# DISSOLVED GAS ANALYSIS OF MINERAL OIL INSULATING FLUIDS

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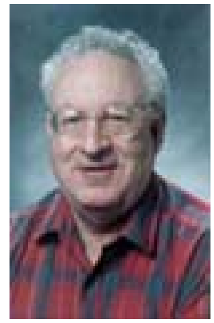


Insulating materials within transformers and related equipment break down to liberate gases within the unit. The distribution of these gases can be related to the type of electrical fault and the rate of gas generation can indicate the severity of the fault. The identity of the gases being generated by a particular unit can be very useful information in any preventative maintenance program. This technique is being used quite successfully throughout the world. This paper deals with the basics underlying this technique and deals only with those insulating fluids of mineral oil origin.

Obvious advantages that fault gas analyses can provide are:

| | |
|---|---|
| 1. | Advance warning of developing faults |
| 2. | Determining the improper use of units |
| 3. | Status checks on new and repaired units |
| 4. | Convenient scheduling of repairs |
| 5. | Monitoring of units under overload |

The following sections will deal with the origins of the fault gases, methods for their detection, interpretation of the results,and philosophies on the use of this technique. Some limitations and considerations that should be kept in mind concerning the use of this technique will also be discussed. Finally an appendix containing some actual case histories will be covered.

**Fault Gases**

The causes of fault gases can be divided into three categories; corona or partial discharge, pyrolysis or thermal heating, and arcing. These three categories differ mainly in the intensity of energy that is dissipated per unit time per unit volume by the fault. The most severe intensity of energy dissipation occurs with arcing, less with heating, and least with corona.

A partial list of fault gases that can be found within a unit are shown in the following three groups:

1. Hydrocarbons and hydrogen

| | |
|---|---|
| Methane | $CH_4$ |
| Ethane | $C_2H_6$ |
| Ethylene | $C_2H_4$ |
| Acetylene | $C_2H_2$ |
| Hydrogen | $H_2$ |

2. Carbon oxides

| | |
|---|---|
| Carbon monoxide | $CO$ |
| Carbon dioxide | $CO_2$ |

3. Non-fault gases

| | |
|---|---|
| Nitrogen | $N_2$ |
| Oxygen | $O_2$ |

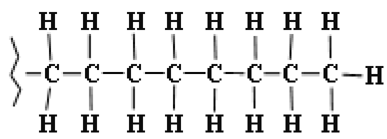
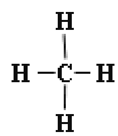
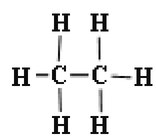
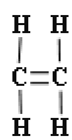
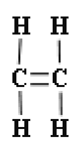
These gases will accumulate in the oil, as well as in the gas blanket of those units with a headspace, as a result of various faults. Their distribution will be effected by the nature of the insulating materials involved in the fault and the nature of the fault itself. The major (minor) fault gases can be categorized as follows by the type of material that is involved and the type of fault present:

| | |
|---|---|
| 1. Corona | |
| a. Oil | $H_2$ |
| b. Cellulose | $H_2$ , $CO$ , $CO_2$ |
| 2. Pyrolysis | |
| a. Oil | |
| Low temperature | $CH_4$ , $C_2H_6$ |
| High temperature | $C_2H_4$ , $H_2$ ( $CH_4$ , $C_2H_6$ ) |
| b. Cellulose | |
| Low temperature | $CO_2$ ( $CO$ ) |
| High temperature | $CO$ ( $CO_2$ ) |
| 3. Arcing | $H_2$, $C_2H_2$ ($CH_4$, $C_2H_6$, $C_2H_4$) |

Mineral oil insulating fluids are composed essentially of saturated hydrocarbons called paraffins, whose general molecular formula is $C_nH_{2n+2}$ with n in the range of 20 to 40. The cellulosic insulation material is a polymeric substance whose general molecular formula is $[C_{12}H_{14}O_4(OH)_6]_n$ with n in the range of 300 to 750.

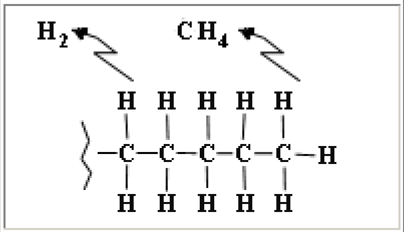
The structural formula of the mineral oil and those of the hydrocarbons and hydrogen fault gases are shown in Figure 1.

**Figure 1.** Structure of insulating oil and fault gases.

| | | |
|---|---|---|
| Mineral Oil |  | $C_nH_{2n+2}$ |
| Hydrogen | H−H | $H_2$ |
| Methane |  | $CH_4$ |
| Ethane |  | $C_2H_6$ |
| Ethylene |  | $C_2H_4$ |
| Acetylene |  | $C_2H_2$ |
| Carbon Dioxide | O=C=O | $CO_2$ |
| Carbon Monoxide | C≡O | CO |
| Oxygen | O=O | $O_2$ |
| Nitrogen | N≡N | $N_2$ |

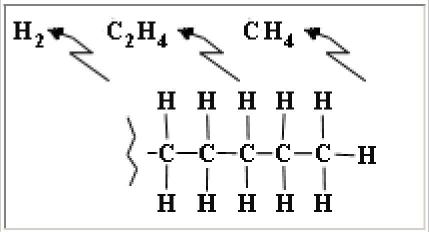
Figures 2, 3, 4, and 5 illustrate the processes occurring with corona, pyrolysis, and arcing in oil and pyrolysis of cellulose respectively. Typical fault gas distributions are also shown.

**Figure 2.** Corona in Oil



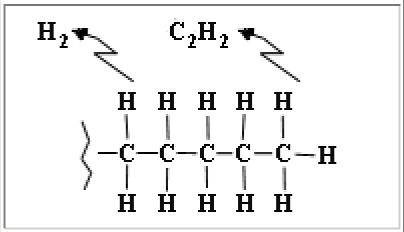

| | |
|---|---|
| $H_2$ | 88% |
| $C0_2$ | 1 |
| C0 | 1 |
| $CH_4$ | 6 |
| $C_2H_6$ | 1 |
| $C_2H_4$ | 0.1 |
| $C_2H_2$ | 0.2 |

**Figure 3.** Pyrolysis in Oil



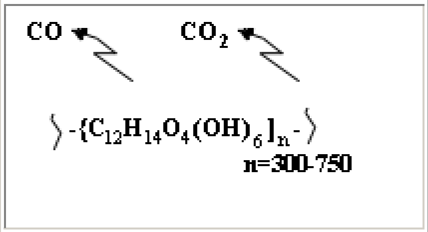

| | |
|---|---|
| $H_2$ | 16% |
| $C0_2$ | trace |
| C0 | trace |
| $CH_4$ | 16 |
| $C_2H_6$ | 6 |
| $C_2H_4$ | 41 |
| $C_2H_2$ | trace |

**Figure 4.** Arcing in Oil




| | |
|---|---|
| $H_2$ | 39% |
| $C0_2$ | 2 |
| C0 | 4 |
| $CH_4$ | 10 |
| $C_2H_4$ | 6 |
| $C_2H_2$ | 35 |

**Figure 5.** Pyrolysis of Cellulose



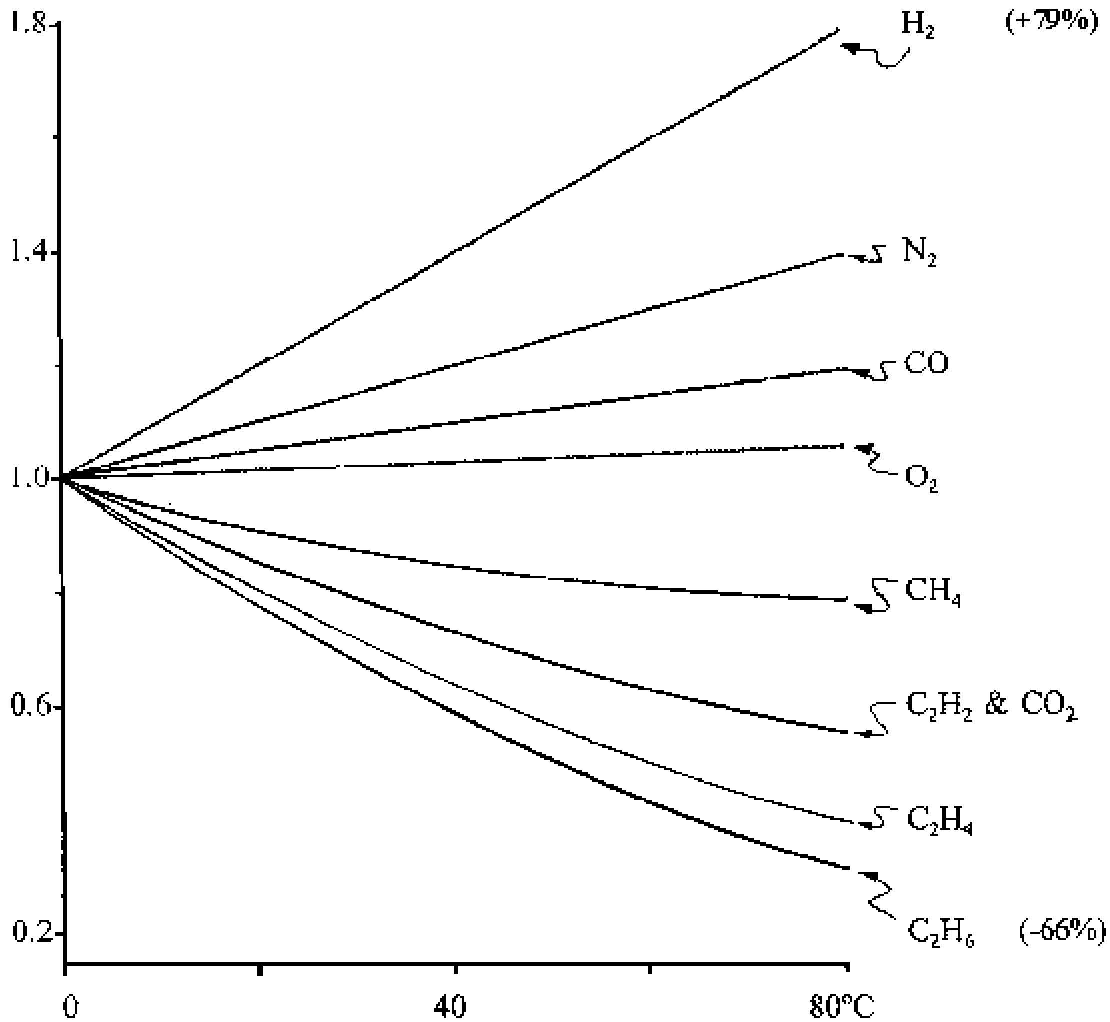

| | |
|---|---|
| $H_2$ | 9% |
| $C0_2$ | 25 |
| C0 | 50 |
| $CH_4$ | 8 |
| $C_2H_4$ | 4 |
| $C_2H_2$ | 0.3 |

The solubilities of the fault gases in mineral oil as well as their temperature dependence are also important factors for consideration in fault gas analyses. Table 1 lists the saturation solubilities for the fault gases. It should be noted that there is almost two orders of magnitude difference.

| **Table 1.**Solubility of Gases in Transformer Oil. Static Equilibrium at 760 mm Hg and 25$^o$C. | |
|---|---|
| Hydrogen | 7 % by volume |
| Nitrogen | 8.6 % |
| Carbon monoxide | 9 % |
| Oxygen | 16 % |
| Methane | 30 % |
| Carbon dioxide | 120 % |
| Ethane | 280 % |
| Ethylene | 280 % |
| Acetylene | 400 % |

between the least soluble (hydrogen) and the most soluble (acetylene) gas. The majority of gases that are indicative of faults are also those that are in general the more soluble in the oil. When rates of gas generation are being followed it is important to take into account the solubilities of these gases as a function of the oil temperature (Fig. 6). Over a temperature range of 0 to 80$^o$C some gases increase in solubility up to 79% while others decrease their solubility up to 66%.

**Figure 6.** Relative Solubilities as a Function of Temperature.



## Methods of Fault Gas Detection

Three methods will be discussed and their advantages and disadvantages will be compared. The first method and probably the most widely used technique at the present time is the one that determines the total combustible gases ( TCG ) that are present in the gas above the oil. The major advantage of the TCG method compared to the others that will be covered is that it is fast and applicable to use in the field. In fact it can be used to continuously monitor a unit. However, there are a number of disadvantages to the TCG method. Although it detects the combustible fault gases (hydrogen, carbon monoxide, methane, ethane, ethylene, and acetylene), it does not detect the noncombustible ones (carbon dioxide, nitrogen, and oxygen). This method is only applicable to those units that have a gas blanket and not to the completely oil-filled units of the conservator type. Since most faults occur under the surface of the oil, the gases must first saturate the oil and diffuse to the surface before accumulating in the gas blanket above the oil. These processes take time, which delays the early detection of the fault. The major disadvantage of the TCG method is that it gives only a single value for the percentage of combustible gases but does not identify which gases are actually present. It is this latter information that is most useful in determining the type of fault that has occurred.

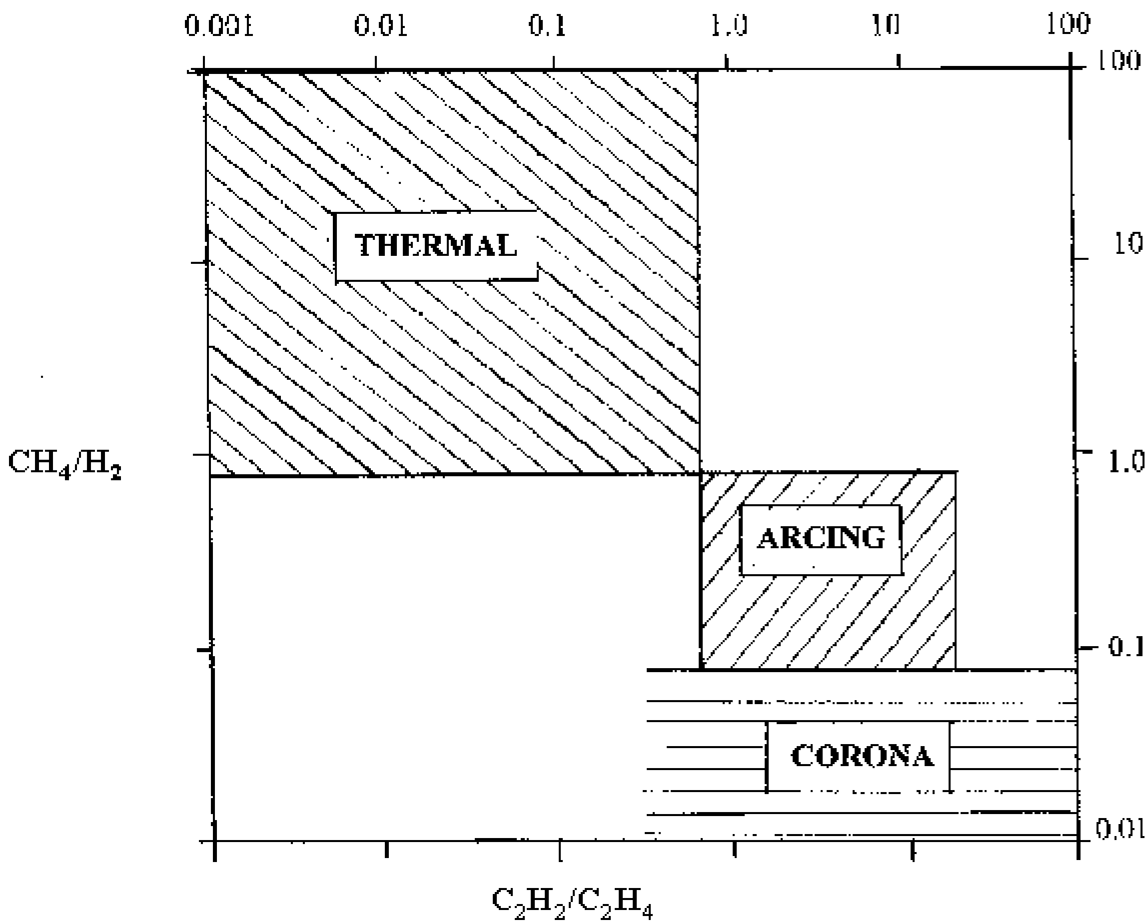
The second method for the detection of fault gases is the gas blanket analysis in which a sample of the gas in the space above the oil is analyzed for its composition. This method detects all of the individual components; however, it is also not applicable to the oil-filled conservator type units and it also suffers from the disadvantage that the gases must first diffuse into the gas blanket. In addition, this method is not at present best done in the field. A properly equipped laboratory is preferred for the required separation, identification, and quantitative determination of these gases at the part per million level. The third and most informative method for the detection of fault gases is the dissolved gas analysis ( DGA ) technique. In this method a sample of the oil is taken from the unit and the dissolved gases are extracted. Then the extracted gases are separated, identified, and quantitatively determined. At present this entire technique is best done in the laboratory since it requires precision operations. Since this method uses an oil sample it is applicable to all type units and like the gas blanket method it detects all the individual components. The main advantage of the DGA technique is that it detects the gases in the oil phase giving the earliest possible detection of an incipient fault. This advantage alone outweighs any disadvantages of this technique.

Methods of Interpretation

The most important aspect of fault gas analysis is taking the data that has been generated and correctly diagnosing the fault that is generating the gases that have been detected. Several methods that are currently in use will be covered.

One of the earliest methods is that of Dornenburg[3] in which two ratios of gases are plotted on log-log axes (Fig. 7). The area in which the plotted point falls is indicative of the type of fault that has developed.

**Figure 7.** Dörnenburg Plot.



The Central Electric Generating Board ( CEGB ) of Great Britain has been using a method developed by Rogers[4] in which the magnitudes of four ratios of gases are used to generate a four digit code as shown in Table 2. The code number that is generated can be related to a diagnostic interpretation as shown in Table 3.

**Table 2.**
C. E. G. B. Fault Gas Ratios.[4]

| RATIO | RANGE | CODE |
|---|---|---|
| $CH_4/H_2$ | $\leq 0.1$<br>$> 0.1 < 1$<br>$\geq 1 < 3$<br>$\geq 3$ | 5<br>0<br>1<br>2 |
| $C_2H_6/CH_4$ | $< 1$<br>$\geq 1$ | 0<br>1 |
| $C_2H_4/C_2H_6$ | $< 1$<br>$\geq 1 < 3$<br>$\geq 3$ | 0<br>1<br>2 |
| $C_2H_2/C_2H_4$ | $< 0.5$<br>$\geq 0.5 < 3$<br>$\geq 3$ | 0<br>1<br>2 |

**Table 3.**
C. E. G. B. Diagnostics.

| **CODE** | | | | **DIAGNOSIS** |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | Normal |
| 5 | 0 | 0 | 0 | Partial discharge |
| 1,2 | 0 | 0 | 0 | Slight overheating < 150°C |
| 1,2 | 1 | 0 | 0 | Slight overheating 150 - 200°C |
| 0 | 1 | 0 | 0 | Slight overheating 200 - 300°C |
| 0 | 0 | 1 | 0 | General conductor overheating |
| 1 | 0 | 1 | 0 | Winding circulating currents |
| 1 | 0 | 2 | 0 | Core and tank circulating currents, overheated joints |
| 0 | 0 | 0 | 1 | Flashover, no power follow through |
| 0 | 0 | 1,2 | 1,2 | Arc, with power follow through |
| 0 | 0 | 2 | 2 | Continuous sparking to floating potential |
| 5 | 0 | 0 | 1,2 | Partial discharge with tracking (note CO) |
| CO2 / CO > 11 | | | | Higher than normal temperature in insulation |

Table 4 shows the guidelines developed at California State University-Sacramento in cooperation with Pacific Gas & Electric Company to indicate the normal and abnormal levels of the individual gases.

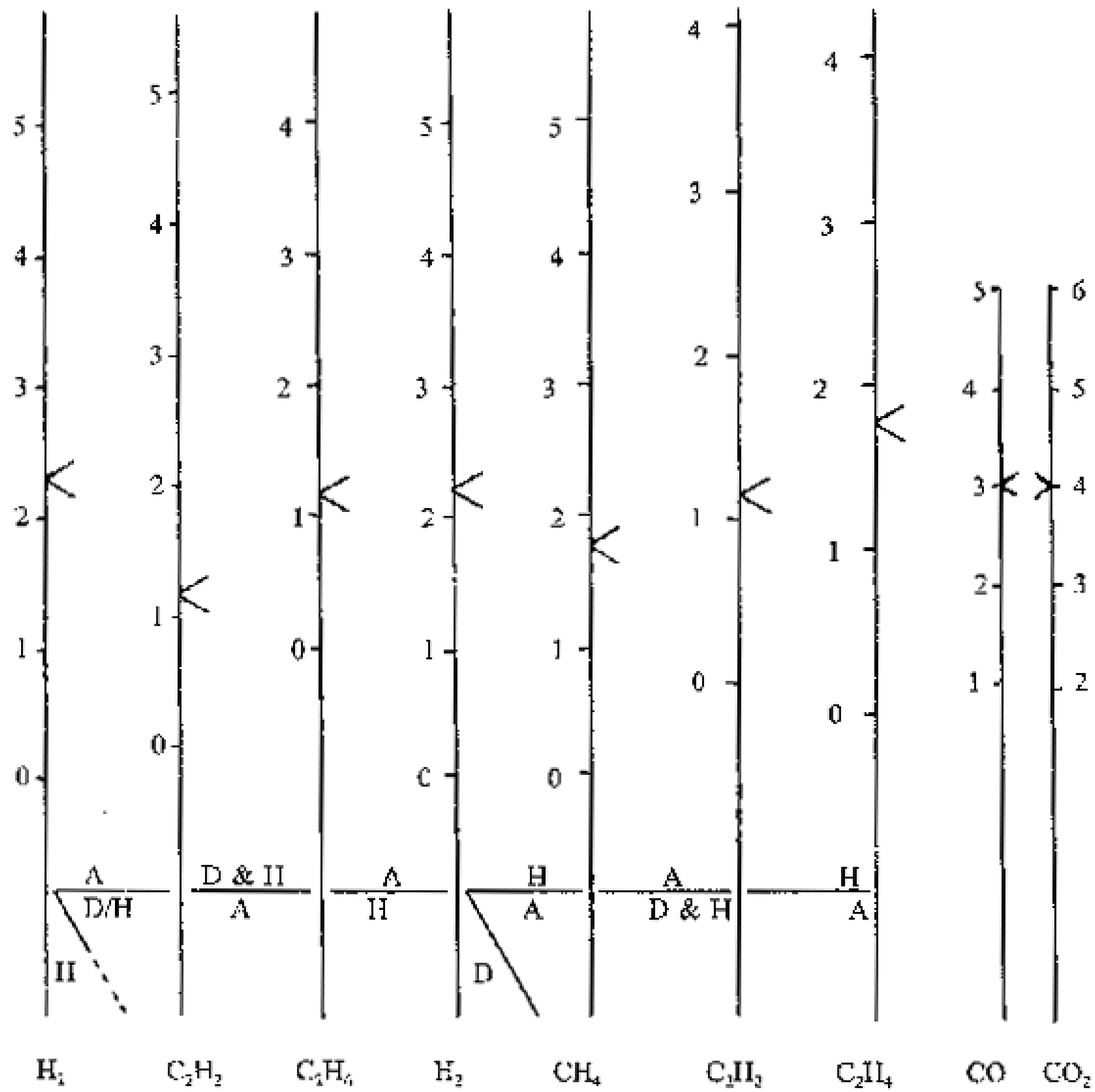
| **Table 4.** C. S. U. S. Guidelines.[7] | | | |
|---|---|---|---|
| Gas | Normal (<) | Abnormal (>) | Interpretation |
| Hydrogen | 150 ppm | 1000 ppm | Corona, Arcing |
| Methane | 25 | 80 | Sparking |
| Ethane | 10 | 35 | Local overheating |
| Ethylene | 20 | 150 | Severe overheating |
| Acetylene | 15 | 70 | Arcing |
| Carbon monoxide | 500 | 1000 | Severe overheating |
| Carbon dioxide | 10,000 | 15,000 | Severe overheating |
| Nitrogen | 1 to 10 % | N.A. | N.A. |
| Oxygen | 0.2 to 3.5% | N.A. | N.A. |
| Total Combustibles | 0.03 % | 0.5 % | N.A. |

Currently Northern Technology & Testing is using the following flag points for the various fault gases shown below in Table 5.

| **Table 5.** N. T. T. Flagpoints | |
|---|---|
| Gas | Flagpoint (>) |
| Hydrogen | 1500 ppm |
| Methane | 80 |
| Ethane | 35 |
| Ethylene | 150 |
| Acetylene | 7 |
| Carbon monoxide | 1000 |
| Carbon dioxide | 10,000 |

Finally a logarithmic nomograph method developed by Mr. J. O. Church of the U. S. Bureau of Reclamation will be discussed. The basic principles are illustrated in Figure 8. The sliding logarithmic scales and their relative positions are based on data originally published by Dornenburg and Strittmatter.[5] The slope of the line between the tie-points on adjacent vertical scales is indicative of the type of fault in the unit. Each vertical scale has a threshold value labeled with an arrow. For the slope of a line to be considered significant, at least one of the two tie-points should lie above a threshold value. If neither tie-point lies above a threshold value then the fault indication of that slope is not considered significant. The appendix contains a full size version of this nomograph.

**Figure 8.** Logarithmic Nomograph.



It should be pointed out that all of the above methods are constantly being revised and updated as more and more useful background information is gained.

**Testing Philosophies**

Depending on their needs, customers can make various uses of fault gas analyses and a variety of methods are undoubtedly in use today.

Westinghouse[6] recommends the routine use of TCG to monitor units and depending on the values obtained further action such as DGA analysis may be recommended (Table 6).

| **Table 6.** Frequency of Testing (Westinghouse).[6] | | |
|---|---|---|
| 1. | TCG 0 - 0.1 % | Very low, no further action. |
| 2. | TCG 1 - 2 % | Low, monitor TCG monthly. |
| 3. | TCG 3 - 5 % | Moderate, conduct DGA, evacuate unit, purge with nitrogen, and monitor every two weeks. |
| 4. | TCG over 5 % | Large, conduct DGA, evacuate unit, purge with nitrogen, monitor daily. If rate increases remove from service and correct fault. |

The C.E.G.B. has a rigorous schedule of testing all their units using the DGA technique exclusively (Table 7).[4]

| **Table 7.** Frequency of Testing (C.E.G.B.)[4] | |
|---|---|
| 1. | All new units before and after factory proving tests. |
| 2. | All new 400 & 250 KV transmission units on first commission, every three months for first year, then yearly. |
| 3. | All generation units over 300 MVA monthly. |
| 4. | When abnormal result is obtained, frequency of testing is adjusted consistent with severity of the indicated fault. |

The Pacific Gas & Electric Company[7] along with a number of our other clients have been convinced of the advantage of routinely sampling all of their units via the DGA technique and they have started such a program. They sample all of their units at least twice yearly. The various gases in each unit are monitored and deviations from the baseline established for each particular unit are indicative of the type and severity of developing faults.

## Limitations and Considerations

It has to be recognized that conditions within a transformer are not homogeneous and the system is never at true equilibrium. Temperature and pressure gradients as well as different types of flow characteristics contribute to the overall complexity of the system. With these limitations one would not expect duplicate samples to agree better than to about ten percent and in some cases the agreement may be poorer.

A unit with an active fault generates gases at rates considerably greater than one undergoing normal aging. We have observed wide variations in duplicate samples from units with active faults and it was thus apparent that the system was far from homogeneous. Under such conditions perhaps it is more meaningful to look at trends rather than absolute values of individual gases. In contrast, duplicate samples from units without active faults have shown more consistent agreement.

There have been efforts made to relate the rate of generation of gas with the severity of a developing fault. The volume of the system has to be considered when talking about rates of gas evolution. The gases are reported in terms of concentration (e.g.ppm) and the total gas generated by a fault will be dependent on the total volume of the system when calculated from the concentrations that were determined. For example if two units, one with a small total volume and the other with a large total volume of oil, are subjected to equally severe faults that generate the same amounts of gases, the concentration of these gases in the smaller unit will be higher than the same gases in the larger unit.

To determine rates of gas generation it is necessary to collect samples at different times. Normal aging of the insulating oil will give rise to a slow accumulation of gases over a semiannual sampling period. A moderate accumulation of gases over a monthly interval can indicate an incipient fault, while a rapid accumulation (i.e. over 10% per month) of gases is indication of an active fault.

A number of our customers who have applied Rogers' method for analyzing their data have informed us that they seldom if ever see a "normal" unit. It is well to remember that this method was developed for use within the C.E.G.B. system and their norm may not be the same as for another operating system. One problem that arises in using this method is that no significance is given to the magnitude of the numbers used to calculate the ratio and then to generate the code digit. Thus when the numbers themselves are small, fluctuations in the values can cause a very large change in the ratio and hence the generated digit. The nomographic method described earlier in essence is the same type of analysis as that of Rogers but the imposition of the threshold values limits the significance of the results when the individual values themselves are small.

Another consideration that cannot be stressed enough is the knowledge of the past history of a unit and the operating philosophies of the customer. Often we have been consulted regarding certain results that were indicative of a fault only to find that when the history of the unit was revealed the results could be rationalized by a past occurrence and were not the result of a continuing fault. Some clients have to operate their units at or above rated capacities while others may be more conservative in their operation. Under these different operating conditions, gas evolution from "normal" aging of the insulating fluid will be greater in the former case than in that of the latter case.

Finally it should be kept in mind that when a fault is indicated there are other techniques that can be brought to bear on the problem to assist in the interpretation. For instance if arcing is indicated then analysis of the fluid for trace amounts of metals dispersed in the fluid can be indicative of the location of the fault within the unit. The presence of aluminum can indicate arcing near the bushings or windings, copper can come from the windings, and iron can come from the core and the shell of the unit. These three metals are considered to be those that comprise the major construction of a unit. Other metals such as tin, lead, zinc, and silver are minor components and their presence can indicate the involvement of such things as connectors and solder joints.

**Conclusion**

The technology presently exists and is being used to detect and determine fault gases below the part per million level. However there is still much room for improvement in the technique, especially in developing the methods of interpreting the results and correlating them with incipient faults. It is also important to realize that even though there is further need for improvement in the technique, the analysis of dissolved fault gases represents a practical and effective method for the detection of incipient faults and the determination of their severity. In addition to utility companies, many industries and installations that have on-site transformers are recognizing that the technique of dissolved fault gas analysis is an extremely useful, if not essential, part of a well developed preventative maintenance program.

## Appendix I - Case Histories

This section will cover some analyses along with the indicated diagnosis and post-mortem findings. Values with an asterisk (*) exceed the CSUS guideline values discussed earlier.

| **Case I** | 5/6/74 | 5/28/74 | 1/16/76 |
|---|---|---|---|
| Hydrogen | 495 ppm | 80 ppm | 21 ppm |
| Oxygen | 7488 | 9561 | 4539 |
| Carbon Dioxide | 2999 | 2952 | 917 |
| Ethylene | 2438* | 2480* | 98 |
| Ethane | 276* | 326* | 23 |
| Acetylene | 2 | 0 | 0 |
| Nitrogen | 87,480 | 111,210 | 77,570 |
| Methane | 1775* | 619* | 24 |
| Carbon Monoxide | 293 | 268 | 159 |
| Total | 10.32% | 12.75% | 8.34% |

Diagnosis: Severe local overheating and sparking not involving cellulose.

Nomograph: Heating

This unit had no history of any problem and was scheduled to handle an overload while a transmission line was reconductored. However, prior to the overloading, an oil sample was subjected to DGA and gases were found that indicated severe heating with no involvement of cellulose. This was confirmed as a partly destroyed no-load tap changer contact that would have failed in service shortly, even without an overload. Further investigation of the other eleven units at this site showed that all had undersized contacts, which were subsequently replaced.

| Case II | 2/27/75 |
|---|---|
| Hydrogen | 231 ppm |
| Oxygen | 1043 |
| Carbon Dioxide | 2194 |
| Ethylene | 5584* |
| Ethane | 1726* |
| Acetylene | 0 |
| Nitrogen | 71,154 |
| Methane | 3997* |
| Carbon Monoxide | 0 |
| Total | 8.59% |

Diagnosis: Severe local overheating and sparking not involving cellulose.

Nomograph: Heating

This unit was found to have a defective core ground strap that exhibited signs of severe heating and it was repaired before it parted.

| Case III | 7/23/74 | 8/17/74 |
|---|---|---|
| Hydrogen | 127 ppm | 2 ppm |
| Oxygen | 1947 | 1119 |
| Carbon Dioxide | 2024 | 132 |
| Ethylene | 32 | 0 |
| Ethane | 0 | 0 |
| Acetylene | 81* | 0 |
| Nitrogen | 78,887 | 16,020 |
| Methane | 24 | 7 |
| Carbon Monoxide | 0 | 0 |
| Total | 8.31% | 1.73% |

Diagnosis: Arcing not involving cellulose.

Nomograph: Arcing

This unit was found to have arcing between the tank and a high voltage lead. The lead was simply reformed in another direction and the problem was solved. Similar other units at the same site also had the same problem of improper installation.

| Case IV | 1/14/77 |
|---|---|
| Hydrogen | 217 ppm |
| Oxygen | 23,230 |
| Carbon Dioxide | 1544 |
| Ethylene | 458* |
| Ethane | 14 |
| Acetylene | 884* |
| Nitrogen | 72,690 |
| Methane | 286 |
| Carbon Monoxide | 176 |
| Total | 9.95% |

Diagnosis: Severe local overheating and arcing not involving cellulose.

Nomograph: Arcing

This unit was found to have suffered a high voltage lead failure under oil.

| **Case V** | 8/5/76 | 10/22/76 | 10/22/76(LTC) |
|---|---|---|---|
| Hydrogen | 54 ppm | 246 ppm | 9474* ppm |
| Oxygen | 1039 | 1122 | 35,061 |
| Carbon Dioxide | 1303 | 2069 | 1156 |
| Ethylene | 4 | 21 | 6552* |
| Ethane | 0 | 0 | 353* |
| Acetylene | 0 | 53 | 12,997* |
| Nitrogen | 80,112 | 91,153 | 136,307 |
| Methane | 0 | 43 | 4066* |
| Carbon Monoxide | 106 | 218 | 553 |
| Total | 8.26% | 9.49% | 20.66% |

Diagnosis: Severe local overheating and arcing not involving cellulose.

Nomograph: Arcing

This unit had a rapidly developing fault that resulted in an explosion in the tap changer compartment.

| **Case VI** | 5/12/76 |
|---|---|
| Hydrogen | 507 ppm |
| Oxygen | 1222 |
| Carbon Dioxide | 2562 |
| Ethylene | 1440* |
| Ethane | 297* |
| Acetylene | 17 |
| Nitrogen | 102,925 |
| Methane | 1053* |
| Carbon Monoxide | 22 |
| Total | 11.00% |

Diagnosis: Severe local overheating and sparking not involving cellulose.

Nomograph: Heating

This unit was found to have severely burned low voltage coils.

| Case VII | 2/15/76 |
| --- | --- |
| Hydrogen | 416 ppm |
| Oxygen | 2422 |
| Carbon Dioxide | 14,316 |
| Ethylene | 867* |
| Ethane | 74* |
| Acetylene | 0 |
| Nitrogen | 85,141 |
| Methane | 695* |
| Carbon Monoxide | 200 |
| Total | 10.42% |

Diagnosis: Severe local overheating not involving cellulose.

Nomograph: Heating and arcing.

This unit was found to have a 1" steel bolt to a copper shunt completely burned through. The bolt was most likely severely heated to the point where it parted then arcing occurred across this region.

| Case VIII | 9/17/76(before fault) | 9/17/76(after fault) |
| --- | --- | --- |
| Hydrogen | 47 ppm | 441 ppm |
| Oxygen | 14,083 | 13,784 |
| Carbon Dioxide | 1113 | 1123 |
| Ethylene | 8 | 224* |
| Ethane | 0 | 43* |
| Acetylene | 0 | 261* |
| Nitrogen | 53,814 | 54,120 |
| Methane | 12 | 207* |
| Carbon Monoxide | 115 | 161 |
| Total | 6.92% | 7.04% |

Diagnosis: Severe local overheating and arcing not involving cellulose.

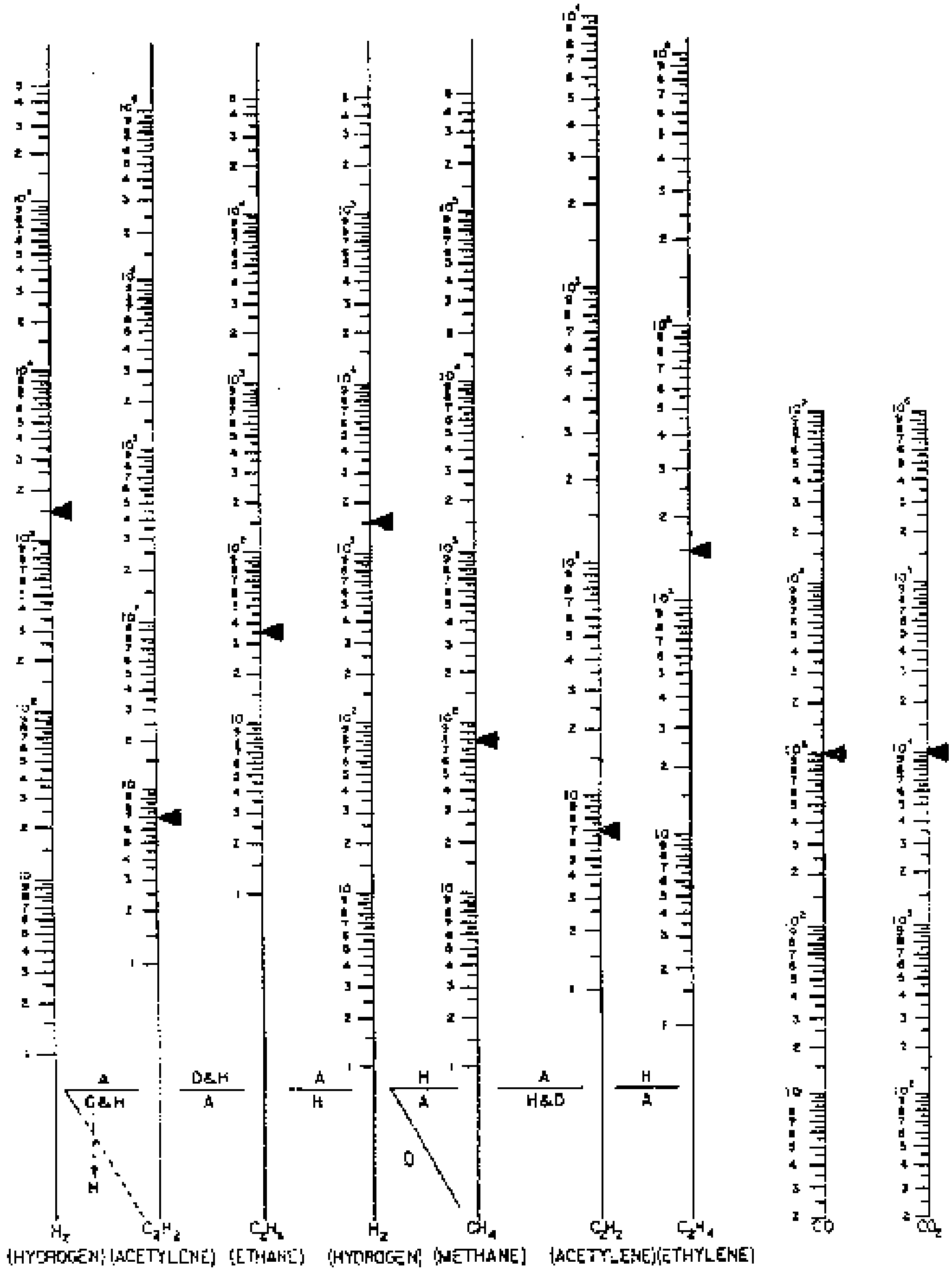
Nomograph: Arcing

This is an interesting case that very dramatically illustrates the early detection of a fault via the DGA technique. This was a mobile unit that was being operated without its cooling system being turned on. Realizing that some damage might have already been done to the system, a sample of oil was collected prior to shutting down the unit. During the shut down procedure, a major fault occurred involving a large arc to ground. Another sample was immediately taken for analysis. The first sample showed nothing of any concern; however, in the very short time span of the shutdown and occurrence of the fault one sees the very large and rapid increase of the gases indicative of this type of fault.

**Appendix II**

The following page is a full size version of the logarithmic nomograph described earlier in this paper.

**Full size version of the Logarithmic Nomograph.**



## References

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