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

IEEE Power Engineering Society

Sponsored by the
Transformers Committee

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IEEE Power Engineering Society

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Abstract: This guide is intended to apply to silicone-immersed transformers for which the silicone fluid was the fluid supplied when the transformer was originally manufactured. It does not address transformers that have been retro-filled. The theory of combustible gas generation in a silicone-filled transformer, recommended procedures for sampling and analysis, recommended actions based on the interpretation of results, and a bibliography of related literature are addressed in this guide.

Keywords: dissolved gas analysis, silicone

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Introduction

This introduction is not part of IEEE Std C57.146-2005, IEEE Guide for the Interpretation of Gases Generated in Silicone-Immersed Transformers.

Since its introduction in 1974, silicone dielectric fluid has become widely accepted in power and distribution transformers. As the number of in-service transformers grows and their average age increases, the need for early detection of incipient fault conditions becomes more important.

Experience has shown that the detection of certain gases generated in a mineral-oil-filled transformer is frequently the first available indication of an abnormal condition that, if not corrected, may eventually lead to failure. To apply this predictive capability to silicone-immersed transformers, work has been done to understand how their gassing characteristics relate to mineral-oil-immersed transformers.

In a silicone-immersed transformer, generated gases can be found dissolved in the fluid or in the gas blanket above the fluid. The detection of an abnormal condition requires an evaluation of the amounts and types of generated gas present and the continuing rate of generation. Some indication of the source of the gases and whether solid insulation is involved may be gained by determining the identity of the generated gases.

This guide was originally started in June of 1995 as IEEE P1258, Trial Use Guide for the Interpretation of Gases Generated in Silicone-Immersed Transformers. It was never published. This present version contains essentially all the same descriptions and procedures as the original version, with minor editing in order to comply with the latest IEEE style.

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

1. Overview

1.1 Scope

This guide is intended to apply to silicone-immersed transformers in which the silicone fluid was the fluid supplied when the transformer was originally manufactured. This guide also addresses the following:

- The theory of combustible gas generation in a silicone-filled transformer
- Recommended procedures for sampling and analysis
- Recommended actions based on the interpretation of results
- A bibliography of related literature

1.2 Purpose

The purpose of this guide is to assist the transformer operator in evaluating dissolved gas analysis (DGA) data obtained for silicone-filled transformers. Other techniques such as fixed instruments and gas space analysis may well have utility for silicone-filled units; however, due to a lack of data at this time, this guide will focus only on DGA.

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ASTM D 2945, Standard Test Method for Gas Content of Insulating Oils.[1]

ASTM D 3487, Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus.

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

ASTM D 3612, Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography.

ASTM D 3613, Standard Practice for Sampling Insulating Liquids for Gas Analysis and Determination of Water Content.

ASTM D 4652, Standard Specification for Silicone Fluid Used for Electrical Insulation.

3. Definitions, acronyms, and abbreviations

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B1][2] should be referenced for terms not defined in this clause.

3.1 Definitions

3.1.1 dissolved gas analysis (DGA): The extraction, detection, and quantification of gases dissolved in insulating fluid.

3.1.2 total combustible gas (TCG): The sum (in percent) of all combustible gases including carbon monoxide and excluding oxygen reported as a percent of the transformer gas space.

3.1.3 total dissolved combustible gas (TDCG): The sum of all combustible gases that are dissolved in the insulating fluid.

3.2 Acronyms and abbreviations

DGA	dissolved gas analysis
TCG	total combustible gas
TDCG	total dissolved combustible gas

4. General theory

4.1 General

Silicone fluids used in transformers are polydimethylsiloxane fluids, which are considerably different in composition than transformer mineral oils. Figure 1 shows a typical chemical structure. Although many of the gases generated under thermal and electrical stress are the same for mineral oils and silicone fluids, there are differences in proportions of these gases. As indicated in Table A.1, some gases have a different solubility in silicone fluid than in mineral oil. Annex B shows typical gas concentrations for the various conditions, which can generate fault gases in silicone-immersed transformers. Thus, different concentrations of those gases would be expected in the silicone fluid than in mineral oil.

[2] The numbers in brackets correspond to those of the bibliography in Annex D.

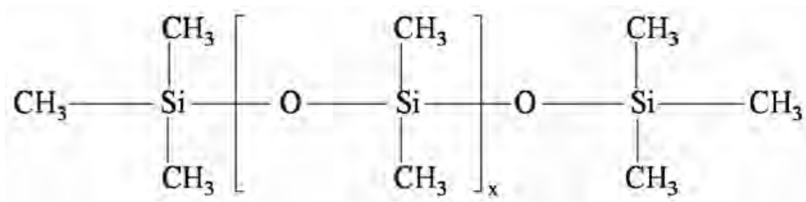

Figure 1—Chemical structure of silicone transformer fluid (50cS), polydimethylsiloxane

4.2 Causes of gas formation

The two principal causes of gas formation within an operating transformer are thermal and electrical stresses. Abnormally high conductor temperatures produce gases from thermal decomposition of the silicone fluid and solid insulation. Gases are also produced from decomposition of the silicone fluid and solid insulation exposed to partial discharge activity and the high temperatures associated with an electrical arc.

4.2.1 Fluid thermal decomposition

Overheating of silicone fluid results in partial degradation of the fluid and generation of low molecular weight gases. Gas composition is dependent on the dissolved oxygen content in the silicone fluid, the proximity of bare copper, and temperature. As the concentration of dissolved oxygen increases, methane (CH_4) production decreases and small amounts of hydrogen (H_2), carbon monoxide (CO), and ethylene (C_2H_4) are also generated. If the silicone fluid contains a high concentration of dissolved oxygen, large volumes of both carbon monoxide and carbon dioxide (CO_2) will be generated. Minor components include methane and ethylene. In-service silicone fluid typically contains dissolved oxygen. Even though dissolved oxygen is present, overheating of silicone fluids in the presence of bare copper results in the production of predominantly methane.

4.2.2 Cellulosic thermal decomposition

Overheating of cellulosic insulation in a silicone-immersed transformer will result in the production of both carbon monoxide and carbon dioxide. The ratio of carbon monoxide to carbon dioxide is temperature dependent. Hydrocarbon gases are not usually generated in significant quantities from the cellulosic insulation alone, and therefore the absence of these gases may help distinguish between overheating of the silicone fluid and overheating of the cellulosic insulation.

Cellulose degradation products such as 2-furfuraldehyde and other furan derivatives, which are soluble in the silicone fluid, may provide useful information about cellulose decomposition. This analysis can determine when solid or fluid insulation, or both, have been subject to overheating.

4.2.3 Partial discharge decomposition

Hydrogen and methane are the predominant gases generated by partial discharges in a silicone-immersed transformer. Small amounts of carbon monoxide, acetylene, and ethane may also be generated.

4.2.4 Electrical arcing decomposition

The major gases generated during arcing in a silicone-immersed transformer are hydrogen, methane, carbon monoxide, and low levels of acetylene. The gases generated from the silicone fluid contain a much greater ratio of hydrogen to acetylene in comparison to the gases generated from a mineral-oil-filled transformer. The presence of any amount of acetylene in a silicone-immersed transformer may be an indication of a potentially serious problem.

4.3 Application to equipment

All silicone-immersed transformers generate gases to some extent at normal operating temperatures. Occasionally, a gas generating abnormality occurs within an operating transformer such as local or general overheating, dielectric problems, or a combination of these. In electrical equipment, these abnormalities are called “faults.” The various types of conditions and faults are described in 4.2.1 through 4.2.4. The various fault types 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 or electrical faults. Interpretation of the individual gases can become difficult when there is more than one fault, or when one type of fault progresses to another fault type, such as an electrical problem developing from a thermal problem.

Attempts to assign greater significance to gas measurements than justified by the natural variability of the generating and measuring events themselves could lead to errors in interpretation. However, in spite of these limitations, these gas-generating mechanisms are the only existing basis for the analytical rules and procedures developed in this guide.

4.4 Establishing baseline data

The use of the procedures outlined in this guide presumes that the operator has no previous data or history from which to make an informed operating decision. Therefore, establishing a benchmark for gas concentrations in new, repaired, or operating transformers and following with a routine monitoring program is a key element in the application of this guide.

When a transformer is first placed in service, weekly or monthly sampling is recommended, followed by longer intervals, such as yearly. In addition, the transformer should be resampled before the end of the warranty period. The length of the sampling interval should be based on previous experience and good engineering judgment. Ultimately, the choice of the sampling program is the responsibility of the operator.

4.5 Recognition of a gassing problem

Information has been acquired over the past several years in an attempt to diagnose incipient fault conditions in silicone-immersed transformers. This information is of a general nature and 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.

Schemes employing key gases or relative proportions of key gases have been employed for providing a tentative diagnosis when previous information is either unavailable or indicated no fault condition existed. Key gas methods require detectable or minimum levels of gases to be present, or norms to be exceeded, before they can provide a useful diagnosis.

5. Procedures for obtaining samples of silicone liquid from the transformer and for laboratory analysis

5.1 Sampling of silicone liquid

All samples of silicone fluid from electrical apparatus being taken for the purpose of dissolved gas-in-oil analysis should be taken in accordance with the latest edition of ASTM D 3613.[3]

[3] For information on references, see Clause 2.

5.2 Determination of total dissolved gas

Determination of total dissolved gas should be made in accordance with ASTM D 2945 or ASTM D 3612.

5.3 Determination of individual dissolved gases

Determination of the individual dissolved gases should be made in accordance with ASTM D 3612. Table A.1, a comparison of gas solubilities in silicone and oil, is included in Annex A for reference.

6. Suggested operating procedures utilizing the detection and analysis of combustible gases

6.1 General

From an operational point of view, it is important to establish the following priorities:

a) *Detection*—Detect the generation of any gases that exceed threshold values and utilize appropriate guidelines so the possible abnormality may be recognized at the earliest possible time in order to minimize damage or avoid a failure.

b) *Evaluation*—Evaluate the implications of the measured gas levels on the serviceability of the transformer, using a set of guidelines or recommendations.

c) *Action*—Take the recommended action, beginning with increased surveillance and confirming or supplementary analysis and leading to either a determination of load sensitivity, reducing the load on the transformer, or actually removing the unit from service.

An operating procedure utilizing the gas data should be developed immediately following the initial detection of combustible gases. Figure 2 is a flowchart for the suggested process from the initial detection of combustible gas to the final assessment of the status of the transformer.

6.2 Evaluation of transformer condition using individual and TDCG concentrations

It can be difficult to determine whether a transformer is behaving normally if it has no previous dissolved gas history. Also, considerable differences of opinion exist for what is considered a “normal transformer” with acceptable concentrations of gases.

For cases when there is no previous dissolved gas history, a threshold level has been developed to indicate if the transformer is operating satisfactorily. The threshold levels apply to both concentrations of separate gases and the total concentration of all combustible gases. Results exceeding threshold levels should prompt additional investigation. Proceed as given in Figure 2. Action should be taken to compare results and establish a trend. Fault(s) may be present. Annex B may be useful in determining the nature of the fault.

Table 1 lists the threshold level dissolved gas concentrations for the individual gases and TDCG. This table is used to make the original assessment of a gassing condition on a new or recently repaired transformer or is used if there are no previous tests on the transformer for dissolved gases or if there is no recent history. Users of this guide are advised that the dissolved gas concentrations contained in Table 1 are consensus values based on the limited experiences of laboratories performing these tests. The transformer operator may decide to use different dissolved gas concentrations for the individual gases (particularly acetylene) and TDCG based on engineering judgment and experience with other similar transformers.

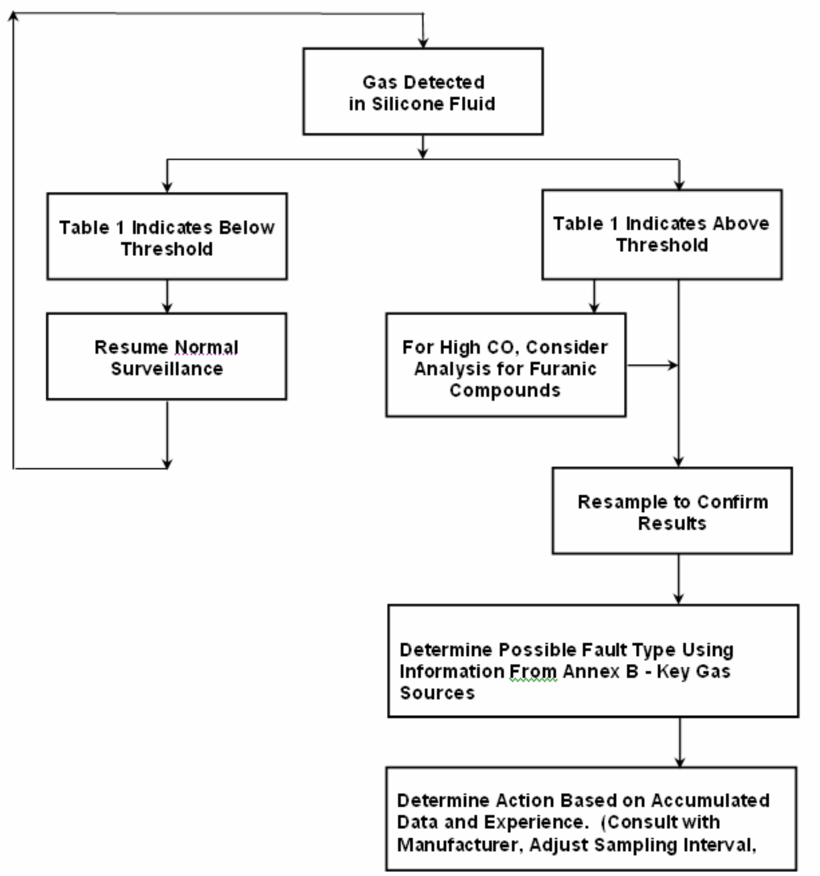

Figure 2—Flowchart of suggested operating procedure utilizing the detection and analysis of combustible gases in silicone-immersed transformers

The condition for a particular transformer is determined by comparing measured levels for individual gases or the TDCG with the threshold values in Table 1. An example of the use of this method is included in Annex C.

Table 1—Dissolved gas concentration threshold levels (ppm[a])[4]

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG[b]
Threshold level (ppm)	200	100	1	30	30	3 000	30 000	3 361

NOTE 1—Table 1 assumes that no previous tests on the transformer for DGA have been made or that no recent history exists. If a previous analysis exists, it should be reviewed to determine if the situation is stable or unstable.

NOTE 2—There have been no round-robin studies to determine the variability in test results in silicone fluid. However, an ASTM round-robin study indicated variability in mineral oil gas analysis between labs. Variability should be considered when having gas analysis made by different labs.

[a] The numbers shown in Table 1 are in parts of gas per million parts of fluid (ppm) volumetrically and are based on limited field data and laboratory experiments. Transformers may contain combustible gases because of the operation of internal expulsion fuses or load-break switches. The threshold levels in Table 1 are also not applicable to other apparatus in which load-break switches operate under the fluid.
[b] The TDCG value does not include carbon dioxide, which is not a combustible gas.

[4] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

6.3 Determining the operating procedure and sampling interval from the TDCG levels

When sudden increases in the dissolved gas content of the silicone fluid in operating transformers occur and an internal fault is suspected, an increasing gas generation rate indicates a problem of increasing severity; therefore, a shorter sampling interval is recommended.

Once the source of gassing is determined by analysis, inspection, consultation, (or combinations thereof), and the risk has been assessed, then engineering judgment should be applied to determine the final sampling interval and operating procedure.

6.4 Evaluation of possible fault type by the key gas method

The preceding discussion of the dependence on temperature of the types of silicone fluid and cellulose decomposition gases provides the basis for the qualitative determination of fault types from the gases that are typical, or predominant, at various temperatures. These significant gases and proportions are called “key gases.” Figure B.1 through Figure B.4 indicate average results of small- and large-scale experiments of several studies performed on silicone fluids. These determine the “key gases” and relative proportions for the four general fault types.

Annex A

(informative)

Gas solubility

Table A.1—Ostwald solubility coefficients for silicone fluid and mineral oil

Component gas	Ostwald solubility[a] coefficient (K) (See NOTE 1)	
	Silicone fluid	Mineral oil
Hydrogen (H_2)	0.057	0.0429
Nitrogen (N_2)	0.143	0.0745
Carbon monoxide (CO)	0.096	0.102
Oxygen (O_2)	0.175	0.138
Methane (CH_4)	0.514	0.337
Carbon dioxide (CO_2)	1.401	0.900
Acetylene (C_2H_2)	(See NOTE 2)	0.938
Ethylene (C_2H_4)	(See NOTE 2)	1.35
Ethane (C_2H_6)	(See NOTE 2)	1.99
NOTE 1—The Ostwald coefficient values shown in this table are for a silicone transformer fluid meeting the requirements of ASTM D 4652 and an oil meeting the specification of ASTM D 3487, and having a density of 0.880, measured at 25 ºC, and one atmosphere. NOTE 2—Values have not been determined experimentally.		

[a] Values have not been determined experimentally.

Annex B

(informative)

Key gas sources—based on averages from small- and large-scale experiments

B.1 Thermal fluid

Decomposition products include carbon monoxide, carbon dioxide, and methane, together with smaller quantities of hydrogen and ethane. See Figure B.1. Traces of other hydrocarbons may be formed. The principal gas is carbon monoxide. Oxygen must be present to form carbon oxides, and fluid in transformers with higher levels of oxygen will tend to produce more carbon oxides. With lower levels of oxygen, the decomposition process favors methane.

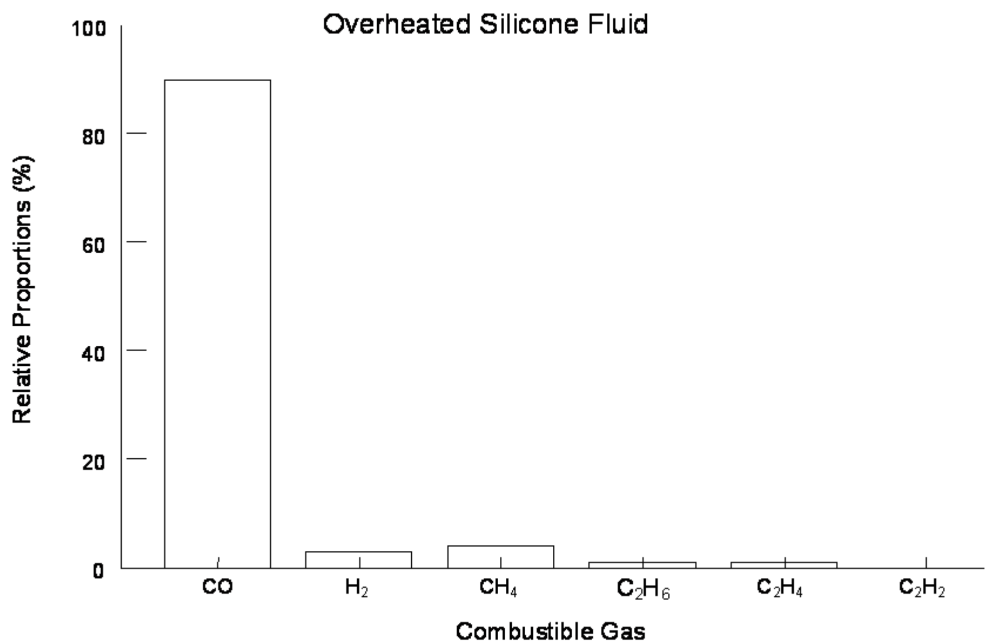

Figure B.1—Thermal fluid

B.2 Thermal cellulose

Large quantities of carbon dioxide and carbon monoxide are evolved from overheated cellulose. See Figure B.2. The principal gas is carbon monoxide.

B.3 Electrical partial discharge

Low-energy electrical discharges produce hydrogen and methane, with small quantities of carbon monoxide, acetylene, ethylene, and ethane. See Figure B.3. The principal gas is hydrogen.

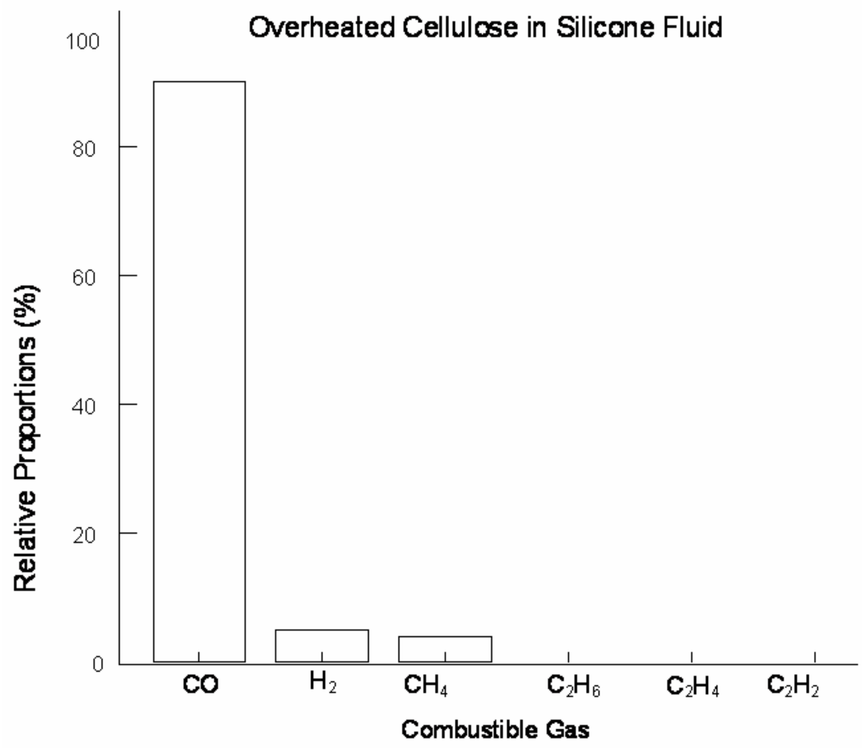

Figure B.2—Thermal cellulose

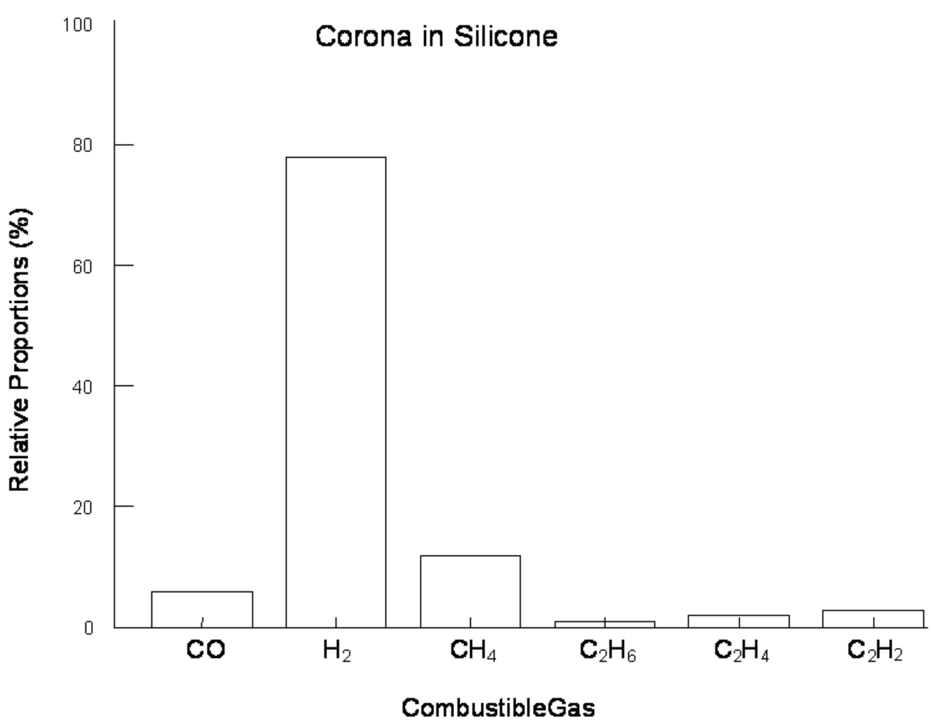

Figure B.3—Electrical partial discharge

B.4 Electrical arcing

Large amounts of hydrogen and acetylene are produced, with minor quantities of methane and ethylene, carbon dioxide and carbon monoxide. See Figure B.4. The principal gas is acetylene. As arc energy increases, so does the ratio of acetylene to hydrogen.

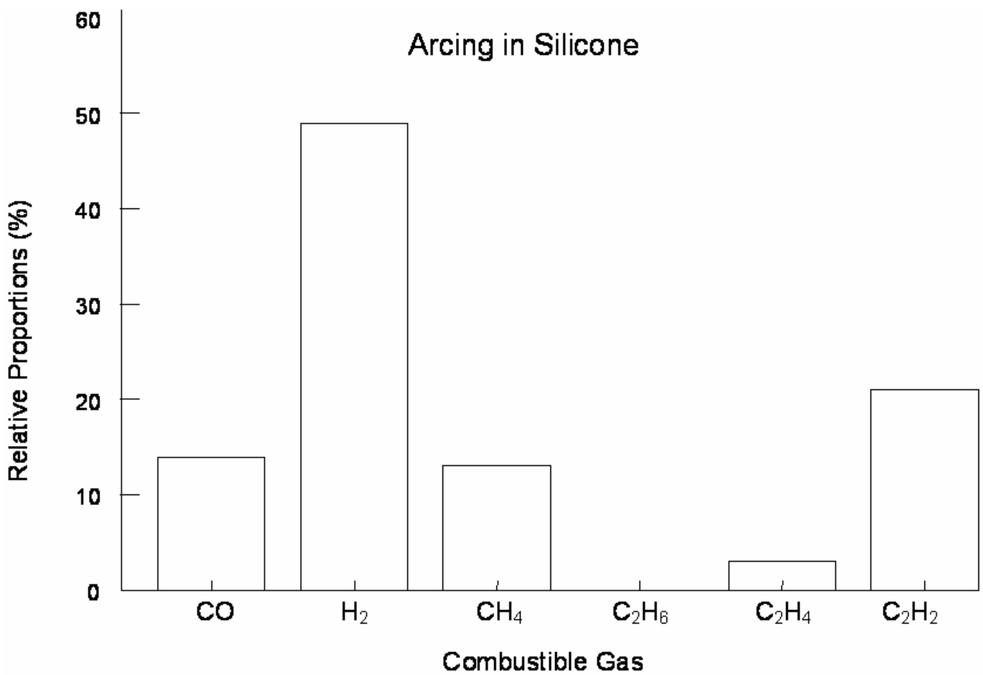

Figure B.4—Electrical arcing

Annex C

(informative)

Example

The following is an example of the use of this procedure.

A 3500 kVA silicone-immersed transformer was sampled and analyzed after about three years of service. No previous baseline data were available. The test record showed the following results:

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	TDCG	CO_2	O_2
ppm	0	8	0	2	2	277	289	1562	2096

These results indicated a normal transformer. None of the key gas or TDCG levels exceeded the threshold values. Approximately 13 months later, a problem was suspected in the unit. The unit was sampled again. The test results follow:

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	TDCG	CO_2	O_2
ppm	54 800	2 790	448	308	39	3 190	61 575	8 650	26 200

The results indicate every key gas as well as the TDCG being well above the threshold values. This unit was scheduled and planned for an orderly shutdown. Inspection revealed arcing activity in one winding, which was rewound. An in-service failure may have been avoided.

Another consideration is that acetylene may be generated from two different fault conditions, i.e., partial discharge (low-energy discharge) or arcing. In the case of partial discharge, very low concentrations of acetylene will be generated relative to hydrogen. This could be a cause for concern even though the TDCG is not abnormally high. The most severe condition is arcing. When high-energy arcing occurs, the ratio of acetylene to hydrogen is higher. An active arcing condition requires immediate attention. Testing indicates that this ratio increases with increases in arcing energy.

Annex D

(informative)

Bibliography

[B1] IEEE 100™, *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition.[5, 6]

[B2] IEEE Std C57.104™-1991, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.

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