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IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers

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of the
IEEE Power Engineering Society**

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Abstract: Detailed procedures for analyzing gas from gas spaces or gas-collecting devices as well as gas dissolved in oil are described. The procedures cover: (1) the calibration and use of field instruments for detecting and estimating the amount of combustible gases present in gas blankets above oil, or in gas detector relays; (2) the use of fixed instruments for detecting and determining the quantity of combustible gases present in gas-blanketed equipment; (3) obtaining samples of gas and oil from the transformer for laboratory analysis; (4) laboratory methods for analyzing the gas blanket and the gases extracted from the oil; and (5) interpreting the results in terms of transformer serviceability. The intent is to provide the operator with positive and useful information concerning the serviceability of the equipment. An extensive bibliography on gas evolution, detection, and interpretation is included.

Keywords: gas analysis, oil, oil-filled transformers, transformers

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IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers

1. Introduction

The detection of certain gases generated in an oil-filled transformer in service is frequently the first available indication of a malfunction that may eventually lead to failure if not corrected. Arcing, corona discharge, low-energy sparking, severe overloading, pump motor failure, and overheating in the insulation system are some of the possible mechanisms. These conditions occurring singly, or as several simultaneous events, can result in decomposition of the insulating materials and the formation of various combustible and noncombustible gases. Normal operation will also result in the formation of some gases. In fact, it is possible for some transformers to operate throughout their useful life with substantial quantities of combustible gases present. Operating a transformer with large quantities of combustible gas present is not a normal occurrence but it does happen, usually after some degree of investigation and an evaluation of the possible risk.

In a transformer, generated gases can be found dissolved in the insulating oil, in the gas blanket above the oil, or in gas collecting devices. The detection of an abnormal condition requires an evaluation of the amount of generated gas present and the continuing rate of generation. Some indication of the source of the gases and the kind of insulation involved may be gained by determining the composition of the generated gases.

1.1 Scope

This guide applies to mineral-oil-immersed transformers and addresses:

- 1) The theory of combustible gas generation in a transformer
- 2) The interpretation of gas analysis
- 3) Suggested operating procedures
- 4) Various diagnostic techniques, such as key gases, Dornenberg ratios, and Rogers ratios
- 5) Instruments for detecting and determining the amount of combustible gases present
- 6) A bibliography of related literature

1.2 Limitations

Many techniques for the detection and the measurement of gases have been established. However, it must be recognized that analysis of these gases and interpretation of their significance is at this time not a science, but an art subject to variability. Their presence and quantity are dependent on equipment variables such as type, location, and temperature of the fault; solubility and degree of saturation of various gases in oil; the type of oil preservation system; the type and rate of oil circulation; the kinds of material in contact with the fault; and finally, variables associated with the sampling and measuring procedures themselves. Because of the variability of acceptable gas limits and the significance of various gases and generation rates, a consensus is difficult to obtain. The principal obstacle in the development of fault interpretation as an exact science is the lack of positive correlation of the fault-identifying gases with faults found in actual transformers.

The result of various ASTM testing round robins indicates that the analytical procedures for gas analysis are difficult, have poor precision, and can be wildly inaccurate, especially between laboratories. A replicate analysis confirming a diagnosis should be made before taking any major action.

This guide is, in general, an advisory document. It provides guidance on specific methods and procedures to assist the transformer operator in deciding on the status and continued operation of a transformer that exhibits combustible gas formation. However, operators must be cautioned that, although the physical reasons for gas formation have a firm technical basis, interpretation of that data in terms of the specific cause or causes is not an exact science, but is the result of empirical evidence from which rules for interpretation have been derived. Hence, exact causes or conditions within transformers may not be inferred from the various procedures. The continued application of the rules and limits in this guide, accompanied by actual confirmation of the causes of gas formation, will result in continued refinement and improvement in the correlation of the rules and limits for interpretation.

Individual experience with this guide will assist the operators in determining the best procedure, or combination of procedures, for each specific case. Some of the factors involved in the decision of the operator are: the type of oil preservation system, the type and frequency of the sampling program, and the analytical facilities available. However, whether used separately or as complements to one another, the procedures disclosed in this guide all provide the operator with positive and useful information concerning the serviceability of the equipment.

1.3 References

The following references should be used in conjunction with this guide:

- [1] ASTM D2945-90, Test Methods for Gas Content of Insulating Oils.¹
- [2] ASTM D3305-84 (Reaff. 89), Method for Sampling Gas from a Transformer.
- [3] ASTM D3612-90, Test Methods for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography.
- [4] ASTM D3613-87, Methods for Sampling Electrical Insulating Oils for Gas Analysis and Determination of Water Content.

1.4 Definitions

The following definitions of terms are used in this guide:

¹ASTM publications are available from the Customer Service Department, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103, USA.

key gases: Gases generated in oil-filled transformers that can be used for qualitative determination of fault types, based on which gases are typical or predominant at various temperatures.

partial discharge: An electric discharge that only partially bridges the insulation between conductors, and that may or may not to the conductor.

TCG: Total combustible gas.

TDCG: Total dissolved combustible gas.

2. General Theory

The two principal causes of gas formation within an operating transformer are thermal and electrical disturbances. Conductor losses due to loading produce gases from thermal decomposition of the associated oil and solid insulation. Gases are also produced from the decomposition of oil and insulation exposed to arc temperatures. Generally, where decomposition gases are formed principally by ionic bombardment, there is little or no heat associated with low-energy discharges and corona.

2.1 Cellulosic Decomposition

The thermal decomposition of oil-impregnated cellulose insulation produces carbon oxides (CO , CO_2) and some hydrogen or methane (H_2 , CH_4) due to the oil (CO_2 is not a combustible gas). The rate at which they are produced depends exponentially on the temperature and directly on the volume of material at that temperature. Because of the volume effect, a large, heated volume of insulation at moderate temperature will produce the same quantity of gas as a smaller volume at a higher temperature.

2.2 Oil Decomposition

Mineral transformer oils are mixtures of many different hydrocarbon molecules, and the decomposition processes for these hydrocarbons in thermal or electrical faults are complex. The fundamental steps are the breaking of carbon-hydrogen and carbon-carbon bonds. Active hydrogen atoms and hydrocarbon fragments are formed. These free radicals can combine with each other to form gases, molecular hydrogen, methane, ethane, etc., or can recombine to form new, condensable molecules. Further decomposition and rearrangement processes lead to the formation of products such as ethylene and acetylene and, in the extreme, to modestly hydrogenated carbon in particulate form. These processes are dependent on the presence of individual hydrocarbons, on the distribution of energy and temperature in the neighborhood of the fault, and on the time during which the oil is thermally or electrically stressed. These reactions occur stoichiometrically; therefore, the specific degradations of the transformer oil hydrocarbon ensembles and the fault conditions cannot be predicted reliably from chemical kinetic considerations. An alternative approach is to assume that all hydrocarbons in the oil are decomposed into the same products and that each product is in equilibrium with all the others. Thermodynamic models permit calculation of the partial pressure of each gaseous product as a function of temperature, using known equilibrium constants for the relevant decomposition reactions. An example of the results of this approach is shown in Fig 1 due to Halstead. The quantity of hydrogen formed is relatively high and insensitive to temperature; formation of acetylene becomes appreciable only at temperatures nearing 1000 °C. Formation of methane, ethane, and ethylene each also have unique dependences on temperature in the model. The thermodynamic approach has limits; it must assume an idealized but nonexistent isothermal equilibrium in the region of a fault, and there is no provision for dealing with multiple faults in a transformer. However, the concentrations of the individual gases actually found in a transformer can be used directly or in ratios to estimate the thermal history of the oil in the transformer from a model and to adduce any past or potential faults on the unit. As the simplest example: the presence of acetylene suggests a high temperature fault, perhaps an arc, has occurred in the oil in a transformer; the presence of methane suggests that—if a fault has occurred—it is a lower energy electrical or thermal fault. Much work has been done to correlate predictions from thermodynamic models with actual behavior of transformers.

2.3 Application to Equipment

All transformers generate gases to some extent at normal operating temperatures. But occasionally a gas-generating abnormality does occur within an operating transformer such as a local or general overheating, dielectric problems, or a combination of these. In electrical equipment, these abnormalities are called "faults." Thermal, corona, and arcing faults are described in 3.1, 3.2, and 3.3. Internal faults in oil produce the gaseous byproducts hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6). When cellulose is involved, the faults produce methane (CH_4), hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2). Each of these types of faults produce certain gases that are generally combustible. The total of all combustible gases may indicate the existence of any one, or a combination, of thermal, electrical, or corona faults. Certain combinations of each of the separate gases determined by chromatography are unique for different fault temperatures. Also, the ratios of certain key gases have been found to suggest fault types. Interpretation by the individual gases can become difficult when there is more than one fault, or when one type of fault progresses to another type, such as an electrical problem developing from a thermal one.

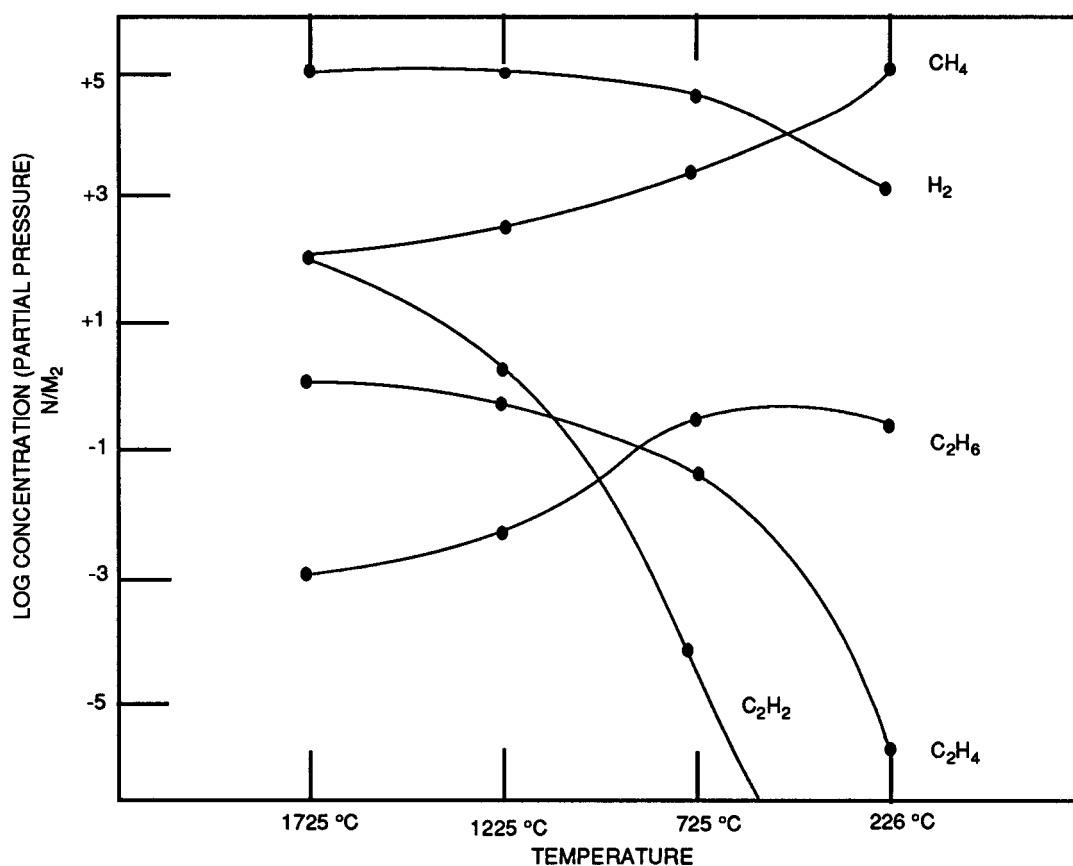


Figure 1— Halstead's Thermal Equilibrium Partial Pressures as a Function of Temperature

Attempts to assign greater significance to gas than justified by the natural variability of the generating and measuring events themselves will lead to gross errors in interpretation. However, in spite these gas-generating mechanisms are the only existing basis for the analytical rules and procedures developed in this guide. In fact, it is known that some transformers continue to operate for many years in spite of above average rates of gas generation.

2.4 Establishing Baseline Data

Establishing a reference point for gas concentration in new or repaired transformers and following this with a routine monitoring program is a key element in the application of this guide. Monitoring the health (serviceability) of a transformer must be done on a routine basis and can start anytime, not just for new units.

Generally, daily or weekly sampling is recommended after start-up, followed by monthly or longer intervals. Routine sampling intervals may vary depending on application and individual system requirements. For example, some utilities sample generator step-up (GSU) transformers four to six times a year, units rated over 138 kV twice a year, and some 765 kV units are sampled monthly.

2.5 Recognition of a Gassing Problem—Establishing Operating Priorities

Much information has been acquired over the past 20 years on diagnosing incipient fault conditions in transformer systems. This information is of a general nature but is often applied to very specific problems or situations. One consistent finding with all schemes for interpreting gas analysis is that the more information available concerning the history of the transformer and test data, the greater the probability for a correct diagnosis of the health of the unit.

A number of simple schemes employing principal gases or programs using ratios of key gases have been employed for providing a tentative diagnosis when previous information is unavailable or indicated no fault condition existed. Principal gas or ratio methods require detectable or minimum levels of gases to be presents or norms to be exceeded, before they can provide a useful diagnosis.

3. Interpretation of Gas Analysis

3.1 Thermal Faults

Referring to Fig 1, the decomposition of mineral oil from 150 °C to 500 °C produces relatively large quantities of the low molecular weight gases, such as hydrogen (H_2) and methane (CH_4), and trace quantities of the higher molecular weight gases ethylene (C_2H_4) and ethane (C_2H_6). As the fault temperature in mineral oil increases to modest temperatures, the hydrogen concentration exceeds that of methane, but now the temperatures are accompanied by significant quantities of higher molecular weight gases, first ethane and then ethylene. At the upper end of the thermal fault range, increasing quantities of hydrogen and ethylene and traces of acetylene (C_2H_2) may be produced. In contrast with the thermal decomposition of oil, the thermal decomposition of cellulose and other solid insulation produces carbon monoxide (CO), carbon dioxide (CO_2), and water vapor at temperatures much lower than that for decomposition of oil and at rates exponentially proportional to the temperature. Because the paper begins to degrade at lower temperatures than the oil, its gaseous byproducts are found at normal operating temperatures in the transformer. A GSU transformer, for example, that operates at or near nameplate rating will normally generate several hundred parts per million (ppm) of CO and several thousand parts per million of CO_2 without excessive hot spots.

The ratio of CO_2/CO is sometimes used as an indicator of the thermal decomposition of cellulose. This ratio is normally more than seven. For the CO_2/CO ratio, the respective values of CO_2 and CO should exceed 5000 ppm and 500 ppm in order to improve the certainty factor, i.e., ratios are sensitive to minimum values. As the magnitude of CO increases, the ratio of CO_2/CO decreases. This may indicate an abnormality that is degrading cellulosic insulation.

3.2 Electrical Faults—Low Intensity Discharges

Referring to Fig 1, low intensity discharges such as partial discharges and very low level intermittent arcing produce mainly hydrogen, with decreasing quantities of methane and trace quantities of acetylene. As the intensity of the discharge increases, the acetylene and ethylene concentrations rise significantly (see Table 6).