipment under normal and not-so-normal operating conditions. Depending on the specific condition, the type, concentration and distribution of such gases varies and this provides clues to the specific condition faced by the equipment. The latter conditions are caused by many factors such as departure from the intended electric field, quality of assembly, material asperities, and any abnormal electric stresses encountered by the terminations.

Results and Discussion

Sampling was done for both the filling fluid and headspace of the terminations. While the fluid was sampled for all the six terminations (two each of Joslyn, G&W and Kabeldon terminations), gas samples from the headspace were taken only for four terminations, two each from Joslyn and Kabeldon. The absence of headspace in the G&W termination design (Chapter 1) ruled out headspace sampling.

The results from headspace gas analysis of Kabeldon and Joslyn terminations together with DGA results of fluid samples taken from all terminations at the NEETRAC testing facilities are presented in Tables 6-1 and 6-2, respectively. The terminations were installed in three separate circuits, namely, 1, 2 and 3 at the North and South ends on a short cable run.

Extremely small gas concentrations and absence of hydrogen characterized the headspace samples, Table 6-1. A trace of acetylene was observed in the headspace of one of the Kabeldon terminations, Circuit #1, North end. This indicates that the partial discharge activity in Kabeldon termination of Circuit #1 is stronger than that in the other Kabeldon termination. Although hydrogen was observed in most fluid samples, it was not observed in the headspace. Based on the level of hydrogen observed in the fluid, still much larger concentration of hydrogen is expected in the headspace. Apparently, hydrogen was lost before it was analyzed.

Table 6-1
Gas Composition in the Terminations Headspace

Termination	Kabeldon		Joslyn	
Gas (ppm)/ Location	#1 North	#2 North	#3 North	#2 South
Methane (ppm)	3.2	92.3	13.7	16.5
Ethane	0.06	0.74	0.15	0.57
Ethylene	0.08	0.74	0.09	0.40
Acetylene	0.06	0.00	0.00	0.00
Propane	0.10	0.73	0.10	0.60
Propylene	0.04	0.20	0.04	0.35
Isobutane	0.29	1.67	0.26	0.92
n-butane	0.09	0.17	0.10	0.92
Isobutylene	8.64	49.3	0.20	0.99

Low hydrogen, low ethylene and complete absence of acetylene characterized the dissolved gas distribution of fluid samples taken from these terminations. This gas distribution suggests that there is very minute level of partial discharge activity. The level of hydrogen in the fluid samples and the presence of any acetylene in the headspace can assess the intensity of partial discharge activity. Such a level indicates that, with the exception of termination #2 at the South end stand (Joslyn), all other terminations show some degree of partial discharge activity, either already occurred or taking place.

On the basis of hydrogen concentration, terminations showing the highest level of partial discharge activity were in circuits #1 and #3 at the South end (both G&W), followed by terminations in circuits # 1 and #2 a the North end (Kabeldon). A summary of results is shown in Table 6-3.

Table 6-2
DGA Results for Test Terminations

Termination	G&W		Joslyn		Kabeldon	
Filling Fluid	Polybutene		Silicone		High Vis. Polybutene	
Gas (ppm)/ Location	#1 South	#3 South	#2 South	#3 North	#1 North	#2 North
Methane	27	26	423	1274	99	396
Ethane	22	8.4	20	21	19	22
Ethylene	7.1	6.0	3.8	3.0	2.8	3.0
Acetylene	0.0	0.0	0.0	0.0	0.0	0.0
Propane	3.6	2.8	17	19	51	55
Propylene	14	9.8	5.6	6.4	15	16
Isobutane	2.9	1.8	228	256	162	163
n-butane	3.5	4.1	62	65	16	17
t-2-butene	0.0	0.0	0.0	0.0	0.0	0.0
1-butene	2.1	1.8	23	23	3.6	3.3
Isobutylene	20	18	173	160	7,309	7,549
Hydrogen	216	189	Nd	16	64	87
C. Monoxide	600	546	102	55	63	114
C. Dioxide	3,166	3,519	9,400	5,070	1,486	1,329
Oxygen	207,852	212,980	45,719	161,655	5,187	3,585
Nitrogen	2,350,346	2,393,530	603,330	2,195,194	55,006	61,357

Table 6-3
Summary of PD Activity

Termination	Description	Liquid Phase H_2 (ppm)	Headspace C_2H_2 (ppm)	PD Activity
#1 South	G&W	216	0.00	Low
#2 South	Joslyn	Nd	0.00	No PD
#3 South	G&W	189	0.00	Low
#1 North	Kabeldon	64	0.06	Higher than counterpart
#2 North	Kabeldon	87	0.00	Low
#3 North	Joslyn	16	0.00	Low

The work performed in Chapter 3 has indicated that a higher yield of acetylene is observed in hydrocarbon-based fluids compared to silicone fluids under arcing conditions. However, the discharge activity prevalent in the NEETRAC testing is too low to reflect this observation. Methane is commonly found in chemically crosslinked polyethylene insulation. Varying amounts of methane are lost from the cable during thermal treatment and storage, as discussed in Chapter 5. It was reported in Chapter 5 that the concentration of methane can also vary along the length of the same cable (Table 5-1). In addition, termination materials may also contribute the generation of methane. All these factors explain the different concentrations of methane observed in the six terminations at NEETRAC. It should be stressed that methane is not a key gas to monitor the condition of extruded transmission cable terminations as mentioned in chapters 3 and 5. Further work is needed to understand the contribution of the cable insulation and termination materials to the evolution of methane.

According to the DGA results, the level of PD in these terminations is small. It should be pointed out, that DGA relies on accumulation of gases formed by PD activity and/or thermal activity. If the PD activity is weak or the exposure time short, the accumulation of gases will be slow and limited. The terminations being assessed have only been exposed to rated voltage for short periods of time, and without load. Furthermore, the lack of load in the circuit limits the temperature raise and reduces the degree of fluid convection only to that brought about by external solar heating of the porcelain housing. These operating conditions are deemed insufficient to simulate long-term gas accumulations and mixing that would occur in in-service terminations, and hence the unexpectedly low level of gases observed at all NEETRAC terminations.

Comparison of PD intensity among different terminations was not intended, the focus was to differentiate between the two terminations supplied by the same manufacturer. It is felt that the minute differences in hydrogen concentration observed amongst the different sets of terminations could be more influenced by differences in termination design than the intensity of PD activity. For example, a very low concentration of hydrogen was observed in the one Joslyn termination compared to Kabeldon or G&W, while the highest concentration of hydrogen was observed in G&W terminations. This is attributed to the absence of headspace in the G&W.

In the Joslyn design, the stress cone is placed under large solid spacers, Chapter 1. Accordingly, to take a proper fluid sample one has to access the fluid closer to the bottom of the termination utilizing a narrow tubing pushed through the clearance between the porcelain housing and the spacers. Lack of a suitable tube prevented accessing the fluid at the bottom of the termination and the fluid sample was taken from the top section of the termination. This could explain the lower concentration of hydrogen observed for the Joslyn terminations.

Unlike the Joslyn design, the stress cone area in the G&W design is surrounded by fluid that can be readily sampled from a valve at the bottom of the termination. In the Kabeldon design, the fluid close to the stressed regions can be sampled by means of a long tube inserted into the termination.

Conclusions and Recommendations based on NEETRAC Testing

The generally low concentration of hydrogen and other gases is attributed to low level PD activity coupled with short exposure-times and lack of load. Dissolved gas analysis is an integrating technique that requires accumulation of gases over a certain period of time while the PD activity is taking place or has occurred. It should be stressed that in the DGA technique the time element to allow accumulation and mixing is not any less important than the level of PD activity. Moreover, in extruded cable terminations, the gases have to find their way out of the stress cone region. Cable load cycling facilitates gas movement and mixing due temperature induced fluid convection

The prevailing PD activity in any of the test terminations was not sufficient to result in the accumulation of acetylene in the liquid phase. Based on DGA results, the following conclusions are made:

- Of all the six terminations, only one termination (Joslyn Circuit 2 , South end) is free of PD activity
- The North end Kabeldon termination in Circuit #1 shows more PD activity than its companion
- The South end G&W termination in Circuit #1 shows more activity than its companion
- While there is a differing degree of PD activity among the six terminations, it is not sufficient to impair their operation

The amount of gas observed in these terminations is very low. Only a minute amount of acetylene was observed in one of the terminations. Low hydrogen content in the fluid samples was observed in all but one case (Joslyn, Circuit #2, South end) where the concentration of hydrogen was below detection limit. If these results had been obtained from terminations of in-service cable systems, it would have been concluded that the terminations were in good order and that no signs of unusual stresses are present. It is recommended that terminations with such gas patterns should be sampled every three to four years.

If the observed acetylene level is between 1 ppm and 3 ppm, the termination should be re-sampled monthly to establish the concentration trend. In case of steady increase, the termination should be opened and examined. However, an extruded cable termination with acetylene over 3 ppm should be taken out of service and inspected.

7
GUIDELINES FOR SAMPLING AND DGA INTERPRETATION OF EXTRUDED CABLE TERMINATIONS

Extruded cable terminations should be sampled for DGA on a regular basis. Utility industry experience shows that most of extruded cable termination failures occur within the first few years of operation. Poor workmanship during the installation is considered to be the most common cause of the early failures; material defects are almost rare. If a termination is experiencing any problems, it will lead to the generation of key gases that could serve as an early warning of a pending failure.

Based on the work performed during this project, the following guidelines are proposed for DGA sampling and DGA interpretation for extruded cable terminations:

New Terminations:

1. Establish the baseline data soon after energization, within days
2. Sample 6 months after being placed in service
3. Sample 18 months after being placed in service
4. Sample 36 months after being placed in service
5. Sample every 3 years

Old Terminations:

1. Create baseline data and follow with sampling every 3 years

The suggested guidelines for the interpretation of extruded cable DGA are given in Table 7-1. This table is based on four key gases and one ratio.

Hydrogen, which is generated by electrical stress in silicone and polybutene fluids, can exist at relatively high concentrations in the absence of acetylene and ethylene. Ethylene and propylene can be generated before acetylene is observed. However, due to the effects of gas solubility, hydrogen concentration in the fluid is generally low in terminations with an air-blanket on the top of the termination fluid. Because of its low solubility, hydrogen escapes to the headspace. All other key gases have higher solubility than hydrogen and will remain dissolved in the filling fluid. Consequently, hydrogen can be more easily lost when removing the top termination flange than any of the other gases. For this reason, hydrogen has been placed lower in the list of key gases and more importance has been attached to acetylene, ethylene and ethylene/ethane ratio.

Accordingly, a termination can encounter problems even at low hydrogen concentrations, provided that acetylene is present.

Table 7-1
Suggested Guidelines for Extruded Termination DGA Interpretation

Gases Observed	Range	Condition	Action
Acetylene Ethylene Ethylene/Ethane Hydrogen Propylene	0 < 20 < 0.5 < 300 < 20	OK	Resample according to schedule above
Acetylene Ethylene Ethylene/Ethane Hydrogen Propylene	1 – 3 > 50 > 1 > 500 > 50	Abnormal electrical stresses	Resample in 1 month and check if gas levels increase
Acetylene Ethylene Ethylene/Ethane Hydrogen Propylene	> 3 > 50 > 1 > 500 > 50	Abnormal electrical stresses	Termination should be checked for internal damage

The key gases have been listed in order of importance. This means that is sufficient for one or more of the top gases to surpass the limit to call for an abnormal condition. It should be emphasized that additional fieldwork should be done to further refine the guidelines.

8
OVERALL CONCLUSIONS AND RECOMMENDATIONS

Based on the work performed during this project, the following conclusions and recommendations are made:

- The filling fluid utilized in most extruded transmission cable terminations can be sampled, whether or not there is a sampling bottom port. While G&W and Alcatel designs always incorporate bottom ports, Joslyn and Kabeldon designs do not provide a sampling bottom port. The Joslyn termination design rules out the provision of a bottom port, as the fluid does not reach the termination bottom. However, all termination designs have an opening on the top flange, and the fluid can be always accessed through this opening.

It is recommended that utilities request the termination manufacturer to provide a bottom valve, as G&W invariably provides one. Such a valve can be readily added to all available designs, Joslyn excepted due the fluid not reaching the bottom of the termination.

- The European termination designs are essentially the same, and significantly different from the U. S. designs. The two principal U. S. designs, namely, G&W and Joslyn, which represent a large proportion of U. S. 69 through 138 kV extruded cable terminations in service, are significantly different from each other.
- Application of electrical stresses at PD inception levels always resulted in the generation of gases in silicone and polybutene fluids.
- Under PD activity, hydrogen and acetylene are the only gases generated in silicone fluid. However, hydrogen, acetylene and ethylene are observed in polybutene.
- Under breakdown conditions, polybutene (hydrocarbon-based fluid) yields a larger amount of acetylene and lower amount of hydrogen compared to silicone. Such a difference in gas distributions is attributed to the large difference in molecular structure of these fluids.
- Only hydrogen was observed to evolve from a silicone fluid at PD onset, while under similar conditions, acetylene was observed to evolve from a polybutene fluid. It could also be related to the molecular structure.
- Key gases of interest to extruded cable terminations were observed to increase in concentration, both as a result of increasing time exposure at a fixed electrical stress, and as a result of increasing electrical stress at fixed time exposure.

The DGA of extruded cable termination fluid has potential as a diagnostic tool. This is also supported by appearance of acetylene and exceedingly large concentrations of ethylene for the 345 kV extruded terminations associated with long-term 345 kV extruded cable tests. It should be stressed that the samples were taken after the terminations had had experienced some problems. It is possible that periodic sampling might have demonstrated the value of DGA.

The EDOSS (EPRI Disposable Oil Sampling System) method appears to be the only viable approach to perform DGA analysis on extruded cable terminations. The extremely small volume (5 cc) required in the EDOSS method is invaluable. The traditional DGA method (ASTM 3612) requires 50-100 cc of the sampled fluid, ruling out its use over the life of the termination.

- A pumping system, with reverse flow capability, was developed for the sampling of extruded cable terminations. This system makes possible the sampling of viscous fluids employed at low pressure in such terminations, while at the same time conserving the relatively small volume of termination fluid by returning it by means of reverse flow action.
- The sampling of termination headspace holds potential. It may be sufficient to sample just the headspace and not sample the fluid for termination designs where such a headspace is present e.g., Joslyn, Kabeldon and Alcatel. This would make the DGA process extremely simple. The growing interest in headspace sampling for transformers should serve as a good parallel.

It is recommended that the gas analysis of termination be pursued. At the same time, this work will enable to generate additional much-needed DGA field data on filling fluids. This approach should be pursued in the field along with much more fieldwork involving fluid sampling.

- DGA guidelines for old and new terminations have been presented. It is recommended that an extruded cable termination be sampled soon after energization for baseline data. The next sampling should be performed after 6 months, 18 months and 36 months; thereafter at 3-year intervals.

It is recommended to perform additional DGA fieldwork to refine the guidelines.