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

STANDARDS

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std C57.104™-2019
(Revision of IEEE Std C57.104-2008)

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

IEEE Std C57.104™-2019
(Revision of IEEE Std C57.104-2008)

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

Developed by the

Transformers Committee
of the
IEEE Power and Energy Society

Approved 13 June 2019

IEEE SA Standards Board

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Abstract: Detailed procedures for interpreting Dissolved Gas Analysis results are described in this guide. The document details: 1) Overview of gas generation in transformer and DGA process; 2) The purpose and application of DGA; 3) DGA quality verification and DGA limitations; 4) DGA interpretation and norms; 5) Fault type definitions and identification; 6) Case studies and interpretation example. The intent is to provide the operator with useful information concerning the serviceability of the equipment. An extensive bibliography on gas evolution, detection, and interpretation is included.

Keywords: DGA, gas analysis, IEEE C57.104™, mineral oil, mineral oil-immersed transformers, transformers

---

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2019 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 1 November 2019. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-1-5044-5973-0 STD23756
Print: ISBN 978-1-5044-5974-7 STDPD23756

IEEE prohibits discrimination, harassment, and bullying.
For more information, visit http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html.
No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading "Important Notices and Disclaimers Concerning IEEE Standards Documents." They can also be obtained on request from IEEE or viewed at http://standards.ieee.org/ipr/disclaimers.html.

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association ("IEEE-SA") Standards Board. IEEE ("the Institute") develops its standards through a consensus development process, approved by the American National Standards Institute ("ANSI"), which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed through scientific, academic, and industry-based technical working groups. Volunteers in IEEE working groups are not necessarily members of the Institute and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to: results; and workmanlike effort. IEEE standards documents are supplied "AS IS" and "WITH ALL FAULTS."

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SAStandards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in revisions to an IEEE standard is welcome to join the relevant IEEE working group.

Comments on standards should be submitted to the following address:

Secretary, IEEE SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854 USA

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under U.S. and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Photocopies

Subject to payment of the appropriate fee, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. A current IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every ten years. When a document is more than ten years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit IEEE Xplore at http://ieeexplore.ieee.org/ or contact IEEE at the address listed previously. For more information about the IEEE SAor IEEE's standards development process, visit the IEEE SAWebsite at http://standards.ieee.org.

Errata

Errata, if any, for all IEEE standards can be accessed on the IEEE SAWebsite at the following URL: http://standards.ieee.org/findstds/errata/index.html. Users are encouraged to check this URL for errata periodically.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SAWebsite at http://standards.ieee.org/about/sasb/patcom/patents.html. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Participants

At the time this IEEE guide was completed, the Insulating Fluids—DGA Guide Working Group had the following membership:

Claude Beauchemin, *Chair*
Don Platts and **Norman A. Field**, *Vice Chairs*
Susan McNelly, *Secretary*

William Boettger
Paul Boman
Stephan Brauer
Juan Castellanos
Jonathan Cheatham
Muhammad Ali Masood Cheema
Luiz Cheim
Larry Christodoulou
C. Clair Claiborne
Paul Cox
John Crouse
Frank Damico
Stephanie Denzer
Paul Dolloff
Don Dorris
Lee Doyle
James Dukarm
Michel Duval
James Fairris
Roger Fenton
Marcos Ferreira
George Forrest
George Frimpong
Rainer Frotscher
Shawn Galbraith
James Gardner
Jeffrey Golarz
David Hanson
Roger Hayes
Thang Hochanh
John John
Arvin Joshi
Zan Kiparizoski
Michael Lau
Kumar Mani
Terence Martin
Douglas McCullough
James McIver
Hali Moleski
Emilio Morales-Cruz
Jerry Murphy
David Murray
Paul Mushill
Ali Naderian
Joe Nims
Jayme Nunes Jr.
Arturo Nunez
Poorvi Patel
Nicholas Perjanik
Branimir Petosic
Oscar Pinon
Thomas Prevost
John Pruente
Jimmy Rasco
Robert Rasor
Jeffrey Ray
Scott Reed
Oleg Roizman
Mickel Saad
Pugazhenthi Selvaraj
Mark Shem-Tov
Richard Simonelli
Sanjib Som
Brian Sparling
Kevin Sullivan
Charles Sweetser
James Thompson
Robert Thompson
Alwyn VanderWalt
Michel Veillette
David Wallach
Evanne Wang
Daniel Weyer
Trenton Williams
Deanna Woods
Kwasi Yeboah

In addition, the following members have participated in ballot resolution:

Paul Boman
Muhammad Ali Masood Cheema
Luiz Cheim
Don Dorris
James Dukarm
Michel Duval
Marcos Ferreira
Kumar Mani
Hali Moleski
Jerry Murphy
Arturo Nunez
Thomas Prevost
Brian Sparling
David Wallach

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

Saleman Alibhay
Tauhid Haque Ansari
Stephen Antosz
Donald Ayers
Peter Balma
Thomas Barnes
Barry Beaster
Robert Beavers
W.J. (Bill) Bergman
Enrique Betancourt
Wallace Binder
Thomas Bishop
Thomas Blackburn
William Bloethe
William Boettger
Paul Boman
Stephan Brauer
Gustavo Brunello
Demetrio Bucaneg Jr.
Thomas Callsen
Paul Cardinal
Juan Castellanos
Donald Cherry
Michael Chirico
Kurt Clemente
Craig Colopy
Stephen Conrad

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Jerry Corkran
John Crouse
Willaim Darovny
Glenn Davis
Stephanie Denzer
Scott Digby
Dieter Dohnal
Gary Donner
James Dukarm
Donald Dunn
James Fairris
Jorge Fernandez Daher
Norman A. Field
Hugo Flores
Joseph Foldi
George Forrest
Bruce Forsyth
George Frimpong
Robert Ganser
Eduardo Garcia
Ramsis Girgis
Jalal Gohari
Edwin Goodwin
James Graham
William Griesacker
Randall Groves
Said Hachichi
John Harley
Roger Hayes
Thang Hochanh
Werner Hoelzl
Philip Hopkinson
Richard Jackson
John John
Laszlo Kadar
Innocent Kamwa
John Kay
Peter Kelly
Gael Kennedy
Sheldon Kennedy
Isidoro Kerszenbaum
Gary King
James Kinney
Zan Kiparizoski
Axel Kraemer
Alexander Kraetge
Neil Kranich
Jim Kulchisky
John Lackey
Donald Lamontagne
Benjamin Lanz
Michael Lauxman
Aleksandr Levin
Weijun Li
Thomas Lundquist
Kumar Mani
Richard Marek
J. Dennis Marlow
Lee Matthews
Omar Mazzoni
James McBride
William McBride
Mark McNally
Susan McNelly
Charles McShane
Joseph Melanson
Daniel Mulkey
Jerry Murphy
David Murray
Paul Mushill
Ali Naderian Jahromi
K.R.M. Nair
Arthur Neubauer
Joe Nims
Lorraine Padden
Bansi Patel
Dhiru Patel
Paulette Payne Powell
Brian Penny
Howard Penrose
Christopher Petrola
Ugo Piovan
Don Platts
Alvaro Portillo
Bertrand Poulin
Tom Prevost
Jimmy Rasco
Lakshman Raut
Timothy Charles Raymond
Scott Reed
Jean-Christophe Riboud
Johannes Rickmann
John Roach
Diego Robalino
Oleg Roizman
Zoltan Roman
Rodrigo Ronchi
Ryandi Ryandi
Daniel Sabin
Dinesh Sankarakurup
Daniel Sauer
Roderick Sauls
Bartien Sayogo
Stephen Schroeder
Ewald Schweiger
Hemchandra Shertukde
Suresh Shrimavle
Hyeong Sim
Richard Simonelli
Jerry Smith
Gary Smullin
Steve Snyder
Sanjib Som
Brian Sparling
Thomas Spitzer
Craig Stiegemeier
Gary Stoedter
Allan St Peter
Charles Sweetser
Susmitha Tarlapally
Ed TeNyenhuis
Juan Thierry
James Thompson
Michael Thompson
Robert Thompson
Ryan Thompson
James Van De Ligt
Alwyn Van DerWalt
Jason Varnell
Gerald Vaughn
Roger Verdolin
John Vergis
Jane Verner
Loren Wagenaar
David Walker
David Wallace
David Wallach
Haifei Wang
Daniel Ward
Joe Watson
Kenneth White
Deanna Woods
Luis Zambrano
Shibao Zhang
Peter Zhao
Leo Zibert
Waldemar Ziomek

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

When the IEEE SA Standards Board approved this guide on 13 June 2019, it had the following membership:

Garu Hoffman, *Chair*
Ted Burse, *Vice Chair*
Jean-Philippe Faure, *Past Chair*
Konstantinos Karachalios, *Secretary*

Masayuki Ariyoshi
Stephen D. Dukes
J. Travis Griffith
Guido Hiertz
Christel Hunter
Joseph L. Koepfinger*
Thomas Koshy
John D. Kulick
David J. Law
Joseph Levy
Howard Li
Xiaohui Liu
Kevin Lu
Daleep Mohla
Andrew Myles
Annette D. Reilly
Dorothy Stanley
Sha Wei
Phil Wennblom
Philip Winston
Howard Wolfman
Feng Wu
Jingyi Zhou

*Member Emeritus

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Introduction

This introduction is not part of IEEE Std C57.104-2019, IEEE Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers.

IEEE Std C57.104™-1991 was officially withdrawn by IEEE based on recommendation by the Transformers Committee of the IEEE Power and Energy Society at the end of 2005. IEEE Std C57.104-2008 was issued with minor changes to address some of the most pressing issues identified from the 1991 version (such as correcting typos, factual errors, and the values listed in Table 1 of the 1991 version of the guide) for use by the industry.

Upon publication of the 2008 document, the working group immediately began the process of further revision to the guide to reflect additional advances in current knowledge and trends, and to incorporate relevant and new material presented during several meetings of both the IEEE Std C57.104 Working Group Task Force (WG TF) leaders and general IEEE Transformer Committee meetings. In addition, results from the analysis of more than a million pieces of laboratory DGA data has resulted in revision of several tables in this guide.

Changes in this revised guide are as follows:

— All clauses reviewed and updated.
— Reduction of Table 1 from four conditions to three DGA status based on 90th and 95th percentile values.
— Modification of Table 1 to include several subcategories and split between Table 1 (90th percentile) and Table 2 (95th percentile) based on results of a large statistical study (Annex A).
— Removal of TCG and TDCG interpretation and associated Table 2 and Table 3.
— Introduction of delta and rate tables: Table 3 and Table 4.
— New interpretation flowchart and methodology with illustrative examples (Annex B).
— Updated fault definitions in Annex C.
— Introduction of the Duval Triangle and pentagon interpretations methods in 6.2 and in Annex D and removal of the Doernenberg and key gas methodology from main text.
— Addition of case studies in Annex E.
— Addition of Normalized Energy Intensity (NEI) methodology in Annex F.
— Preservation of deleted material with historical values in Annex G.
— An updated bibliography in Annex H.

IEEE Standards downloads and executable files

Files are available in the IEEE Std C57.104-2019 directory located at: https://standards.ieee.org/downloads.

Acknowledgments

Permissions have been granted as follows:

Material reprinted with permission from The Hartford Steam Boiler Inspection and Insurance Company, "TOGA® Presentation; Case Study Review" © 2012."

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Contents

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

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

1. Overview

Over the years, since transformer dissolved-gas analysis (DGA) was first used in the 1960s, accumulated experience and new technology have led to significant improvements. Gas formation processes and severity assessment are now better understood. Chart-based methods and slide rules have been replaced by modern computer-based technologies that bring improved communications, data management, graphical and computational aids, analysis, and electronic reports. Instrument technology has advanced greatly, providing better laboratory instruments, as well as field-portable gas analyzers and on-line gas monitors.

The fundamental purpose of DGA is to discriminate between normal and abnormal conditions. More specifically, DGA aims to provide a reliable and economical method of detecting faults, which may present unacceptable possibility of damage or near-term failure. In transformers, a fault is revealed by the production of new gases. In many cases, active faults generate gases at such a high rate that detection and assessment do not require finesse. On the other hand, the gases generated by a subtle, incipient, or intermittent fault can sometimes be difficult to distinguish from the background of residual gases already present in the transformer during “normal” operation. This situation can arise because of normal variations in gas concentrations due to load and environmental conditions; unavoidable random “noise” from measurement uncertainty (method repeatability and reproducibility), as well as data quality issues arising from poor sampling technique, exposure of samples to air, or mislabeling of samples. As with any decision process based on data subject to “random” interference, a method must be developed to minimize the number of false positives while also minimizing the number of false negatives, i.e., failures to detect real abnormalities.

DGA is one of the most widely used diagnostic tools for transformer condition assessment because experience has proven it to be an effective tool.

Even so, DGA has limitations that warrant some precautions in interpretation, such as:

— Samples can be incorrectly collected, identified, or processed. The veracity of dissolved gas data should be checked before remedial or emergency action is undertaken (i.e., a confirmation sample).

— Unusual causes of gas formation can misdirect DGA diagnosis. For example, when a pattern consistent with “stray gassing” is observed, the possibility of that explanation should be carefully considered before further action is taken.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

— Gas concentrations alone are not a sufficient indicator of transformer condition. An understanding of how the gases were produced, and at what rates, is usually needed for judging the significance of the gases found in a sample.

— Multiple phenomena occurring simultaneously, or at different times, can confuse analysis. Examination of changes in gas concentrations helps to reveal the active processes.

— Rates and accelerations of gas formation provide the best basis for evaluating process development, but proper determination of gas formation rates and accelerations requires several measurements over time.

— Characterizing the rate and pattern of gas formation is not always sufficient to identify the origin of gas generation. Comparison with historical information, industry trends, and documented case histories can be helpful. Additional diagnostic tools, such as on-line and off-line electrical, mechanical or acoustic testing, internal inspection and other insulating liquid testing, may be needed.

This guide is based on the collective experience of the industry in using the strengths of DGA and managing its limitations to detect abnormal gas formation, identify its most probable causes, and follow its development to assess the severity of a developing abnormality.

1.1 Scope

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

a) The theory of combustible gas generation in a transformer

b) The interpretation of gas analysis

c) Suggested operating procedures

d) Various diagnostic techniques, such as Key Gases, Rogers Ratios, Duval Triangle, and other methods

e) Case studies and examples

f) Evaluation criteria and guidelines

g) A bibliography of related literature

1.2 Purpose

The purpose of this document is to provide a guide for evaluating dissolved gases analysis results from mineral oil-immersed transformers using statistical based analytical tools and fault interpretation methods.

1.3 Limitations to use of this document

This guide is applicable to mineral oil-immersed transformers and reactors of all types, sizes, voltage classes, construction, and usages, except those excluded in 1.3.

This guide is not applicable to DGA samples taken during factory testing. For DGA samples taken during factory temperature rise tests, refer to IEEE Std C57.130™ [B105].[1]

[1] The numbers in brackets correspond to those of the bibliography in Annex H.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

This guide is not applicable to load tap changers (LTC) and to transformers with main tank insulating liquid in contact with LTC insulating liquid, for example, a common expansion tank (refers mostly to in-tank type LTCs) or common air space inside the expansion tank. Load Tap Changer DGA, is covered by IEEE Std C57.139 ™ [B106].

This guide is not applicable to transformers using any insulating liquid other than mineral oil. Transformers using an ester-based liquid, are covered by IEEE Std C57.155™ [B109]. Transformers using silicone liquid, are covered by IEEE Std C57.146™ [B107].

The user of this guide must consider the internal components of the transformer when choosing to apply the guide to specific transformer types such as wind turbine transformers or network transformers. Such transformers may have auxiliary components such as load break switches (as an example) immersed in the same oil as the transformer itself. As such a component produces an electrical arc and combustible gases as a normal part of its operation, the user of this guide must consider the possibilities that:

— The transformer oil DGA results may be almost entirely a result of switch operation, and not an accurate reflection of the health of the transformer itself.

— The gases produced by the switch operation may be much greater than the gases produced by the transformer itself, and therefore may mask any problems associated with the transformer that might otherwise be detectable via DGA interpretation.

Note that the initial analysis of the data received in preparation of this guide clearly indicated that DGA results from transformers identified as wind turbine or network transformers often had excessively elevated typical values, in some case two orders of magnitude higher that the rest of the DGA database. There was no information to indicate if the transformers were healthy or under extreme distress. Therefore, the DGA data subset from wind turbine and network transformers was not included in the study to obtain the norms used in this guide. Consequently, if the user of this guide applies the norms presented herein to such transformer types, the result may often be high DGA status levels.

In the case of wind turbine transformers in particular, they have special operating conditions in that they are closely connected to power electronics and have frequently and widely fluctuating loads. Some of the earlier generation designs of these transformers were not adequately robust for such operating conditions, and hence the often elevated gas values are seen. For further insight into wind turbine transformer design and their particular DGA issues, refer to "Wind Power Transformer Design" [B102] and "Unusual DGA results in wind turbine transformers" [B129].

Sampling of transformer insulating liquid for DGA should be done by suitably trained personnel following standard procedures such as ASTM D923.[2] The measurement of gas concentrations should be performed by an analytical laboratory according to the methods defined in ASTM D3612, or by suitably trained personnel using a portable instrument, or by a suitably connected on-line monitoring device.

The interpretation of DGA data should be performed by a suitably trained and experienced person. Computer analysis of the DGA results with tools such as spreadsheets, databases, analytical software, or maintenance management systems, can be used when evaluating the health and condition of a transformer. Any other relevant information, such as transformer nameplate, factory test reports, operational and maintenance records, in service test results and environmental conditions, should also be considered in such evaluation. An aggregate of all available information is generally considered the optimal approach when a detailed interpretation is required. The nature of the interpretation also depends upon the context or application of the DGA.

For various reasons, some of which are explained in this guide, DGA results can sometimes be indeterminate or misleading, and sometimes DGA can fail to detect or identify a fault that may be present.

[2] Information on references can be found in Clause 2.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Drastic or costly measures should not be taken based on DGA results alone, particularly not on an individual, isolated DGA sample, without confirmation by additional DGA results and/or other tests such as electrical performance tests, expert consultation, and due regard to local operating conditions, requirements, and safety issues. It should also be noted that DGA is a detection and diagnostic tool, not a predictive technique. It can only detect an existing or past condition and has no capability to "predict" any future condition. However, when a condition exists, DGA can be used to track and evaluate its evolution over time.

1.4 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (shall equals is required to).[3,4]

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (should equals is recommended that).

The word *may* is used to indicate a course of action permissible within the limits of the standard (may equals is permitted to).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (can equals is able to).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). 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 D923, Standard Practices for Sampling Electrical Insulating Liquids.[5]

ASTM D3612, Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography.

IEC 60567, Oil-filled electrical equipment—Sampling of gases and of oil for analysis of free and dissolved gases—Guidance. [6]

IEEE Std C57.93™, IEEE Guide for Installation and Maintenance of Liquid-Immersed Power Transformers. [7,8]

IEEE Std C57.143™, IEEE Guide for Application for Monitoring Equipment to Liquid-Immersed Transformers and Components.

[3] The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.
[4] The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.
[5] ASTM publications are available from the American Society for Testing and Materials (http://www.astm.org/).
[6] IEC publications are available from the International Electrotechnical Commission (http://www.iec.ch) and the American National Standards Institute (http://www.ansi.org/).
[7] IEEE publications are available from The Institute of Electrical and Electronics Engineers at http://standards.ieee.org/.
[8] The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

IEEE Std C57.152™, IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. [9]

continuous monitoring: A test protocol in which a transformer is tested at very short time intervals (e.g., daily or several times per day) for characterization of abnormal gas formation, and very early warning of severely abnormal gas formation. This protocol could utilize suitably connected on-line monitoring devices.

DGA status: Classification of DGA results based on statistical norms.

DGA test protocols: A program of DGA applied to a transformer or to a transformer population.

dissolved-gas analysis (DGA): The identification, measurement, and interpretation of gases dissolved in the insulating liquid of electrical equipment.

dissolved-gas analysis norms: Reference values for gas concentrations, rates of change, and ratios that are used to define various degrees of abnormality or unacceptability.

electrical discharge fault: Arcing or sparking between conductive components at different potential.

NOTE—See Annex C.1.

failure: A transformer is considered to have failed when, due to defect, damage, or deterioration, it becomes incapable of remaining in its intended service and either ceases to function (for example by catastrophic failure) or has to be taken out of service for repair or replacement.

fault: A fault is an unplanned occurrence or defect in a transformer that allows an abnormal internal diversion of energy, which could cause damage and lead to failure or increased risk of failure.

gas concentrations: The concentration of a gas dissolved in insulating liquid is expressed in microliters per liter (µL/L), also referred to as parts per million by volume (ppm v/v), both expressed at standard temperature and pressure (STP) conditions (0 °C and 101.325 kPa).

initial verification: A set of DGA performed when a new or repaired transformer is entered into service, or when a DGA screening test protocol is resumed for a transformer after several years without sampling (e.g., after a storage period).

partial discharge fault: An electric discharge that only partially bridges the insulation between conductors, and that could occur adjacent to a conductor.

NOTE—See Annex C.1.

[9] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

rate: Constant gas generation over a certain period, expressed in μL/L/year. In the context of this guide, rate is computed by linear best fit from 3 to 6 consecutive DGA covering a period of at least 4 months to a maximum of 24 months.

screening: A test protocol in which all transformers in a population are tested at regular time intervals (e.g., every year) to identify units which may require additional attention or remedial action. This protocol is used to identify transformers with potential fault activity.

surveillance: A test protocol in which a transformer is tested at relatively short time intervals (e.g., months, weeks, or days) for the purpose of detecting and characterizing any gas formation that may occur and provide early warning of a rapidly worsening condition. This protocol is used to confirm fault activity and determine fault severity. It could also be used when unit condition changes, such as after a relocation of the unit or a loading increase.

thermal fault: An excessive temperature rise, in the insulation or any internal component.

NOTE—See Annex C.1.

3.2 Acronyms and abbreviations

C	possible carbonization of paper
D1	discharges of low energy
D2	discharges of high energy
DGA	dissolved gas analysis
GIOS	gas in oil standard
GSU	generator step-up transformer
LTC	load tap change (previously designed OLTC)
μL/L	microliter per liter; equivalent to ppm v/v (parts per million, volume/volume)
ND	not determined or not detected
NEI	normalized energy intensity
O	overheating of paper or mineral oil
OLTC	on load tap changer (deprecated, replaced by LTC)
PD	partial discharges
QA	quality assurance program
R	catalytic reactions
S	stray gassing

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

STP standard temperature and pressure (0 °C and 1 atm)

T1, T2, T3 thermal faults

4. The nature, purpose, and application of dissolved-gas analysis

Transformer mineral 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 of gas generation 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 mineral oil is thermally or electrically stressed.

The quantity of hydrogen formed can be relatively high and can be insensitive to temperature for some fault types, such as some stray gassing, partial discharges (PD) and catalytic faults. Formation of acetylene becomes appreciable only at temperatures nearing 1000 °C. Formations of methane, ethane, and ethylene also each have unique dependences on temperature. See Figure 1.

The thermal decomposition of mineral oil-impregnated cellulose insulation produces carbon oxides and some hydrogen or methane from the mineral oil. The rate at which they are produced depends exponentially on the temperature and directly on the volume of material at that temperature.

4.1 The nature of dissolved-gas analysis

Dissolved gas analysis (DGA) is the identification, measurement, and interpretation of the gases dissolved in the insulating liquid. The principal gases used in identification of faults (so-called "fault gases") are hydrogen (H_2); methane (CH_4); ethane (C_2H_6); ethylene (C_2H_4); acetylene (C_2H_2); carbon monoxide (CO); and carbon dioxide (CO_2). Oxygen (O_2) and nitrogen (N_2) are also measured and used in the interpretation, although they are not fault by-products.

The gases containing both of the elements carbon (C) and hydrogen (H_2) are called hydrocarbons, and the gases CO and CO_2 are called carbon oxides. Hydrogen, the hydrocarbon gases, and carbon monoxide are combustible gases, while oxygen, nitrogen, and carbon dioxide are non-combustible gases. Other gases that may be dissolved in the insulating liquid, such as argon (Ar) and higher molecular weight hydrocarbon gases, are ordinarily ignored for transformer DGA. Other light gases, such as propane and propylene, are also generated, but are not used in this guide.

The concentration of a gas dissolved in insulating liquid is expressed in microliters per liter (μL/L), also referred to as parts per million by volume (ppm v/v). The concentration of a gas in the gas mixture collected from a gas space is often expressed as percent by volume. All these quantities are corrected to standard temperature and pressure (0 °C and 101.325 kPa) for reporting in accordance with ASTM D3612. Rates of gas generation are commonly expressed in microliters per liter per day (μL/L/d), ppm per day (ppm/d), microliters per liter per year (μL/L/y), or ppm per year (ppm/y).

An appropriate sampling procedure, such as ASTM D923, should be followed to obtain a representative insulating liquid sample. To minimize gas loss and air contamination, a gas-tight glass syringe is the preferred sampling vessel. The sample is usually sent to an analytical laboratory, where a standard procedure, such as ASTM D3612, is followed for separating dissolved gas from the insulating liquid and using a gas chromatograph to measure the concentrations of individual dissolved gases. A field-portable

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

gas analyzer, which may or may not be a chromatograph, may be used for a quick determination of gas concentrations from a syringe sample. The use of gas monitors, connected directly to the transformer and automatically collecting and analyzing several samples per day, is increasingly common.

The result of a laboratory analysis is an electronic or paper report identifying the transformer, specifying the sample date, other sampling and processing information, and the concentrations of the gases listed above. Laboratory DGA reports often include interpretive or diagnostic remarks, as well as the data. Many laboratories also provide the analysis results in a data file upon request. Portable gas analyzers and gas monitors typically provide results in the form of an electronic report or a data file. Some portable gas analyzers omit one or more of the atmospheric gases (oxygen, nitrogen, carbon dioxide) from the analysis, and likewise some gas monitors measure only hydrogen or a few of the principal DGA gases.

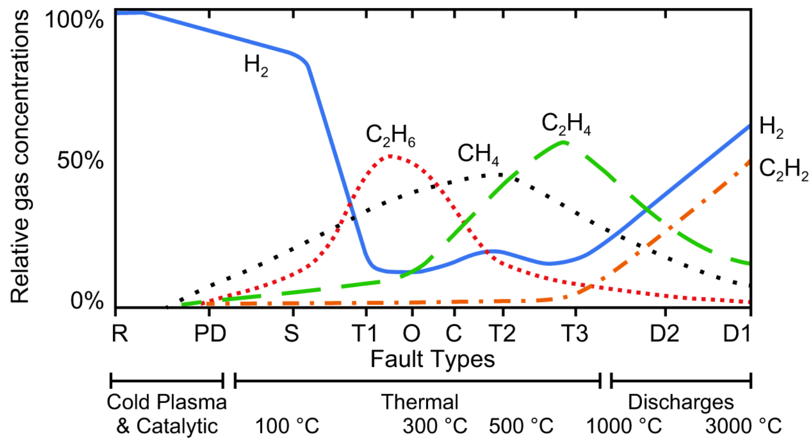
It is necessary to subject DGA data to a quality check before interpretation. When results are accepted, their interpretation should take into account any earlier DGA results that may be available. The interpretation of transformer DGA results is the main subject of this guide.

The interpretation of gases dissolved in insulating liquid is based on the premise that a liquid immersed transformer in sound condition generates little or no fault gas under normal operating conditions. In preparation for service, the transformer is filled with unused mineral oil, which typically has also been vacuum processed during filling, so that it normally starts out with no dissolved combustible gas, a very small concentration of carbon dioxide, and low concentrations of dissolved oxygen and nitrogen. The transformer insulating liquid preservation system protects it from exposure to air (for a sealed transformer) and from moisture ingress. Under normal operation, the heat generated in the windings and core is absorbed by the insulating liquid and transported to the tank walls and cooling system, keeping the internal temperatures of the transformer within a range where thermal aging of the insulation system is acceptable (for a more information on thermal aging of insulation, see IEEE Std C57.91™ [B104]). Under normal circumstances, some gases, mainly carbon dioxide, carbon monoxide, and hydrogen, are generated very slowly by the aging of the cellulosic insulation and the insulating liquid. Significant concentrations of hydrogen and hydrocarbon gases can be generated within the mineral oil at normal service temperatures, rated loading or from material interaction (such as some metal passivators), even if no fault is present. This phenomenon is known as “stray gassing” (see C.2).

An internal defect, an abnormal system event or anomaly, or operation in environmental conditions outside the designed ranges can result in excessive energy dissipation in the transformer insulation system and may also cause harmful mechanical stress on windings and other internal structures. Some of the diverted energy acts on the insulating liquid or cellulose insulating material resulting in the generation of gases that dissolve in the insulating liquid and are also distributed to all available gas spaces in the transformer. The particular combination of gases that is generated in mineral oil depends on the nature of the fault process and is related to the energy level and temperature at the fault location, as schematically illustrated in Figure 1 (see “Ongoing activities at IEEE, IEC and CIGRE on DGA” [B87]).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.



NOTE—See 3.2 for faults acronym and Annex C for faults type definition

Figure 1—Relative percentage of dissolved gas concentrations in mineral oil as a function of temperature and fault type

4.2 The purpose of DGA

The underlying purpose of DGA, in addition to the more obvious purpose of attempting to detect and identify a possible fault, is to improve safety and equipment reliability while reducing cost. Safety and reliability are improved through awareness of transformer condition, early detection of faults, and monitoring of suspect transformers. Cost reduction is achieved by avoidance or mitigation of transformer damage and failures, and also by optimization of operation and maintenance.

4.3 The application of DGA

It is helpful to distinguish ways in which DGA is used:

— Basic risk management

— Detection and monitoring of abnormalities

— Quality assurance metric

— Fault type identification

— In-service tripping investigation

Methods of fault type identification are described in 6.2 and Annex D. Case studies of DGA application are presented in Annex E.

4.3.1 Basic risk management

DGA before placing a transformer into service provides an initial baseline, and periodic DGA screening throughout a transformer's lifetime is performed to evaluate its operating condition and to prioritize attention to any transformer that may be generating combustible gases. The frequency of routine DGA screening may be based on considerations such as the economic cost of a forced outage, service criticality, contractual requirements (e.g., an insurance policy), and safety.

Other considerations are the warranty status, replacement cost, and relative importance of the transformer. Annual DGA screening is common.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

If the expected economic cost of forced outage or of replacement is very high, online monitoring or frequent (monthly or quarterly) periodic DGA may be justified. IEEE Std C57.143 contains useful guidance regarding the use of gas monitors in transformer asset management.

Abnormal DGA results can provide early warning of a developing problem, can identify the nature of the process that is generating the fault gases, and (via rates of change or increment magnitudes) can indicate how energetic the process is. Experience has shown that not all abnormal gassing events are necessarily related to transformer deterioration or permanent damage. A complete transformer condition assessment should also include other considerations as much as possible, such as electrical test results, recent or historical systems events, and physical inspection. As explained in 1.3 and 6.1, high gas levels do not necessarily predict a future failure.

Users should have in place a transformer DGA protocol or program taking into consideration the DGA status as described in 5.3. This protocol could vary due to several parameters such as transformer type, size, age, criticality, personnel availability, maintenance practice, and other economic considerations.

The general practice, when there is no indication of an abnormality in the operation of the transformer, is to sample the transformer insulating liquid for DGA on a time basis, with the period between samples typically ranging from a few months (for the larger or most critical units), to 1 or 2 years. In some cases, the use of an on-line gas monitor could be part of this protocol.

It should be noted that longer periods between DGA samples can increase the possibility of a fault going unobserved while the transformer deterioration progresses toward failure.

4.3.2 Detection and monitoring of abnormalities

If DGA samples are taken and the results are studied with sufficient frequency, then some major faults are easy to detect because of significant production of fault gas. It is possible, although challenging, to distinguish the lesser gas production of incipient or intermittent faults from the normal temperature-driven variation of residual gas, especially under the influence of measurement uncertainty, occasional sampling problems, or gas loss. However, some ancillary device problems, mechanical, or externally caused failures are not preceded by any DGA forewarning.

When abnormal gas generation is confirmed, the DGA results could be used to identify the apparent fault type (see 6.2 and Annex D). Beyond fault identification, gas increments or rates of gas formation indicate the relative severity of the fault. Changes in increments, rates, or evolution of the fault type (e.g., from a lower energy fault type to a higher energy fault type) may indicate worsening or moderation of the fault process. Unless the gassing behavior is so extreme as to motivate immediate shutdown, it may be prudent to take DGA samples more frequently and monitor long enough to determine the gas formation rates, to investigate whether the abnormality is transient, intermittent, or on-going, and to determine whether the fault type and severity seems to be evolving. If, for operational reasons, it is necessary to continue operating a gassing transformer, more frequent DGA surveillance may provide early warning of increased gas generation, which may indicate that the transformer's condition is worsening.

4.3.3 Quality assurance metric

Another application of DGA is verification of previous DGA measurements and measurement quality assurance. DGA is sometimes performed to provide confirmation of earlier DGA results or gas monitor readings.

Duplicate samples can be used to check laboratory consistency, while gas-in-oil standard solutions (gas-in-oil samples of known, precise gas quantities usually purchased from a certified gas sample supplier) can be used to check both consistency and accuracy. Specific guidelines are provided in 5.1 and 5.2.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

4.3.4 DGA samples following a transformer trip

Laboratory DGA samples can be taken as an initial response to a transformer relay alarm or trip (see IEEE Std C57.152-2013, Table 1 [B108]). Relay trips may result in no external indications of transformer damage, therefore, electrical testing and DGA is used to evaluate the condition for continued operation (see "Guide for Transformer Fire Safety Practices" [B73] and "Transformer reliability survey" [B74]). The amount of time after a transformer trip should be noted when obtaining a DGA sample. The location of a fault inside of the transformer and the insulating liquid flow rate have a direct relation to the amount of time for the combustible gases to be distributed throughout the transformer insulating liquid and reach the sampling port of the transformer tank. As examples, a forced flow cooling system may have a short gas transport time if the circulating pumps remain in operation following the trip, while natural convection flow on a very cold day or with a low load prior to the trip can take more than 24 h to completely distribute dissolved gases. Therefore, additional DGA samples may need to be scheduled to monitor for a stable dissolved gas-in-oil condition.

The device or relay that alarmed or caused the transformer to trip will likely suggest the additional testing protocols to be followed. For example, protocol for the trip of a distant breaker may include taking a DGA sample from the downstream transformer even though the breaker is immediately reclosed, and the transformer was brought back into service. But protocol for a differential current trip, normally associated with an internal transformer fault, may suggest that electrical testing of the transformer is required as a condition for continued service, in addition to DGA testing.

The decision to return a transformer to service will depend on the electrical test results, physical inspection results, and is influenced by system needs. Post-trip DGA results should be compared to the previous transformer DGA history and reviewed for changes in the types of gases reported and their concentrations, which may indicate a change in the equipment condition. Suspected changes to the equipment condition should be verified with a confirmation DGA sample. This is also crucial as a baseline for comparing future DGA results.

4.4 DGA sampling context

The interpretation of DGA data should be performed with due regard to the purpose of the sampling. The following basic sampling contexts are the most common ones encountered:

a) **Initial sample**—An initial DGA sample is one that is interpreted without regard to previous samples. For example, a sample taken before or shortly after energizing a new transformer as part of initial test protocol (see 5.3.1), after major repairs or modifications, or on a transformer that has no previous DGA data associated with it would be considered an initial sample. The gas concentrations and other measurement data associated with an initial sample can be used as baseline values for comparison with later data.

b) **Periodic screening sample**—A periodic screening sample is one of a series collected at regular time intervals (for example, six months or one year) for verifying that a transformer is operating normally. See 5.3.2.

c) **Surveillance sample**—A surveillance sample is one of a series collected at shorter intervals (compared to periodic screening intervals) for characterizing a suspected fault or keeping close watch on a transformer's condition during start-up, testing, high stress circumstances, or other exceptional operating conditions. See 5.3.3.

d) **Continuous monitoring sample**—A continuous monitoring sample is one of a series of samples collected at a high rate (typically from more than one per day to one every few days) for maintaining a close watch on a transformer's condition (see 5.3.4). An on-line dissolved gas monitor could also be used for that purpose. Continuous monitoring is typically applied in cases of higher economic risk; for example, protection of extremely critical or expensive transformers,

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

continuous condition assessment to help extend the service life of older transformers, or investigation and operational safety when a transformer is being operated with a fault or under extreme stress. The use of an on-line dissolved gas monitor with remote data collection capability is a safer alternative than manually extracting an on-site sample from a transformer that is severely gassing and may fail catastrophically without warning.

e) **Incident investigation sample**—An incident investigation sample is a sample taken after an incident (e.g., gas relay tripping, close-in fault, etc.) to investigate whether the transformer has been damaged.

f) **Quality assurance sample**—A quality assurance (QA) sample is one processed for the purpose of evaluating measurement accuracy, repeatability, or reproducibility. QA samples are not for transformer condition analysis. QA samples may be purchased or may be prepared as a gas-in-oil standard (see ASTM D3612). Where accuracy is not being evaluated and greater variation is tolerable, QA checking may be done using consecutive or split transformer samples.

g) **Verification sample**—A verification or “check” sample is one that is drawn from a transformer and submitted for analysis and comparison with anomalous DGA results from a recent sample from the same transformer or recent gas monitor readings. See 5.2.

4.5 Procedures for obtaining samples from the transformer for laboratory analysis

All samples of insulating liquid taken from electrical apparatus for dissolved gas-in-oil analysis should be taken in accordance with ASTM D923. A gas-tight, glass syringe is the preferred container for DGA sample. The sampling procedure should always ensure that the samples are taken safely, without compromising the transformer insulating liquid level, without contaminating the sample with air, and without allowing air to enter the transformer during the sampling process.

Under certain fault conditions, some portions of the insulating liquid may have higher dissolved gas concentrations for several hours before complete mixing with the bulk of the insulating liquid has occurred. In these cases, where possible, samples should be obtained from more than one location on the transformer and a confirmation sample should be taken the following day.

Particular care should be taken that good sampling procedures are in place and are followed at all times. Proper personnel training for DGA sampling should be an integral part of the DGA policy. Particular attention should also be given on properly filling out the form accompanying samples, especially since DGA is applied to a large range of apparatus (main tank, bushings, cable, LTC, etc.) with different DGA interpretation methods (e.g., different types of insulating liquid).

All due safety precautions should be taken when sampling is performed. Particular attention in this respect should be given to avoid possible ingress of air into the transformer.

CAUTION

Sampling from a transformer tank when negative pressure is known or suspected should never be done, as it will result in air ingress and possible immediate or future catastrophic failure of the transformer.

Purging the sampling valve should be performed each time to avoid air ingress and to help guarantee a representative sample. To properly purge, the sampling system should be open to atmosphere when the transformer valve is initially opened to allow any trapped air to escape. The sample should be taken only when the valve has been purged of all trapped air and of stagnant insulating liquid. See “Where Does the Air Go? (Second Edition)” [B121].

Correct information about transformers, especially serial number and location, sampling compartment and location, reason for sampling, kV and MVA ratings, preservation type, type of insulating liquid,

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

transformer manufacturer and manufacturing year, cooling type, and nature of service (GSU, transmission, etc.) is helpful for DGA database management and proper interpretation of DGA data. Accurate identification and other relevant transformer information should also be supplied to the analytical laboratory.

5. DGA data interpretation

The interpretation of DGA data begins with the detection of an abnormal condition. When found, it should be followed by severity assessment and fault identification. The fault detection and severity assessment part of DGA consists of comparing the gas levels and rates of change, to their respective norms and assigning a status condition according to which norms (if any) were exceeded. When there is an indication of a problem, a fault identification or diagnosis should be obtained by a reliable technique, such as the Duval Triangle method. See 6.2 and Annex D. Graphical visualizations of the data in various ways as discussed in Annex E and Annex D often provides insights into fault identification, evolution, and severity. Other relevant information, such as maintenance activity records, electrical diagnostic test results, lightning strike occurrences, load history, etc., should be consulted to seek a better understanding of what may be causing the gassing activity, and to confirm or modify the DGA condition assessment. See Annex E for case studies of DGA interpretation.

The interpretation of DGA results can begin only after a data quality review to identify and correct data quality problems has been performed. It is important to understand that a review of data cannot identify all possible data quality problems. Therefore, when unexpected or alarming results are obtained, it is highly advisable to collect and process another sample to confirm results.

5.1 Data quality review

This subclause contains the recommended practices to be followed to ensure the quality of the DGA results data. The working group realizes that a data review at the level of detail provided in 5.1.1 to 5.1.8 is not practical for many users. Therefore, any data points that seem to be unusual, compared to the history of the prior samples, should be investigated.

A data quality review is necessary to identify signs of data corruption, which could confuse or mislead the interpretation of the data. Data corruption can occur throughout data management, work management, sampling, analysis, and reporting phases of producing DGA data. Each phase has its characteristic data issues.

Data management and work management systems sometimes contain and propagate incomplete and inaccurate equipment identification and information. Long after corrections are made, forms generated with incorrect information can be copied and used, sometimes for years. This type of error could also cause duplication of equipment in database or result in incorrect DGA interpretation (e.g., DGA from an LTC identified as from the main tank).

Sampling provides several opportunities for data corruption. For example, the sampler, using a blank field data form, can incorrectly transcribe nameplate information; using a preprinted field data form can reduce errors identifying the equipment. The sampler can introduce errors by waiting to label the samples after they have all been collected. The sampler can provide information on the field data form that is different from the information on the sample container, can collect the sample from the wrong sampling point, can use contaminated tubing and fittings, or can contaminate the sample with air. Laboratory testing also provides several opportunities for data corruption. Transcription errors, swapped samples, carryover contamination, air contamination, calibration errors, gas identification, and quantization errors are the most likely types.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Data quality review most often amounts to comparing current test information to prior test information. In the case of an initial sample, the reviewer is limited to reality checks. Confirming an error and identifying its source may require access to the sample records. In some cases, problems can be resolved by asking the laboratory to check their records. When data quality problems cannot be corrected, it is recommended to resample the equipment.

5.1.1 Transcription and typographical errors

Transcription and typing errors show up in characteristic ways. A sequence of values that are all shifted by one position, a skipped or missed value in a sequence of values, two values that are swapped, digits that are added or lost in a value and swapped digits in a value usually appear as abrupt changes in individual values or as strange individual values. For example, oxygen concentration shown as 508 when its previous values had been around four or five thousand; a digit was omitted. Another example: ethylene reported as 87 following several samples around 8, with no evidence of any other combustible gas change; this type of error could be caused by a dropped decimal point. Transcription or typing errors in an equipment identifier result in a misidentified unit.

5.1.2 Missing or duplicated data

Occasionally some values may be accidentally omitted or deleted from the data. Sometimes the data for an earlier sample may be reported again instead of the latest data. This is particularly likely when all gas concentrations, μL/L, are the same as the previous sample (normally some variation is to be expected, especially for the high values, such as CO_2, N_2 and O_2).

5.1.3 Misidentified or swapped sample

An incorrect or incomplete serial number or other equipment identifier may associate a sample with equipment that it did not come from, or with equipment that simply does not exist. There can also be problems with identification of the sampling point (e.g., main tank instead of LTC) or incorrect notation of the sample date. A swap of samples causes the same misidentification.

5.1.4 Sample mishandling

5.1.4.1 Air exposure

A leaky syringe, poor sampling technique, or mishandling of the sample can expose the sample to air, resulting in loss of much of the hydrogen, often accompanied by an increase of oxygen and nitrogen. A very low hydrogen concentration (especially if hydrogen was higher in earlier samples), with an O_2/N_2 ratio above 0.2 (for sealed transformer), or O_2 and N_2 reported levels above saturation values, may indicate that the sample was exposed to air. Air exposure of a sample from a breather type transformer, where the insulating liquid is normally saturated with air, could be more difficult to detect.

5.1.4.2 Air contamination

Entrainment of air during sampling, handling or processing results in oxygen, nitrogen, oxygen/nitrogen ratio and total gas concentration changes. The amount of change ranges from barely perceptible to extreme. Without knowledge of the adulterating process, rates and changes of fault gases calculated from these should be considered suspect.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

5.1.5 Cross contamination

The results of carryover contamination during sampling (e.g., reusing sampling tubes) or processing (e.g., storage in contaminated tank) can vary widely. Appearance of a trace gas or gases, appearance of a fault and change of fault identification are all characteristic of this problem. As with any question of quality, a significant change of condition should prompt confirmation with a follow-up test.

5.1.6 Inconsistent values

A single sample, which is drastically different from earlier samples from the same equipment, may belong to a different piece of equipment (e.g., from the LTC compartment instead of main tank), or it may indicate a fault. Confirmation by resampling may be necessary. If there are large inconsistencies in several successive samples, there could be a sampling or measurement problem.

5.1.7 Chronically absent or low hydrogen

If the hydrogen concentration is always extremely low, even when other combustible gases are not, and especially when hydrogen is also chronically low in other transformers, there may be a problem with sampling technique, leaky syringes, or measurement. It may be necessary to submit a quality control standard (with known gas concentrations) to confirm that the laboratory or portable gas analyzer is measuring hydrogen correctly.

5.1.8 Inconsistent O_2/N_2 ratio

Isolated large increases in the O_2/N_2 ratio, especially when correlated with decreases in hydrogen, may indicate an air exposure problem. Mistyped values for oxygen or nitrogen can cause the O_2/N_2 ratio to assume unusual or impossible values. The saturation value for air dissolved in mineral oil normally gives an O_2/N_2 ratio between 0.4 and 0.5. If the ratio begins to approach that value for sealed transformers, it would be prudent to look for air leaks. For transformers with a bladder equipped conservator, rapidly increasing concentrations of oxygen can indicate a leaky or ruptured bladder. For a transformer with an open breather, the O_2/N_2 ratio will change little (near 0.4 to 0.5), but the total reported amount of O_2 and N_2 levels could increase above saturation values in case of air ingress into the sample.

5.2 Reliability of DGA results

5.2.1 Accuracy

Highly inaccurate gas concentration measurements can lead to incorrect assessment of fault severity or misidentification of the fault type. In extreme cases, errors can lead to inappropriate and costly mitigative action such as premature removal from service. Failure to notice severe conditions when they do occur can result in unnecessary outages, damage, or failures.

Recommendations to have accuracies better than ±15% on DGA results to avoid misidentification of faults can be found in IEC 60567 and in "Report on Gas Monitors for Oil-Filled Electrical Equipment" [B71]. Several laboratories meet this requirement, but several others do not (with measurement errors as high as ±60% or more for some gases).

It should be noted however that, at the time of the preparation of this guide, no reproducibility or repeatability values are presently available in ASTM D3612 for method C (head space) to help DGA users

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

verify whether the DGA results they receive from their laboratories and on-line monitors are accurate enough or not. Such guidelines are presently available only from IEC and CIGRE. Laboratory quality control is a key aspect of choosing a laboratory but can be a very time-consuming activity. One example of quality check for laboratories is the ASTM Committee D27 Proficiency Testing Program.

The practical recommendation to DGA users in case of critical transformers with abnormally high gas levels or with high gassing rates, where DGA results provided by different laboratories and on-line monitors are widely different (especially if they indicate drastically different actions to be taken on the transformer), is to verify the general accuracy of the DGA results from a given source using gas-in-oil standards (GIOS) and following IEC 60567 and "Report on Gas Monitors for Oil-Filled Electrical Equipment [B71].

GIOS can be prepared by DGA laboratories, following Annex A1 of ASTM D3612 or section 6.3 of IEC 60567. They can also be purchased commercially. An example where the reproducibility of several DGA laboratories was evaluated with GIOS is given in Table 1 of ASTM D3612 for method A. The procedure for evaluating the accuracy of on-line monitors is indicated in Appendix B of "Report on Gas Monitors for Oil-Filled Electrical Equipment" [B71], which also uses GIOS.

At gas concentrations below about five times the DGA method detection limit (a few µL/L, depending on the method and the gas), relative measurement uncertainty can be large. It is not recommended to base fault type identification or practical decisions on such low values without some confirmation of their accuracy. It is not recommended to attempt fault identification using the methods described in 6.2 and Annex D if all of the gas levels are below the Table 1 values.

Particular caution in interpretation should be used when acetylene is the only gas above the Table 1 [1 to 2 µL/L (ppm)] values but is still below five times the detection limits. Fault identification in such a case may be unreliable.

A DGA expert, a person with experience in both transformer operation and DGA results interpretation, might attempt fault identification, after applying additional rules, when all gases are below the Table 1 values, but are above five times the detection limits and the laboratory processes are proven to meet accuracy requirements. This could provide advance information on incipient faults. However, as noted above, the results may be highly unreliable due to the low levels of gases present and should be used with caution.

5.2.2 Consistency

When DGA results consistently fluctuate widely (30% or two to three times the values in Table 3) from one sample to the next, it usually indicates sampling or analytical errors. Therefore, the results should not be used for fault identification or severity assessment, unless the reasons for these fluctuations have been established. If the most recent sample is very different from previous samples, engineering judgement may be required, and resampling is recommended.

Operations that can affect gas concentration should be identified. For example, venting of sealed main tanks [e.g., 4, pressure relief operation during thermal transits and leaks (sometimes resulting in pressure gauge reading zero)] can lower combustible gas and increase atmospheric gas concentrations. Changes in system parameters could cause variations in reported gas concentrations, for example, load changes. It is often difficult to quantify the effects of these factors compared to the gross changes in reported gas concentrations. Transformer monitoring of gases, moisture, temperatures, load, fans and other parameters can be useful in correlating changes and understanding what may have caused them.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

5.3 Context of DGA data interpretation

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

a) **Detection**: Detect the generation of any gases that exceed “normal” quantities and utilize appropriate guidelines, so the possible abnormality may be recognized at the earliest possible time to minimize damage or avoid a failure. If this analysis concludes that a fault exists, then proceed with evaluation.

b) **Evaluation**: Evaluate the impact of an abnormality on the serviceability of the transformer, using a set of guidelines or recommendations. Expert opinion, operator experience, and unit specific conditions should be part of the evaluation.

c) **Action**: Take the recommended action, beginning with increased surveillance and confirming or supplementary analysis. For example, if a thermal fault is suspected, which may be load sensitive, load reduction (if possible) may help with the diagnosis. If it is not possible, then alternatives, as drastic as removal of the unit from service, may need to be considered. This guide does not cover the procedure required to determine what remedial or operating action may be necessary. This is ultimately the sole responsibility of the transformer owner.

It is useful to look at graphs of gas levels over time (see Annex D) for quick visual detection of suspicious changes, parallel long-term upward rates, or inconsistencies. Whenever a fault is suspected, past and present data should be analyzed and plotted, using one of the methods, such as the Duval Triangles, found in 6.2.3 and Annex D, to see whether there is a consistent pattern or evidence of orderly fault evolution.

The recommended action and resampling interval can be based on the fault diagnosis and the verified DGA status, plus the use of expert judgment. Because of the potentially serious consequences and high cost of misinterpreting transformer test data, an inflexible interpretation, based on an exclusively mechanical scoring approach, without the application of expert judgment, is highly inadvisable.

It is helpful to define DGA status levels to establish sampling intervals and maintenance activities on operational transformers. See 6.1.2 for more information.

— **DGA Status 1:** Screening DGA results are acceptable. Continue routine operation.

— **DGA Status 2:** Incipient or modest recent gas production or moderately elevated gas level. Resample for confirmation and monitor possible gas evolution.

— **DGA Status 3:** High gas levels or continuing significant gas production. Mitigative actions or other responses should be considered (i.e., continous monitoring).

5.3.1 Initial verification test protocol

When a new transformer is added to a DGA program, or when DGA sampling is resumed for a transformer after several years without sampling, an initial verification is recommended. This is also applicable when there is no prior DGA history for the transformer, or when insulating liquid processing, repairs, or other factors “reset” the transformer’s DGA history. In such cases, there may not be any prior DGA data providing a basis for calculating combustible gas increments or rates of change.

It is suggested to take a sample before and during commissioning procedures and several more samples over a short period of time (a few weeks to a few months) following energization to establish a DGA baseline and ensure that no abnormal gassing is taking place.

For new and repaired transformers, if any of the combustible gas concentrations are above their respective detection limits without a reasonable explanation (such as residual gas from an earlier fault diffusing into the insulating liquid from the paper insulation in a repaired transformer), it may be prudent to schedule

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

another sample to be taken immediately to check for active gas production. A diagnostic method may be applied to see what the initial sample's pattern of gas concentrations matches, but the diagnosis cannot be considered unless a second sample confirms active fault gas production in a pattern that confirms the diagnosis.

The usual outcome of an initial verification test program would be either the assignment of DGA Status 1 with a recommendation to carry on with DGA periodic screening test protocol per company DGA policy, or the assignment of DGA Status 2 with a recommendation to sample more frequently to check for evidence of change and to discuss the test results with the manufacturer. If a resample confirms an elevated level of gases, contact the manufacturer to review the situation and evaluate the follow-up action.

It is to be noted that typically in an initial verification context, gas level norms lower than Table 1 are used. Often, for new transformers under warranty, the manufacturer will supply its own norms.

See 5.13 of IEEE Std C57.93-2007 for an example of installation sample protocol.

5.3.2 Periodic screening test protocol

Most DGA results fall into this category.

The method of interpreting screening DGA data is explained in 6.1 and in the Figure 2 flowchart. If, the DGA status is 1, and there are no apparent reasons for concern, no fault interpretation is necessary, and no special action is needed. The interpretation of the DGA data is complete and the next sample should be taken according to the DGA screening test protocol.

If analysis of a test result produces a DGA status of 2, or if any unusual shift in gas pattern suggests an anomaly, a fault diagnosis should be obtained using a reliable method (see 6.2 and Annex D).

If the fault diagnosis reveals an issue of a low temperature fault (T1), or stray gassing (S), this would be treated as a less urgent issue, however a low temperature fault (T1) may affect the future life of the insulation system.

If there is an indication of high-energy arcing (D2) or a high-temperature thermal fault (T3), or if paper insulation appears to be involved in the fault, another analysis step may be prudent. Some users will consider extra steps with increased surveillance, as recommended for a unit with a DGA status of 3.

If a DGA status of 3 is obtained, then a fault diagnostic and a DGA surveillance test protocol are warranted. See 5.3.3.

5.3.3 Surveillance test protocol

The purpose of the DGA surveillance test protocol is usually either:

— To confirm the absence of suspicious gas activity
— To characterize and diagnose suspicious gas formation
— To provide early warning of dangerous changes or a fault reaching the pre-failure runaway stage

Gas history charts, a stacked chart showing all individual combustible gases, and the Duval Triangles with multiple samples are the most useful graphical tools for surveillance and monitoring.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

A short-term rate of increase should be compared with their respective norms to obtain an updated status code. This may be increased if there is evidence of accelerating combustible gas formation. If there is evidence of a fault, a Duval Triangle or pentagon (see 6.2 and Annex D), with all surveillance data plotted on it, can be used to diagnose the fault and to watch for consistency or evolution of the fault type. For example, it could help to see if a thermal fault evolves toward a higher temperature fault.

If the results of a surveillance test indicate a serious or deteriorating situation, it will lead to a Status 3 evaluation. That should lead to consideration of starting a continuous monitoring test protocol, as suggested in 5.3.4.

It may be prudent at this point, that the user consult experts and the transformer manufacturer, as no two transformers are the same. What could be perfectly normal for a given transformer, could be a sign of a dangerous condition in another transformer. In such context, experience from experts is an invaluable tool. See Annex E for additional information.

5.3.4 Continuous monitoring test protocol

The continuous monitoring test protocol should be used when there is a clear indication that the transformer is not operating normally and is generating gas in a significant manner. This protocol should be considered for units with a DGA Status 3, although this should not be automatic. It should be implemented only after a complete review of the DGA results, together with all other available information. Monitoring may be started temporarily until further investigation is completed; or permanently, if the situation is deemed sufficiently serious to warrant it.

In continuous monitoring, the transformer is subjected to frequent sampling and tested at very short, time intervals (e.g., daily or several times per day) for accurate characterization of normal or abnormal gas formation, and very early warning of severely abnormal gas formation. This protocol may lead to the temporary or permanent installation of a suitable on-line monitoring device on the transformer.

The high sampling rate of on-line monitors permits early detection of abnormalities and accurate characterization of rates. Multiple readings may be combined using statistical methods to arrive at improved estimates of the dissolved gas concentrations, and to average over short-term cyclic gassing behavior. Because of the high volume of data generated by on-line monitoring, graphical visualization is essential. Time series graphs with rate values are useful in detection of the onset of increased gassing activity. The technique of plotting DGA results on a Duval Triangle or pentagon is useful in detecting changes in the nature of the fault (see 6.2.3 and Annex D). Also, since rates are obtained in real time over a short period, care should be taken to account for the intrinsic fluctuations of the DGA levels generated by the monitoring process. Gassing rates should be calculated using statistical methods and using trailing data spanning over a long enough time duration to control the likelihood of nuisance gas rate alarms.

In a continuous monitoring test protocol, the various norms used in screening DGA interpretations no longer apply, especially in regard to rates of gas generation. For on-line monitoring, it is not uncommon to use higher rate values than the ones used for laboratory DGA. Each situation is unique.

5.4 Selecting norms values

It is important to understand some of the impacts and limitations of selecting a set of DGA norms for identifying suspicious behavior in a transformer. The choice of 90^{th} and 95^{th} percentiles for norms in this guide is conventional. For some transformer populations other criteria could be chosen based on engineering judgment and local operating and maintenance requirements. The norms shown in Table 1, Table 2, Table 3, and Table 4 were obtained by statistical analysis of a large database of laboratory DGA results. The agglomerated data used to obtain these norms came from several sources in North America, which had notable percentile value differences between themselves. They might not be representative of

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

what could be obtained with a different data set from different sources or countries. See 6.1.2.5 and Figure A.8 for an example of variability between sources.

It should also be understood that while high-fault gas levels in a transformer suggest an eventful past, gas levels, whether high or not, in themselves are not necessarily a direct assessment of the condition of the transformer, if they are stable. A transformer with twice the gas level of another transformer, is not necessarily twice as likely to fail. On the other hand, active fault gas formation, even with low gas levels, indicates that something might be wrong and may necessitate an investigation or other follow-up activities.

The methodology used in this guide will generate a certain amount of "false positive" cases where extra investigation will simply confirm that there is nothing of concern in the transformer condition. A norm chosen at the 90th percentile (Table 1) will select 10% of all the DGA results for review. Table 3 (95th percentile of Delta) will add about 5% of the DGA results to this. If Table 1 and Table 3 contain values for more than one gas, and that any one gas above a norm is enough to flag the DGA results, it is reasonable to expect that about 40% of all DGA results will need further review. This could be a large number for a major DGA program and should be considered in the implementation of the program. See NOTE 1 below.

In a similar manner, Table 2 uses the 95th percentile as the norm, so it should be expected that 5% of results will exceed these values. If those with an elevated rate of rise are added (Table 4), it is expected that about 20% of the DGA results will be evaluated as Status 3. See NOTE 1 below.

NOTE 1—It should be noted that these values will be true for a large set of DGA results having the same general characteristics as the set used to obtain the norms used in this guide. For smaller sets (for example from a single station), or for notably different DGA populations, a different proportion of selected DGA could be obtained. See Figure A.8 for an example of variations between populations.

This might represent a large investment in time and resources that should be considered by the transformer owner. There is always some trade-off between having too many transformers in normal conditions flagged as "investigate" against the possibility of not detecting a potentially catastrophic condition. If the norms are set too low, excessive investigation will result and faith in the program could be affected. If the norms are set too high, there is an increased possibility of missing a faulty transformer.

Part of the planning and set-up of any DGA program should include deciding what norms to use and which procedure to follow when those norms are exceeded. It is also critical to ensure that sufficient resources are available to handle the level of investigation generated. Transformer owners and operators are strongly encouraged to perform their own study based on their own data, if available, to confirm that the selected norms are adequate for their transformer fleet.

One finding from the analysis of the DGA results (approximately 1.5 million samples) is that certain parameters, most notably the ratio of O_2/N_2 and the transformer age, have a large influence on the typical levels of gases. Other subsets of the data, such as insulating liquid volume, rating, and voltage class, did not produce significant differences, so they were not included.

NOTE 2—The O_2/N_2 ratio was proposed for evaluation as a proxy for distinguishing sealed units from free breathing ones. This approach was used to evaluate the large database where this information was mostly absent, and the break point based on the data suggested the limit of <0.2 or >0.2. An O_2/N_2 ratio ≤ 0.2 is observed in most N_2-blanketed transformers and in about 60% of membrane-sealed ones. An O_2/N_2 ratio > 0.2 is observed in all air-breathing transformers and in about 40% of membrane-sealed transformers. However, it should not be inferred from this approach that by looking at the O_2/N_2 ratio found in a specific sample that it is possible to determine if the transformer is sealed or breathing, as other factors could influence this ratio.

The norms supplied in this document should be considered only as a general guideline based on the best estimate that could be obtained with the data available when this guide was prepared (voluntarily supplied by members of the revision working group, see Annex A). Values in Table 1, Table 2, Table 3, and Table 4 might need to be adjusted to meet specific user requirements or for a specific transformer population.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

6. Suggested interpretation procedures for DGA results

6.1 General

This clause describes the process of interpreting a DGA report to obtain a "DGA status" number. However, the DGA status is only one input to the process of determining a transformer's condition.

There is no direct and infallible method using DGA to obtain an exact evaluation of a transformer's condition. There are several reasons why the DGA status can be very different from the transformer's true condition, some of which are as follows:

a) There are several possible causes of the presence of gas in a transformer. Some of those are related to fault conditions (e.g., arcing, overheating, PD), others are related to more benign conditions (e.g., stray gassing, contamination, previous fault now inactive, and mild core overheating [B96]).
b) Some pre-failure conditions simply do not generate gas. (e.g., mechanical or insulating system weakness).
c) Some normal conditions do generate gases. (e.g., normal aging, and insulating liquid oxidation).
d) The DGA data used to develop this procedure and norms came from in-service transformers for which their condition information (faulty or not) at the time of the DGA was unavailable. Therefore, there was no possibility to directly correlate one with the other, only to evaluate the DGA results distribution assuming most of the data came from healthy transformers.

Therefore, the methodology presented here will classify the DGA results, not the transformer condition. Users should not equate "DGA status" to "transformer condition." It could be presumed that one is possibly related to the other, but there can be no guarantee in this respect. Transformers could fail without any prior gas generation, while others could be operating with high levels of gases.

This guide classifies DGA results into 3 groups, "DGA Status 1," "DGA Status 2," and "DGA Status 3," using three tables of norms, as follows:

— DGA Status 1: Low gas levels and no indication of gassing. (Unexceptional DGA)
— DGA Status 2: Intermediate gas levels and/or possible gassing. (Possibly suspicious DGA)
— DGA Status 3: High gas levels and/or probable active gassing. (Probably suspicious DGA)

Table 1 and Table 2 define low (below Table 1), intermediate (between Table 1 and Table 2), and high (above Table 2) gas levels. Table 3 defines possible gassing. Table 4 defines probable active gassing.

Other DGA interpretation procedures exist and the method used in this guide should not be considered the only possible procedure. For an example of an alternative approach, see Annex F and H.2.3.When an increase in gas levels is detected, most users will tend to assume that there is an active fault within the transformer. However, before beginning the process of trying to confirm its existence and identify its cause, it is advisable to review the material in 5.1 and 5.2. The possibilities identified there should be investigated before any action is taken to remove a transformer from service for further investigation, maintenance, or replacement. A valid interpretation of DGA results can begin only after a data quality review, to identify and correct possible data quality problems, has been performed. It is also important to consider that a review of data cannot necessarily identify all possible data quality issues. Therefore, when surprising or alarming results are obtained, it is highly advisable to collect and process another sample to confirm results.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

6.1.1 DGA interpretation procedure

After data quality and confirmation issues have been addressed, interpretation of the DGA data can be undertaken. Prior DGA results should be used for characterization of increments and rates. If abnormal DGA results are found, any available supplementary information, such as test and maintenance records, load data, environmental conditions, etc., should be consulted for possible clues as to the origin and nature of the abnormalities. Comparison of DGA data from sister units, i.e., transformers built to similar specifications, is useful for spotting unusual results and for revealing common patterns, which may provide a better understanding of the data.

Figure 2 is a flow chart that provides a suggested process to review the DGA results.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

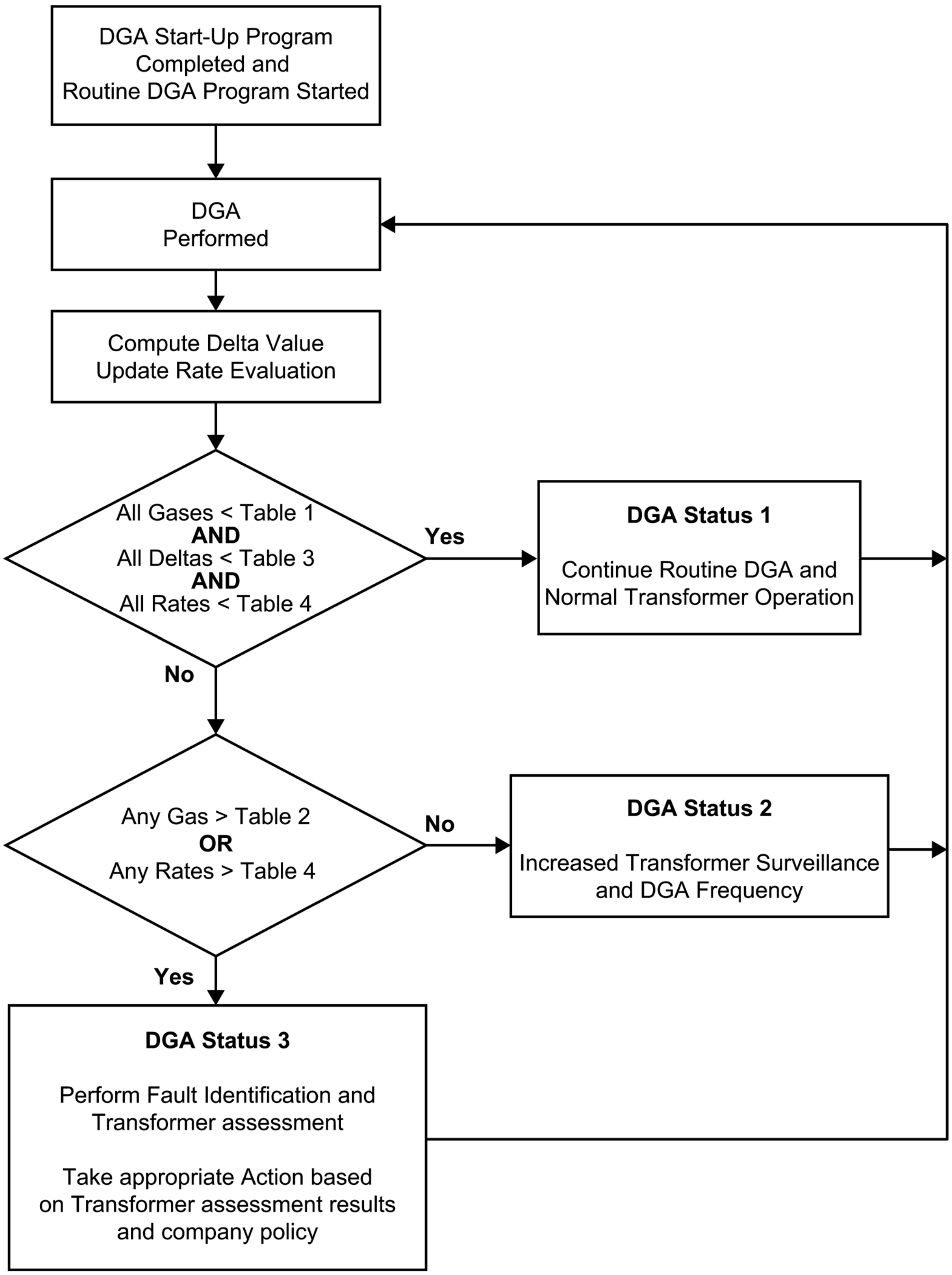


Figure 2—DGA interpretation flow chart (see 6.1 and 6.1.2 for status definition)

Table 1 is based on the 90th percentile of the population of DGA results (gas levels).

Table 2 is based on the 95th percentile of the population of DGA results (gas levels).

Table 3 is based on the 95th percentile of deltas between two consecutive laboratory DGA results [Δ µL/L, (Δ ppm)], without any adjustment due to time (no normalization per year). This is dominated principally by DGA result fluctuations caused by the analysis process itself. Table 3 is used to decide when a difference between the latest DGA result and the previous one is above the normal DGA fluctuations and might indicate a gas increase. In such cases, a confirmation sample is suggested.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table 4 is based on 95th percentile of rate computed with multi-point (3 to 6) linear regression [μL/L/year (ppm/year)]. As the number of points increase, fluctuations caused by the laboratory DGA analysis process cancel each other (average out), and this table is dominated principally by transformer gas evolution. Table 4 is used to decide when a sequence of DGA results indicates probable active gassing.

The following procedure explains the Figure 2 flowchart and refers to Table 1 through Table 4 in 6.1.3.

- Step 1: After completion of a start-up DGA program (see 5.3.1), periodic DGA are performed as per company routine policy.

- Step 2: Compute the O_2/N_2 ratio. Compute the absolute variation [delta μL/L (ppm)] for each gas from the previous routine sample. Update multipoint rate values using the last 3 to 6 data points over the last 4 to 24 mo period, if available. If more than 6 data points are available, use the six most recent data points, not exceeding two years, to compute the rates.

  NOTE—Rates will not be available if the transformer is sampled only once per year.

- Step 3: If age is known, compare all gas values to the applicable column of Table 1, according to the O_2/N_2 ratio and age. If age is unknown, use the values in the column "Unknown" (under "Transformer age year header) of the applicable table. If the O_2/N_2 ratio is not available, the O_2/N_2 ratio >0.2 section should be used.

  NOTE—When the O_2/N_2 ratio is near 0.2, it could happen that successive DGA test results change back and forth between <0.2 and >0.2 due to intrinsic DGA variability. In such cases it is recommended to use the >0.2 section.

- Step 4: If all gas levels are below the applicable values in Table 1, compare the delta values to the applicable sections of Table 3. Compare rate values to the applicable sections of Table 4, if available.

  - Step 4a: If all gas delta values are below the applicable section of Table 3, and all rates values are below the applicable section of Table 4 (if available), then a DGA status of 1 is indicated. Continue routine sampling as per company policy. See 6.1.2.1.

  - Step 4b: If any delta is greater than the value in the applicable sections of Table 3, or any calculated generation rate is greater than the applicable sections of Table 4, perform a confirmation DGA within a month and then perform Step 4c.

  - Step 4c: Compute the absolute variation (delta) between the reference sample (the one used as reference in Step 4b) and the confirmation sample. Compute rates with the confirmation sample replacing the previous value.

  - Step 4d: If the confirmation sample does not indicate an increase from the previous sample (i.e., all gas variations delta are below the applicable section of Table 3 and all rates below the applicable section of Table 4 norms), and all gas level values are also still below the applicable section of Table 1, DGA status is 1. Continue routine sampling per the company policy or manufacturer requirements. See 6.1.2.1.

  - Step 4e: If the second sample confirms an increase (Delta) has occurred but all gas level values are below the applicable section of Table 1 and all multi-point rates are below the applicable section of Table 4 values, then a DGA status of 2 is indicated. See 6.1.2.2.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

— Step 5: If any one gas level is between the values in the applicable sections of Table 1 and Table 2 with no gas levels above the applicable sections of Table 2, and all multi-point rates are below the applicable section of Table 4, then a DGA status of 2 is indicated. See 6.1.2.2.

If only 1 sample per year is taken, there will not be enough samples to calculate the multipoint gas generation rates for comparison to Table 4, so only Table 3 would be used in such cases. If Table 3 values are exceeded, a confirmation sample is required, which will allow the computation of the rates (e.g., 3 samples in 2 years).

— Step 6: If any one gas level is above the applicable section of Table 2, or if any rate is above the applicable section of Table 4, a DGA status of 3 is indicated. See 6.1.2.3.

— Step 7: For DGA in status 3, gas evolution should be monitored for a significant period of time. If during that period of time there is no significant positive rate observed, then a lower DGA status could be considered, after consultation with a DGA expert. See 6.1.2.3.

— Step 8: For extremely high concentrations, deltas, or rates, consult a DGA expert. See 6.1.2.4.

See B.2, B.3 and B.4 for examples of the application of this procedure.

6.1.2 DGA status

The classification process and recommendations below are based on gas levels and level variation norms obtained from a statistical analysis of a large population of DGA results (90^{th} and 95^{th} percentiles). This procedure is a guideline only and should not preclude any specific company policy or prudent management. See 5.4.

6.1.2.1 DGA Status 1

Transformers with DGA Status 1 are considered as probably normal, per DGA results statistics. Routine DGA and insulating liquid testing should be performed per the owner's internal policy or manufacturer's recommendations. Normal transformer operation can be continued.

6.1.2.2 DGA Status 2

Transformers with DGA Status 2 are considered as possibly suspicious and warrant additional investigation. Possible causes of gas generation using DGA should be investigated. If the fault diagnosis reveals an issue of Partial Discharges (PD), low temperature fault (T1), or stray gassing (S), this would be treated as a less urgent issue, but still may affect future life of the insulation system.

Otherwise, increased sampling frequency should be maintained or started. On-line dissolved gas monitoring may also be considered. Establishing multi-point rates is recommended if not already available.

Transformers having a DGA Status 2 due only to gas levels exceeding the values in Table 1 (especially if the only high levels are for carbon oxides), could be reassigned to routine sampling if there is no sign of active gassing during a year or more of increased sampling frequency (all samples below Table 3 and Table 4).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

6.1.2.3 DGA Status 3

Transformers with DGA Status 3 are considered as probably suspicious. On-line dissolved gas monitoring may be considered if close monitoring is necessary. Probable causes of gas generation using DGA interpretation procedures (see 6.2 and Annex D) should be investigated. The transformer should be placed under increased surveillance and additional transformer testing is recommended. Consultation with the transformer manufacturer or a transformer expert is also recommended. If after complete review of the available information, the transformer condition is deemed acceptable for continuous operation, then it is suggested to simply maintain surveillance typical of a lower DGA status. An example of this would be a transformer having a DGA Status 3 due only to gas levels exceeding the values in Table 2 (especially if the only high levels are for carbon oxides) when several samples taken over a year or more indicate no sign of active gassing (all samples below Table 3 and Table 4).

6.1.2.4 Extreme DGA results

As mentioned in Clause 1, in many cases, active faults generate gases at such a high rate that detection and assessment do not require finesse, or significant work. Gas levels or changes that are much larger than those provided in Table 2 and Table 3 warrant immediate extra investigation, which may include additional oil analysis and physical or electrical testing. Internal inspection might be considered if a confirmation sample rules out sampling error and fault interpretation indicates a possible cause that can be visually observed. For example, if an increase in C_2H_4 of 200 µL/L (ppm) or a level of C_2H_6 of 1000 µL/L (ppm) is observed, these would be considered extreme. In such cases, immediate investigation and operating restrictions should be initiated, at least until the cause of the large value is either dismissed as "erroneous" (sampling error for example) or fully understood and the unit has been deemed acceptable for continued operation. In all cases, expert opinion, operator experience, and specific unit conditions should be part of the evaluation. See B.4 for an example.

6.1.2.5 Caution in establishing and using DGA status value

Norms based on statistics should be considered as indicative only. It should not be taken for granted that a transformer is operating properly, simply because its gas levels are below norms. It can only be assumed that there is simply a lack of DGA evidence of abnormality. Likewise, a transformer with DGA Status 2 or Status 3 (i.e., being above statistical norms) is not necessarily faulty. It can only be concluded that its behavior is somewhat unusual and warrants additional investigation and/or precautions to be implemented, either simple or extensive, as evaluated by the DGA expert.

During the study to obtain the norm values, it was observed that large variations of results (percentiles) occurred between various sources, see Annex A for an example (this was also observed in other studies). Gas levels are a function of many parameters, not all of them understood or known. For example, variations in load pattern, geographical location, manufacturing process, maintenance practice, vintage, type of insulating liquid, rating, voltage class, or type of transformer could result in different gas levels and statistics. It is important to realize that these variations could be very large between sources (factors more than 2 to 1 have been observed) and affect the results of the interpretation process presented here. The information on these parameters that could have possibly been used in the study to refine the results was often simply not available or unreliable. For these reasons, numbers in Table 1 through Table 4 have been rounded to at most two significant digits and should not be considered, at any time, as "universal," "absolute," "authoritative," or "immutable" references. Transformer owners and operators are strongly encouraged to perform their own study based on their own data when available. See Annex A.

In some cases, it has been observed that transformers with an energized load tap changer may have some insulating liquid leakage from the tap changer compartment into the main tank. In such cases, some of the gases (especially C_2H_2 and C_2H_4) would be considerably higher than the value in Table 1 and Table 2. This could be interpreted as an internal fault, rather than just a leak. The apparent gassing will continue until the

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

leak is repaired, and the remnant gases will remain in the main tank until the transformer insulating liquid is vacuum processed.

DGA is a powerful tool to detect anomalies in transformers. However, it is not the only tool available to transformer owners. The use of DGA results to monitor transformers should not be assumed to be a replacement for other prudent operating, management, and monitoring practices. This is especially true of a transformer assessment following the detection of an anomaly. Conclusions or actions should never be based exclusively on a single DGA results.

6.1.3 DGA status norms

DGA status norms are shown in Table 1 through Table 4:

Table 1—90th percentile gas concentrations as a function of O_2/N_2 ratio and age in μL/L (ppm)

	O_2/N_2 Ratio ≤ 0.2				O_2/N_2 Ratio > 0.2			
	Transformer Age in Years				Transformer Age in Years			
Gas	Unknown	1 – 9	10 – 30	>30	Unknown	1 – 9	10 – 30	>30
Hydrogen (H_2)	80	75		100	40	40		
Methane (CH_4)	90	45	90	110	20	20		
Ethane (C_2H_6)	90	30	90	150	15	15		
Ethylene (C_2H_4)	50	20	50	90	50	25	60	
Acetylene (C_2H_2)	1	1			2	2		
Carbon monoxide (CO)	900	900			500	500		
Carbon dioxide (CO_2)	9000	5000	10000		5000	3500	5500	

NOTE—During the data analysis, it was determined that voltage class, MVA, and volume of mineral oil in the unit did not contribute in significant way to the determination of values provided in Table 1.

Table 2—95th percentile gas concentrations as a function of O_2/N_2 and age in μL/L (ppm)

	O_2/N_2 Ratio ≤ 0.2				O_2/N_2 Ratio > 0.2			
	Transformer Age in Years				Transformer Age in Years			
Gas	Unknown	1 – 9	10 – 30	>30	Unknown	1 – 9	10 – 30	>30
Hydrogen (H_2)	200	200			90	90		
Methane (CH_4)	150	100	150	200	50	60		30
Ethane (C_2H_6)	175	70	175	250	40	30	40	
Ethylene (C_2H_4)	100	40	95	175	100	80	125	
Acetylene (C_2H_2)	2	2		4	7	7		
Carbon monoxide (CO)	1100	1100			600	600		
Carbon dioxide (CO_2)	12500	7000	14000		7000	5000	8000	

NOTE—During the data analysis, it was determined that voltage class, MVA, and volume of mineral oil in the unit did not contribute in significant way to the determination of values provided in Table 2

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table 3— 95th percentile values for absolute level change between successive laboratory DGA samples in µL/L (ppm)

		Maximum µL/L (ppm) variation between consecutive laboratory DGA samples	
		O_2/N_2 Ratio ≤ 0.2	O_2/N_2 Ratio > 0.2
Gas	Hydrogen (H_2)	40	25
	Methane (CH_4)	30	10
	Ethane (C_2H_6)	25	7
	Ethylene (C_2H_4)	20	
	Acetylene (C_2H_2)	Any Increase	
	Carbon monoxide (CO)	250	175
	Carbon dioxide (CO_2)	2500	1750

NOTE—Contribution of voltage class, MVA, and volume of mineral oil in the unit was not studied for Table 3 as they have not been retained for Table 1 and Table 2. Data was insufficient to study age influence.

Table 4—95th percentile values from multi-points (3-6 points) rate analysis of laboratory DGA samples with all gas levels below Table 1 values, in µL/L/year (ppm/year)

		Maximum µL/L/year (ppm/year) rate in function of the period between first and last point of the laboratory DGA series (3 to 6 samples)			
		O_2/N_2 Ratio ≤ 0.2		O_2/N_2 Ratio > 0.2	
		Period between first and last point of the series			
		4-9 Months	10-24 Months	4-9 Months	10-24 Months
Gas	Hydrogen (H_2)	50	20	25	10
	Methane (CH_4)	15	10	4	3
	Ethane (C_2H_6)	15	9	3	2
	Ethylene (C_2H_4)	10	7	7	5
	Acetylene (C_2H_2)	Any increasing rate		Any increasing rate	
	Carbon monoxide (CO)	200	100	100	80
	Carbon dioxide (CO_2)	1750	1000	1000	800

NOTE—Contribution of voltage class, MVA, and volume of mineral oil in the unit was not studied for Table 4 as they have not been retained for Table 1 and Table 2. Data was insufficient to study age influence.

See 5.4 for general considerations on the selection of norm values.

See Annex A for a description of the methodology used to produce the numbers provided in Table 1, Table 2, Table 3, and Table 4.

6.1.4 Impact of DGA limitations

Norm values used in this guide have been obtained from a statistical study of DGA results supplied by several utilities and laboratories. DGA is a complex analytical process, and as such it has some limitations

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

that are important to consider for avoiding erroneous interpretation. Precautions for identifying faulty results before interpretation are outlined in 5.1 and 5.2. However, even when there is no error in the DGA process itself, some of the DGA intrinsic limitations have an impact on the selection and use of norms.

It is generally recognized by the industry experts that increasing gas levels are more of a concern than the levels themselves. Therefore, it is important to have some guidelines on acceptable gas generation rates.

However, the work performed in the analysis of laboratory DGA results indicated that obtaining a meaningful evaluation of the gassing rates requires more than the common practice of using two consecutive DGA to compute a yearly rate. Instead, this guide uses two different tables [Table 3 (delta without normalization) and Table 4 (multi point rates)] to evaluate the gassing tendency of a DGA set to overcome the effect of normal random fluctuations of the DGA process. See B.1 for a more detailed explanation of the why and how of this process.

It is also recognized that all faults are not of the same concern, so the type of fault should also be considered, not just the gas levels or the gas evolution.

As DGA interpretation is still more of an art than a science, the consultation of a transformer expert with DGA interpretation experience is strongly encouraged.

6.2 Fault type identification from DGA results

Since the introduction of DGA in the 1960s, several methods of interpretation have been developed. The large number of these methods, and the fact that some of them are specific to the utility that introduced them, precludes the presentation of all of them in this guide. Two common methods (Rogers Ratios and Duval Triangle 1) are presented in this clause. Additional methods are presented in Annex D. Fault nomenclature and descriptions are presented in Annex C.

6.2.1 General

All fault identification methods (Rogers Ratios, Doernenburg Ratios, Key gas, Duval Triangles 1-4-5 and Pentagons 1-2) can be used only if µL/L (ppm v/v) values are reliable and accurate enough. Guidelines as to when the accuracy of DGA results should be verified and guidelines as to when fault identification methods should be used or not are given in 5.2.1.

Hydrogen (H_2) is created primarily from corona partial discharge and stray gassing of oil, also from sparking discharges and arcs, although C_2H_2 is a much better indicator in such cases. It can also be caused by chemical reaction with galvanized steel.

Methane (CH_4), Ethane (C_2H_6), and Ethylene (C_2H_4) are created from heating of oil or paper.

Acetylene (C_2H_2) is created from arcing in oil or paper at very high temperatures above 1000 °C. Transformers without internal fuses, switches or other arcing devices that may have operated should not create any C_2H_2 under normal operating conditions. It is not uncommon to find increased levels of H_2 or C_2H_4 when C_2H_2 is detected.

The ranges of temperatures where these gases are mostly produced in oil can be seen in Figure 1. It can also be seen in Figure 1, that mixtures of these gases are always formed at any temperature. By looking at their relative proportions in oil, it is possible to identify the faults that have produced them, using one of the methods described in 6.2 or Annex D.

Carbon Monoxide (CO) and Carbon Dioxide (CO_2) are created from heating of cellulose or insulating liquid.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

6.2.2 Rogers Ratios Method

The Rogers Ratios Method is summarized in Table 5. It uses three gas ratios indicating five different types (cases) of faults, depending on the values of the ratios in column 2 through column 4 of Table 5.

Table 5— Rogers Ratios Method

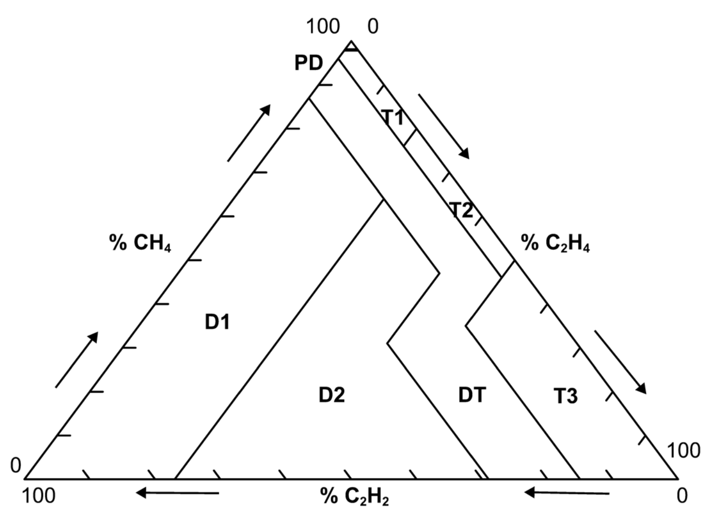
Case	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Suggested fault diagnosis
0	< 0.1	0.1 to 1.0	< 1.0	Unit normal
1	< 0.1	< 0.1	< 1.0	Low-energy density arcing—PD[a]
2	0.1 to 3.0	0.1 to 1.0	> 3.0	Arcing—High-energy discharge
3	< 0.1	0.1 to 1.0	1.0 to 3.0	Low temperature thermal
4	< 0.1	> 1.0	1.0 to 3.0	Thermal < 700 °C
5	< 0.1	> 1.0	> 3.0	Thermal > 700 °C

[a] There is a tendency for the ratios C_2H_2/C_2H_4 and C_2H_4/C_2H_6 to increase to a ratio above 3 as the discharge develops in intensity.

The limitation of the Rogers Ratios Method is that it cannot identify faults in a relatively large number of DGA results (typically 35%), because they do not correspond to any of the cases in column 1 of Table 5, even when µL/L (ppm) values are high and there is obviously a fault.

6.2.3 Duval Triangle 1

The Duval Triangle 1 Method is illustrated in Figure 3:



NOTE—See 3.2 for faults acronym and Annex C for faults type definition

Figure 3—Duval Triangle 1 Method

The Duval Triangle 1 Method uses three gases corresponding to the increasing energy content or temperature of faults: methane (CH_4) for low energy/ temperature faults, ethylene (C_2H_4) for high temperature faults, and acetylene (C_2H_2) for very high temperature/energy/arcing faults. On each side of the triangle are plotted the relative percentages of these three gases.

This method allows identification of the six basic types of faults indicated in Annex C.1, plus mixtures of electrical/ thermal faults in zone DT. Table 6 gives the numerical values for fault zone boundaries of Duval Triangle 1 Method expressed in ($\%CH_4$), ($\%C_2H_4$), and ($\%C_2H_2$).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table 6—Fault zone boundaries for Figure 3

Gas% / Fault	% CH_4	% C_2H_4	% C_2H_2
PD	≥ 98	—	—
T1	< 98	< 20	< 4
T2	—	≥ 20 and < 50	< 4
T3	—	≥ 50	< 15
DT	—	< 50	≥ 4 and < 13
	—	≥ 40 and < 50	≥ 13 and < 29
	—	≥ 50	≥ 15 and < 29
D1	—	< 23	≥ 13
D2	—	≥ 23	≥ 29
	—	≥ 23 and < 40	≥ 13 and < 29

NOTE 1—See 3.2 for fault acronyms and Annex C for fault type definitions.

The procedure for calculating and displaying DGA points in Duval Triangle 1 are in D.4.[10]

NOTE 2—For a more detailed interpretation of fault types PD, T1, T2 and T3, see Annex D, Duval Triangles 4 and 5, and Duval Pentagons 1 and 2.

The advantages of the Duval Triangle 1 Method are that it always proposes a fault identification (it is a "closed" system as compared to 2-gas ratios methods), with few erroneous diagnosis (it is based on a large number of inspected cases of faulty transformers in service), and it allows the ability to visually and rapidly follow the evolution of faults with respect to time in a transformer. Conversely, because it always gives a diagnostic, it should be used only to identify a fault when other information indicates that a fault is likely to exist. The fact that a possible fault type is identified is not in itself a confirmation of the presence of a fault.

The Rogers Ratio Method and Duval Triangle 1 Method should not be used on samples with very low gas levels, which can be unreliable and inaccurate. See 5.2 for further information.

[10] Free algorithms for using the Duval Triangles Methods are available in the IEEE Std C57.104-2019 directory located at: https://standards.ieee.org/content/dam/ieee-standards/standards/web/download/C57.104-2019_downloads.zip.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Annex A

(informative)

Data research and findings

A.1 Data collection and preparation

The purpose of this annex is to present a historical synopsis of the efforts of the IEEE Std C57.104 Guide Working Group, and specifically those efforts of the Data Task Force (DTF). The DTF has presented the details of the data analysis, to the extent possible, without causing any jeopardy or harm to any of the commercial entities who provided data to the WG for study and analysis. These details include the total number of data sets collected; the total number of data sets used; the methods used by the DTF to identify and cull outliers, bad data, or erroneous inputs; the statistical analysis methods used and the findings of the analyses; assumptions made and the logic used to make them; final presentation of data tables and statistical norms.

The task of revising and updating a guide on DGA interpretation began with accumulating a large data base of recent DGA results. Older revisions of the guide and methods of interpretation utilized DGA result datasets which were no longer available, and the size and scope of them were not well known. As such, the first task for this Working Group was to accumulate a new dataset. This new dataset would be based on relatively recent data from known sources, current methods of insulating liquid sampling, and current methods of laboratory analysis of the dissolved gases. The dataset is sufficiently large, and from a variety of data sources, to remove all doubt of statistical bias.

The Working Group requested voluntary DGA data contributions from transformer end-users (electrical utilities) and laboratories. Contributors provided data voluntarily, on good faith that the data would be utilized only for the purposes of writing this revised guide. The new raw dataset (“raw” meaning prior to any data elimination) contained more than 1 500 000 individual DGA results. In addition to the dissolved gas concentrations, as many of the following variables as possible were requested to accompany each individual DGA result: insulating liquid type (request was made to supply only data for mineral oil-immersed transformers); equipment type; transformer type; number of phases; MVA; voltage; age; manufacturer or; serial number or identification number; preservation system; insulating liquid volume; weight; sampling date; and analysis date.

The approach was to gather as much information as possible about each sample, which could potentially prove useful during the forthcoming data analysis and interpretation. Indeed, having some of the above information for each sample was essential during the initial “clean up” of the raw dataset.

With the raw dataset in hand, the data “clean up” process began. The primary goal of this process was to discard any data points deemed inapplicable or unreliable, resulting in a processed or “clean” dataset comprised of high quality data. Having a large raw dataset to begin with allowed a strict protocol of filtration.

Some of the data points were discarded for lack of essential information such as: gas concentration, liquid type, valid sample date and unique identifier.

Additional data was discarded for the following reasons:

— Equipment Type: Some of the DGA results did not belong to transformers but to load tap changers, storage tanks, or other equipment.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

— Operational Status: For the relatively few transformers which provided this information, the data point was discarded if the sample came from a transformer that was known not to be in service.

Upon completing the above process, further filtering of the dataset was applied to eliminate duplicate results; defined as two DGA results with the same ID and the same analysis date.

Next, corrections were made to some of the data points due to incorrect use of units associated with two data variables; these two variables were MVA and kV. Some DGA records could be corrected by examining other accompanying variables such as insulating liquid volume and transformer type. While these corrections were cumbersome, this was necessary so as to not discard or misuse a disproportionate number of large or small transformers in the dataset. Alternatively, when size was recorded in values of 1000 MVA or larger, and there was no other accompanying information to judge otherwise, the size was changed to kVA, with the understanding that there could be a very small error introduced for the rare case when the transformer was indeed 1000 MVA or larger. The same operation was performed for kV.

Finally, the processed dataset was made anonymous by compiling the data from all contributors together, removing contributor names, and replacing transformer serial numbers or identifiers with generic identifiers.

Following preparation of the data, the data was analyzed to obtain percentile values as a function of several criteria for diverse sub-populations (age, rating, O_2/N_2 ratio, etc.). Those values were used to prepare Table 1, Table 2, Table 3, and Table 4.

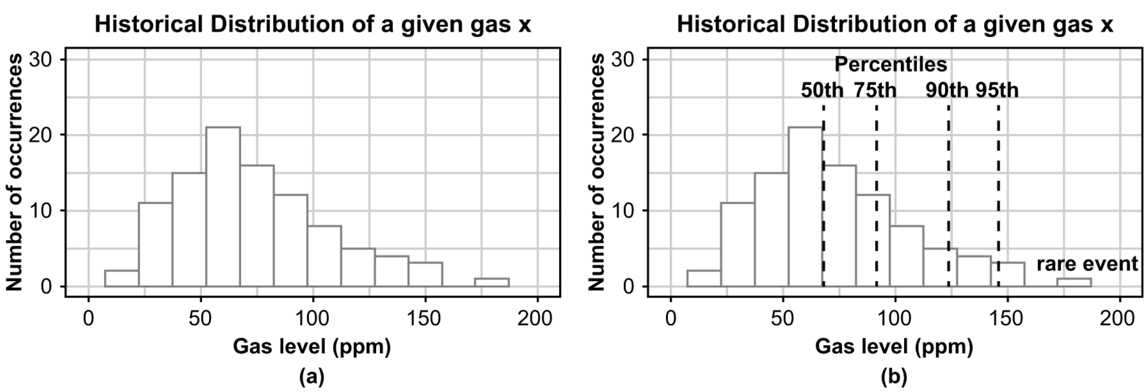


Figure A.1—Example of population distribution and percentile

Figure A.1(a) is an illustration of a generic historical distribution of a given gas x, heavily skewed to the right. Looking at the distribution, most of the time the gases are concentrated on the lower end (left side of the distribution), but there are a few samples that do occur on the higher end (e.g., above the 90th percentile).

Figure A.1(b) is an illustration of the relative location of "typical" percentiles used in multiple industries. The same concept may be applied to distributions skewed to the left or to normal distributions. Although there are several formulas to calculate percentiles, the concept is very straightforward and simply requires a calculation of the given percentage (e.g. 90th percentile or the 90% limit) of the numerically ordered data in ascending order.

The 90th percentile is commonly used to indicate the "norm" of a given parameter since it encompasses a large majority of the data and only leaves out 10% of the distribution. Note, that while there was no rounding up or rounding down of any figures in the processed dataset, some of the results from data analysis were rounded in the presentation of the results. To not round the result would imply a level of

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

accuracy which did not exist. The presentation of the 90th and 95th percentile values for dissolved gas concentrations, deltas and rates were rounded as follows:

The following rounding scheme was used for Table 1, Table 2, Table 3, and Table 4.

1 to 10:	Unit	500 to 1000:	Nearest 100
10 to 50:	Nearest 5	1000 to 2500:	Nearest 250
50 to 100:	Nearest 10	2500 to 5000:	Nearest 500
100 to 250:	Nearest 25	Above 5000:	Nearest 1000
250 to 500:	Nearest 50		

In addition to the rounding, adjacent numbers in Table 1, Table 2, Table 3, and Table 4 have been agglomerated in single value when they differed by less than 35%.

A.2 Dataset characteristics

The dataset used to generate the values in Table 1, Table 2, Table 3, and Table 4 had the following characteristics:

- Number of data suppliers: 18 (some sources have been broken by regions)
- Total number of DGA analysis: 1 391 436
- Total number of Transformers: 313 076
- Total number of DGA results supplied with transformer age information: 618 715
- Total number of DGA results supplied with transformer rating information: 738 188

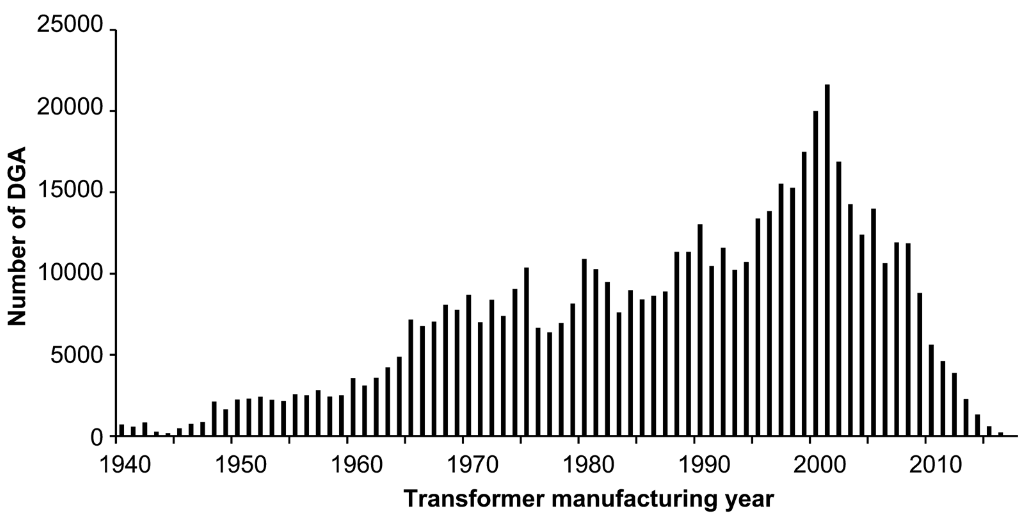


Figure A.2—Distribution of DGA in function of transformer manufacturing year

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

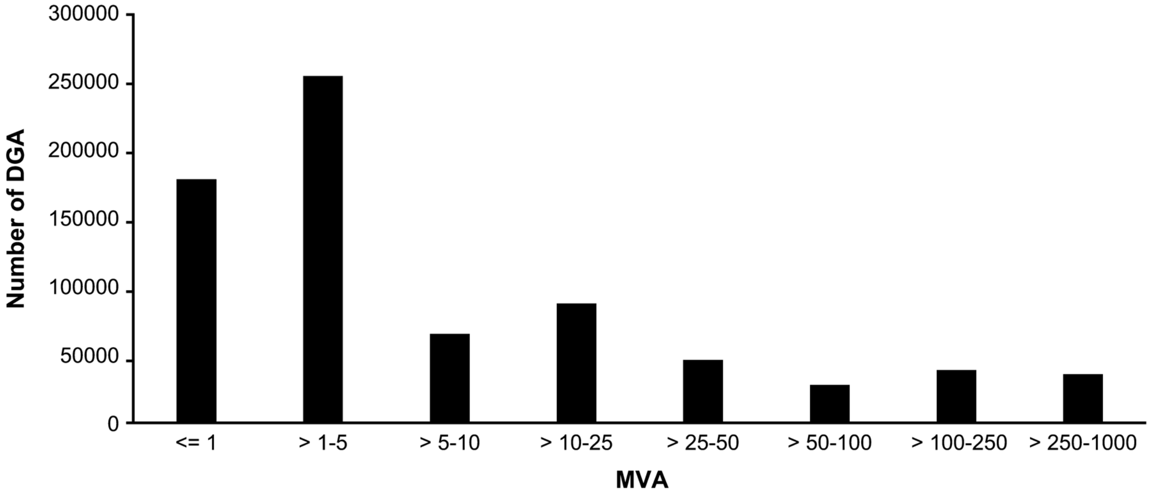


Figure A.3—Distribution of DGA in function of transformer rating

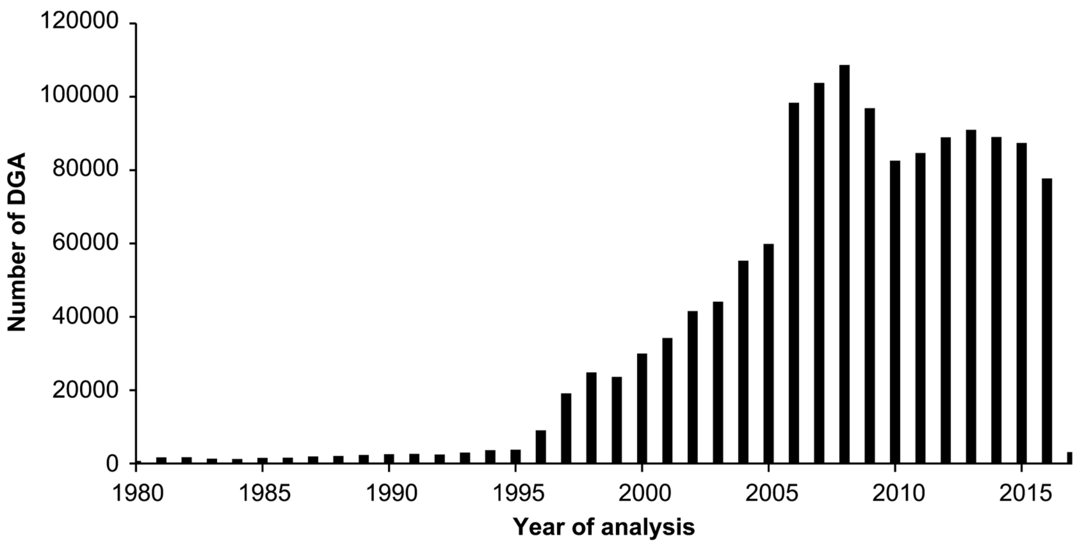


Figure A.4—Distribution of DGA in function of year of analysis

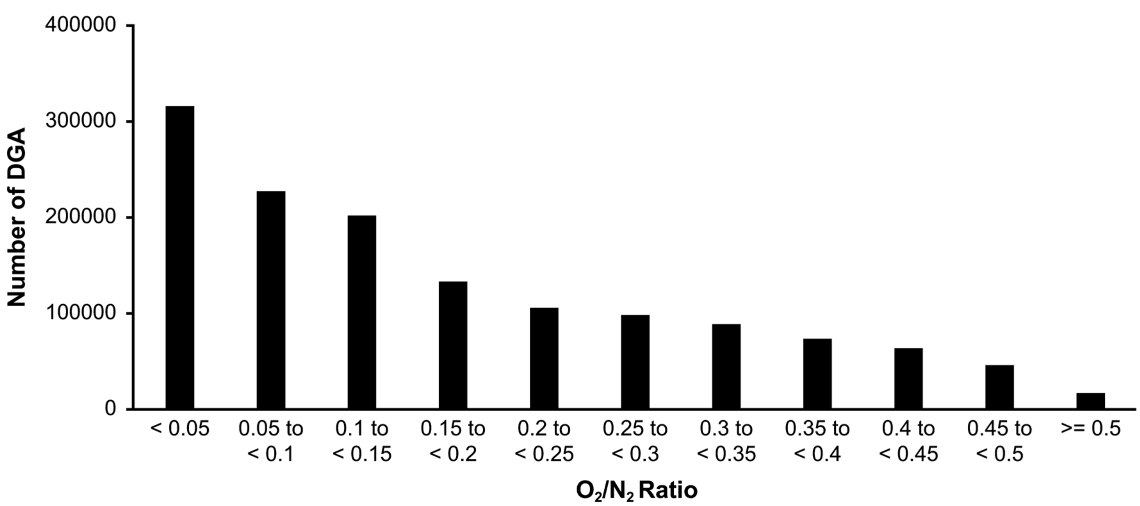


Figure A.5—Distribution of DGA in function of O_2/N_2 ratio

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

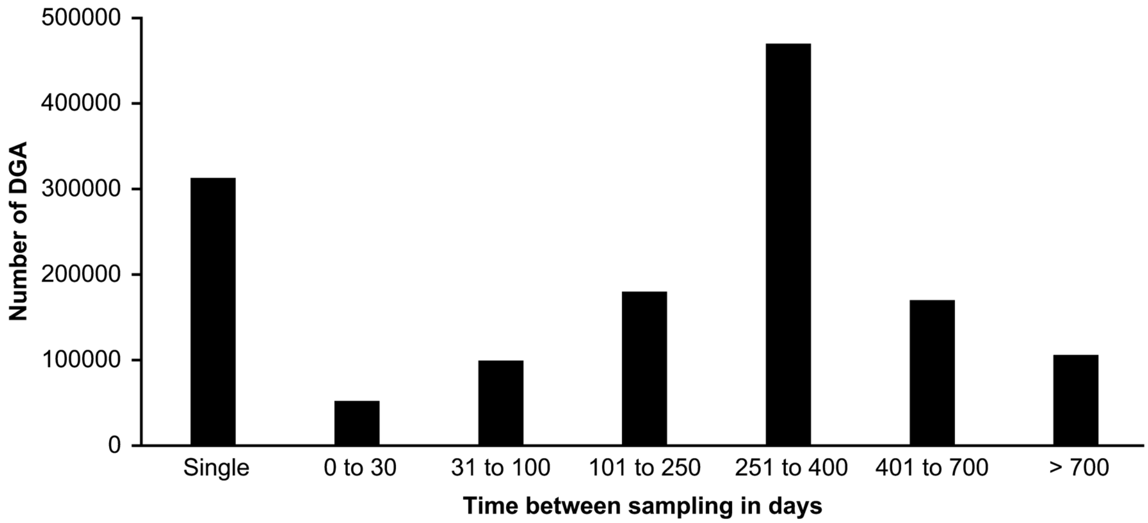


Figure A.6—Distribution of DGA in function of time between sampling

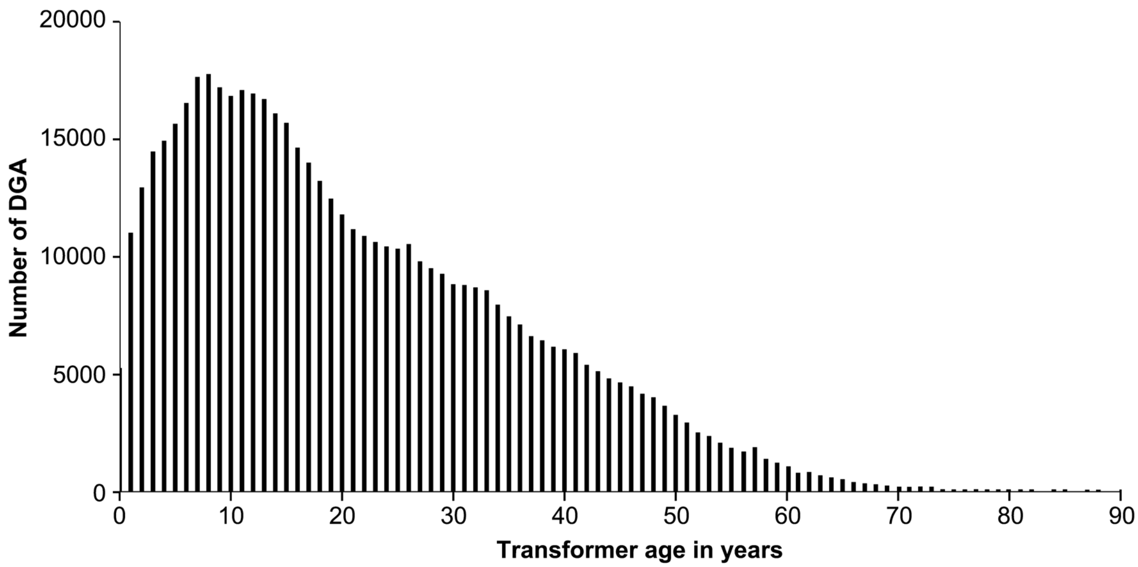


Figure A.7—Distribution of DGA in function of transformer age at the time of sampling

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

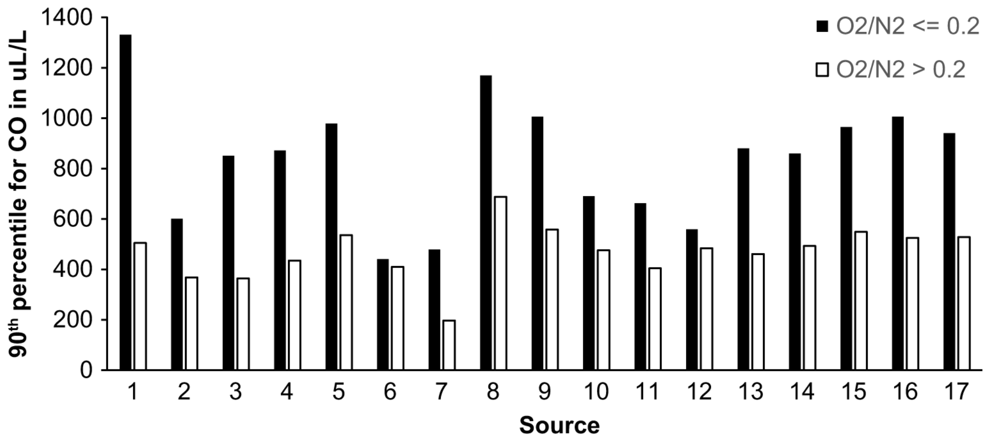


Figure A.8—Example of the variations of percentile values observed between the different DGA dataset sources (90th percentile for CO)

Table A.1—Distribution of DGA in function of O_2/N_2 ratio and age

	$O_2/N_2 \leq 0.2$				$O_2/N_2 > 0.2$			
	Age in years							
	All	**1 to 9**	**10 to 30**	**> 30**	**All**	**1 to 9**	**10 to 30**	**> 30**
Number of DGA	876 314	84 215	179 829	113 264	495 561	59 320	86 983	72 039
% of DGA	63.0%	6.1%	12.9%	8.1%	35.6%	4.3%	6.3%	5.2%

NOTE—The columns labeled “All” include all DGA results with valid O_2 and N_2 values (98.6% of the data received, after removal of DGA due to other invalid data), independent of the “Age” information. The columns labeled “1 to 9”, “10 to 30” and “>30” contain only the DGA results supplied with valid Age (excluding Age < 1 year), O_2 and N_2 values.

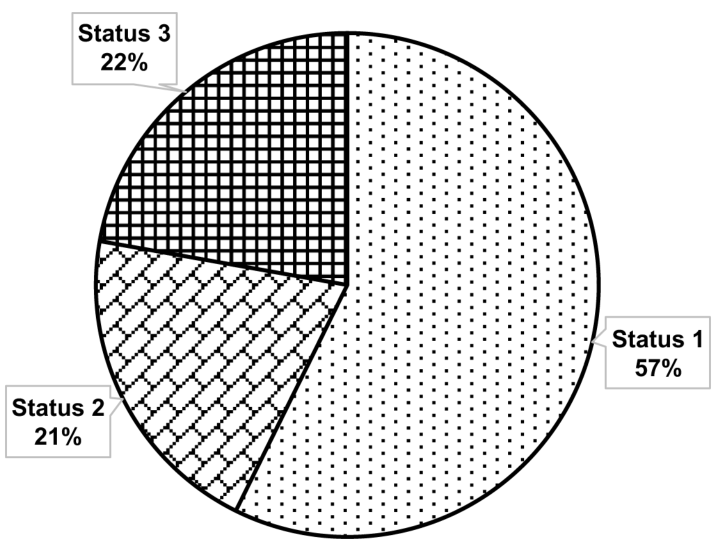


Figure A.9—Distribution of DGA status in the study dataset

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

A.3 Future work

The procedure to interpret DGA results presented in this guide is, by its very nature, a work in progress.

Progress in the understanding of DGA contributes to the development of DGA interpretation techniques. It will continue to evolve due to a wide variety of industry changes:

a) New material and new material processing
b) New transformer designs
c) New applications of transformers
d) Changes in data availability and quality
e) Changes in the operation and use of transformer
f) Change in the expectation of what DGA interpretation should supply to the transformer owners

This guide represents the best interpretation of the data available at the time of redaction, based on the experience of the experts contributing to this document. The industry should strive to continue to upgrade and improve it.

Several opportunities for improvement have been identified during the revision work that resulted in the present guide. While some effort was put into pursuing these topics, resolution of them remains too elusive to be included in this current guide. A list of these topics is provided as follows:

— Reduce the number of DGA marked as "Investigate" without losing the capability to detect abnormal situations.
— Obtain a better correlation between DGA results and actual fault detection and identification.
— Adapt DGA interpretation to specific applications, such as windfarm, network, GSU, distribution.
— Build an industry wide database of DGA, including all pertinent transformer information, to support the future evolution of this guide.
— Adapt application of DGA interpretation to the use of online DGA monitors, specifically regarding the rate of change calculations.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Annex B

(informative)

DGA data—Evaluating the rate of gas level change

The purpose of this annex is to present general observations on the influence of DGA limitations on rate evaluation with a tutorial application example of the procedure described in 6.1.1.

Trending DGA data can provide insight into changing equipment conditions. Trending can also be helpful to determine the effects of load and other conditions on possible active faults. In these situations, the establishment of a baseline and adequate sampling frequency to observe the variations in the rates of change are necessary. Large changes in the gas generation rate verified through a DGA confirmation sample should place the transformer into a diagnostic observation classification.

Care should be taken when applying rate diagnostics due to possible varying conditions between and among historic sample results. Factors like the insulating liquid temperature at the time of sampling, differing DGA methods between laboratories, and sample quality can make rates of change determinations impossible for one or more of the historic sample data sets. A basic understanding of the DGA method used is necessary so that data from incompatible sources do not generate an alarm condition (e.g., trying to compare on-line DGA results with laboratory based results). This can also apply to results received from different laboratories, e.g., results obtained from methods ASTM D3612A and ASTM D3612C, although it does not prevent a general comparison of the gas profile qualitative analysis.

The length of time between samples can make the rate of change calculation irrelevant as the diagnostic method. An example would be samples taken one day apart and theoretically containing the maximum amount of laboratory equipment error giving a false indication of a large change in the gas generation rate. A closely spaced confirmation sample is normally meant to verify a change in the gas concentrations allowing us to draw conclusions on the equipment condition. There is also the prospect of a gas generation event like a lightning strike compared to an active gassing source that consistently generates a specific amount of gas every day.

Another cautionary item is relevant equipment changes between samples. After maintenance operations that allow intentional or unintentional degassing, like a bushing replacement or insulating liquid processing, have been performed, the establishment of a new DGA baseline should be done. Processing may degas the insulating liquid, but a certain quantity of gas will normally remain in the cellulose insulation material. This residual combustible gas will influence future samples and should not be mistaken for real gas generation. The sample quality also has a direct impact on the ability to trend the results (see 5.1 and 5.2).

B.1 Impact of DGA limitations on the selection and use of rate norms

As a first approach, obtaining the appropriate percentiles rate values to detect DGA anomalies is simply a matter of performing the same statistic computations as for gas levels (see 5.4), but with the analysis applied to the difference between consecutive samples. As rate is generally defined as μL/L/year (ppm/year), it could be possible to perform a simple rate computation by taking the difference between gas levels of two consecutive DGA results and dividing it by the number of days between them, times 365, to obtain μL/L/year (ppm/year), and then obtain the 90th or 95th percentile of the rates population computed in this manner.

However, there is a serious issue with this approach: the 90th and 95th percentile values of rates computed with a certain time interval group (e.g., yearly DGA) are not the same for a different interval group (e.g., quarterly DGA). The difference is quite large and grows exponentially as a function of the inverse of time difference between DGA results (the shorter the interval, the higher the 90th and 95th percentile

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

values). In other words, it is impossible to obtain a percentile value in this manner that could be applicable to all pairs of samples, independently of the time between them. The normalization to a common time interval (year) simply does not work.

The reason for this counter intuitive result lies in DGA imperfections. Variations between DGA results are known to happen. Part of those variations could be explained by changes in a transformer's condition, such as load or temperature. However, the DGA process itself is also a source of variations. Those variations have several causes, explanation of which is beyond the scope of this guide. Consequently, it should not be expected that two strictly identical samples will produce exactly the same DGA results, even when there is no issue with sampling or DGA process.

In terms of the analysis process, these normal variations are called "reproducibility" and "repeatability."

> Reproducibility is the difference observed for the same sample between different laboratories, or different operators, or different analytical equipment, or at different times. This applies to typical DGA.
>
> Repeatability is the difference observed between repeated analyses of the same sample, by the same operator in a single laboratory, on the same analytical equipment in a short period of time (repeatability is sometimes called "Precision").

Note that those two values are NOT related to "accuracy," which is the difference between a result and the "true" value (also called "bias" when applied to a method).

Most of the time (when there is no active gas generation in the transformer), those variations are larger than what is actually taking place in the transformer. Those variations are simply unrelated to the operation of the transformer itself and could generate simple rate computation results that have nothing to do with the condition of the transformer. Worse, the rates computed from these random variations will be also strongly dependent of the time separating the samples.

For example, assume there are two consecutive samples for a transformer that differ by 2 µL/L (2 ppm) due to the intrinsic variability of the DGA results (not the transformer gas levels). Computing a simple yearly rate from these two results will give a value of 2 µL/L/year (2 ppm/year) if the two samples are a year apart. However, if the two samples are a month apart, then the computed value will be 24 µL/L/year (24 ppm/year). If the two samples are a day apart, then the computed rate will be 730 µL/L/year (730 ppm/year). Clearly this would result in radically different diagnostic if applied without discernment.

On the other hand, data analysis has clearly shown that the typical differences between two consecutive samples (deltas) are mostly unrelated to the time between the samples. They are about the same for samples taken a week or a month apart as for samples taken a year or two apart. For a simple rate computation, the difference of time between samples generate vastly different rate values with the same DGA variations, which make percentile values of simple rates unusable.

One way to reduce the impact of these intrinsic DGA process variations on the rate determination is to use more than two samples in the computation. As the variations caused by the DGA process are random, they will tend to cancel each other.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

To overcome those limitations of the DGA process, two tables have been developed for this guide to evaluate gas levels increase:

— Table 3: 95th percentile of delta between two consecutive laboratory DGA without any time normalization (Absolute Delta).

  Table 3 indicates when the difference between two DGA exceeds the typical variations expected from the DGA process. This could indicate either some active gassing or it could simply be a statistical anomaly that could be ruled out by a follow-up sample.

— Table 4: 95th percentile of rates (slopes) obtained from 3 to 6 consecutive laboratory DGA over a period of 4 to 24 months (rates) normalized in µl/l/year (ppm/year).

  Table 4 indicates when the rates of gas evolution exceed the typical rates of gas level in the general population of transformer (i.e., with gas levels below Table 1) and might indicate an active gassing situation.

A general rule is that any results that do not “fit the pattern” should be confirmed by a new sample, unless an obviously critical situation is observed. In such (rare) cases, precautionary actions, during the time a confirmation analysis is performed, might be advisable.

B.2 Example 1

Please note that the data below is only a tutorial example to illustrate the procedure of Figure 2 and 6.1.1. Each transformer being unique, a real-life situation would be different. This example is typical of most transformers.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table B.1—Multi-points rate tutorial example 1

Point number	Days	µL/L	Delta µL/L	Table 3 norms	µL/L/year	Period in days	Table 4 norms
1	0	5	N/A	N/A	N/A	0	N/A
2	14	9	4	20	N/A	14	N/A
3	27	7	-2	20	N/A	27	N/A
4	40	8	1	20	N/A	40	N/A
5	96	9	1	20	N/A	96	N/A
6	150	7	-2	20	2.1	150	10
7	275	5	-2	20	-4.3	261	10
8	399	6	1	20	-2.4	372	7
9	524	5	-1	20	-2.6	484	7
10	651	38	33	20	13.4	555	7
11	672	6	1	20	-1.6	576	7
12	771	7	1	20	0.1	621	7
13	782	9	2	20	2.0	507	7
14	910	11	2	20	3.6	511	7
15	1042	8	-3	20	3.1	518	7
16	1162	9	1	20	1.7	490	7
17	1282	8	-1	20	-0.1	511	7
18	1402	10	2	20	-0.2	620	7

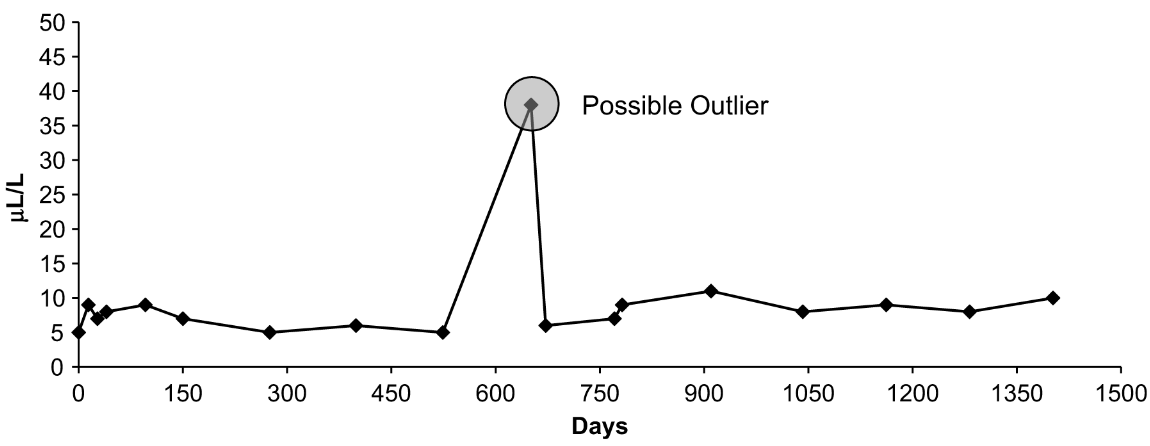


Figure B.1—Multi-points rate example 1

Table B.1 data (plotted in Figure B.1) is an illustrative example (not from a real case) of a series of DGA data points that could be evaluated to determine if an active fault is possibly present in a transformer. In that example, 18 DGA reports are provided from a two years old transformer recently placed under elevated load with an initial period of frequent sampling followed by regular sampling every three months. The discussion is limited to a single gas (C_2H_4) for clarity, but the same process should be applied to all the other gases. Figure B.1 is a graph of data that helps to visualize gas evolution over time.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table B.1 column headers are explained as:

- Point number: sample number from the start of the periodic screening program
- Days: number of days from the first sample of the regular periodic screening program
- µL/L: DGA result in µL/L (ppm)
- Delta µL/L: delta from the previous point in µL/L (ppm)
- Table 3 norm: the applicable norm for delta (Table 3)
- µL/L/year: computed rate (linear best fit of the last three to six valid points for all periods greater than four months and less than two years)
- Period in days: the sampling period for the rate computations (number of days between the first and the last points of the series used in the linear best fit)
- Table 4 norm: the corresponding norm from Table 4

The transformer, in this example, is a two year old unit with an O_2/N_2 ratio < 0.2. For this unit, the Table 1 norm is 20 µL/L (ppm), the Table 2 norm is 100 µL/L (ppm), the Table 3 norm is 20 µL/L (ppm), and the Table 4 norms are between 7 to 10 µL/L/year (ppm/year).

Sample 1 is below the norm of Table 1, therefore the DGA is Status 1. Table 3 does not apply as there is no prior sample.

Sample 2 through Sample 5 are below the norm of Table 1 and their computed delta are below Table 3 norm. Rates are not available due to the period between first and most recent point being less than four months, so as per step 4a of 6.1.1, DGA is Status 1.

Starting at Sample 6, the rate could be computed as the minimal period for rate computation (four months) has been met. The last six samples are included in the rate computation.

Sample 6 through Sample 9 are below Table 1 norm, with the delta below the Table 3 norm. The rate is below Table 4 norm, so as per step 4a of 6.1.1, DGA is Status 1.

With Sample 10, although the gas level value is below Table 1, the delta between Sample 9 and Sample 10 exceed Table 3 norm and the computed rate of point 5 to point 10 exceed Table 4 norm. DGA is, therefore, in Status 3.

This could either be the first indication of gassing or it could be the result of a bad sample. An emergency confirmation sample is requested, as per step 4b of 6.1.1.

Sample 11 is the result of the confirmation sample. As per step 4c, the delta is computed between Sample 9 and Sample 11. The resulting delta of 1 µL/L is well below the Table 3 norm, indicating that Sample 10 is a bad sample. Rate is recomputed with point 5 to point 11, omitting point 10, and gives a result of –1.6 µL/L/year and confirms that Sample 10 was bad. As per step 4d, DGA is Status 1. Point 10 is removed from all future rate computations.

The Sample 12 through Sample 18 values are all below Table 1, all deltas are below Table 3, and all rates are below Table 4 (point 10 not used for rate computation) for a DGA Status 1, confirming Sample 10 was indeed a bad sample.

Regular screening DGA test protocol is maintained.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

B.3 Example 2

Please note that the data below is only a tutorial example to illustrate the procedure of Figure 2 and 6.1.1. Each transformer being unique, a real-life situation would be different. It should be noted that this tutorial example is more complex that most usual cases encountered in normal operation. This is done purposively to illustrate some of the steps of 6.1.1.

Table B.2—Multi-points rate tutorial example 2

Point number	Days	µL/L	Delta µL/L	Table 3 norms	µL/L/year	Period in days	Table 4 norms
1	0	5	N/A	N/A	N/A	0	N/A
2	17	9	4	20	N/A	17	N/A
3	68	11	2	20	N/A	68	N/A
4	80	14	3	20	N/A	80	N/A
5	122	34	20	20	75	122	7
6	150	30	-4	20	69	150	7
7	157	30	0	20	68	140	7
8	179	39	9	20	85	111	7
9	204	32	-7	20	53	124	7
10	303	33	1	20	1.3	181	7
11	359	38	5	20	8.2	209	7
12	384	66	28	20	33	227	7
13	410	31	-35	20	0.2	253	7
14	561	27	-4	20	-8.0	382	5
15	649	48	21	20	6.9	445	5
16	736	41	-7	20	7.8	433	5
17	751	61	20	20	17	392	5
18	816	58	-3	20	28	406	5

Table B.2 data (plotted in Figure B.2) is an illustrative example (not from a real case) of a series of DGA data points that could be evaluated to determine if an active fault is possibly present in a transformer. In that example, 18 DGA reports are provided from a transformer returned to service after repair and under close surveillance (frequent DGA results). (The discussion is limited to a single gas (C_2H_4) for clarity, but the same process should be applied to all the other gases.) See description of Table B.1 in B.2 for the column header description.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

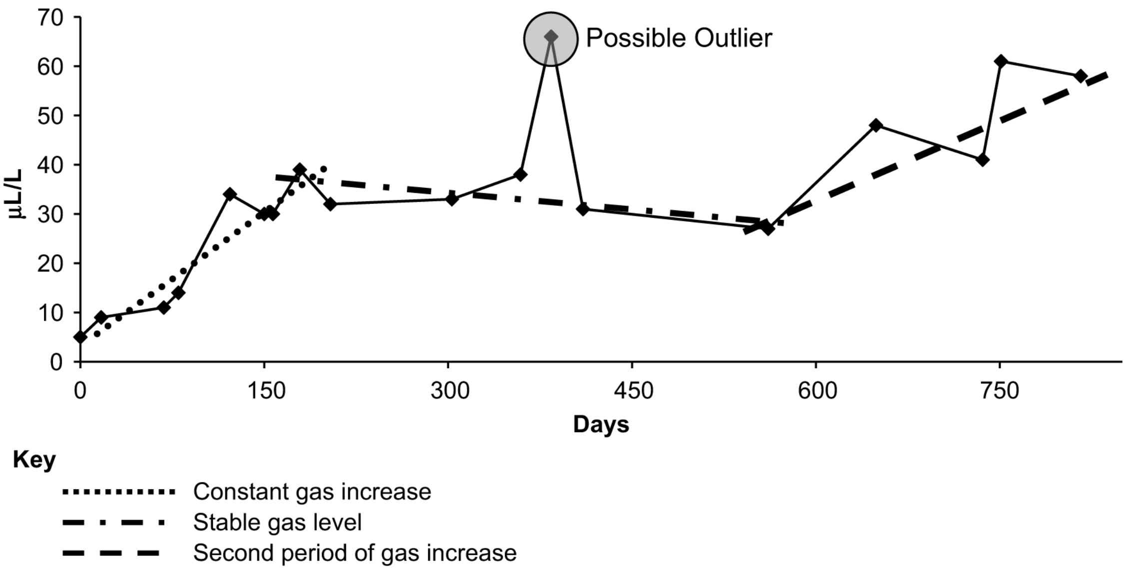


Figure B.2—Multi-points rate example 2

Plotting Table B.2 data in function of time (Figure B.2) reveals the following:

— One group of data (point 1 through point 8) indicating a constant gas increase (small dashes line)

— A second group of data indicating a stable gas level (point 8 through point 14) (dashes-dots line)

— A possible outlier (point 12) (shaded circle)

— A third group of data indicating a second period of gas increase (point 14 through point 18) (large dashes line)

Those different periods, and the outlier, are easy to see when all the points are available and placed in a graph, such as Figure B.2.

However, in practice, an operator will have access to only one new point at the time and would have to make an evaluation in "real time" with the new data, without the benefit of knowing what the evolution will be.

Computing a simple gas generation rate by subtracting the previous value from the last and dividing by the period between the samples seems to be an obvious way to analyze new points. However, as discussed in B.1, this could be misleading due to the inherent variability of the DGA process. It is preferable to apply a multi-point linear best fit (available in most spreadsheets) over a significant period of time for rate computation to reduce the impact of these normal DGA variations.

This tutorial example is for C_2H_4 data from an eleven-year-old unit with an O_2/N_2 ratio above 0.2. The Table 1 C_2H_4 level norm is 60µL/L (ppm), Table 2 is 125 µL/L (ppm), Table 3 Delta norm is 20 µL/L (ppm), and Table 4 is between 7 µL/L/year (ppm/yr) (4 to 9 mo) and 5 µL/L/year (ppm/year) (9 to 24 mo) for the period covered in this example.

If the procedure outlined in Figure 2 and described in 6.1.1 is applied, the following interpretation is obtained:

Point 1 through point 4 are in DGA status 1 for both levels (Table 1) and delta µL/L (delta ppm) (Table 3).

With point 5, the procedure of Figure 2 indicates that the maximum allowable delta (Table 3) is reached, [20 µL/L (ppm)] indicating possible gassing activities. The DGA status could become 2 if a new sample confirms the change. Point 1 through point 5 are used to compute a linear best fit, as the period between

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

point 1 and 5 exceeds 4 mo. It can be observed that the rate is 75 µL/L/year (ppm/year), which is above the Table 4 norm, indicating probable gassing activity and placing the DGA in status 3.

Gassing activity is monitored for confirmation with point 6 through point 8. Point 1 through point 6 confirms a rate above Table 4 [69 µL/L/year (ppm/year)], and the DGA as status 3. The point 8 delta is below the norm of Table 3. However, the rate computed from point 2 through point 8 (6 most recent points) is 85 µL/L/year (ppm/year), which is above the Table 4 norm, confirming a constant gassing activity and a DGA status 3.

A transformer assessment is performed at that point, with the assistance of a DGA expert, to evaluate what action should be taken. Adjustment to the transformer operating condition is performed.

Point 9 through point 11 seem to indicate a reduction of the gassing activity. The rate computed with point 5 through point 10 gave a value of 1.3 µL/L/year (ppm/year), which is essentially flat and below Table 4. Since gas level is also below the Table 1 norm, the DGA is back in status 1.

However, point 12 indicates a sudden jump, even with the new operating conditions, exceeding the value of Table 3. The rate computed on the last 6 points (point 7 through point 12) is 33 µL/L/year (ppm/year). This could either be a sample error or an indication of a deterioration of the existing condition due to new gassing activity. A priority confirmation sample is taken along with implementing extra precautions in the transformer operation while awaiting the confirmation sample results. The new sample (13) does not confirm the sudden increase; indicating that point 12 is probably an error. After review, the decision is taken to not make any new adjustment, but to maintain the restrictions implemented after point 8 and to continue close surveillance. Point 12 is considered an outlier and is removed from subsequent rate computations (shaded cell of Table B.2).

Point 14 confirms the apparent lack of activity [the rate for point 8 to point 14 (last six valid points) is –8.0 µL/L/year (ppm/year), excluding the outlier] but then point 15 exceeds the maximum delta of Table 3, so close surveillance is maintained and DGA is now status 2. Rate computed from point 10 to point 16 seem to indicate new gassing activity with a rate above Table 4 norm, with the point 17 value just above Table 2 norm and the delta from point 16 to point 17 equal to the Table 3 norm. The linear best fit computed rate for point 11 to point 17 is 17 µL/L/year (ppm/year), which is less than the first segment, but nevertheless still above Table 4, indicating that a gassing condition is still active, placing the DGA in status 3 again. Point 18 confirms the gassing with a rate of 28 µL/L/year (ppm/year) for point 13 to point 18.

This is a tutorial example only. Each individual case will be different.

B.4 Example 3

This example illustrates a case of a transformer that experienced a sudden and large or extreme increase after a long period of gassing inactivity. This case is typical of most gassing events. It is an extreme situation that is obvious and does not require any finesse or norms to interpret, once confirmation samples have been obtained.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

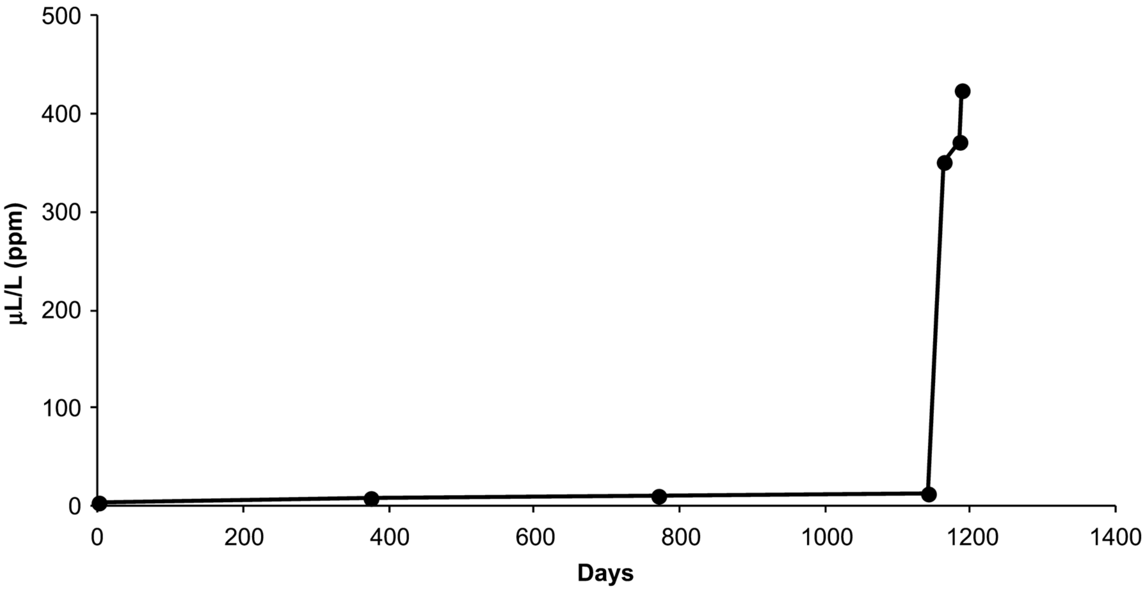


Figure B.3—Example of an extreme DGA evolution

B.5 General application

It should be remembered that each situation is unique, and no process can be totally universal. Therefore, a new set of data would be different than the examples presented here (see Annex E for real life examples). However, the procedure should follow the general lines of 6.1.2, but could be adapted depending of the situation. When data indicate a possible transformer anomaly, consultation with the transformer manufacturer, the transformer specialist, the owner and the operator should be undertaken.

It is generally recognized among transformer experts that actual gas levels are less significant than active gassing. A high level of gas could be the result of a previous event, no longer active, or a slow accumulation over a long period that presents no immediate issue (especially for CO and CO_2). On the other hand, a sign of ongoing gassing, even when levels are still low, is an indication of some phenomena occurring in the transformer and should always warrant extra investigation.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Annex C

(informative)

Typical faults

The purpose of this annex is to identify and classify the typical faults one might encounter when operating a power transformer, and to also discuss these fault types in brief detail.

C.1 The six basic types of faults

The six basic types of faults indicated below and abbreviated in Table C.1 can be identified by DGA results, using methods described in 6.2 and Annex D.3.

— Partial discharges (PD) of the cold plasma (corona) type, resulting in possible X-wax deposition on paper insulation.

— Discharges of low energy (D1), in mineral oil and/or paper, evidenced by larger carbonized perforations through paper (punctures), carbonization of the paper surface (tracking), carbon particles in mineral oil (as in tap changer diverter operation), or partial discharges of the sparking type, inducing pinhole or carbonized perforations (punctures) in paper.

— Discharges of high energy (D2), in mineral oil and/or paper, with power follow-through, evidenced by extensive destruction and carbonization of paper, metal fusion at the discharge extremities, extensive carbonization in mineral oil and, in some cases, tripping of the equipment, confirming the large current follow-through.

— Thermal faults, in mineral oil and/or paper, below 300 ºC if the paper has turned brownish (T1), and above 300 ºC if it has carbonized (T2).

— Thermal faults of temperatures above 700 ºC (T3) if there is strong evidence of carbonization of the mineral oil, metal discoloration (800 ºC) or metal fusion (>1000 ºC).

Table C.1—Abbreviations of basic faults

PD	Partial discharges of corona type
D1	Discharges of low energy or partial discharges of sparking type
D2	Discharges of high energy
T1	Thermal fault, t < 300 ºC
T2	Thermal fault, 300 ºC < t < 700 ºC
T3	Thermal fault, t > 700 ºC

C.2 Additional sub-types of faults

The additional sub-types of faults indicated in Table C.2 can be identified using methods described in D.3 to D.5.

— Stray gassing of mineral oil (S) at temperatures < 200 °C (in mineral oil only), because of the chemical instability of mineral oils produced by some modern refining techniques. It could also occur due to incompatibility between materials (e.g., such as some metal pasivators).

— Overheating (O) of paper or mineral oil < 250 °C (therefore without carbonization of paper and loss of its electrical insulating properties).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

— Possible carbonization of paper (C).

— Thermal faults T3 in mineral oil only (no paper involved) (T3-H) .

— Catalytic reactions (R) between water and galvanized steel in oil sampling valves of transformers or with tank stell (rust) (R faults are very rare).

These fault subtypes have been described in detail in the IEEE PES Transformers Committee Tutorial "Interpretation of Dissolved Gas Analysis in Electrical Equipment with Duval Triangles and Pentagons" [B92] and in "The Duval Pentagon—A new complementary tool for the interpretation of DGA in transformers," [B90] and supported by several inspected cases.

Table C.2—Abbreviations of fault subtypes

S	Stray gassing at temperatures < 200 °C,
O	Overheating < 250 °C without carbonization of paper
C	Possible paper carbonization
T3-H	Thermal fault T3 in mineral oil only
R	Catalytic reaction

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Annex D

(informative)

Fault identification methods

The purpose of this Annex is to present fault identification methods. These methods include various data ranges, classifications, tables, ratio analysis, and use of visual aids such as Duval's Triangle and Pentagon.

D.1 Key Gas method

The Key Gas method is summarized in Table D.1:

Table D.1—Key Gas method

Key Gas	Fault type	Typical proportions of generated combustible gases
Ethylene (C_2H_4)	Thermal mineral oil	Predominantly Ethylene with smaller proportions of Ethane, Methane, and Hydrogen. Traces of Acetylene at very high fault temperatures.
Carbon-Monoxide (CO)	Thermal mineral oil and cellulose	Predominantly Carbon Monoxide with much smaller quantities of Hydrocarbon Gases Predominantly Ethylene with smaller proportions of Ethane, Methane, and Hydrogen
Hydrogen (H_2)	Electrical low energy partial discharge (PD)	Predominantly Hydrogen with small quantities of Methane and traces of Ethylene and Ethane.
Hydrogen and Acetylene (H_2, C_2H_2)	Electrical high energy (arcing)	Predominantly Hydrogen and Acetylene with minor traces of Methane, Ethylene and Ethane. Also, Carbon Monoxide if cellulose is involved.

When the main gas formed in DGA results is one of the four key gases in column 1, together with the secondary gases in column 3, the type of fault is provided in column 2.

The limitation of the Key Gas method is that it results in many inconclusive or wrong fault identifications (typically 50%) when applied automatically with software. This is because often it is not clear which is the main gas formed, also because the main gas formed may not be one of those used in the Key Gas method. Furthermore, CO is not always a good indicator of a fault in paper (see D.8).

When applied manually by experienced DGA users, the number of wrong fault identifications with the Key Gas method is lower (typically 30%) but still high.

D.2 Doernenburg Ratios method

The Doernenburg Ratios method is illustrated in Table D.2:

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table D.2—Doernenburg Ratios method

Suggested fault diagnosis	Ratio 1 (R1) CH_4/H_2 Extracted from mineral oil | gas space		Ratio 2 (R2) C_2H_2/C_2H_4 Extracted from mineral oil | gas space		Ratio 3 (R3) C_2H_2/CH_4 Extracted from mineral oil | gas space		Ratio 4 (R4) C_2H_6/C_2H_2 Extracted from mineral oil |gas space	
1 – Thermal decomposition	> 1.0	> 0.1	< 0.75	< 1.0	< 0.3	< 0.1	> 0.4	> 0.2
2 – Corona (low intensity PD)	< 0.1	< 0.01	Not significant		< 0.3	< 0.1	> 0.4	> 0.2
3 – Arcing (high intensity PD)	> 0.1 < 1.0	> 0.01 < 0.1	> 0.75	> 1.0	> 0.3	> 0.1	< 0.4	< 0.2

It is a historic method less used today. It has the same limitation as the Rogers Ratios method. See G.4 for more information.

D.3 Duval Pentagon 1 method

The Duval Pentagon 1 method is illustrated in Figure D.1.

The Duval Pentagon 1 uses all five hydrocarbon gases (H2, C_2H_6, CH_4, C_2H_4 and C_2H_2). The order of gases at the five summits of Pentagons 1 and 2 correspond to the increasing energy or temperature of the faults producing these gases (from H_2 to C_2H_2).

The six basic types of faults of (PD, D1, D2, T1, T2 and T3) indicated in Annex C.1 can be detected with Duval Pentagon 1, as in the case of Duval Triangle 1 (see 6.2.3), as well as stray gassing of mineral oil (S) indicated in Annex C.2.

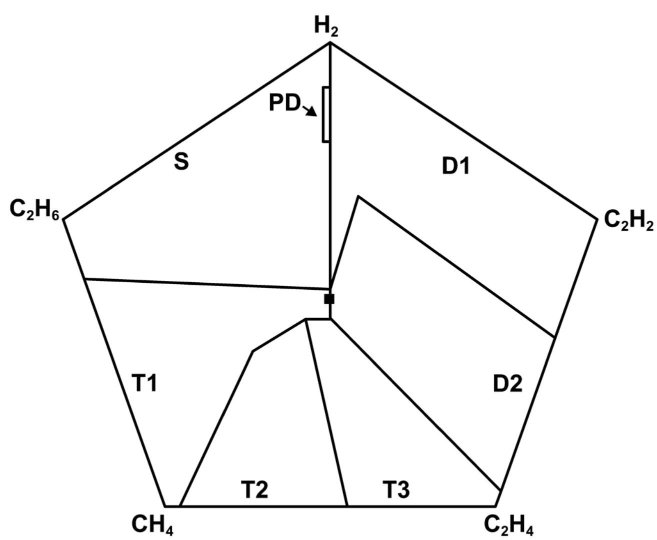


Figure D.1—Duval Pentagon 1 method

The procedure for calculating and displaying DGA points in Duval Pentagon 1 are described in “The Duval Pentagon—A new complementary tool for the interpretation of dissolved gas analysis in transformers,” [B90].

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

The numerical values of the (x, y) coordinates of zone boundaries in Pentagon 1 are indicated below [the dot of Figure D.1 is at coordinates (0,0) and the apex H2 is at coordinates (0, 40)][11]:

— PD: (0, 33), (–1, 33), (–1, 24.5), (0, 24.5);
— D1: (0, 40), (38, 12), (32, –6.1), (4, 16), (0, 1.5);
— D2: (4, 16), (32, –6.1), (24.3, –30), (0, –3), (0, 1.5);
— T3: (0, –3), (24.3, –30), (23.5, –32.4), (1, –32); (–6, –4);
— T2: (–6, –4), (1, –32.4), (–22.5, –32.4);
— T1: (–6, –4), (–22.5, –32.4), (–23.5, –32.4), (–35, 3), (0, 1.5); (0, –3);
— S: (0, 1.5), (–35, 3.1), (–38, 12.4), (0, 40), (0, 33), (–1, 33), (–1, 24.5), (0, 24.5);

D.4 Duval Triangles 1, 4 and 5 methods

The Duval Triangle 1 method is described in 6.2.3. The general methodology as Triangle 1 is applied to obtain interpretations with Triangle 4 and Triangle 5 and is as follows:

In a DGA report, if (C_2H_2) = x; (C_2H_4) = y; (CH_4) = z, in µL/L (ppm), first calculate the sum ($x + y + z$), then the relative % of each gas $\% C_2H_2 = 100x/(x+y+z)$; $\% C_2H_4 = 100y/(x+y+z)$; $\% CH_4 = 100z/(x+y+z)$.

These relative % values are the coordinates of the DGA point in Duval Triangle 1. As illustrated, for example, in Figure D.2 where x = 25 µL/L (ppm) of CH_4, y = 15 µL/L (ppm) of C_2H_4 and z = 10 µL/L (ppm) of C_2H_2.

Relative % values are CH_4 = 50%, C_2H_4 = 30% and C_2H_2 = 20%; in zone D2.

[11] Free algorithms for using the Duval Pentagons methods are available in the IEEE Std C57.104-2019 directory located at: https://standards.ieee.org/content/dam/ieee-standards/standards/web/download/C57.104-2019_downloads.zip.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

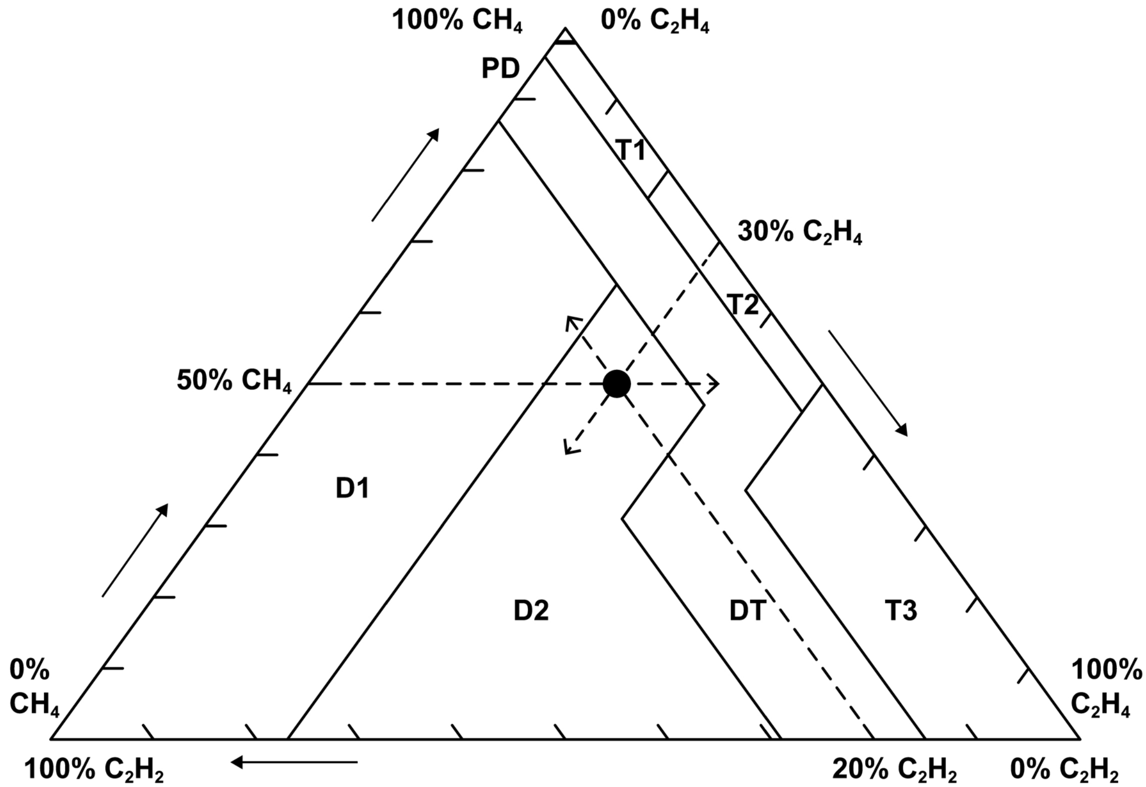


Figure D.2—Example of Duval Triangle 1 representation

Duval Triangles 4 and 5 are built and used in the same manner but use different gases and zones. Duval Triangle 4 uses H_2, CH_4 and C_2H_6 and Duval Triangle 5 uses CH_4, C_2H_4 and C_2H_6.

Duval Triangles 4 and 5 can be utilized to obtain more information about sub-types of thermal faults described in C.2. See also 6.2.3.

When low energy or low temperature faults are identified using the Duval Triangle 1 (PD, T1 or T2), more information can be obtained with Duval Triangle 4.

When high, or very high, temperature faults have been identified with Duval Triangle 1 (T2 or T3), more information can be obtained using the Duval Triangle 5.

The Duval Triangle 4 method is illustrated in Figure D.3.

The Triangle 4 method allows for distinguishing between faults S, O, PD, R (see C.2), which are of relatively minor concern in transformers, and potentially more dangerous faults C, which involve possible carbonization of paper. Faults R will appear at the very top of Triangle 4 (H_2 only).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

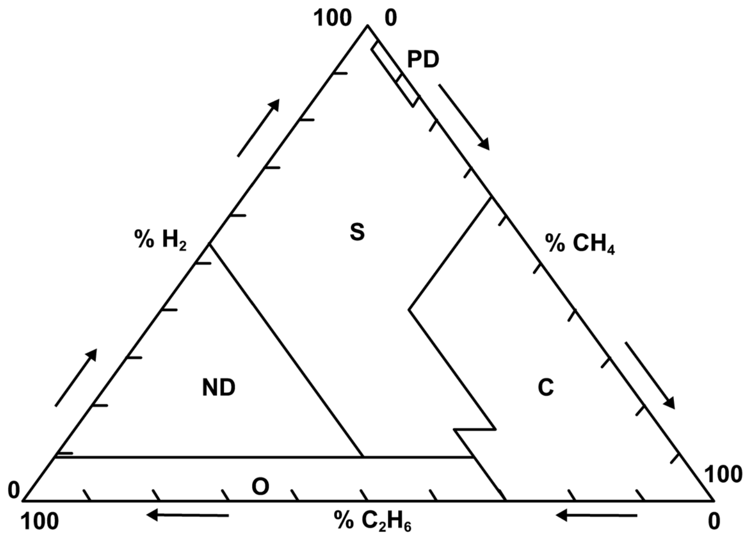


Figure D.3—Duval Triangle 4 method for low temperature faults

Numerical values for fault zone boundaries of Duval Triangle 4 method are the following, expressed in %H2, %CH4 and %C2H6:

Table D.3—Fault zone boundaries for Figure D.3

Gas% / Fault	% H_2	% CH_4	% C_2H_6
PD	—	≥ 2 and < 15	< 1
S	≥ 9	—	≥ 30 and < 46
	≥ 15	—	≥ 24 and < 30
	—	< 36	≥ 1 and < 24
	—	< 36 and ≥ 15	< 1
	—	< 2	< 1
O	< 9	—	≥ 30
C	—	≥ 36	≥ 24
	<15	—	≥ 24 and < 30
ND	≥ 9	—	≥ 46

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

The Duval Triangle 5 method is illustrated in Figure D.4:

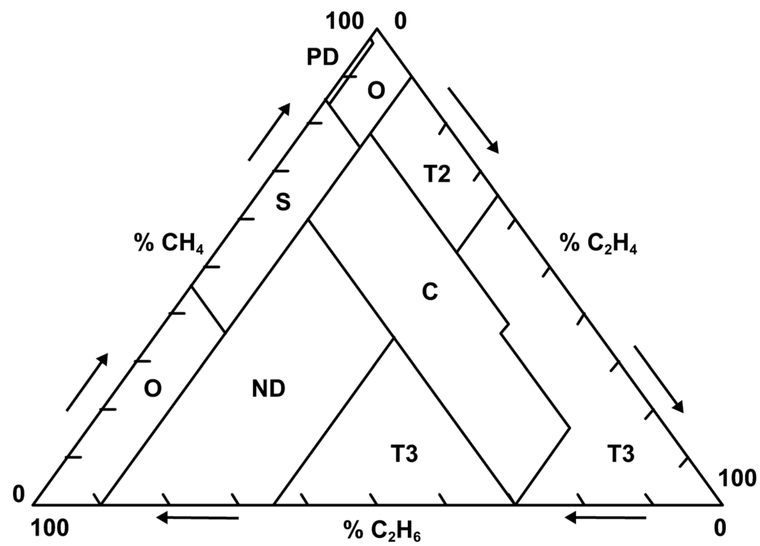


Figure D.4—Duval Triangle 5 method for high temperature fault

The Triangle 5 method allows a user to distinguish between high temperature faults T3/T2 in mineral oil only, of lesser concern in transformers, and potentially more dangerous faults C involving possible carbonization of paper.

Numerical values for fault zone boundaries of Duval Triangle 5 method are the following, expressed in %CH4, %C2H4 and %C2H6:

Table D.4—Fault zone boundaries for Figure D.4

Gas% / Fault	% CH_4	% C_2H_4	% C_2H_6
PD	—	< 1	≥ 2 and < 14
O	—	≥ 1 and < 10	≥ 2 and < 14
	—	< 1	< 2
	—	< 10	≥ 54
S	—	< 10	≥ 14 and < 54
T2	—	≥ 10 and < 35	< 12
T3	—	≥ 35	< 12
	—	≥ 50	≥ 12 and < 14
	—	≥ 70	≥ 14
	—	≥ 35	≥ 30
C	—	≥ 10 and < 50	≥ 12 and < 14
	—	≥ 10 and < 70	≥ 14 and < 30
ND	—	≥ 10 and < 35	≥ 30

Note that:

a) Triangles 4 and 5 should never be used for faults identified first with Triangle 1 as electrical faults D1 or D2.

b) Triangle 4 should be used only in case of faults identified first as faults PD, T1 or T2 in Triangle 1.

c) Triangle 5 should be used only in case of faults identified first as faults T2 or T3 in Triangle 1.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

d) DGA points occurring in zones C indicate a possibility of carbonization of paper, not a 100% certainty, and further investigations with carbon oxides and furans should be undertaken.

The procedure for calculating and displaying DGA points in Duval Triangles 4 and 5 is the same as for Triangle 1 in 6.2.3.[12]

Numerical values of zone boundaries are indicated in Table D.3/Figure D.3 and Table D.4/Figure D.4.

D.5 Duval Pentagon 2 method

If thermal faults (T1, T2, and T3) have been identified with Duval Pentagon 1, more information can be obtained on these faults with Duval Pentagon 2, as in the case of Duval Triangles 4 and 5.

The Duval Pentagon 2 method is illustrated in Figure D.5.

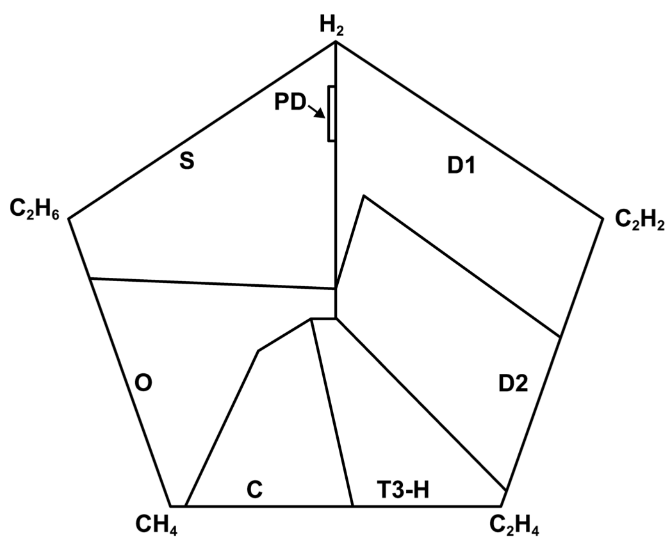


Figure D.5—Duval Pentagon 2 method

The Pentagon 2 method allows for detection of the 3 basic types of electrical faults (PD, D1 and D2) as in Duval Pentagon 1, and to further distinguish between the 4 additional sub-types of thermal faults of D.2 (S, O, C and T3 in mineral oil only).

In Duval Pentagon 2, faults T3 in mineral oil only are indicated as T3-H, where H is for "Huile" or "oil" in French.

NOTE—DGA points occurring in zone C indicate a possibility of carbonization of paper, not a 100% certainty, and further investigations with carbon oxides and furans should be undertaken.

The procedure for calculating and displaying DGA points in Duval Pentagons is described in "The Duval Pentagon—A new complementary tool for the interpretation of dissolved gas analysis in transformers," [B90].

[12] Free algorithms for using the Duval Triangles methods are available in the IEEE Std C57.104-2019 directory located at: https://standards.ieee.org/content/dam/ieee-standards/standards/web/download/C57.104-2019_downloads.zip.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

The numerical values of the (x, y) coordinates of zone boundaries of Pentagon 2 are indicated below: [13]

— PD: (0, 33), (–1, 33), (–1, 24.5), (0, 24.5);

— D1: (0, 40), (38, 12), (32, –6.1), (4, 16), (0, 1.5);

— D2: (4, 16), (32, –6.1), (24.3, –30), (0, –3), (0, 1.5);

— S: (0, 1.5), (–35, 3.1), (–38, 12.4), (0, 40), (0, 33), (–1, 33), (–1, 24.5), (0, 24.5);

— T3-H: (0, –3), (24.3, –30), (23.5, –32.4), (2.5, –32.4), (–3.5, –3);

— C: (–3.5, –3), (2.5, –32.4), (–21.5, –32.4), (–11, –8);

— O: (–3.5, –3), (–11 ,–8), (–21.5, –32.4), (–23.5, –32.4), (–35, 3.1), (0, 1.5), (0, –3).

D.6 Mixtures of faults

Duval Triangles 1, 4, 5 and Pentagons 1, 2 methods, as well as all other diagnosis methods (Key Gas, Rogers Ratios, Doernenburg Ratios), were initially developed for detecting single faults only.

However, multiple faults (mixtures of faults) often occur rather than single faults and may be more difficult to identify with certainty. For instance, actual mixtures of faults T3+D1 may sometimes appear in terms of gas formation as faults D2 in Triangle 1, Pentagon 1, and other diagnosis methods (Rogers Ratios, etc.), while actual mixtures of faults T3 in mineral oil (T3-H) and O may appear as faults C in Triangle 5 and Pentagon 2.

Mixtures of faults may be suspected when fault identifications provided by Duval Triangles 1, 4, and 5 and Pentagons 1 and 2 for the same DGA results are different. This is because each graphical representation is more sensitive to some gases and some faults than to others. For example, Triangle 4 and the Pentagons are more sensitive to H2 and faults S and PD, while Triangle 1 and Triangle 5 are more sensitive to C_2H_4 and faults T3.

If the position of the DGA point changes with time in the Triangles and the Pentagons, this indicates that a new fault has formed over the old one or another source of gas formation (a different type of fault has become active) exists. To get a better identification of this new fault, gas concentrations from the previous DGA results may be subtracted from the most recent ones. The subtracted (delta) values will thus be due only to the new fault. If delta values are negative for some gases, this means that no additional amounts (zero µL/L) of these gases have been formed because of the new fault since the previous sample, and that some of those gases previously formed have started to escape from the transformer. When identifying the new fault, negative delta values should, therefore, be replaced by zero µL/L. Note the previous discussion of the topics of repeatability and reproducibility, which may also contribute to a negative calculated difference.

The possible presence of multiple faults may be useful information during the inspection of transformers.

D.7 When to use the Duval Pentagons and Triangles

If interest is only in the six basic types of faults in C.1 and by single faults, the display of DGA points would be done using the Pentagon 1 or Triangle 1.

If there is also an interest in the additional sub-types of faults in C.2, Pentagon 2 and Triangles 4 or 5 should be used.

[13] Free algorithms for using the Duval Pentagons methods are available in the IEEE Std C57.104-2019 directory located at: https://standards.ieee.org/content/dam/ieee-standards/standards/web/download/C57.104-2019_downloads.zip.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

When detection of mixtures of faults is desired, the diagnosis provided by the pentagons and the triangles can be compared. If they do not agree, this may be an indication of multiple faults. Use subtracted (delta) values as indicated in D.6 to further identify these multiple faults.

D.8 Interpretation of CO and CO_2

Until recently, CO and CO_2 were considered as good indicators of paper involvement in faults (see D.1). Recent investigations at CIGRE (see [B72]), and in preparation of IEC 60599 [B103] revision, however, have shown that this is not always the case. The present view on the interpretation of CO and CO_2 is the following.

a) High concentrations of CO (> 1000 μL/L (ppm)) and/or low CO_2/CO ratios (< 3), WITHOUT the formation of significant amounts of hydrocarbon gases, are NOT an indication of a fault in paper, particularly in closed transformer, but are rather due to mineral oil oxidation under conditions of limited supply of O_2.

b) High concentrations of CO (> 1000 μL/L (ppm)) and low CO_2/CO ratios (< 3), TOGETHER WITH the formation of significant amounts of hydrocarbon gases, may be an indication of a fault in paper. This should be confirmed, however, by Pentagon 2 and Triangles 4, 5, and other observations (e.g., carbon oxides and furans).

c) High concentrations of CO_2 (> 10 000 μL/L (ppm)), high CO_2/CO ratios (> 20) and high values of furans (>5 μL/L (ppm)) are an indication of the slow degradation of paper at relatively low temperatures (<140 °C), down sometimes to very low degrees of polymerization (DPs) of paper (e.g., 150 to 100). In the very large majority of cases, however, this does not prevent the transformer from operating normally, even in the presence of an external short circuit. However, there are concerns that the low DP paper may not always withstand strong transient over-currents or short circuits. See “Significance and detection of very low degree of polymerization of paper in transformers” [B93].

d) Concentrations of CO and CO_2 below Table 1 of this guide, corresponds to normal gassing in transformers without faults.

e) Zero or very low rates of change of CO and CO_2 do not necessarily mean the absence of a fault in paper. Localized faults in small volumes of paper often do not produce detectable amounts of CO and CO_2 compared to the usually high background of these gases in service. However, they often produce significant amounts of the other hydrocarbon gases, allowing the detection of faults in paper with Pentagon 2 and Triangles 4 or 5.

D.9 Other useful gas ratios for fault identification

D.9.1 The O_2/N_2 ratio

Decreasing values of this ratio indicate overheating and oxidation of mineral oil and can be used to confirm thermal faults identified in this annex.

Increasing values may indicate leaks in the air preservation system of transformers (membrane or nitrogen blanket).

D.9.2 The C_2H_2/H_2 ratio

Values of this ratio >3 may indicate leaks or contamination from the tap-changer compartment into the main tank. If such contamination is suspected, it should be investigated.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Annex E

(informative)

Case studies[14]

E.1 Unintentional core ground

Background—Transformers have many components that interact and affect equipment operation. The transformer insulation system is typically comprised of cellulose material (paper insulation) and insulating liquid-like mineral oil. Contamination of the insulating liquid or a loss of insulation material can produce an energy source that generates gases from the insulating liquid or cellulose material. The cellulose material is the paper wrapping around conductors and pressboard used for insulation clearance and spacer material. Component movement can displace the pressboard or tear the paper which can decrease the insulation resistance. This one-year-old power transformer was operating in a substation at 161 kV to 13.8 kV with a base capacity of 30 MVA.

Technical Explanation—Transformers require an iron core to increase electro-magnetic field interactions between the windings. The iron core has one intentional ground point typically bolted at the top of the core or through a connection to a core ground bushing. Other possible iron core contact points to ground are insulated with cellulose or man-made materials. Grounds can develop when these materials become displaced or damaged, which can allow the iron core to come into contact with a ground point. Also, debris buildup can reduce the insulation resistance allowing current flow which creates an energy source like heat. The current flow can vary with the insulation resistance of the unintentional core ground and can reach several hundred amps. This current flow can produce temperatures capable of fusing metal along with combustible gases and carbon. High currents can burn away the intentional core ground connection leaving an unreliable ground connection which will allow a potential to accumulate on the iron core.

Analysis—Following a close proximity short circuit event to the transformer, the transformer in this case study developed a gassing issue. Table E.1 shows DGA history sample results so the combustible gas concentrations are above the $O_2/N_2 \leq 0.2$ in the transformer age in years category of 1 to 10 years. The DGA sample results in Table E.1 are also above the Table 2 concentrations for the same category, and are a case of extreme DGA for CH_4 and C_2H_4 (see 6.1.2.4). The confirmation sample (data point 3) and monitoring sample (data point 4) confirms the active gassing source for a Status 3. The event occurred between data points 1 and 2. Data point 1 combustible gas results are very low and should not be used in the diagnostic models like Duval Triangle.

Table E.1—DGA sample results for unintentional core ground in µL/L (ppm)

Data point	Sample date:	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	N_2	O_2
1	4-Feb-03	0	0	0	0	0	23	188	108 233	13 364
2	13-Jan-04	95	421	128	695	7	25	360	76 540	2 304
3	28-Jan-04	104	404	138	678	5	31	343	83 976	4 503
4	10-Feb-04	120	554	199	839	9	30	378	86 795	2 387

The data point 2 sample reports a large increase in combustible gas levels that was verified with a confirmation sample. Data point 4 from February 10, 2004 indicates that the gassing source is active as

[14] Material reprinted with permission from The Hartford Steam Boiler Inspection and Insurance Company, "TOGA® Presentation; Case Study Review" © 2012.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

indicated by the ethylene gas concentration delta of 161 µL/L (ppm) reported in Table E.2. Depending on the hydrocarbon gas, an increase in the temperature source will generally affect the gas generation rate. An increasing gas rate of change is normally associated with a deteriorating condition.

Table E.2—DGA delta µL/L (ppm) between successive sample

Data point	Sample dates	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
2	13-Jan-04	95	421	128	695	7	–2	172
3	28-Jan-04	9	–17	10	–17	–2	6	–17
4	10-Feb-04	16	150	61	161	4	–1	35

The Rogers Ratios diagnostic model uses combustible gas results combined in ratios to obtain a diagnosis. The criterion was based on field inspection experience. The original Rogers Ratios model with four ratios reported a core heating issue that is consistent with an unintentional core ground.

The Duval Triangle diagnostic method for data points 2, 3, and 4 in Table E.3 was reported in the T3 region and with fairly consistent results between the three samples, while Pentagon 2 indicates high temperature fault in mineral oil.

Table E.3—Duval Triangle ratios for unintentional core ground

Data point	% CH_4	%C_2H_4	%C_2H_2
2	37.5%	61.9%	0.6%
3	37.2%	62.4%	0.5%
4	39.5%	59.8%	0.6%

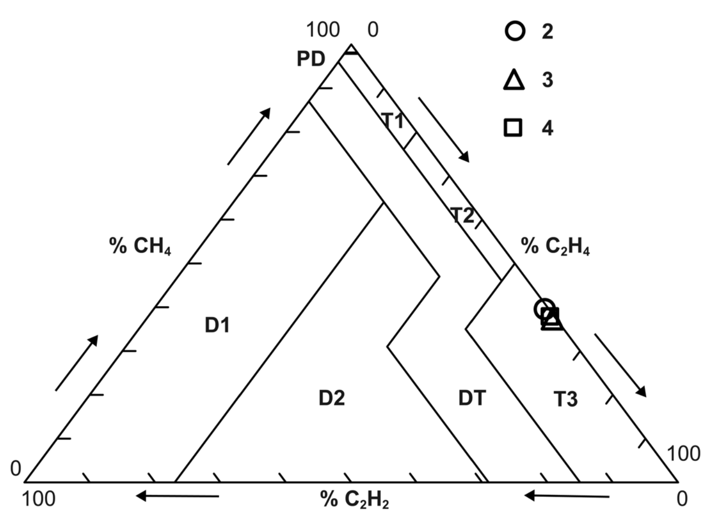


Figure E.1—Duval Triangle 1

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

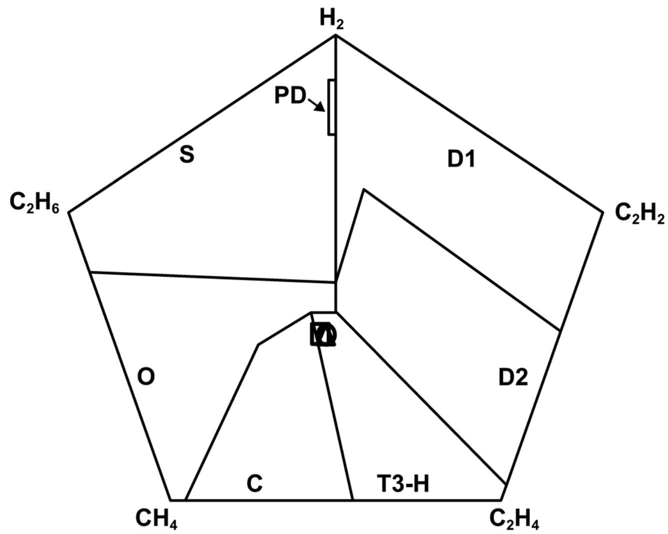


Figure E.2—Duval Pentagon 2

The result of the analysis was to repair the unintentional core ground by de-tanking the PA winding and replacing the core clamp bolts.

E.2 LV connections issues

The 161 kV to 13.8 kV, 30 MVA transformer in this case was placed into operation and immediately began generating combustible gases. The confirmation samples reported a similar DGA gas profile and increasing combustible gas concentrations. Two of the initial DGA samples are given in Table E.4.

Table E.4—Initial DGA results for connections issues

Data point	Sample dates	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	N_2	O_2
1	20-May-08	35	181	51	473	2	21	184	101 590	2 414
2	11-Jun-08	177	560	195	1,188	20	21	184	58 900	2 104

Table E.4 shows the initial DGA sample results (samples taken after the transformer was first energized) and indicate that combustible gas concentrations are above the Table 2 values for $O_2/N_2 \leq 0.2$ in the transformer age category of 1 to 10 years. The confirmation sample (data point 2) confirms the active gassing source with deltas above Table 3 for a Status 3 and for CH_4 and C_2H_4 a case of extreme DGA (see 6.1.2.4).

The transformer OEM was involved in the investigation and opted for an internal inspection. The electrical testing and internal inspection did not find the gassing source so the transformer was returned to service with an increased sampling frequency. The transformer was returned to Status 2 and it was closely monitored.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

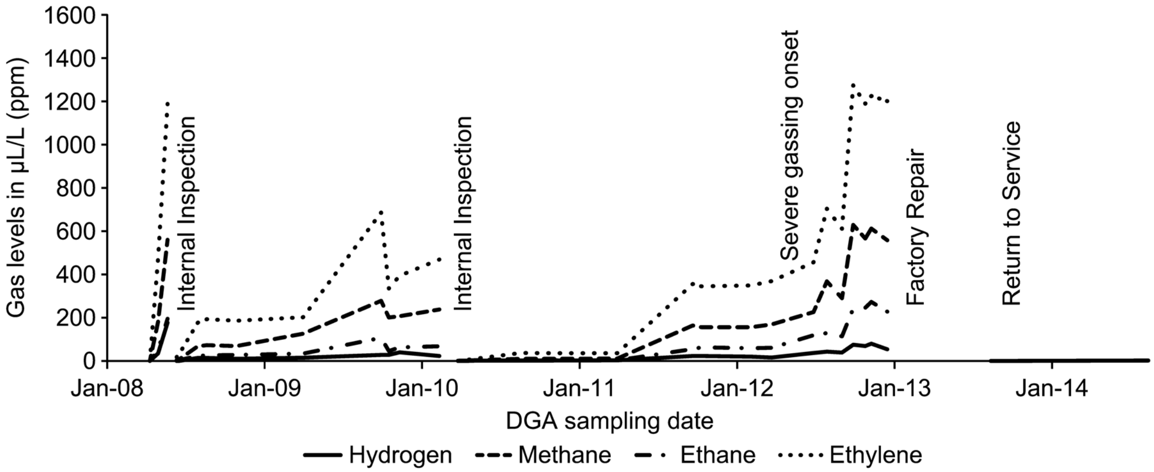


Figure E.3—DGA evolution from initial startup to repair

The Duval Triangle diagnostic method ratios, calculated in Table E.5 and plotted in Figure E.4, indicated an elevated temperature in the T3 region. The carbon monoxide for this transformer ranged between 20 µL/L (ppm) and 40 µL/L (ppm). The lack of carbon monoxide and carbon dioxide leads one to presume that there were no significant amounts of cellulose material, like insulation paper, near the fault. The OEM performed electrical tests, which eliminated concerns about an unintentional core ground. There continued to be a concern with a loose or high resistance connection.

Table E.5—Duval Triangle ratios

Data point	1	2
Sample date	20-May-08	11-Jun-08
% CH_4	28%	32%
%C_2H_4	72%	67%
%C_2H_2	0%	1%

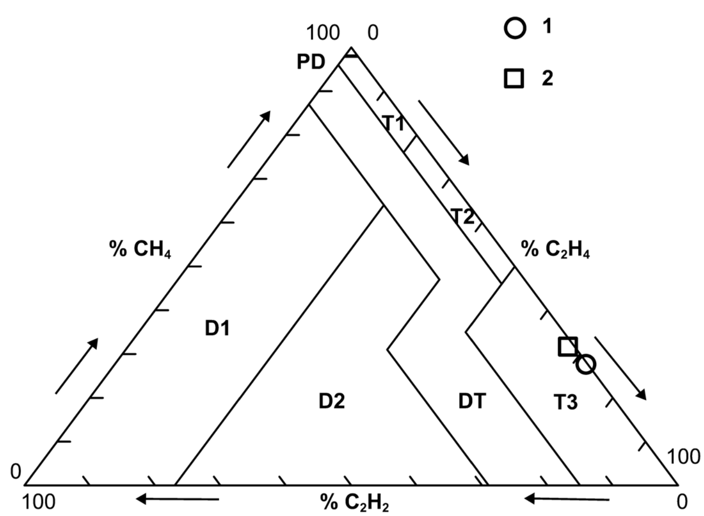


Figure E.4—Duval Triangle 1

Two years later, the transformer received a second internal inspection by the OEM after a period of higher gas generation rate, still without finding the gassing source, and was returned to service. After five years of

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

operation, with similar DGA gas profiles and sporadic gassing that appears to follow periods of higher electrical loads, the transformer was returned to the factory following a period of high gassing rate. See Table E.6 and Figure E.3.

Table E.6—Final DGA combustible gas concentrations in µL/L (ppm) prior to factory repair

Data point	Sample dates	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	O_2	N_2	NEI_{Oil}
1	25-Apr-12	16	169	61	369	0	48	540	6 203	85 528	2.56
2	24-Jul-12	37	226	119	456	0	23	292	8 550	72 084	3.40
3	28-Aug-12	43	368	129	704	0	56	581	14 738	105 148	5.09
4	24-Sep-12	39	290	114	611	0	41	429	7 748	58 216	4.32
5	24-Oct-12	75	629	242	1,274	1	55	493	7 202	70 047	9.13
6	16-Nov-12	69	566	246	1,189	0	47	457	5 574	65 599	8.52

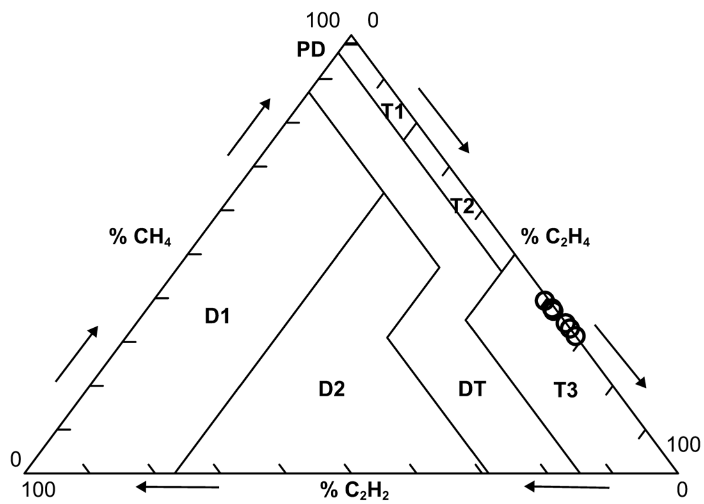


Figure E.5—Duval Triangle 1 for data prior to third investigation

Table E.6 contains DGA results of the large change in combustible gas concentrations, which prompted the transformer's removal from service and its return to the factory for inspection and untanking. Figure E.5 is the Duval Triangle 1 for the same data, indicating a T3 fault, same as previous occurrences. A significant development, which led to the decision to return the transformer to factory, was the reporting of a trace amount of acetylene and a large change in ethylene. The calculated NEI_{Oil} (see Annex F) for data point 1 is 2.56, which increases over the next several samples to reach a maximum of 9.13 at data point 5, indicating a deterioration of the gassing source. The data point 6 sample was a confirmation sample and the laboratory observed a trace amount of acetylene on the gas chromatogram chart that was below the minimum level of detection.

The transformer was untanked and faulty low voltage compression fittings were found. The cellulose insulation wrap was charred and falling apart from the heat generated by the high resistance connections. The low voltage compression fittings were replaced, and the transformer was returned to service.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

E.3 Internal transformer arcing causes relay protective action

Background—The transformer in this case study supplies a municipal distribution substation, so the loss of the transformer does not represent a significant loss-of-energy-not-served exposure in the event of a failure. Typically, an annual sample frequency is recommended for this equipment application with the routine sample being taken in August. The August 2015 sample reported no abnormal results so the next routine sample was scheduled for the next year.

Table E.7 Data Point 1 from August 2015 routine sample analysis reported an oxygen to nitrogen ratio of 0.03, which is consistent with previous samples. This is an important consideration when trending the results from historic samples. The carbon dioxide and carbon monoxide gas concentrations are low and consistent with previous sample, which indicates normal aging of the cellulose insulating material. Carbon oxides increase over time as the cellulose and insulating liquid ages, which is expected, so they are monitored for large changes. A large increase in carbon dioxide is consistent with accelerated cellulose rate of aging. There are low amounts of combustible gases like methane, ethane, and ethylene which are expected either through errors in the sample analysis process or previous exposure to operating temperatures. There were no recommendations made to the equipment owner based on the Data point 1 (August 2015) sample results, which is in Status 1.

Technical Explanation—The electrical transformer is a 39-year-old transformer rated 161 kV to 69 kV with a 13.8 kV tertiary winding and a base capacity of 48 MVA. The transformer preservation system used a sealed tank design with a nitrogen blanket, so the Table 3 $O_2/N_2 \leq 0.2$ and the ≥30 age in years category is used for the evaluation.

The automatic differential current protection relay removed the transformer from service on December 7, 2015. There were no external indications for the protective relay trip cause and the electrical tests did not report results that exceeded the expected ranges. The electrical tests included a turn-to-turn ratio, insulation resistance, winding resistance, power factor, and excitation current electrical tests. A cursory internal inspection of the transformer main tank did not find the reason for the electrical trip. The transformer was 39 years in operation at the time of the fault. The tripping investigation sample (data point 2 of Table E.7) confirms the active gassing source with the C_2H_2 level above the Table 2 norm and with the deltas above Table 3 norms for a DGA Status 3.

Data Point 2 was taken about 12 hours after receiving a transformer protective electrical trip for differential current. The combustible gases and carbon dioxide gas concentrations reported in the post trip Sample 2 are similar to the historical results with the notable exception of acetylene. Acetylene is normally associated with arcing activity. The other combustible gases are near the historical ranges with the concentrations at or near the laboratory minimum reporting levels. The generation of acetylene combined with the transformer trip warranted additional electrical testing and possibly an internal inspection. A DGA confirmation sample would normally be requested, but there was a need to return the transformer to service.

Data Point 3 was taken after completing the electrical testing and internal inspection. The liquid was reclaimed which included degassing the insulating liquid. A limited amount of residual gases was expected to be seen in subsequent samples even if the gassing source became inactive. The transformer was energized and immediately tripped from an electrical protection relay. Data Point 4 was taken shortly after the transformer tripped the second time from the protective relay action. Data Point 4 reported increases in the combustible gas concentrations with a similar gas profile to Data Sample 2. Data Point 4 following the second protective relay action remained in Status 3, with C_2H_2, a case of extreme DGA, requiring immediate action (see 6.1.2.4).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table E.7—DGA history in µL/L

Data point	Sample dates	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	N_2	O_2
1	8-Aug-15	0	16	35	3	0	16	954	65 400	117
2	7-Dec-15	40	26	41	17	29	33	974	74 232	254
3	17-Dec-15	0	2	2	1	1	4	95	3 770	388
4	18-Dec-15	154	60	12	124	163	82	126	112 000	1 330

Analysis—The standard industry practices of annual sample frequency for transformer insulating liquid is widely used with some exceptions for equipment with a significant financial impact. This transformer was 39-years-old and even though the actual fault is not known at this time, it is likely a breakdown of the insulation system. End-of-life failures due to cellulose aging can be sudden and without warning precursors seen in other types of transformer faults.

One method to identify faults is the Duval Triangle method. This method plots calculated ratios show in Table E.7 from the sample results.

The Duval Triangle analysis method placed the DGA gas profile in the D2 region and it identifies high energy electrical arcing as the possible gassing source. The low amount of combustible gas concentrations may indicate a fault deep in the windings. The gases could be sequestered in the mineral oil and cellulose material surrounding the fault. Another thought is a limited amount of insulating liquid between winding turns meant there was no lower temperature zones to generate other gases. There has not been a forensic tear down inspection on the transformer to identify the fault location and type.

Table E.8—Duval Triangle ratios

Data point	Sample date	$\%CH_4$	$\%C_2H_4$	$\%C_2H_2$
2	7-Dec-15	36%	24%	40%
4	18-Dec-15	17%	36%	47%

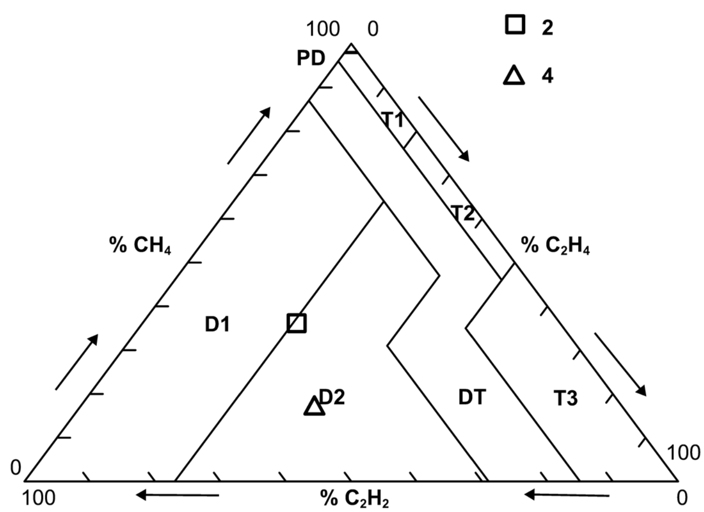


Figure E.6—Duval Triangle 1

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

E.4 De-energized tap changer (DETC) high resistance connection

Background—This case study reports the dissolved gas results for a power plant auxiliary transformer (unit transformer) that is directly connected to the electrical generator. The transformer is a 1995 vintage. An unexpected transformer failure would cause a unit trip shutting down the power plant until the transformer is switched out of the circuit and plant power restored through a station service power transformer. The unit transformer (auxiliary power plant transformer directly connected to the generator) was on a six months DGA sample frequency because of the potential economic impact to plant operation in the event of an unexpected failure.

Some transformer designs use a manual tap-changing device on the high-voltage windings that allow insertion or removal of windings to adjust the transformer voltages to the system specifications. Some transformer designs are equipped with a manually-operated tap changing device (operated with the transformer de-energized), placed in the high voltage winding that allows the addition or subtraction of turns to adjust the voltage output to the system. These DETCs (De-Energized Tap Changers) are designed with both stationary and moveable contacts connected via a shaft to an external operating handle. The mechanism cannot be operated on an energized transformer, so the mechanism is typically locked in place. Component movement can displace pressboard or tear insulation paper which can decrease the insulation resistance. A high-resistance electrical connection can produce an elevated temperature, which is reported with a DGA.

Technical explanation—The formation of a high-resistance connection can be from improper contact pressure, contact material deterioration, film formation on contact surface or improper operation of the mechanism. The high-resistance connection generates heat that forms combustible gases like hydrogen, methane, ethane and ethylene. The leads connecting the DETC to the windings are typically cellulose insulation wrapped leads so elevated temperatures can also generate small amounts of carbon gases like carbon monoxide and carbon dioxide. The elevated temperatures will cause the contacts to deteriorate and carbon to form on contact surfaces that reduce contact surface areas and generate higher temperatures. This failure mechanism reports increasing rates of gas generation over time.

Table E.9—DGA results for a high resistance connection in µL/L (ppm)

Data point	Sample date	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	N_2	O_2
1	26-Jan-10	3	9	3	3	0	653	3 603	76 587	6 085
2	9-Dec-10	14	67	26	119	1	705	4 002	76 256	6 423
3	22-Mar-11	18	80	32	149	1	727	3 951	78 592	7 188
4	14-Jun-11	13	66	33	243	0	816	3 531	45 599	1 431

Analysis—In Table E.9, data point 1 shows the typical routine sample that reported DGA results consistent with historic samples. The subsequent routine sample from Table E.8, data point 2 reported a change in the DGA gas profile and combustible gas concentrations, which indicated an abnormal gassing profile. The transformer was 15 years in operation at the time of the abnormal DGA. Table E.9 shows the DGA sample ethylene (C_2H_4) is above the Table 1 $O_2/N_2 \leq 0.2$ value for a transformer in the 10 year to 30 year category. The Table E.9 DGA ethylene (C_2H_4) result is also above the Table 2 concentrations for the same category. The confirmation sample (data point 3) and monitoring sample (data point 4) confirms the active gassing source with multi-point sample rate of change exceeding Table 4 for a Status 3. The data point 2 concentrations exceed Table 1 and Table 3 norms, so a confirmation sample was taken as Table E.9 data point 3. The data point 4 sample, dated June 14, 2011, reported an increase in the ethylene gas concentration of 94 µL/L (ppm). An increasing gas rate of change is normally associated with a deteriorating condition like an increase in gassing temperature source.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table E.10—Delta µL/L (ppm v/v) between successive samples

Data point	Sample dates	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
1	26-Jan-10	NA	NA	NA	NA	NA	NA	NA
2	9-Dec-10	11	56	23	116	1	52	338
3	22-Mar-11	4	13	6	30	0	22	765
4	14-Jun-11	-1	-14	1	96	-1	89	-5757

The Duval Triangle ratios are calculated in Table E.11 with data points 2 and 3 reporting similar profiles. Figure E.6 Duval ratio plot places the gassing source temperature in the T3 region (>700 °C). A comparison of the Duval Triangle results given in Table E.11 indicates a possible deterioration in the unit's condition.

Table E.11—Duval Triangle ratios

Data point		2	3	4
Date		9-Dec-10	22-Mar-11	14-Jun-11
% CH_4		36%	35%	21%
% C_2H_4		64%	65%	79%
% C_2H_2		1%	0%	0%

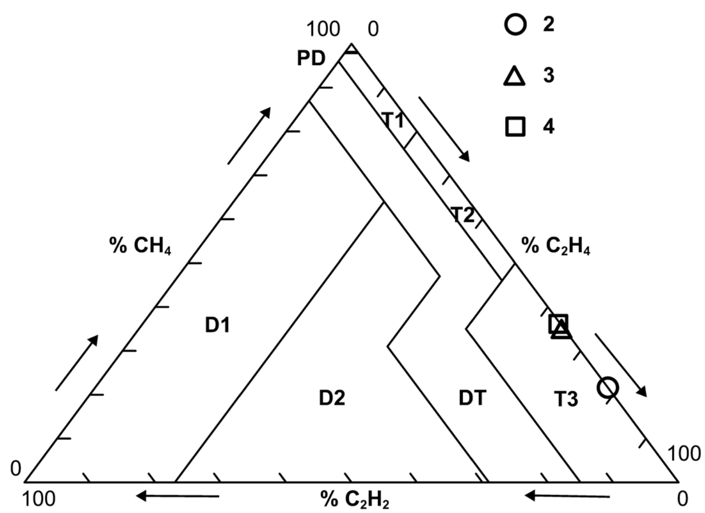


Figure E.7—Duval Triangle 1

Summary—The power plant was shut down for a scheduled outage during which the transformer was electrically tested and internally inspected for indications of the gassing source. The DETC contacts were covered with coke formed from an elevated temperature. The winding insulation resistance should have indicated a change from historical results, but the test equipment current source may not have been sufficient to produce the abnormal result. The DETC contacts were removed from the circuit with the installation of shunts.

E.5 Broken connector on fuse holder

Background—The change in the DGA gas profile for a 1987 vintage 4 160/480 V, 500 KVA transformer was noted during a routine sample. This transformer supplied the compressor of a refrigeration system at a

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

food processing plant. The failure of this transformer could cause the loss of a large inventory of frozen food, so it was part of a DGA program despite its small size. The transformer has a sealed tank preservation system with a nitrogen blanket. The DGA gas profile indicated arcing activity that was confirmed with a second DGA sample. The large increase in carbon dioxide gas concentration was possibly due to burning cellulose material (paper insulation) or overload condition.

Technical explanation—This transformer was designed with fuse holders between the line connections and the 4 160 volt windings. The winding was connected to the fuse holder through bolted connections.

Table E.12 data point 1 was a routine sample, similar to previous samples, and presented no anomaly. The transformer was 18 years in operation at the time of the abnormal DGA so the $O_2/N_2 \leq 0.2$ norms for a transformer in the 10 year to 30 year category are referenced. For point 2, acetylene (C_2H_2) and ethylene (C_2H_4) results are above Table 2 norms. In fact, the C_2H_2 delta is typical of extreme DGA results (see 6.1.2.4), so a confirmation sample was taken (Table E.12, data point 3), which confirmed the increase.

The Duval Triangle Ratios for data point 2 and 3 are calculated in Table E.13 and give a D1 diagnostic.

Table E.12—DGA results for broken connector on fuse holder in μL/L (ppm)

Data point	Sample date	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	N_2	O_2
1	11 Feb 2005	4	2	0	0	0	47	785	76 784	7715
2	23 Nov 2005	166	63	8	117	645	51	4435	64 414	16 502
3	15 Dec 2005	188	89	15	129	631	72	5769	64 189	16 338

Table E.13—Duval Triangle 1 rations

Data point	2	3
	23-Nov-05	**15-Dec-05**
% CH_4	8%	10%
%C_2H_4	14%	15%
%C_2H_2	78%	74%

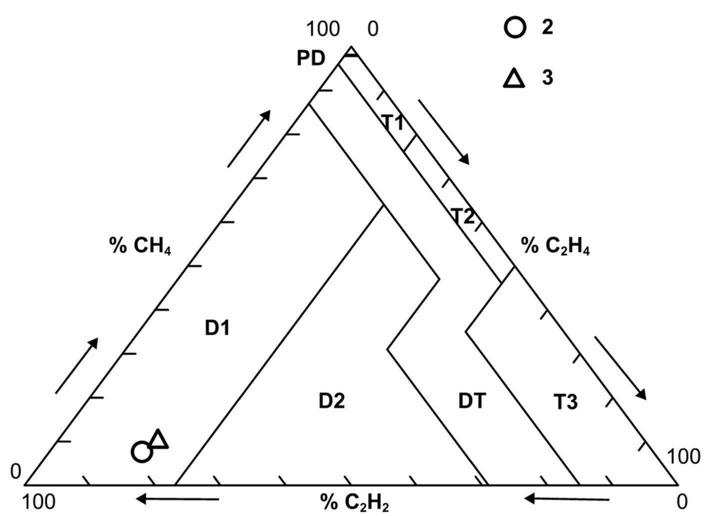


Figure E.8—Duval Triangle 1

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Summary—The transformer was removed from service in the off-season during a scheduled outage period. The electrical winding resistance test reported the H1 to H0 resistance at about 240 mΩ compared to the other phases of near 160 mΩ, which isolated the gassing source to the H1–H0 winding. An internal inspection identified a broken fuse holder connection, which was repaired on site. The transformer insulating liquid was reclaimed and degassed. The unit was offline for one-day.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Annex F

(informative)

Evaluation of fault severity—alternative method

Recent research suggests an alternative approach to transformer DGA fault detection and severity assessment. Instead of comparing fault gas concentrations and rates with limits, the method employs indexes of the energy required to form the fault gas concentrations observed in a mineral oil sample. The indexes are responsive to all DGA-detectable fault types. The basic principle of the method is that active fault gas formation suggests an internal problem or overly stressful operating conditions, while absence of active fault gas formation is uninformative as to the state or condition of the transformer. Statistical models based on transformer DGA and failure data indicate that the additional risk of forced outage due to active gassing is roughly proportional to the amount of increase in the hydrocarbon gas energy index since the gassing began.

Low molecular weight hydrocarbon gases (methane, ethane, ethylene, and acetylene) dissolved in a transformer's mineral oil are formed primarily when the mineral oil is "cracked" by exposure to intense thermal or electrical stress associated with overloading or faults. Hydrogen is formed in the same way but, significant amounts of it can also be formed in other ways. The hydrocarbon gases, in the order listed above, are characteristically formed at increasingly high fault temperatures because of the different amounts of energy required to create a molecule of each gas from mineral oil. Methane is the primary hydrocarbon gas formed by PD and T1 faults. Ethane and (to a slightly lesser degree) methane are the primary gases formed by T2 faults, ethylene is the primary gas formed by T3 faults, and acetylene is associated almost exclusively with faults involving electrical arcing or sparking. The differential production of the hydrocarbon gases depending on fault energy is the basis for the Duval Triangle method of fault type identification.

Mineral oil decomposition at or near normal operating temperatures, can be caused by non-fault-related chemical and electrochemical reactions with oxygen, dissolved water, contaminants, or solid materials in contact with the mineral oil. Gas production of that nature—usually of hydrogen but sometimes of methane, ethane, or ethylene—is called "stray gassing." Gas production that is suspected to be stray gassing is to be excluded from consideration for the detection, assessment, and identification of faults. Likewise, when a transformer is suspected of losing fault gas by leakage or any other means, the fact of gas loss should be taken into account in DGA interpretation.

The carbon oxide gases, carbon monoxide (CO) and carbon dioxide (CO_2) are formed slowly by the gradual degradation of cellulosic insulation by dissolved water and oxygen, catalyzed by acidic byproducts of oxidation of the mineral oil. Arcing, partial discharge, and overheating of conductors in proximity to cellulose insulation can rapidly produce large amounts of carbon oxides and hydrogen by carbonizing the cellulose.

The hydrocarbon gases methane, ethane, ethylene, and acetylene are formed in mineral oil primarily as the result of fault energy decomposing the mineral oil. Recent research has shown that a Normalized Energy Intensity calculated from those concentrations (NEI_{oil}) is useful for judging relative severity of faults affecting the liquid insulation. Similarly, another Normalized Energy Intensity quantity (NEI_{paper}) calculated from the concentrations of CO and CO_2 is useful for assessing faults affecting the solid insulation, especially paper wound around conductors. The coefficients of the gas concentrations in the NEI formulas below are the respective standard heats of formation of the gases from a typical mineral oil molecule (NEI_{oil}) or a typical monomer of cellulose (NEI_{paper}).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Computation of NEI_{oil}:

$$\mathrm{NEI}_{\mathrm{oil}} = (77.7 \times [CH_4] + 93.5 \times [C_2H_6] + 104.1 \times [C_2H_4] + 278.3 \times [C_2H_2]) / 22400 \quad \text{(F.1)}$$

Computation of NEI_{paper}:

$$\mathrm{NEI}_{\mathrm{paper}} = (101.4 \times [\mathrm{CO}] + 30.2 \times [\mathrm{CO}_2] / 22400 \quad \text{(F.2)}$$

In Equation F.1 and Equation F.2, the chemical formulas in brackets denote gas concentrations in µL/L (ppm), corrected to standard temperature and pressure (273.15 K and 101.325 kPa). The units of NEI are kilojoules per kiloliter (kJ/kL). In cases where significant ethane stray gassing is suspected, the quantity $NEI3_{oil}$, calculated by setting the ethane concentration to zero in the NEI_{oil} formula, may be used in place of NEI_{oil}. For brevity, only NEI_{oil} is mentioned below, but the discussion is applicable to $NEI3_{oil}$.

A transformer that is actively producing fault gas may need investigation, surveillance, or mitigative action appropriate to the apparent fault type (determined from recent gas increments by means of the Duval Triangle or other fault identification method) and the amount of increase in NEI since the gassing began. Accelerating NEI increase or evolution of the fault type from lower-energy faults (PD, T1, T2) to higher-energy faults (T3, D1, D2) may signal that the problem is worsening, with the potential of reaching a runaway condition and failing the transformer

The response of NEI_{oil} to all fault types has been shown to be sufficiently uniform that consideration of individual hydrocarbon fault gases is not necessary for fault severity assessment. However, separate attention should be paid when carbon oxide gas (CO or CO_2) are present. If NEI_{paper} is increasing, especially if the CO_2/CO ratio is also significantly decreasing, there may be a fault affecting insulating paper. Furthermore, since acetylene production is associated primarily with sparking or arcing, which should not be ongoing in a transformer in good condition under normal operating circumstances, some sites may wish to have a policy of watching for active production of acetylene, especially at low levels where NEI_{oil} is not changing very much.

Experience with this NEI-based method at a large US electric utility suggests that an NEI_{oil} increment of 0.5 or an $NEI3_{oil}$ increment of 0.3 over any time interval should raise concern for the transformer's condition, and larger increments warrant correspondingly more concern. Active gassing of that magnitude should not be ignored unless its cause is understood to be harmless.

Example 1—A power transformer experienced a NEI_{oil} increase of 0.43 over a sampling interval of 550 days, then 1.76 over a sampling interval of 365 days, and then 3.81 over a sampling interval of 400 days The apparent fault type was T3 in each case, based on gas increments plotted on the Duval Triangle.

After an NEI_{oil} increment of 0.43 (close to the suggested limit of 0.5) was detected, additional sampling could have been scheduled after, say, 90 days to check for confirmation of active gassing, following which investigation and possible infrared inspection or other testing could have been performed to identify the cause of the gassing so that it could be dealt with. That, however, was not done in this case. With the NEI_{oil} increment more than doubling as of each of the next two routine annual samples and getting very large, urgent investigation and possible mitigation would need to be considered. The level of concern would be even higher if NEI_{paper} trended upward or if CO_2/CO trended downward during the time that NEI_{oil} was increasing, because of the possibility of paper insulation being degraded by the process causing the gassing.

Example 2— This example is a re-analysis of the LV connection issues case study presented in E.2 In the initial period, NEI_{oil} increased from 3.06 on 20 May 2008 to 8.53 on 11 June 2008, an increase of 5.47 kJ/kL (eleven times the suggested limit) in less than a month, which is a very severe event. The fault type, identified by applying the Duval Triangle to the respective methane, ethylene, acetylene gas

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

increments of 380, 715, 18, is T3. No suspicious changes in NEI_{paper} or CO_2/CO were observed. As noted in the case history, an internal inspection of the transformer revealed nothing at this point. Later, following a similar gassing incident, the transformer was de-tanked at the factory, and internal damage was discovered. Some charring of cellulose conductor insulation was found, but the quantity of paper affected was evidently insufficient to change carbon oxide gas concentrations by much over five years.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Annex G

(informative)

Historical material

This annex contains text removed from the previous version of this document (IEEE Std C57.104-2008). The content of this annex is not part of IEEE Std C57.104 and is presented here for documentation purpose only. The number in parenthesis in clause heads refers to the clause number of IEEE Std C57.104-2008). Numbers within text might refer to the 2008 numbering or the appendix numbering.

NOTE—Some of the information presented here could be obsolete and no longer represent the generally accepted opinion of most experts on DGA interpretation. The text in this annex was not updated in any manner in regard of IEEE Std C57.104 2008, to the exception of the numbering of clauses, tables, and figures.

G.1 (4) 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 partial discharge.

G.1.1 (4.1) 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.

G.1.2 (4.2) 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 Figure G.1 due to Halstead. The quantity of hydrogen formed is

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

relatively high and insensitive to temperature; formation of acetylene becomes appreciable only at temperatures nearing 1000 °C.

Formations 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.

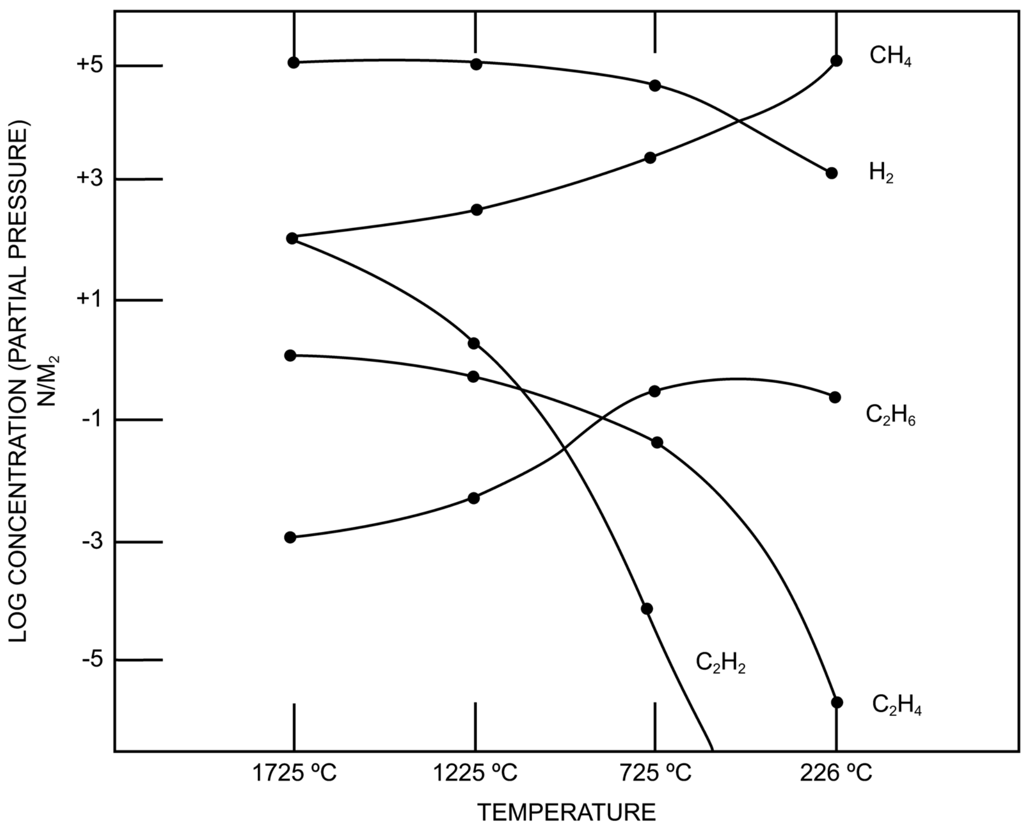


Figure G.1—(Figure 1) Halstead's Thermal Equilibrium Partial Pressures as a function of temperature

Attempts to assign greater significance to gas than justified by the natural variability of the generating and measuring events themselves can 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.

G.2 (6.3) Determining the gas space and dissolved gas-in-oil equivalents

All samples of gas from the gas blanket above the oil should be taken in accordance with ASTM D 3305.

Gas space and oil equivalents are used to compare the results of analysis of the gas space (TCG) with results from analysis of the gases dissolved in the oil (TDCG). Comparisons of gas ratios obtained from the

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

gas space can then be compared to similar ratios of gases extracted from the oil. It should be noted that the calculated equivalent values of TCG_e and experimentally measured values of TCG probably do not show close agreement, since the equation for obtaining the equivalents assumes the existence of equilibrium between the gas blanket and the oil. This condition may not exist, particularly in the case of an actively progressing fault or in sample from gas relay. However, the equation is valuable for the determination of a limiting value for the expected total combustible gas concentration in the gas blanket. The dissolved gas equivalent of the TCG_e is obtained using Equation G.1:

$$TCG_e = \sum_{C_1}^{Cn} \left[\frac{\frac{F_c}{B_c}}{\sum_{G_1}^{G_n} \frac{F_g}{B_g}} \right] \times 100 \tag{G.1}$$

where:

TCG_e = An estimate of the percent of combustible gas in the gas space
C_x = Each combustible gas dissolved in oil
G_x = Each gas dissolved in oil (combustible and noncombustible)
F_c = The concentration expressed in μL/L (ppm) of combustible gas g dissolved in oil
B_c = The Ostwald solubility coefficient of combustible gas g
F_g = The concentration of a particular gas dissolved in oil
B_g = The Ostwald solubility coefficient of particular gas

Table G.1—Ostwald coefficients

Gas	Ostwald Coefficient (*B*) (25°C)
H_2 [a]	0.0429
O_2	0.138
CO_2	0.900
C_2H_2 [a]	0.938
C_2H_4 [a]	1.35
N_2	0.0745
CO [a]	0.102
C_2H_6 [a]	1.99
CH_4 [a]	0.337
NOTE—Ostwald coefficients are for an oil with a density of 0.880 at STP.	

[a] Combustibles

G.3 (6.5.1) Determining the transformer condition and operating procedure utilizing TCG in the gas space

When sudden increases in the combustible gas concentrations or generating rates in the gas space of an operating transformer occurs and an internal fault is suspected, the procedure recommended in Table G.2 should be used.

Table G.2 indicates the recommended initial sampling intervals and operating procedures for various levels of TCG (in percent).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

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.

Table G.2—Actions based on TCG and TCG rate

	TCG levels (%)	TCG rate (%/day)	Sampling intervals and operating procedures for gas generation rates	
			Sampling interval	Operating procedures
Condition 4	≥5	>.03	Daily	Consider removal from service. Advise manufacturer
		.01-.03	Daily	
		<.01	Weekly	Exercise extreme caution. Analyze for individual gases. Plan outage. Advise Manufacturer
Condition 3	<5 to ≥2 >-2 to <5	>.03	Weekly	Exercise extreme caution. Analyze for individual gases. Plan outage. Advise manufacturer.
		.01–.03	Weekly	
		<.01	Monthly	
Condition 2	<2 to ≥.5 >-0.5 to <2	>.03	Monthly	Exercise caution. Analyze for individual gases. Determine load dependence.
		.03–.01	Monthly	
		<.01	Quarterly	
Condition 1	<0.5	>.03	Monthly	Exercise caution. Analyze for individual gases. Determine load dependence.
		.01–.03	Quarterly	Continue normal operation.
		<.01	Annual	

Example—A transformer has a TCG level of 0.4% and is generating gas at a constant rate of 0.035% TCG per day. Table G.2 indicates Condition 1. It should be sampled monthly, and the operator should exercise caution, analyze for individual gases, and determine load dependence

G.4 (6.7.1) Evaluation of possible fault type by the Doernenburg Ratio method

The Doernenburg method suggests the existence of three general fault types. The method utilizes gas concentrations from which Ratios 1, 2, 3, and 4 are calculated. The step-by-step procedure (flow chart) is shown in Figure G.2.

The values for these gases are first compared to special concentrations—L1—Table G.3 (see Steps 2, 3, and 4 in Figure G.2) to ascertain whether there really is a problem with the unit and then whether there is sufficient generation of each gas for the ratio analysis to be applicable. Then the ratios in the order Ratio 1, Ratio 2, Ratio 3, and Ratio 4 are compared to limiting values, providing a suggested fault diagnosis as given in Table G.2 This table gives the limiting values for ratios of gases dissolved in the oil and gases obtained from the transformer gas space or gas relay.

The flow chart in Figure G.2 illustrates the step-by-step application of the Doernenburg ratio method for gases extracted from the transformer oil only. Exactly the same procedure is followed for gases obtained from the gas space or gas relays, except the limiting values for the ratios will be those appropriate for gas space (Table G.4).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Descriptions of the steps indicated in Figure G.2:

- Step 1: Gas concentrations are obtained by extracting the gases and separating them by chromatograph.
- Step 2: If at least one of the gas concentrations [in µL/L (ppm)] for H_2, CH_4, C_2H_2, and C_2H_4 exceeds twice the values for limit L1 (seeTable G.4) and one of the other two gases exceeds the values for limit L1, the unit is considered faulty; proceed to Step 3 to determine validity of the ratio procedure.
- Step 3: Determining validity of ratio procedure: If at least one of the gases in each ratio R1, R2, R3, or R4 exceeds limit L1, the ratio procedure is valid; otherwise, the ratios are not significant, and the unit should be resample and investigated by alternate procedures.
- Step 4: Assuming that the ratio analysis is valid, each successive ratio is compared to the values obtained from Table G.4 in the order R1, R2, R3, and R4.
- Step 5: If all succeeding ratios for a specific fault type fall within the values given inTable G.4, the suggested diagnosis is valid.

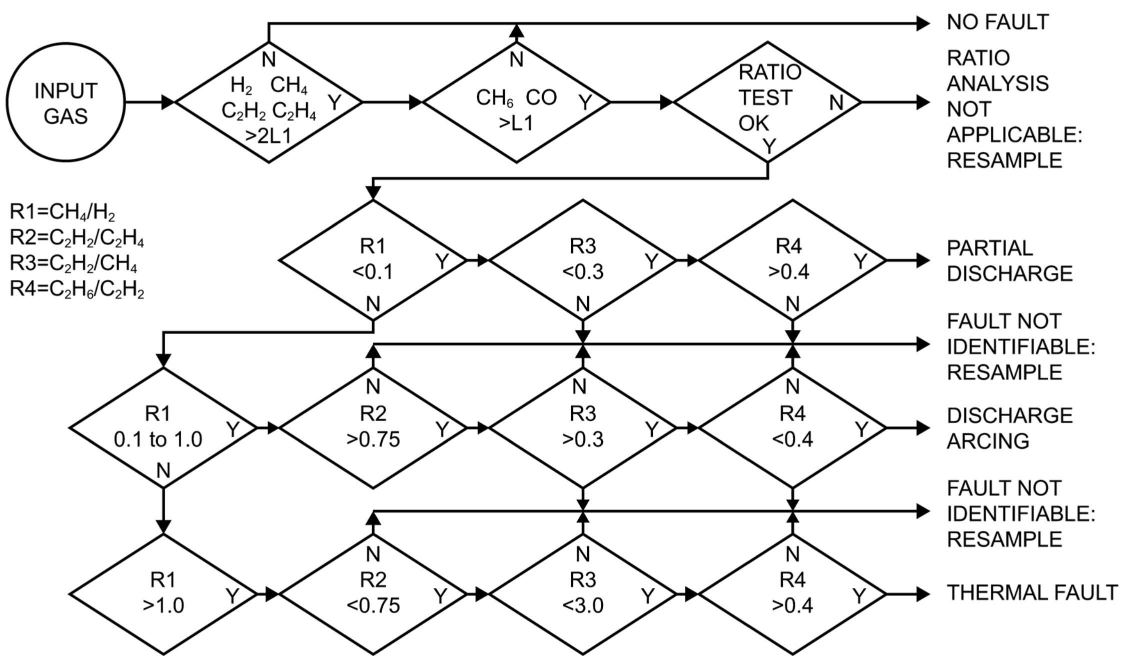


Figure G.2—(Figure 4) Doernenburg ration method flow chart

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Table G.3—Limit concentrations of dissolved gas

Key gas	Concentrations *L*1 (µL/L (ppm v/v))
Hydrogen (H_2)	100
Methane (CH_4)	120
Carbon Monoxide (CO)	350
Acetylene (C_2H_2)	1
Ethylene (C_2H_4)	50
Ethane (C_2H_6)	65

Table G.4—Ratios for key gases—Doernenburg

Suggested fault diagnosis	Ratio 1 (R1) CH_4/H_2		Ratio 2 (R2) C_2H_2/C_2H_4		Ratio 3 (R3) C_2H_2/CH_4		Ratio 4 (R4) C_2H_6/C_2H_2	
	Oil	Gas space	Oil	Gas space	Oil	Gas space	Oil	Gas space
1—Thermal decomposition	>1.0	>0.1	<0.75	<1.0	<0.3	<0.1	>0.4	>0.2
2—Partial discharge	<0.1	<0.01	Not significant		<0.3	<0.1	>0.4	>0.2
3—Arcing (high intensity PD)	>1.0 <1.0	>0.01 <0.1	>0.75	>1.0	>0.3	>0.1	<0.4	<0.2

G.5 (7) Instruments for detecting and determining the amount of dissolved gases present

G.5.1 (7.1) Portable instruments

Many of the gases generated by a possible malfunction in an oil-filled transformer are combustible. The on-site detection and estimation of combustible gases in the transformer in the field using a portable combustible gas meter can be the first and the easiest indication of a possible malfunction, and it may form the basis for further testing or an operating decision.

When a more accurate determination of the total amount of combustible gases or a quantitative determination of the individual components is desired, a laboratory analytical method using a gas chromatograph or mass spectrometer may be used.

WARNING

Gases generated in transformers can be explosive.

Strict precautions must be observed when sampling the gases from the transformer.

G.5.2 (9.4) Determination of individual gases present in the gas blanket

Analysis of the individual gases present in the gas blanket above the oil may be made by using ASTM D3612, beginning at Section 10 of that standard. Section 13.1 and Section 13.2 of ASTM D3612 are not applicable in this case.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

Annex H

(informative)

Bibliography

The purpose of this annex is to present a number of reference materials for the purpose of identifying a good cross-section of the most relevant resource material(s) reviewed and considered in the development of the art and science of Dissolved Gas Analysis (DGA) of transformer insulating liquid. This annex also serves as a historical archive of papers and other resources that were developed, written and documented throughout the course of the history of mineral oil use as a dielectric medium in power transformers.

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

H.1 Gas evolution

[B1] Basseches, H., and Barnes, H. W., “Gassing of liquid dielectric under electrical stress, influence of voltage and pressure,” Industrial and Engineering Chemistry, vol. 50, no. 6, pp. 959–966, 1958.

[B2] Basseches, H., and McClean, D. A., “Gassing of liquid dielectrics under electrical stress,” Industrial and Engineering Chemistry, vol. 47, no. 9, part I, pp. 1782–1794, 1955.

[B3] Berberich, L. J., “Influence of gaseous electric discharge of hydrocarbon oils,” Industrial and Engineering Chemistry, vol. 30, 1938.

[B4] Blodgett, R. B., and Bartlett. S.C., “Parameters for predicting gassing of oils under electric stress,” IEEE PA, vol. 55, pp. 528–536, 1961.

[B5] Clark, F. M., “The role of dissolved gases in determining the behavior of mineral insulating oils,” Journal of the Franklin Institute, vol. 215, p. 39, Jan. 1933.

[B6] Degnan, W. J., and Doucette, G. G., “Improved method of oil preservation and its effect on gas evolution,” IEEE PA, vol. 28, pp. 657–666, 1958.

[B7] Forster, J. A., and McCrae, G. G., “Gassing tendency tests on service-aged insulating oils,” Doble Conference Proceedings, Sec. 10-1501, 1974.

[B8] Hornsby, E. A., Irving, R., and Patterson, E. A., “New criterion of the gassing tendencies of insulating oils,” Proceedings of the Institution of Electrical Engineers, vol. 112, no. 3, pp. 590–596, Mar. 1965.

[B9] Kaufman, R. B., Pierce, J. L., and Uhlig, E. R., “The effect of transformer-oil-preservation methods on the dielectric strength of oil,” IEEE PA, vol. 34, pp. 1315–1321, 1958.

[B10] Krasucki, Z., Church, H. F., and Garton, C. G., “A new explanation of gas evolution in electrically stressed oil impregnated paper insulation,” Journal of the Electrochemical Society, vol. 107, no. 7, pp. 598–602, 1960.

[B11] Meador, J. R., and Dillon, N. E., “Transformer oil preservation,” AIEE Transactions on Power Apparatus and Systems, vol. 33, pp. 1208–1211, 1957.

[B12] Morrison, E. L., “Evaluation of thermal stability of electrical insulating paper,” IEEE Transactions on Electrical Insulation, vol. EI-3, pp. 76–82, Aug. 1968.

[B13] Murphy, E. J., “Gases evolved by the thermal decomposition of paper,” Transactions of Electrochemical Society, vol. 83, p. 161, 1943.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

[B14] Pedersen, G., "Gassing of insulating oils under the influence of an electric discharge," Brown Boveri Review, vol. 55, no. 415, pp. 222–228, Apr./May 1968.

[B15] Saito, Y., and Hino, T., "Study of thermal deterioration of enameled wires by the mass spectrometer method," IEEE PA, vol. 50, pp. 653–657, 1960.

[B16] Sheppard, H. R., "The mechanism of gas generation in oil-filled transformers," Doble Conference Index of Minutes, Sec. 6-601, 1963.

[B17] Sloat, T. K, Johnson, J. L., and Sommerman, G. M. L., "Gas evolution from transformer oils under high voltage stress," IEEE Transactions on Power Apparatus and Systems, vol. PA-86, no. 3, p. 374, 1967.

[B18] Szelchely, V. G., "Relation between gas evolution and the physical properties of liquids," Applied Physics, vol. 22, p. 627, 1951.

[B19] Vogel, F. J., Peterson, C. C., and Matsch, L. M., "Deterioration of transformer oil and paper insulation by temperature," AIEE Transactions, vol. 78, no. 1, pp. 18–21 (tables), 1951.

H.2 Detection and interpretation

H.2.1 Gas detector relay

[B20] AIEE Relay Subcommittee, "Relay protection of power transformers," AIEE Transactions, vol. 66, pp. 911–917, 1947.

[B21] Bean, R. L., and Cole, H. L., "A sudden gas pressure relay for transformer protection," AIEE Transactions, vol. 72, no. 3. pp. 480–483, 1953.

[B22] Duffy, F. H., "Gas detector relay experience on Saguenay system," Doble Conference Index of Minutes, Sec. 6-501, 1951.

[B23] Madill, J. T., "Typical transformer faults and gas detector relay protection," AIEE Transactions, vol. 66, pp. 1052–1060, 1947.

[B24] McDermid, W., "Generation of combustible gas in 230 kV oil-filled current transformers," Doble Conference Index of Minutes, Sec. 6-301, 1968.

[B25] Streuli, W. R., "Tranfoscope (gas actuated transformer protective relay of Buchholz type)" Doble Conference Index of Minutes, Sec. 6-01, 1949.

[B26] Sturtevant, D. B., "Experience with Buchholz gas-operated relay," Doble Conference Index of Minutes, Sec. 6-101, 1964.

[B27] Vanlund, J. A., "General electric transformers," Doble Conference Index of Minutes, Sec. 6-301, 1961.

H.2.2 Gas cushion in sealed transformers

[B28] Barrett, R. D., and Parker, J. C., "Experience in testing nitrogen in oil-filled transformers," Doble Conference Index of Minutes, Sec. 6-201, 1963.

[B29] Bellaschi, P. L., "Introduction to symposium on gas analysis for detection of incipient faults in power transformers," Doble Conference Index of Minutes, Sec. 6-101, 1963.

[B30] Crawford, C. E., and Wilson, A. E., "Incipient transformer fault detected by combustible gas monitoring program and ultra sound tests," Doble Conference Index of Minutes, Sec. 6-1201, 1964.

[B31] Cromley, R. J., "Failure and repair of a transformer joint," Doble Conference Index of Minutes, Sec. 6-701, 1963.

[B32] Duke, C. A., Goodroe, C. R., Taylor, R. O., and Thompson, W. W., "Detection of combustible gases in nitrogen sealed power transformers," Doble Conference Index of Minutes, Sec. 6-1001, 1964.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

[B33] Duke, C. A., and Taylor, R. O., “Detection of combustible gases in nitrogen sealed power transformers,” Doble Conference Index of Minutes, Sec. 6-101, 1962.

[B34] Ferguson, M. L., “Combustible gas analysis as a preventive maintenance tool,” Doble Conference Index of Minutes, Sec 6-1801, 1964.

[B35] Ferguson, M. L., “Combustible gas problem,” Doble Conference Index of Minutes, Sec. 6-401, 1965.

[B36] Gillies, D. A., and Muckerhelde, L. H., “Combustible gas monitoring—500 kV current transformers,” Doble Conference Index of Minutes, Sec. 6-201, 1973.

[B37] Graham, W. R., and Riner, R. B., “Incipient fault detection in power transformers,” Doble Conference Index of Minutes, Sec. 6-201, 1965.

[B38] Gochmauer, E. L., “TCG analysis of incipient fault forecasted,” Doble Conference Index of Minutes, Sec. 6-201, 1966.

[B39] Gronberg, W. L., “Detection of incipient power transformer faults with combustible gas jet,” Doble Conference Index of Minutes, Sec. 6-301, 1962.

[B40] Hahn, J. H., “Field untanking and repair of a 230/115 kV, 40/50, 3/66.7 MVA, OA/FA/FA, autotransformers,” Doble Conference Index of Minutes, Sec. 6-101, 1968.

[B41] Horelick, A. L., “Incipient fault detection method proves valuable for transformer protective maintenance,” Transmission and Distribution, p. 34, Jan. 1961.

[B42] McDermid, W., “Generation of combustible gas in 230 kV oil-filled current transformers,” Doble Conference Index of Minutes, Sec. 6-301, 1968.

[B43] Parker, J. C., “Testing nitrogen over oil in power transformers,” Doble Conference Index of Minutes, Sec. 6-1501, 1964.

[B44] Price, R. C., “Transformer failure at the Allen steam plants,” Doble Conference Index of Minutes, Sec. 6-301, 1966.

[B45] Pugh, P. S., and Wagner, H. H., “Detection on incipient faults in transformers by gas analysis,” AIEE C.P., pp. 60–950, 1960.

[B46] Pugh, P. S., and Wagner, H. H., “Detection of incipient faults in transformers by gas analysis,” AIEE Transactions, vol. 80, pp. 189–195, 1961.

[B47] Rickley, A. L., and Clark, R. E., “Combustible gas detection in transformers,” Doble Conference Index of Minutes, Sec. 6-501, 1963.

[B48] Rose, M., “Automatic sampling and measurement of combustible gases in transformers,” Doble Conference Index of Minutes, Sec. 6-801, 1967.

[B49] Sheppard, H. R., “Dangerous conditions are detected by analyzing transformer gases,” Transmission and Distribution, vol. 20, no. 2, pp. 71–74, 1968.

[B50] Sheppard, H. R., “Why is gas generated in oil-filled transformers” Transmission and Distribution, vol. 20, no. 1, pp. 63–65, 1968.

[B51] Syrjamaki, E. M., “Calibration and comparison of fault gas detectors,” Doble Conference Index of Minutes, Sec. 2-101, 1964.

[B52] Thomas, D. J., “Combustible gas in power transformers (its detection and significance),” Doble Conference Index of Minutes, Sec. 6-1010, 1966.

[B53] Thompson, W. W., “Modification of conservator transformers to permit combustible gas surveillance,” Doble Conference Index of Minutes, Sec. 6-601, 1967.

[B54] Wagner, H. H., “Detection of incipient faults in power transformers by gas analysis,” Doble Conference Index of Minutes, Sec. 6-801, 1960.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

[B55] Wagner, H. H., “Development of continuous monitoring total combustible gas (TCG) incipient fault detector,” Doble Conference Index of Minutes, Sec. 6-1901, 1964.

[B56] Wagner, H. H., “Experience with transformer gas-fault detector testings,” Doble Conference Index of Minutes, Sec. 6-701, 1961.

[B57] Wagner, H. H., “Field experiences with the transformer fault gas detector,” Doble Conference Index of Minutes, Sec. 6-601, 1962.

[B58] Wagner, H. H., “Five years experience with transformer TCG incipient fault detector tests,” IEEE Transactions on Power Apparatus and Systems, vol. PAS-84, no. 8, pp. 700–706, 1965.

[B59] Wagner, H. H., “Pennsylvania TCG transformer fault-gas continuous monitor,” Doble Conference Index of Minutes, Sec. 6-701, 1967.

[B60] Wagner, H. H., “Pennsylvania transformers,” Doble Conference Index of Minutes, Sec. 6-701, 1961.

[B61] Wagner, H. H., “Pennsylvania transformer total combustible gas (TCG), incipient fault detector,” Doble Conference Index of Minutes, Sec. 6-302, 1963.

[B62] Wagner, H. H., “Survey of TCG tests on transformers,” IEEE C.P., pp. 6–4209.

[B63] Vanlund, J. A., “Gas analysis for detection of incipient power transformer faults,” Doble Conference Index of Minutes, Sec. 6-401, 1963.

[B64] Vora, J. P., and Aicher, L. C., “Transformer fault gas analysis interpretation,” IEEE Transactions on Power Apparatus and Systems, vol. PAS-84, no. 2, pp. 172–176, discussion on p. 487, 1965.

H.2.3 Dissolved gas in insulating liquid

[B65] Armstrong, Jr., G. W., and Baker, A. E., “Transformer problems detected or confirmed by use of combustible gas analysis,” *Doble Conference Index of Minutes*, Sec. 10-301, 1975.

[B66] Ballaschi, P. L., “Application of fault-gas detection methods on transformer test at the factory,” *Doble Conference Index of Minutes*, Sec. 10-301, 1973.

[B67] Beeler, G., “Combustible gas analysis on Peach Bottom no. 1 transformer,” *Doble Conference Index of Minutes*, Sec. 10-1401, 1974.

[B68] Beer, G., Onerti, A., Bossi, A., and Hirra, C., “Contribution expérimentale à l’étude de la dégradation produits par les descharges partielles dans le papier isolant imprégné à l’huile,” *presented at CIGRE*, paper 15-02, 1970.

[B69] Belanger, G., and Duval, H., “Monitor for hydrogen dissolved in transformer oil,” *IEEE Transformer Electrical Insulation*, vol. EI-12, no. 5, pp. 334–340, Oct. 1977.

[B70] Booker, J. R., “Experience with incipient fault detection utilizing gas chromatography analysis,” *Doble Conference Index of Minutes*, Sec. 10-501, 1973.

[B71] CIGRE Technical Brochure # 409, “Report on Gas Monitors for Oil-Filled Electrical Equipment”, *WG D1.01*, Feb. 2010.[15]

[B72] CIGRE Technical Brochure # 443, “DGA in Non Mineral Oils and Tap Changers and Improved DGA Diagnosis Criteria”, *WG D1.32*, Dec. 2010.

[B73] CIGRÉ Technical Brochure #537, “Guide for Transformer Fire Safety Practices”, *WG A2.33*, 2013.

[B74] CIGRÉ Technical Brochure #642, “Transformer reliability survey”, *WG A2.37*, 2015.

[B75] Clark, F. M., “The role of dissolved gases in determining the behavior of mineral insulating oils,” *Journal of the Franklin Institute*, vol. 215, no. 1, p. 39, 1933.

[15] CIGRE publications are available from the Council on Large Electric Systems (http://www.e-cigre.org/).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

[B76] Collins, R. L., “Hydrogen Detector,” *U.S. Patent* no. 3559457, 1971.

[B77] Coltong, R., “Combustible gas testing on large oil-filled transformers,” *Electrical Insulation Conference* 69C 33E1-37, pp. 115–118, 1969.

[B78] Daoust, R., “Analysis of gases dissolved in transformer oils,” *Doble Conference Index of Minutes*, vol. 39, AIC71, Sec. 10-601, 1972.

[B79] DiGiorgio, J. B., Jakob, E, and Haupert, T., “Transformer fault gas analysis,” minutes of the meeting of Pennsylvania Electr. Assoc. Eng. Sect. Electr. Equip. Comm., Bedford, PA, Oct. 18–19, 1977. (Published by *Pennsylvania Electr. Assoc. Eng. Sect., Harrisburg*, PA, p. 22, 1977.)

[B80] Dind, J., Daoust, R., Regis, and Morgan, J., “Analysis of gases dissolved in transformer oil,” *Doble Conference Index of Minutes*, vol. 38, AIC71, Sec. 6-1101, 1971.

[B81] Dornenberg, E., and Gerber, O. E., “Analysis of dissolved and free gases for monitoring performance of oil-filled transformers,” *Brown Boveri Review*, vol. 54, no. 213, p. 104, 1967.

[B82] Dornenburg, E., and Strittmatter, W., “Monitoring oil cooled transformers by gas analysis,” *Brown Boveri Review*, vol. 61, no. 5, pp. 238–247, May 1974.

[B83] Dukarm, J. J., Duval, M., “Transformer reliability and dissolved-gas analysis,” *2016 CIGRE Canada Conference*, No. CIGRE-807, Vancouver BC, October 2016.

[B84] Duval, M. and Dukarm, J., “Improving the reliability of transformer gas-in-oil diagnosis,” *IEEE Electr. Insul*. Mag., Vol. 21, No. 4, July 2005.

[B85] Duval, M., “Fault gases formed in oil-filled breathing E.H.V. transformers; interpretation of gas analysis data,” *IEEE C.P*., no. C 74, pp. 476–478, 1974.

[B86] Duval, M. “Calculation of DGA Limit Values and Sampling Intervals in Transformers in Service”, *IEEE Electrical Insulation Magazine*, Vol. 24, No. 5, pp. 7-13, September/October 2008.

[B87] Duval, M., “Ongoing Activities at IEEE, IEC and CIGRE on DGA”, *Proceedings of the Transformer & Switchyard Users Group (TSUG) Meeting*, St-Louis, Aug 5, 2013.

[B88] Duval, M., “Latest Duval Triangles-What’s coming”, TechCon North America 2014, Phoenix, AZ, February 4–6, 2014.

[B89] Duval, M., “Identifying and analyzing quick developing faults with DGA”, *SIGAT Conference*, Cartagena, Colombia, May 2014.

[B90] Duval, M., Lamarre, L., “The Duval Pentagon – A new complementary tool for the interpretation of dissolved gas analysis in transformers,” *IEEE Electrical Insulation Magazine*, Vol 30, No. 6, pp. 9-12, September/October 2014.

[B91] Duval, M. “Use of Duval Pentagons and Triangles for the interpretation of DGA in Electrical Equipment”, *TechCon North America 2016*, Paper 13, Albuquerque, NM, February 23 -25, 2016.

[B92] Duval, M., “Interpretation of Dissolved Gas Analysis in electrical equipment with Duval Triangles and Pentagons”, *IEEE PES Transformers Committee Tutorial*, Atlanta, 2016.

[B93] Duval, M., DePablo, A., Hoehlein-Atanasova, I. and Grisaru, M., “Significance and detection of very low degree of polymerization of paper in transformers”, *IEEE Electrical Insulation Magazine*, Vol.33, No.1, pp. 31-38, Jan/Feb 2017.

[B94] Fallou, B., Viale, F., Devaux, A., Fournie, R., Galand, J., Vuarches, P., Davies, I., Rogers, R. R., Reynolds, E. H., and Dornenburg, E., “Application des méthodes d’analyse physico-chimiques à l’étude des dégradations dans l’isolation des materiels électriques,” *presented at CIGRE*, paper 15-07, 1970.

[B95] Glass, R. H., “Dissolved gas analysis of transformer oil,” *Transmission and Distribution*, vol. 29, no. 1, pp. 22–24, 26, 28–29, Jan. 1977.

[B96] Girgis, R., teNyenhuis, E. G., “Hydrogen Gas Generation Due to Moderately Overheated Transformer Cores”, *2009 IEEE Power & Energy Society General Meeting*, 26-30 July 2009.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

[B97] Hahn, J. H., "Field untanking and repair of a 230/115 kV, 40/50, 3/66.7 MVA, OA/FA/FA autotransformer," *Doble Conference Index of Minutes*, Sec. 6-101, 1968.

[B98] Haupert, T. O., and Jakob, F., "A review of the operating and practice of dissolved gas analysis," *Electrical Insulation Oils*, STP 998, pp. 108–115, 1988.

[B99] Haupert, T. O., Jakob, F., and Hubacher, E.J., "Application of a new technique for the interpretation of dissolved gas analysis data," *11th Annual Technical Conference of the International Electrical Testing Association*, pp. 43–51, 1989.

[B100] Heinrichs, F. W., "The impact of fault-detection methods and analysis on the transformer operating decision," *presented at IEEE/PES Transmission and Distribution Conference*, paper 86 T&D 559-9, Anaheim, CA, Sept. 1986.

[B101] Hino, T., and Suganuma, Y., "Rapid measurement of the deterioration of oil-immersed paper," *Electrical Insulation Conference*, 71 C 38EI-41, 129, 1971.

[B102] Hopkinson, P.J., "Wind Power Transformer Design", *2013 Life of a Transformer(TM) Seminar*, San Diego, CA, USA, February 18-21, 2013.

[B103] IEC 60599, "Mineral oil-filled electrical equipment in service - Guidance on the interpretation of dissolved and free gases analysis."[16]

[B104] IEEE Std C57.91™, IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators. [17,18]

[B105] IEEE C57.130™, "Guide for the Use of Dissolved Gas Analysis Applied to Factory Temperature Rise Tests for the Evaluation of Mineral Oil-Immersed Transformers and Reactors."

[B106] IEEE C57.139™, "IEEE Guide for Dissolved Gas Analysis in Transformer Load Tap Changers."

[B107] IEEE C57.146™, "IEEE Guide for Interpretation of Gases Generated in Silicone-Immersed Transformers."

[B108] IEEE C57.152™-2013, "IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors."

[B109] IEEE C57.155™, "IEEE Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester-Immersed Transformers."

[B110] Jakob, F., Dukarm, J. J., "Thermodynamic Estimation of Transformer Fault Severity," Power Delivery, *IEEE Transactions* on, vol.30, no.4, pp.1941-1948, Aug. 2015.

[B111] Jakob, F., Noble, P., Dukarm, J. J., "A Thermodynamic Approach to Evaluation of the Severity of Transformer Faults," Power Delivery, *IEEE Transactions,* vol.27, no.2, pp.554-559, April 2012. DOI: 10.1109/TPWRD.2011.2175950.

[B112] Kauffman, G. H., "Gas bubbles in distribution transformers," *IEEE Transformer Power Apparatus and Systems*, vol. PAS-96, no. 5, pp. 1596–1601, Sept./Oct. 1977.

[B113] Keene, D. J., "Transformer problem detected by fault-gas analysis," *Doble Conference Index of Minutes*, Sec. 10-1301, 1974.

[B114] Kelly, J. J., "Transformer fault diagnosis by dissolved-gas analysis," *presented at IEEE 26th Annual Petroleum and Chemical Industry Conference*, San Diego, CA, pp. 145–151, Sept. 10–12, 1979.

[B115] Kelly, J. J., and Myers, S. D., "The value of gas-in-oil analysis as a guide to the operational conditions existing in a power transformer," *Conference Record of the Thirty-Fourth Annual Conference of Electrical Engineering Problems in the Rubber and Plastics Industries*, 1972.

[B116] Lindeman, K., "Analyze transformer gas to identify faults," *Power*, vol. 114, no. 4, p. 74, 1970.

[16] IEC publications are available from the International Electrotechnical Commission (http://www.iec.ch) and the American National Standards Institute (http://www.ansi.org/).
[17] The IEEE standards or products referred to in Annex H are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.
[18] IEEE publications are available from the Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

[B117] Martin, Jr., W. B., and Taylor, R. O., “Experience with chromatographic analysis of fault gases in power transformers,” *Doble Conference Index of Minutes*, Sec. 10-201, 1973.

[B118] McCrae, G. G., “Experience with incipient faults detection by gas-in-oil analysis,” *Doble Conference Index of Minutes*, vol. 39, 1AC72, Sec. 6-701, 1972.

[B119] Moraru, D., Popesco, C., Stoica, M., and Tanasesco, F. I, “Detection des degradations produites par des decharges partielles pour les types d’isolation papier-huile,” *presented at CIGRE*, paper 15-05, 1970.

[B120] Muller, R., Potthoff, K., and Soldner, K., “Analyse des gas dissous dans l’huile en tant que moyen de surveillance des transformateurs et de détection de defaults naissants,” *presented at CIGRE*, paper 12-02, 1970.

[B121] Platts, D. and Hanson, D., “Where Does the Air Go? (Second Edition)”, *TechCon 2017 North America proceeding*, Houston, TX, February 14-16, 2017.

[B122] Pugh, D. R., “Advances in fault diagnosis by combustible gas analysis,” *Doble Conference Index of Minutes*, Sec. 10-1201, 1974.

[B123] Pugh, D. R., “Combustible gas analysis,” *Doble Conference Index of Minutes*, Sec. 10-401, 1973.

[B124] Raab, E. L., “Symposium on gas chromatography,” *Doble Conference Index of Minutes*, Sec. 10-501A, 1973.

[B125] Rogers, R. R., “IEEE and IEC codes to interpret incipient faults in transformers using gas-in-oil analysis,” *IEEE Transformer Electrical Insulation*, vol. EI-13, no. 5, pp. 349–354, Oct. 1978.

[B126] Rogers, R. R., “U.K. Experience in the interpretation of incipient faults in power transformers by dissolved gas-in-oil chromatographic analysis,” *Doble Conference Index of Minutes*, Sec. 10-201, 1975.

[B127] Sheppard, H. R., “Why is gas generated in oil-filled transformers?” *Transmission and Distribution*, pp. 63–65, Jan. 1968.

[B128] Shirai, H., Shimoji, S., and Ishii, T., “Thermodynamic study on the thermal decomposition of insulating oil,” *IEEE Transformer Electrical Insulation*, vol. EI-12, no. 4, pp. 272–280, Aug. 1977.

[B129] Singh, P., Blackburn, T., “Unusual DGA results in wind turbine transformers”, *Proceedings of TechCon, Australia-New Zeeland 2018*, Sydney, 16 to 18 April 2018.

[B130] Stamm, H., and Schulze, W., “Deterioration of insulators consisting of paper-oil layers and its study by gas chromatography,” *presented at CIGRE*, paper 12-14, 1968.

[B131] Strom, R., and Takahashi, S., “Analysis of fault gases in transformer oil by improved method of gas chromatography,” *Ontario Research Quarterly*, Second quarter, pp. 21–25, 1968.

[B132] Tsukioka, H., Sugawara, K, Mori, E., Hukumori, S., and Sakai, S., “New apparatus for detecting H(2), CO, and CH(4) dissolved in transformer oil,” *IEEE Transactions on Electrical Insulation*, vol. EI-18, no. 4, pp. 409–419, Aug. 1983.

[B133] Wilputte, R., “Contribution à l’étude de l’évolution de gas dans les isolants liquides et solides soumis à l’action de contraintes électriques,” *presented at CIGRE*, paper 15-03.

[B134] Yamada, H., Nomura, Y., Katayma, Y., Ishii, T., Imamura, O., and Isuchiyama, K., “Automatic field monitoring of dissolved gas in transformer oil,” *IEEE Transformer Power Apparatus and Systems*, vol. PAS-100, no. 4, pp. 1538–1544, Apr. 1981.

[B135] Yamaok, M., et al., “GIO analyser (auto-analyser for gases in oil),” *Fuji Electr. Rev. (Japan)*, vol. 19, no. 2, pp. 83–86, 1973.

Copyright © 2019 IEEE. All rights reserved.

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.

IEEE SA
STANDARDS
ASSOCIATION

RAISING THE WORLD'S STANDARDS

Connect with us on:

Twitter: twitter.com/ieeesa

Facebook: facebook.com/ieeesa

LinkedIn: linkedin.com/groups/1791118

Beyond Standards blog: beyondstandards.ieee.org

YouTube: youtube.com/ieeesa

standards.ieee.org
Phone: +1 732 981 0060

IEEE

Authorized licensed use limited to: Lulea University of Technology. Downloaded on November 17,2019 at 00:33:05 UTC from IEEE Xplore. Restrictions apply.