

# Dissolved Gas Analysis - Past, Present and Future

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## I. INTRODUCTION

It has been well over thirty years since dissolved gas analysis, DGA, was introduced as a diagnostic tool for monitoring mineral oil filled transformers. It is now universally accepted as the method of choice to locate incipient thermal and electrical faults. DGA methodology and applicability have evolved significantly since its inception. The evolutionary development includes new laboratory methods, on-line DGA, application to additional types of fluid filled equipment, application to dielectric fluids other than mineral oil and new diagnostic interpretation protocols.

At this time the ASTM has approved two procedures for laboratory DGA and a third method is on the verge of approval. Devices, which periodically or continuously monitor one or more gas in oil concentrations, are available for on-line analysis. DGA was originally developed for transformers, but it is now being applied to load tap changers, oil filled circuit breakers, oil filled bushings and cable oil. Data interpretation methods have been extensively developed for transformers filled with mineral oil and IEEE is currently developing a guide for silicone fluid filled transformers.

## II. LABORATORY METHODS

ASTM procedure, D 3612<sup>1</sup>, provides two different methods for the extraction of dissolved gases from dielectric fluid. Method D 3612-A involves an extraction process that precedes the subsequent gas analysis. The dielectric fluid is delivered into a previously evacuated glass apparatus and is stirred for a sufficient time to extract most of the dissolved gases. The volume of the evacuated glassware must be large in comparison to the volume of dielectric fluid so that most of the dissolved gases leave the fluid phase. The evolved gas is compressed and the volume and temperature are measured. Then, one or more aliquots of the gas are separated and quantified with a gas chromatograph. Each gas concentration in the oil is reported in ppm by volume. ASTM 3612-A is time consuming and labor intensive, but it has low detection limits and generates reproducible data. Mercury is used in the extraction apparatus so precautions must be taken to minimize worker exposure to mercury vapors.

ASTM D 3612-B uses direct injection of an oil sample onto a heated gas stripping column that is in series with a separation column, both of which may be contained within a single gas chromatograph. The advantages of this method are speed and elimination of potential mercury health hazards. One disadvantage is that method B cannot be used with Silicone fluids because excessive foaming will damage the separation columns. Also, since fault gases are very soluble in mineral oil the extent of gas extraction may not be as complete as in the two stage method. The ASTM document states, "The limit of detection for hydrogen specified in Method B is higher than that specified for Method A. This could effect the interpretation of results when low levels of gases are present".<sup>1</sup> ASTM D 3612, which contains a comparison of the detection limits of methods A and B, is summarized in Table 1.

**Table 1**  
Minimum Gas Detection Limits, ppm<sub>vol</sub><sup>1</sup>

<b>Gases</b>	<b>Method D 3612-A</b>	<b>Method D 3612-B</b>
Hydrogen	5	20
Hydrocarbons	1	1
Carbon Oxides	25	2
Atmospheric Gases	50	500

New DGA methodology that involves a two stage process<sup>2</sup> has been developed and is being reviewed by ASTM committee D-27 (Proposed Designation D 3612-C). The first stage of the proposed “headspace” method involves a partitioning of dissolved gases between oil and an inert gas, argon. Oil samples are introduced into a sealed container that has been purged with argon. Samples are then heated and vigorously agitated for an extended period of time. Ostwald partition coefficients are used to correlate gas concentrations in the headspace of the sample container with the initial gas concentrations in the oil. The second stage involves analysis of the evolved gases with a gas chromatograph. The advantages of this headspace method include automation of the extraction and analysis process and elimination of mercury. Detection limit comparisons between the headspace method and D 3612-A are being developed. One area of concern is potential variability of Ostwald coefficients with oil type, though most believe the difference of results due to this factor is not significant.

### III. ON-LINE DGA

In-time maintenance of electrical equipment, performing maintenance on only those units that require it, is a desirable goal. In order to fully implement this objective, equipment would have to be effectively monitored on an ongoing basis. Since DGA is accepted as an excellent diagnostic monitoring tool a great deal of effort has been expended to develop on-line DGA. The two steps required to implement this are automated separation of the fault gases from the oil followed by quantitative analysis. One or more gases can be extracted from the oil and subsequently analyzed with a chromatograph, an infra-red spectrometer or a mass spectrometer. Separation of the gases from the oil can be achieved with a semi-permeable membrane or a mechanical device. The small mobile hydrogen atoms, and to a lesser extent other small molecules such as CO, are most readily separated. The hydrogen can then be measured. Fortunately, hydrogen is formed with any type of fault, partial discharge, heating or arcing and the measurement of this gas can be used to continuously monitor the condition of a transformer. Hydrogen detection methods are best used as trigger devices to indicate when a laboratory DGA is appropriate.

Mechanical extraction devices for separation of gases from oil have also been developed. Oil is fed into a cylinder fitted with a piston that is moved up and down. On the down stroke headspace is created in the cylinder and the gases partition between the oil and the headspace. During the compression stroke the gas is pushed into a reservoir and the cycle is repeated. This multiple stage extraction procedure is potentially more effective than a single stage extraction such as that used in ASTM D 3612-A . The extracted gases can then be

separated and analyzed by gas chromatography or quantified without prior separation by infrared or mass spectroscopy .

On-line DGA is theoretically feasible but reliability, detection limits and economic issues must still be resolved before the method is widely implemented. Detection of a limited number rather than all of the gases may be a sufficiently viable compromise.

#### IV. APPLICABILITY OF DGA

##### A. Fluid Types

Thermal or electrical faults release energy that will result in the partial molecular destruction of dielectric fluids. The extent of the molecular rearrangement depends on the available energy and the nature of the dielectric fluid. Faults will produce gases in mineral oils, high molecular weight hydrocarbons, PCB's, silicone fluids, perchlorethylene and other dielectric fluids. Since DGA interpretation is empirical in nature it has only been effectively applied to dielectric fluids that have been extensively studied. The current IEEE guide<sup>3</sup>, 57.104, covers the application of DGA to mineral oils only. High molecular weight hydrocarbons, also known as less flammable hydrocarbons, contain similar molecules to those present in conventional mineral oil and produce the same gases under similar fault conditions.

The IEEE guide is applicable, without modification, for these fluids. Silicone fluids produce the same fault gases as mineral oils when they are thermally or electrically stressed, but relative concentrations and fault gas concentration ratios are different. A separate IEEE trial-use guide, P1258, has been developed for these fluids<sup>4</sup>. IEEE guides for the other fluids are not currently available.

##### B. Equipment Types

DGA was initially developed to monitor transformers and the success of this method is well known. Fault conditions can exist in any type of electrical equipment and if this equipment contains dielectric fluids, fault gases will be produced. Table 2 shows the correlation between fault types and the various fault gases.

**Table 2**  
Fault Gases

<b>Gases</b>	<b>Indication</b>
Hydrogen	Partial discharge, heating, arcing
Methane, Ethane, Ethylene	"Hot Metal" gases
Acetylene	Arcing
Carbon Oxides	Cellulose insulation degradation

## 1. Load Tap Changers

When a load tap changer, LTC, operates arcing occurs and the expected fault gases, acetylene and hydrogen, are produced. One might initially assume that the presence of these gases masks the gases produced by other faults. Coking and misalignment of contacts are the most common problems that occur in LTCs. Coking is a cumulative problem that starts with an initial deposition on the contact surfaces, which results in increased contact resistance, followed by additional carbon build up on the contacts. This process leads to exponentially increased heating or “thermal runaway” and carbon build up. Youngblood<sup>5</sup> was one of the first investigators to realize that the coking problem would result in the production of the “hot metal gases”, methane, ethane and especially ethylene. The concentration of these gases depends on a number of variables including breathing type, manufacturer, model type, etc. Generic fault gas threshold values, similar to those in the IEEE guide for transformers, have been developed by Youngblood and are given in Table 3.

**Table 3**  
LTC Monthly Watch Criteria<sup>5</sup>

LTC Type	Hydrogen	Acetylene	Ethylene
Free or Desiccant Breather	>1500 ppm	>1000 ppm	>1000 ppm
Sealed	>5000 ppm	>9000 ppm	>1200 ppm
Vacuum	>10 ppm	>5 ppm	> 100 ppm

Charles Baker<sup>6</sup> and others have developed manufacturer specific flag points and this approach, which is illustrated in Table 4, is probably the most promising.

**Table 4**  
Equipment Specific Action Levels  
(McGraw Edison LTC 550)

	Hydrogen	Methane	Ethane	Ethylene	Acetylene	CO	CO <sub>2</sub>
LT1	100	100	100	500	100	100	150
LT2	250	200	200	1200	200	500	300
LT3	500	400	400	2000	400	1000	3000

LT1 = Abnormal

LT2 = High

LT3 = Very High

A typical LTC case history is documented below:

AC TLH-21 138KV x 12KV 50 MVA Free Breather

Date: February 25, 1993

Date	Mfr.	Serial Number	C <sub>2</sub> H <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>2</sub> H <sub>4</sub>	H <sub>2</sub>	CO	CO <sub>2</sub>
02/25/93	AC	018226580301	0	5	1	4	34	71	350

This unit was determined to be operating properly. The low concentrations of hydrogen and acetylene are considered normal for a free breathing unit. The unit was scheduled for annual testing.

Date: February 25, 1994

Date	Mfr.	Serial Number	C <sub>2</sub> H <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>2</sub> H <sub>4</sub>	H <sub>2</sub>	CO	CO <sub>2</sub>
02/25/94	AC	018226580301	44	1812	576	3143	149	33	645

This unit was in “thermal runaway” when tested. Notice the high level of ethylene, which is the key gas for overheating. This unit was already heavily coked when the DGA test was conducted. The unit was removed from service and repaired. The reversing switch and some moveable dial contacts were replaced.

Date: February 27, 1995

Date	Mfr.	Serial Number	C <sub>2</sub> H <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>2</sub> H <sub>4</sub>	H <sub>2</sub>	CO	CO <sub>2</sub>
02/27/95	AC	018226580301	55	9	2	11	22	33	440

The unit is operating normally after completion of the repairs. The LTC was placed on a six month test interval based on its previous failure history.

## 2. Oil Filled Bushings

John Stead presented a paper at the 1996 Doble conference<sup>7</sup> showing how DGA could resolve conflicting Power Factor results for two bushings from the same manufacturer. The DGA data for these two bushings is given in Table 5. This data clearly indicates that partial discharge is occurring in bushing 2. The low ratio of CO<sub>2</sub> / CO indicates severe overheating of the paper in the bushing. Physical inspection confirmed the interpretation of the DGA results.

**Table 5**  
DGA Data for Two Bushings, ppm<sup>7</sup>

<b>Gas</b>	<b>Bushing 1</b>	<b>Bushing 2</b>
Hydrogen	1705	19132
Oxygen	5546	4041
Nitrogen	68216	50767
Carbon Monoxide	441	537
Methane	146	1256
Carbon Dioxide	710	1459
Ethylene	1.8	11
Ethane	71	409
Acetylene	<0.1	0.2

Removal of oil from a bushing is not encouraged by most manufacturers, but the practice is common in Europe.

### **3. Oil Filled Circuit Breakers**

Application of DGA to oil circuit breakers, OCB's, is under investigation by ACTI in cooperation with several utilities. Most OCB's are free breathing and fault gas concentrations could be very dependent on the sampling time. Other tests such as particle size distribution, particle types and metals in the oil are being evaluated for the identification of problem units.

## **V. SUPPLEMENTARY TESTS**

Carbon oxides are produced by the degradation of cellulose insulation or when oil is heated in the presence of oxygen. The extent of cellulose degradation is a critical factor in estimating the condition and life expectancy of solid insulation. Levels of CO and CO<sub>2</sub> and the ratio CO<sub>2</sub> / CO can be used to indicate when further investigation of the cellulose condition is warranted. The two available methods are Degree of Polymerization, DP, and Furanic compound analysis. DP is more definitive, but this invasive procedure requires removal of paper samples from the equipment. Furan analysis is a non-invasive procedure and is recommended if the DGA results indicate cellulose decomposition.

A very interesting example of the effect of transformer overheating was provided to ACTI by Mr. Charles Baker, South Carolina Electric and Gas Co<sup>8</sup>. The transformer in question 33/13.8 kV was run for 4 days without operation of the fans and pumps. The main winding temperature of this three and a half year old transformer reached 150<sup>0</sup> C. Rates of cellulose degradation double for each 6-8 degree rise in temperature. If we assume a normal winding temperature of 90<sup>0</sup>, the sixty degree rise in temperature would correspond in a 2<sup>10</sup> (1024) increase in the rate of cellulose decomposition. Four days at the elevated temperature would correspond to 4096 days, 11.2 years of normal operation. The transformer insulation would then be 14.5 years old. The laboratory analysis showed 0.45 ppm of 2-furfuraldehyde which correspond, using the Chendong equation, to a DP of 530 and an apparent operating time of

25 years. There was no additional data to indicate if the transformer was overheating during the first three and a half years of operation. Baker has recently reported that the transformer failed.

## **VI. FUTURE DEVELOPMENTS**

Proposed changes in DGA laboratory procedures have been noted above. IEEE Guide 57.104 was last revised in 1991 and is currently being revised once more. The committee is proposing a two step process for utilization of DGA laboratory data. The current thinking is that there should be one set of criteria for interpretation of the first DGA result (proposed Table 1) and a second set of criteria for subsequent tests (proposed Table 2). Current deliberations include the concentrations of fault gases that will be classified as "normal" and levels that lead to a recommendation to monitor the transformer at shorter intervals. Once it is determined that one or more gases have exceeded these "normal" levels then the rates of fault gas generation should be determined. Table 2 will then tabulate IEEE recommendations for subsequent test intervals and operational procedures.

## REFERENCES

1. ASTM, Annual Book of ASTM Standards, Volume 10.03, D 3612-96.
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3. IEEE C57.104-1991, "IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers", 1991.
4. IEEE P1258, "IEEE Trial-Use Guide for the Interpretation of Gases Generated in Silicone-Immersed Transformers", 1995.
5. Youngblood, Rick, et. al, "Application of DGA to Detection of Hot Spots in Load Tap Changers", Minutes of the Sixtieth Annual International Conference of Doble Clients, 1993, Sec. 6-4.
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