



IEEE Guide for the Evaluation of Performance Characteristics of Non-Sulfur Hexafluoride Insulation and Arc Quenching Media for Switchgear Rated Above 1000 V

IEEE Power and Energy Society

Developed by the
Switchgear Committee

IEEE Std C37.100.7™-2023

STANDARDS

IEEE Guide for the Evaluation of Performance Characteristics of Non-Sulfur Hexafluoride Insulation and Arc Quenching Media for Switchgear Rated Above 1000 V

Developed by the

Switchgear Committee
of the
IEEE Power and Energy Society

Approved 21 September 2023

IEEE SA Standards Board

Recognized as an American National Standard

Abstract: Existing standards and performance criteria for switchgear rated above 1000 V are reviewed in this guide. Each aspect of performance is discussed within the context of Sulfur Hexafluoride alternatives, how their behavior might differ from existing technologies and how this behavior can lead to changes in the qualification process. Relevant analytical, numerical and test methods are discussed which contribute to the process of performance evaluation and future evolution of the standards.

Keywords: IEEE C37.100.7™, routine test, SF₆, SF₆-alternative, sulfur hexafluoride, switchgear, type test

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

Copyright © 2024 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 22 March 2024. 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 979-8-8557-0425-9 STD26712
Print: ISBN 979-8-8557-0426-6 STDPD26712

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <https://www.ieee.org/about/corporate/governance/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.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers>), appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

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

IEEE Standards documents are developed within IEEE Societies and subcommittees of IEEE Standards Association (IEEE SA) Board of Governors. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers are not necessarily members of IEEE or IEEE SA 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 makes no warranties or representations concerning its standards, and expressly disclaims all warranties, express or implied, concerning this standard, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. IEEE Standards documents do not guarantee safety, security, health, or environmental protection, or guarantee against interference with or from other devices or networks. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. 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 their 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: THE NEED TO PROCURE 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.

Translations

The IEEE consensus balloting 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 is the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards 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, nor 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 the presenter's views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group. Statements made by volunteers may not represent the formal position of their employer(s) or affiliation(s).

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, 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 subcommittees of the IEEE SA Board of Governors 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 evaluating comments or in revisions to an IEEE standard is welcome to join the relevant IEEE working group. You can indicate interest in a working group using the Interests tab in the Manage Profile and Interests area of the [IEEE SA myProject system](#).¹ An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.²

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 constitute 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.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

¹Available at: <https://development.standards.ieee.org/myproject-web/public/view.html>.

²Available at: <https://standards.ieee.org/thank-you/contact/>.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US 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, neither IEEE nor its licensors waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, 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; <https://www.copyright.com/>. 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. An official 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 10 years. When a document is more than 10 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](#) or [contact IEEE](#).³ For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#).⁴ Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

Patents

IEEE standards are developed in compliance with the [IEEE SA Patent Policy](#).⁵

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

³Available at: <https://standards.ieee.org/about/contact>.

⁴Available at: <https://standards.ieee.org/standard/>

⁵Available at: <https://standards.ieee.org/about/sasb/patcom/materials>.

filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SA Website at <https://standards.ieee.org/about/sasb/patcom/patents>. 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.

IMPORTANT NOTICE

Technologies, application of technologies, and recommended procedures in various industries evolve over time. The IEEE standards development process allows participants to review developments in industries, technologies, and practices, and to determine what, if any, updates should be made to the IEEE standard. During this evolution, the technologies and recommendations in IEEE standards may be implemented in ways not foreseen during the standard's development. IEEE standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. 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.

Participants

At the time this IEEE guide was completed, the Performance Evaluation of Sulfur Hexafluoride Alternatives Working Group had the following membership:

Daniel Schiffbauer, *Chair*
George Becker, *Vice Chair*
Victor Hermosillo, *Secretary*

Edwin Almeida	Andres Laso Rubio	James Stage
Eldridge Byron	Hua Liu	Don Steigerwalt
Andrew Chovanec	Javier Mantilla	Patrick Stoller
Michael Crawford	Henning Milnikel	Dragan Tabakovic
Kennedy Darko	John Owens	Vernon Touns
Patrick DiLillo	Pathik Patel	Francois Trichon
Brian Gerzeny	Caryn Riley	Nenad Uzelac
John Hall	Brian Roberts	Mark Waldron
Roy Neil Hutchins	Jon Rogers	Jan Weisker
Todd Irwin	Carl Schuetz	William Wilkie
Rahul Jain	Sushil Shinde	Terrance Woodyard
Christopher Jarnigan	Michael Skidmore	Richard York
David Johnson	Christopher Slattery	Li Yu
Carl Kurinko		Wei Zhang

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

George Becker	Victor Hermosillo	Bartien Sayogo
Steven Bezner	Werner Hoelzl	Daniel Schiffbauer
Wallace Binder	Todd Irwin	Carl Schuetz
Gustavo Brunello	Richard Jackson	Jeffrey Scott
Arben Bufi	Rahul Jain	Devki Sharma
David Burns	John Kay	Sushil Shinde
Ted Burse	Thomas Keels	Garett Sims
Koti Reddy Butukuri	Jim Kulchisky	Michael Skidmore
Eldridge Byron	Carl Kurinko	Jerry Smith
Paul Cardinal	Hua Liu	Gary Smullin
Sean Carr	Weili Liu	James Stage
Andrew Chovanec	Albert Livshitz	David Tepen
Lucas Collette	Neil Mc Cord	Francois Trichon
Michael Crawford	Jeffrey McElray	James Van De Ligt
Kennedy Darko	Peter Meyer	John Vergis
Kurniawan Diharja	David Mitchell	Mark Waldron
Neal Dowling	Daleep Mohla	Lanyi Wang
Edgar Dullni	Timothy Myers	Jeffrey Ward
Douglas J Edwards	Jeffrey Nelson	John Webb
Carl Fredericks	James Niemira	Jan Weisker
Kamal Garg	Miklos Orosz	William Wilkie
Shubhanker Garg	Lorraine Padden	Terry Woodyard
Brian Gerzeny	Larry Putman	Richard York
Lou Grahor	Caryn Riley	Li Yu
John Harley	Jon Rogers	Wei Zhang
	Ian Rokser	

When the IEEE SA Standards Board approved this guide on 21 September 2023, it had the following membership:

David J. Law, *Chair*
Ted Burse, *Vice Chair*
Gary Hoffman, *Past Chair*
Konstantinos Karachalios, *Secretary*

Sara R. Biyabani
Doug Edwards
Ramy Ahmed Fathy
Guido R. Hiertz
Yousef Kimiagar
Joseph L. Koepfinger*
Thomas Koshy
John D. Kulick

Joseph S. Levy
Howard Li
Gui Lin
Johnny Daozhuang Lin
Xiaohui Liu
Kevin W. Lu
Daleep C. Mohla
Andrew Myles

Paul Nikolich
Annette D. Reilly
Robby Robson
Lei Wang
F. Keith Waters
Karl Weber
Philip B. Winston
Don Wright

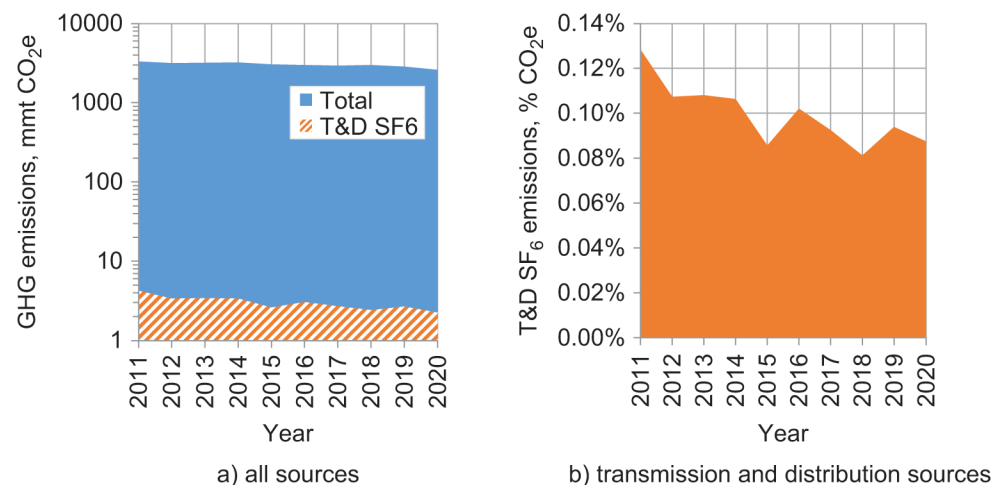
*Member Emeritus

Introduction

This introduction is not part of IEEE Std C37.100.7-2023, IEEE Guide for the Evaluation of Performance Characteristics of Non-Sulfur Hexafluoride Insulation and Arc Quenching Media for Switchgear Rated Above 1000 V.

Since the 1960s, sulfur hexafluoride (SF₆) has become an integral part of the modern electrical grid. Its unique combination of physical properties enables compact, reliable, and cost-effective equipment across the complete range of medium and high-voltage switchgear ratings. However, SF₆ does have the highest known global warming potential of any substance at 25 200 [B67].⁶

In 1997, the Kyoto Protocol identified SF₆ as one of six greenhouse gas categories of concern, leading to increased environmental scrutiny. Then in 2011, the United States Environmental Protection Agency began tracking and reporting SF₆ emissions from sources including the manufacture and use of electrical T&D equipment as shown in Figure 1 [B119].



Data source: United States Environmental Protection Agency. *Facility Level Information on Greenhouse Gases Tool (FLIGHT)*. Accessed June 28, 2022. <https://ghgdata.epa.gov/ghgp/main.do>.

Figure 1—Reported US greenhouse gas (GHG) emissions

In addition to SF₆ emission reduction efforts, manufacturers, and academia have been researching and developing new switchgear based on SF₆-alternative technologies since the early 2000s. This work prompted the formation of several industry groups to study SF₆-alternatives and their impact on equipment standards. Among these are the following:

- CIGRÉ Technical Brochure 589, “The Impact of the Application of Vacuum Switchgear at Transmission Voltages” published in 2014 [B28].
- CIGRÉ Technical Brochure 730, “Dry Air, N₂, CO₂ and N₂-SF₆ Mixtures for Gas-Insulated Systems” published in 2018 [B29].
- IEEE PES-TR64, “Impact of Alternate Gases on Existing IEEE Standards” published in 2018 [B51].
- CIGRÉ Technical Brochure 802, “Application of Non-SF₆ Gases or Gas-Mixtures in Medium and High-Voltage Gas-Insulated Switchgear” published in 2020 [B30].

⁶The numbers in brackets correspond to those of the bibliography in Annex A.

- CIGRÉ Technical Brochure 849, “Electric Performance of New Non-SF₆ Gases and Gas Mixtures for Gas-Insulated Systems” published in 2021 [B31].
- CIGRÉ Technical Brochure 871, “Current Interruption in SF₆-Free Switchgear” published in 2022 [B32].

Of these, IEEE PES-TR64 served as the motivational work for this guide. The relevant conclusions and recommendations from IEEE PES-TR64 and the corresponding material in this guide are listed in [Table 1](#).

Finally, the information summarized here is intended to present state-of-the-art knowledge and to inform. There is no absolute answer when trying to rank SF₆-alternatives, it is rather a question that has multiple answers to be assessed on a case-by-case basis. The conclusions presented are solely based upon the experiments performed by manufacturers and academia. It is important to highlight that these results do not necessarily share the same conditions and methodology, and thus the spectrum of variability, test conditions, procedures, test devices, and gas mixtures used is wide. Although clear trends can be identified, readers are cautioned not to derive absolute conclusions from these.

Acknowledgments

Permissions have been granted as follows:

Figure 43 and Figure 50 are reprinted with permission from CIGRÉ, Technical Brochure 730: Dry Air, N₂, CO₂ and N₂/SF₆ Mixtures for Gas Insulated Systems, © 2018.

Figure 9, Figures 29 through 32, Figure 45, Figure 47, Figure 51 through 54 and Figure 56 were produced by the working group using data with permission from CIGRÉ, Technical Brochure 849: Electric Performance of New Non-SF₆ Gases and Gas-Mixtures for Gas-Insulated Systems, © 2021.

Subclause 7.11 is adapted with permission from CIGRÉ, Technical Brochure 871: Current Interruption in SF₆-Free Switchgear, © 2022.

Figure 49 is reprinted with permission from CIGRÉ, Recent Research in the United States on the Effect of Particle Contamination Reducing the Breakdown Voltage in Compressed Gas-Insulated Systems, © 1976.

The photograph and accompanying data used to produce the graph in Figure 66 is reprinted with permission from the G&W Electric Company.

Contents

1. Overview.....	18
1.1 Scope.....	18
1.2 Purpose.....	18
1.3 Word usage.....	19
2. Normative references	19
3. Definitions, acronyms, and abbreviations	20
3.1 Definitions.....	20
3.2 Acronyms and abbreviations	20
4. Gas characteristics.....	22
4.1 Introduction and guidance	22
4.2 Thermodynamic properties of SF ₆ and alternatives	23
4.3 Gas mixture terminology.....	25
4.4 Ideal thermodynamic behavior of pure and mixed gases	26
4.5 Real thermodynamic behavior of pure and mixed gases.....	29
4.6 Gas composition and pressure for insulation and/or operation	30
4.7 Electrical wear and gas decomposition.....	32
4.8 Gas tightness testing.....	35
5. Environmental performance.....	39
5.1 Introduction and guidance	39
5.2 Global warming potential	40
5.3 Carbon footprint	41
5.4 Environmental life cycle assessment and methodology.....	43
6. Health and safety	46
6.1 Introduction and guidance	46
6.2 Terminology related to health hazards	47
6.3 Toxicity assessment of SF ₆ -alternatives.....	51
6.4 Vacuum interrupter X-radiation emissions testing.....	59
7. Switching and short circuit performance.....	62
7.1 Introduction and guidance	62
7.2 Overview of thermal and dielectric interruption stresses.....	64
7.3 Gas interrupter thermodynamic behavior	65
7.4 Short-time current.....	66
7.5 Thermal interruption test duties.....	66
7.6 Dielectric interruption test duties.....	70
7.7 Capacitive switching	72
7.8 Inductive load switching.....	82
7.9 Electrical endurance	85
7.10 Condition check after short circuit interrupting duty	88
7.11 Gas-insulated disconnect and ground switches ¹³	88
8. Dielectric insulation performance	94
8.1 Introduction and guidance	94
8.2 Self-restoring versus non-self-restoring gaseous insulation	95
8.3 Dry power frequency tests.....	97
8.4 Impulse tests.....	101
8.5 Zero-gauge pressure power frequency test	105
8.6 Routine tests with simplified replacement gas	107

9. Continuous current performance	108
9.1 Introduction and guidance	108
9.2 Continuous current type test	109
9.3 Validation of contact system stability (material compatibility)	111
9.4 Heat transfer characteristics of non-SF ₆ gas mixtures	114
9.5 Thermal overload	116
10. Low temperature performance	117
10.1 Introduction and guidance	117
10.2 Low temperature environmental type test	118
10.3 Low temperature design tests	122
Annex A (informative) Bibliography	125

List of Figures

Figure 1—Reported US greenhouse gas (GHG) emissions	9
Figure 2—Pressure versus temperature: typical isochores and saturation curve	24
Figure 3—Saturation curves of various pure gases.....	25
Figure 4—100% SF ₆ Pressure versus temperature: typical isochores and saturation curve.....	27
Figure 5—Ideal gas mixture saturation curves and isochores.....	28
Figure 6—Pressure versus temperature phase plot for 5% C ₄ -FN, 10% O ₂ , 85% CO ₂	29
Figure 7—Pressure versus temperature phase plots	30
Figure 8—Overview of gas composition and pressure relative to test duties.....	31
Figure 9—Normalized dielectric performance versus C ₄ -FN mole fraction.....	33
Figure 10—Gas circuit breaker interrupter (open position).....	34
Figure 11—Remaining electrical life versus number of 90% SLF interruptions	35
Figure 12—Influence of relative permeation rate of the primary dielectric component in a gas mixture.....	38
Figure 13—Typical carbon footprint analysis of electrical switchgear	42
Figure 14—Comparative dead tank breaker carbon footprint analysis.....	43
Figure 15—Environmental LCA methodologies.....	44
Figure 16—Example multi-criteria LCA of four 72.5 kV DTB technologies.....	45
Figure 17—Comparison of global toxicity classification systems.....	48
Figure 18—ATE _{mix} calculation for toxicity classification.....	50
Figure 19—Example ATE _{mix} calculations for new (not arced) gas.....	53
Figure 20—Acute toxicity of SF ₆ and alternative gases/mixtures before and after arcing.....	58
Figure 21—Interruption process stages.....	65
Figure 22—Illustration of transient pressure rise between SF ₆ and CO ₂ -based alternatives	66
Figure 23—Short line fault fundamental performance curve	67
Figure 24—PAC measurements during SLF testing of a CO ₂ -based GCB	68
Figure 25—Histogram of thermal interruption times after current zero	69
Figure 26—Example of hot dielectric recovery plot.....	71
Figure 27—Cold dynamic withstand test: example of a non-standard design test.....	72
Figure 28—Influence of gas volume on decomposition throughout preconditioning.....	73
Figure 29—High-voltage power frequency dielectric breakdown data.....	75

Figure 30—High-voltage power frequency breakdown voltage	76
Figure 31—Medium-voltage power frequency dielectric breakdown data	77
Figure 32—Medium-voltage power frequency breakdown voltage.....	78
Figure 33—Class C1 isolated bank switching (1200 A rated switching current).....	79
Figure 34—Class C1 back-to-back switching (700 A rated switching current)	79
Figure 35—Class C2 isolated bank switching (1200 A rated switching current).....	80
Figure 36—Class C2 back-to-back switching (700 A rated switching current)	80
Figure 37—Typical chopping current values by gas interrupter technology	83
Figure 38—ILS reignition current.....	84
Figure 39—First line side peaks of short line fault TRVs	86
Figure 40—Typical histogram of thermal re-ignition time.....	87
Figure 41—Influence of ratings on SLF first line side TRV peak	87
Figure 42—Approximate current and voltage ranges for switching duties in GIS	89
Figure 43—DS bus charging characteristics in SF ₆ , dry air, and N ₂	90
Figure 44—Box and whisker plot description	95
Figure 45—Dielectric breakdown data	96
Figure 46—Ratio of power frequency to lightning impulse level.....	97
Figure 47—Ratio of power frequency to lightning impulse breakdown voltage	98
Figure 48—Parameters relevant to particle sensitivity in switchgear.....	99
Figure 49—Particle behavior in SF ₆ and N ₂	100
Figure 50—Particle behavior in SF ₆ , dry air, CO ₂ and N ₂	101
Figure 51—Variation of impulse breakdown levels	103
Figure 52—Voltage–time dielectric breakdown characteristics	104
Figure 53—Positive to negative lightning impulse breakdown ratio.....	105
Figure 54—Power frequency dielectric strength of SF ₆ and alternatives as a function of type test pressure	106
Figure 55—Sensitivity of SF ₆ and alternative gaseous dielectrics to zero gauge pressure.....	106
Figure 56—Power frequency breakdown stress as a function of absolute pressure.....	107
Figure 57—Sliding contact and fixed connection systems	111
Figure 58—Contact system performance factor as a function of time and temperature	113
Figure 59—Temperature rise ratio versus gas pressure	115
Figure 60—Transient (overdamped) and steady-state temperature response	117

Figure 61—Low temperature environmental test procedure	119
Figure 62—100% SF ₆ pure gas behavior with heaters ON and OFF	120
Figure 63—Mixed gas behavior with heaters ON and OFF	120
Figure 64—Qualitative thermal and insulation recovery.....	121
Figure 65—Low temperature design test for insulation and thermal recovery	122
Figure 66—Low temperature liquefaction and re-homogenization.....	123

List of Tables

Table 1—IEEE C37.100.7 response to IEEE PES-TR64 conclusions and recommendations	18
Table 2—Summary of guidance related to gas characteristics	23
Table 3—Thermodynamic properties of several pure substances of interest in GIE	23
Table 4—Antoine constants for several pure substances of interest in GIE	25
Table 5—Decomposition rates of pure gases and gas mixtures	32
Table 6—Example of gas composition evolution due to non-uniform permeation only	38
Table 7—Summary of guidance related to environmental performance	39
Table 8—Atmospheric lifetime and 100-year GWP of several relevant pure substances	40
Table 9—Summary of guidance related to health and safety	46
Table 10—Acute toxicity categories by the Globally Harmonized System	48
Table 11—Modified Haber factors for time normalization of LC ₅₀ data to 4 h	49
Table 12—Acute toxicity and TWA-TLV of SF ₆ and known alternatives	51
Table 13—Summary of measured and calculated ATE _{mix} values	54
Table 14—Characteristics of discharges in gas-insulated equipment	54
Table 15—Decomposition products from partial discharge experiments	55
Table 16—Toxicity evolution of CO ₂ + 4% C4-FN, 540 C accumulated partial discharge	55
Table 17—Toxicity evolution of CO ₂ + 4% C5-FK, 455 C accumulated partial discharge	56
Table 18—Acute toxicity of SF ₆ after interruption	57
Table 19—Acute toxicity of 96% CO ₂ + 4% C4-FN after interruption	57
Table 20—Acute toxicity before and after internal arc test	58
Table 21—Standards addressing VI X-ray emissions	59
Table 22—X-ray shielding material properties	61
Table 23—Time (μs) to first line side TRV peak	88
Table 24—Voltage condition check	88
Table 25—Arc length during DS bus charging	90
Table 26—Summary of guidance related to electrical insulation performance	94
Table 27—Summary of guidance related to continuous current performance	109
Table 28—Standard temperature limits	110
Table 29—Relevant physical properties of typical contact joint materials	113

Table 30—Summary of guidance related to low temperature performance..... 118

Table 31—Low temperature environmental test procedure..... 119

IEEE Guide for the Evaluation of Performance Characteristics of Non-Sulfur Hexafluoride Insulation and Arc Quenching Media for Switchgear Rated Above 1000 V

1. Overview

1.1 Scope

The guide reviews existing standards and performance criteria for switchgear rated above 1000 V. Each aspect of performance is discussed within the context of sulfur hexafluoride alternatives, how their behavior may differ from existing technologies, and how this behavior may lead to changes in the qualification process. Relevant analytical, numerical, and test methods are discussed which may contribute to the process of performance evaluation and evolution of the standards.

1.2 Purpose

The purpose of this guide is to review the performance characteristics of current Sulfur Hexafluoride alternatives in gas insulated equipment (GIE) and compare these with the demands encountered in service. The guide reveals the reasoning behind existing standard requirements and presents information relevant to their adequacy for SF₆-alternatives.

[Table 1](#) summarizes the conclusions and recommendations from IEEE PES TR64 and the related content in this guide.

Table 1—IEEE C37.100.7 response to IEEE PES-TR64 conclusions and recommendations

IEEE PES-TR64 conclusion/recommendation	IEEE C37.100.7 relevant content
Comparison of SF ₆ -alternative technologies is challenging since nearly all research is performed in company laboratories.	While not directly motivated by IEEE PES-TR64, CIGRÉ Technical Brochure development is a pertinent example of industry-academia cooperation in full view of the switchgear community. The work published in CIGRÉ TB 589 [B28], CIGRÉ TB 730 [B29], CIGRÉ TB 802 [B30], CIGRÉ TB 849 [B31] and CIGRÉ TB 871 [B32] is highly relevant to much of the guidance contained within IEEE C37.100.7.

Table continues

**Table 1—IEEE C37.100.7 response to IEEE PES-TR64
conclusions and recommendations (*continued*)**

IEEE PES-TR64 conclusion/recommendation	IEEE C37.100.7 relevant content
Recommendation to probe SF ₆ -alternatives for weaknesses which might not be revealed by standard type tests.	In addition to guidance that affects test standards, nearly every clause of this guide provides examples of design tests that should be used during equipment development. Some examples are gas permeation tests, acute toxicity evaluation, non-standard interruption and switching tests, demonstration of self-restoring insulation behavior, long-term characterization of contact aging and characterization of low temperature insulation recovery of a gas mixture.
Recommendation to follow developments related to gas decomposition.	The guide addresses gas decomposition throughout by incorporating the latest information on decomposition as a parallel mechanism of electrical wear alongside contact erosion and nozzle ablation. Guidance related to both research and standard tests is given.
Recommendation to approach environmental performance from the point of view of the entire life cycle.	Clause 5 reviews three methodologies for environmental performance from the most simple—GWP of the insulating gas, to carbon footprint and finally to comprehensive life cycle assessment.

1.3 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*).^{7,8}

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.

This guide contains no normative references.

⁷The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

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

The terms and definitions applicable to this standard and to related standards for ac high-voltage switchgear shall be in accordance with IEEE Std C37.20.10 [B62] and IEEE Std C37.100.5 [B57].^{10,11} These definitions are not intended to embrace all possible meanings of the terms. They are intended solely to establish the meanings of terms used in power switchgear.

gas leakage: The homogeneous (uniform) flow of gas via small pathways in the equipment envelope, driven by a pressure gradient.

gas permeation: The diffusion of gas molecules across a solid barrier.

gas tightness: The ability of gas-insulated equipment to contain gases over a defined temperature range comprising both gas leakage and permeation of gas.

Global Warming Potential (GWP): An index that provides a relative measure of potential climate impact due to the presence of a substance that acts as a greenhouse gas in the atmosphere. Specifically, it is a measure of how much energy the emissions of a mass of gas will absorb over a period of time, relative to the emissions of the same mass of carbon dioxide.

per- and polyfluoroalkyl substances (PFAS): Fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom.

vapor-liquid equilibrium (VLE): The thermodynamic region of a gas mixture where molecules coexist in both vapor and liquid phases.

3.2 Acronyms and abbreviations

ATE	acute toxicity estimation
ATE _{mix}	acute toxicity estimation of a mixture
C2	class C2 capacitive switching rating
CAS	Chemical Abstracts Service
CB	circuit breaker
CO ₂ e	CO ₂ equivalent
CZ	current zero
DS	disconnecting switch
DTB	dead-tank breaker
E1	class E1 (basic) electrical endurance rating
E2	class E2 (extended) electrical endurance rating

⁹*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹⁰IEEE publications are available from The Institute of Electrical and Electronics Engineers, Inc. (<http://standards.ieee.org/>).

¹¹The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

ECHA	European Chemicals Agency
EHV	extra-high voltage
GC-MS	gas chromatography-mass spectrometry
GHG	greenhouse gas
GHS	Globally Harmonized System of Classification and Labeling of Chemicals
GIE	gas-insulated equipment
GIS	gas-insulated substation
GS	grounding switch
GWP	global warming potential
HGIS	hybrid gas-insulated substation
HSGS	high-speed ground switch
IPCC	Intergovernmental Panel on Climate Change
ILS	inductive load switching
ITH	integrated time horizon
ITRV	initial transient recovery voltage
L60	short line fault test duty at 60% of rated short-circuit current
L60 (75)	class E2 short line fault test duty at 60% of rated short-circuit current
L75	short line fault test duty at 75% of rated short-circuit current
L90	short line fault test duty at 90% of rated short-circuit current
LC ₅₀	lethal concentration with 50% mortality
LCA	(environmental) life cycle assessment
LI	lightning impulse
LTB	live-tank breaker
MTS	mixed technology switchgear
NRG	non-reactive gas
OEL	occupational exposure limits
OEM	original equipment manufacturer
PAC	post-arc current
PF	power frequency
PFAS	per- and polyfluoroalkyl substances
ppmv	parts per million by volume
PTFE	polytetrafluoroethylene
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
RF	radiative forcing
RG	reactive gas
RRRV	rate of rise of recovery voltage

RV	recovery voltage
SDS	safety data sheet
SLF	short-line fault
T10	terminal fault test duty at 10% of rated short-circuit current
T30	terminal fault test duty at 30% of rated short-circuit current
T100	terminal fault test duty at 100% of rated short-circuit current
T&D	transmission and distribution
TD1, TD2	test duty one, test duty two
TLV-TWA	threshold limit value - time-weighted average
TRV	transient recovery voltage
UHV	ultra-high voltage
VCC	voltage condition check
VFT(O)	very fast transient (overvoltage)
VI	vacuum interrupter
VLE	vapor-liquid equilibrium

4. Gas characteristics

4.1 Introduction and guidance

Proper operation in service requires a complete understanding of the thermo- and fluid dynamic behaviors of SF₆-alternative gases and gas mixtures during the design and qualification phases. The following pages provide some detail on commonly used alternative gases and mixtures of those gases employed in GIE. [Table 3](#) lists those covered pure gases along with some basic characteristics in [4.2](#). Other gases might be currently employed in GIE or be introduced at some future date. Gases and mixtures of gases not listed in [Table 3](#) are excluded from this document. Gas mixture terminology is reviewed briefly in [4.3](#). Ideal gas and gas mixture behavior is presented in [4.4](#). This is relevant to individual gases such as SF₆ and gas mixtures that do not condense by design. Condensing (real) gas and gas mixture behavior is addressed in [4.5](#). The thermodynamic behavior of SF₆-alternative gas mixtures and the consequences for testing is considered in [4.6](#). The relevance of both gas mixture composition and pressure on testing is addressed. Gas decomposition, contact erosion, and nozzle ablation are reviewed concurrently as mechanisms of electrical wear in [4.7](#) along with an example showing the importance of test object gas volume. Finally, [4.8](#) reviews gas tightness testing of SF₆-alternative gas mixtures. See [Table 2](#) for a summary of guidance related to alternative gas characteristics and considerations when evaluating their performance.

Table 2—Summary of guidance related to gas characteristics

Item	Guidance
Gas mixture definition	Gases and gas mixtures that do not condense in service can be treated as an ideal gas. If an ideal gas mixture is used only for insulation (no decomposition) and gas permeation is uniform, the mixture can be effectively treated as a single gas by monitoring only the total density in service. However, defined composition is still required for testing and gas handling. Refer to 4.4 for more detailed information.
	Gases and gas mixtures that can condense in service should be treated as real gases. If a real gas mixture is permitted to condense in service, such phenomena should be understood and incorporated into the gas composition and pressure used for type testing. Refer to 4.5 for more detailed information.
	In a gas mixture, the quantity of each component should be defined for testing. Therefore, the term, “type test composition and pressure” is proposed to completely define the type test gas mixture. Total pressure is defined in the usual manner as pressure at an arbitrary temperature (usually +20 °C). Composition can be defined as the mole fraction of each gas component or, alternatively, as the partial pressure of each gas component if the gas behavior is substantially ideal. Refer to 4.6 for more details.
Gas decomposition	Certain gas mixture components are known to dissociate during arcing and not recombine to their original molecules. This phenomenon is normally referred to as, “decomposition” or “consumption.” SF ₆ -alternative equipment should be qualified in the design configuration yielding the most decomposition. This means that most switching and all short circuit type tests should be performed using the equipment configuration with the smallest gas volume (leading to the greatest rate of decomposition). Refer to 4.7 for more details.
Gas tightness	Overall gas tightness of equipment is determined by both gas leakage and gas permeation as discussed in 4.8. A short duration routine test quantifies the leak tightness of a production assembly. Gas permeation, on the other hand, is time and temperature-dependent and requires separate, long-duration material development tests over a range of temperatures. Existing test methods for gas tightness can be adapted to non-SF ₆ gas mixtures by, for example, using one component of the mixture as a trace gas and accounting for the presence of any background trace gas in the atmosphere. Also, trace gases can be added to a gas mixture such as technical air and either subsequently removed or allowed to decompose (e.g., ozone to oxygen).
	Gas species are known to diffuse (permeate) through elastomeric seal materials at different rates. This raises questions about the possibility of an evolving gas mixture over time. An example indicating that the change in gas composition for properly designed equipment leads to less decrease in dielectric strength than uniform leakage is illustrated in 4.8. Therefore, material development tests are essential to put forth a seal system that yields a stable and predictable gas mixture in service. Special consideration should be given to the replacement of seals in service with qualified materials from approved sources.
	If applicable, a vacuum integrity test should be a part of the pass/fail criteria of mechanical and environmental type tests. Refer to 4.8.1 for details.

4.2 Thermodynamic properties of SF₆ and alternatives

Table 3 provides thermodynamic properties for several pure substances of interest which can be used in various equations of state to predict the pure vapor phase isochores as shown, for example, in Figure 2.¹²

Table 3—Thermodynamic properties of several pure substances of interest in GIE

Pure substance	Molecular weight (kg/kmol)	T _c (°C) (See NOTE 3)	P _c (kPa-abs) (See NOTE 4)	R (kJ/kg-K) (See NOTE 5)	ω (See NOTE 6)
SF ₆	146	45.85	3760	0.0569	0.218
N ₂	28	−147.2	3390	0.2968	0.038
O ₂	32	−118.2	5080	0.2598	0.021

Table continues

¹²Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

Table 3—Thermodynamic properties of several pure substances of interest in GIE (continued)

Pure substance	Molecular weight (kg/kmol)	T _C (°C) (See NOTE 3)	P _C (kPa-abs) (See NOTE 4)	R (kJ/kg-K) (See NOTE 5)	ω (See NOTE 6)
CO ₂	44	30.85	7380	0.1889	0.225
C4-FN (See NOTE 1)	195	107.9	2800	0.0426	0.473
C5-FK (See NOTE 2)	266	145.9	2140	0.0313	0.437

NOTE 1—Throughout this document, “C4-FN” refers to C4-fluoronitrile or C₄F₇N
NOTE 2—Throughout this document, “C5-FK” refers to C5-fluoroketone or C₅F₁₀O
NOTE 3—T_C is the critical temperature
NOTE 4—P_C is the critical pressure
NOTE 5—R is the gas constant
NOTE 6—ω is Pitzer’s acentric factor

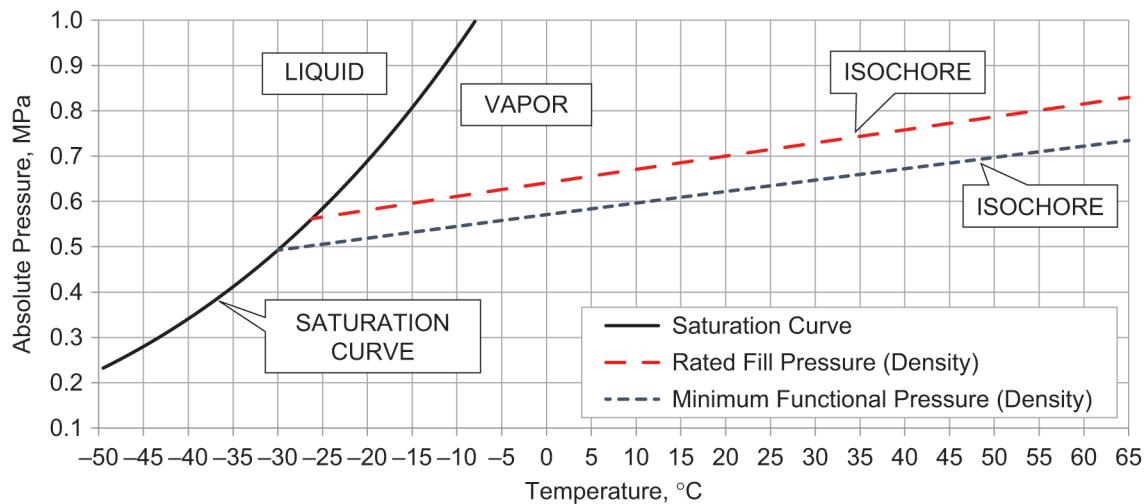


Figure 2—Pressure versus temperature: typical isochores and saturation curve

In addition to vapor phase isochores, the saturation curve can be determined using the Antoine approximation as shown in Equation (1). This is an exponential equation used to describe the saturation curve utilizing three constants:

$$\log P^{sat} = A - \frac{B}{T^{sat} + C} \quad (1)$$

where

T^{sat} is the saturation temperature, °C

P^{sat} is the absolute saturated vapor pressure, MPa

When used with the units indicated in Equation (1), the Antoine constants given in Table 4 allow the calculation of saturation curves for the pure gases shown in Figure 3.

Table 4—Antoine constants for several pure substances of interest in GIE

Pure substance	A	B	C	Valid temperature range (°C)
SF ₆	3.0019	676.24	233.12	−49.2 to +44.9
N ₂	2.8502	285.57	270.09	−209.2 to −147.2
O ₂	2.9620	339.21	268.70	−218.2 to −119.2
CO ₂	3.7132	861.82	271.88	−56.2 to +30.9
C4-FN	2.8724	836.49	221.00	−50.2 to +107.9
C5-FK	3.3905	1178.4	241.84	−38.2 to +145.9

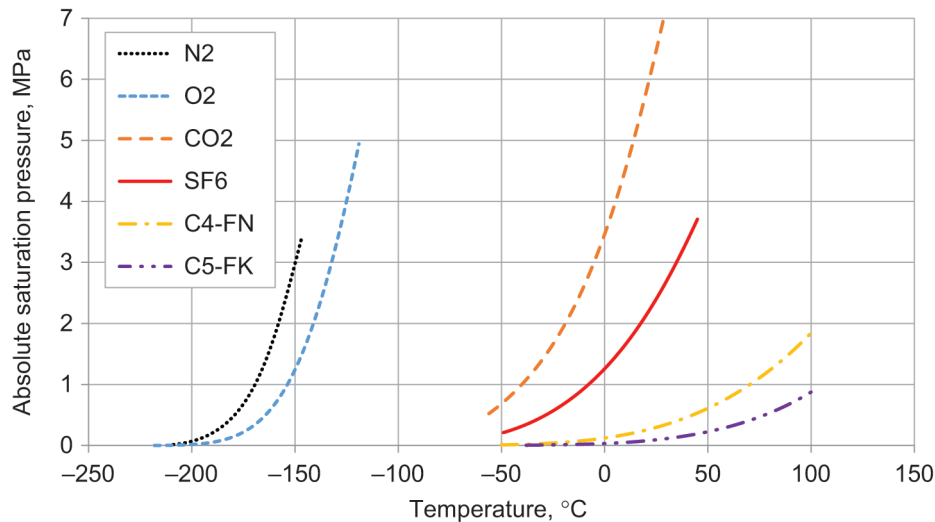


Figure 3—Saturation curves of various pure gases

Figure 3 illustrates saturation curves for several gases in their pure form. GIE relies on gas in the vapor phase to provide insulation and interruption performance. Therefore, the information in Figure 3 is one of the first steps to determine the suitability of SF₆-alternatives for service conditions such as low temperature. It should be noted that Figure 3 is only applicable to pure gases and does not consider the thermodynamic interactions of a gas mixture.

4.3 Gas mixture terminology

The composition of a mixture can be described in several ways. Mole fraction, volume fraction, partial pressure, and mass fraction are all valid terms with potentially different meanings and applications.

Mole fraction is the least ambiguous term since it is explicitly defined as the ratio of the number of moles of a substance to the total number of moles in the mixture as shown in Equation (2). The mole fraction of a mixture changes only by the ingress of external molecules or egress caused by imperfect tightness.

$$\text{mole fraction} = \frac{n_i}{\sum_i n_i} \quad (2)$$

where

n_i is the number of moles of component “i” of the mixture

Depending upon local thermodynamic conditions, the partial pressure and volume fraction of a mixture component is substantially identical to the mole fraction. If conditions favor ideal gas behavior (i.e., far from saturation) then the ideal gas law may be combined with Equation (2) to prove this equivalence as shown in Equation (3), Equation (4), and Equation (5).

$$PV = nRT \quad (3)$$

$$\text{mole fraction} = \frac{n_i}{\sum_i n_i} = \frac{\frac{PV_i}{RT}}{\sum_i \frac{PV_i}{RT}} = \frac{\frac{P}{RT} V_i}{\frac{P}{RT} \sum_i V_i} = \frac{V_i}{\sum_i V_i} = \text{volume fraction} \quad (4)$$

Similarly,

$$\text{mole fraction} = \frac{n_i}{\sum_i n_i} = \frac{\frac{P_i V}{RT}}{\sum_i \frac{P_i V}{RT}} = \frac{\frac{V}{RT} P_i}{\frac{V}{RT} \sum_i P_i} = \frac{P_i}{\sum_i P_i} = \text{partial pressure} \quad (5)$$

where

- P is absolute pressure
- V is volume
- R is the universal gas constant and
- T is the absolute temperature

Since these terms are commonly used during gas handling and analysis, the original equipment manufacturer should provide guidance for specific gas mixtures and the conditions under which the terms, “mole fraction,” “volume fraction,” and “partial pressure” may be used interchangeably with acceptable error.

Mass fraction is also derived from the mole fraction but is equivalent to neither volume fraction nor partial pressure. Equation (6) is used to calculate mass fraction. Mass fraction is used for evaluation of the global warming potential of a gas mixture as shown in 4.3.

$$\text{mass fraction} = \frac{n_i M_i}{\sum_i n_i M_i} \quad (6)$$

where

- M_i is the molecular mass of mixture component “i”

4.4 Ideal thermodynamic behavior of pure and mixed gases

4.4.1 Pure gases

A review of the thermodynamic behavior of pure gases such as SF₆ provides the foundation for later discussions of composition and condensation of non-ideal (real) gas mixtures. Figure 4 illustrates the thermodynamic behavior of pure SF₆ in the range of typical pressures and temperatures for outdoor applications. These data are taken from the National Institute of Standards and Technology (NIST) REFPROP database [B91]. The solid, “saturation curve” defines the boundary between the liquid and vapor phases of a pure substance. Since GIE relies upon media in the vapor phase for operation, the saturation curve should be known with good accuracy. Within the vapor phase, GIE operates along lines of constant density or, “isochores.” The dashed

lines of Figure 4 represent two possible isochores. Isochore A-B is the rated density and is defined by any combination of temperature and pressure along the isochore. Typically, +20 °C is the reference temperature and, in this case, would correspond to 0.7 MPa (absolute). Isochore C-D represents the minimum functional density for which the GIE will meet its intended ratings and is also expressed, for example, as 0.62 MPa (absolute) at +20 °C.

Throughout its service life, GIE can leak gas molecules causing a loss of gas density as illustrated by vertical arrow A-C. Alternatively, a reduction in temperature from A to B causes no gas density reduction until the saturation curve is encountered at B. As temperature is reduced below point B, the GIE follows B-D and some of the gas condenses to liquid, leading to a decrease in vapor phase density. With continued temperature drop, point D is eventually reached corresponding to the minimum functional density of the GIE at its minimum design temperature (−30 °C in this case). Note that while gas emissions and ambient temperature changes can produce variations in vapor phase density, the composition of the pure gas remains constant (100% SF₆).

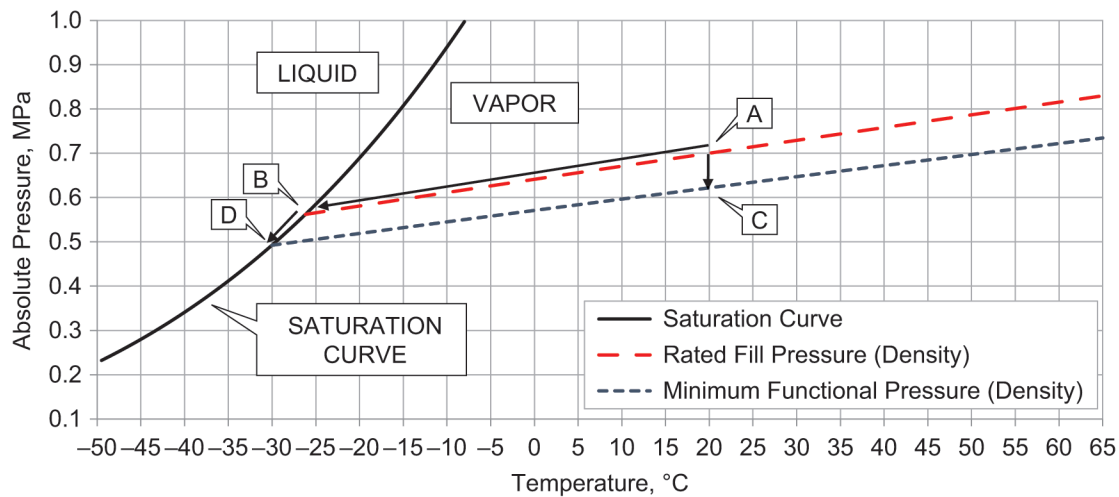


Figure 4—100% SF₆ Pressure versus temperature: typical isochores and saturation curve

Figure 4 illustrates the linear characteristic of pure gas isochores away from saturation (between points A and B). This characteristic is often referred to as ideal gas behavior since it can be accurately described by a simple linear equation such as the ideal gas law. Mixed gases can also exhibit ideal behavior as described in 4.4.2.

4.4.2 Mixed gases

Currently, no single gas is known to possess both the technical and environmental characteristics necessary to provide an economically practical replacement for SF₆. Therefore, gas mixtures are applied in order to take advantage of the individual features of each gas component. However, gas mixtures are thermodynamically more complex when quantifying the condensation (saturation) behavior. For example, the term “saturation curve” is replaced by “dew curve” when discussing gas mixtures. Molecularly similar components like N₂ and O₂ interact in an easily predictable and linear manner, allowing accurate prediction of the mixture dew curve using a simple mixture model such as Raoult’s Law. Raoult’s Law equates the ratio of vapor and liquid phase mole fractions of a mixture component to the ratio of component and total saturation pressure as shown in Equation (7).

$$\frac{y_i}{x_i} = \frac{P_i^*}{P^*} \quad (7)$$

where

y_i is the vapor phase mole fraction of component “i”
 x_i is the liquid phase mole fraction of component “i”
 P_i^* is the saturation pressure of component “i” and
 P^* is the saturation (dew point) pressure of the mixture

Taking the sum of all mixture components and recognizing that the sum of all liquid phase mole fractions is one leads to Equation (8).

$$\sum_i x_i = 1 = P^* \sum_i \frac{y_i}{P_i^*} \quad (8)$$

Solving Equation (8) for the mixture dew point pressure, P^* , yields Equation (9).

$$P^* = \frac{1}{\sum_i y_i / P_i^*} \quad (9)$$

Figure 5a illustrates the dew curve for a mixture of 80% N_2 and 20% O_2 calculated using both Equation (9) and the REFPROP database. Both dew curves have good agreement since this is a mixture of molecularly similar components.

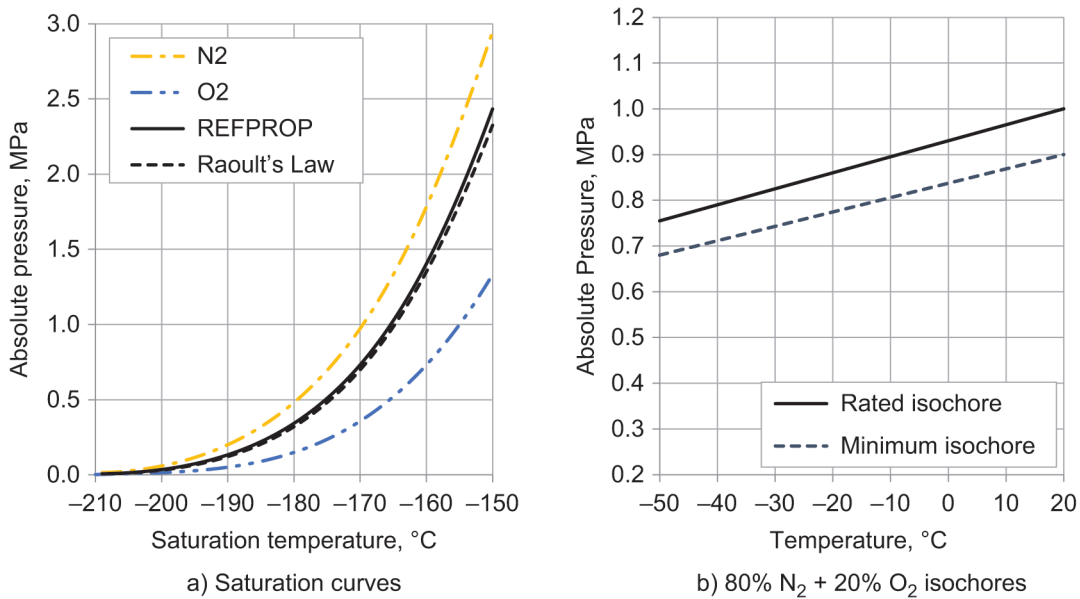


Figure 5—Ideal gas mixture saturation curves and isochores

An important observation from Figure 5b is that for any practical pressure scheme, the saturation temperature of this gas mixture is far below any actual service condition. Therefore, the gas mixture will not condense in service and can be treated as an ideal gas. On the other hand, if a gas or gas mixture is designed to condense in service, real gas behavior can be addressed as shown in 4.5.

4.5 Real thermodynamic behavior of pure and mixed gases

Real gas behavior departs from ideal behavior when the gas is saturated or when gas mixtures contain dissimilar molecules. If the equipment is using a gas mixture that can exhibit real gas behavior in service, then the real gas characteristics should be known because they could influence the equipment performance.

Mixtures of dissimilar molecules might not exhibit simple mixing behavior. In this case, more complex mixture models are required to accurately determine the dew curve. Figure 6a illustrates several notable features of such a gas mixture of 5% C₄-FN, 10% O₂, and 85% CO₂. First, the saturation curve is replaced by a region bounded by the bubble curve and the dew curve. This is known as the vapor liquid equilibrium (VLE) region. As the mixture moves from 100% liquid to VLE, the bubble curve defines the conditions for the formation of the first vapor bubble. Similarly, as the mixture moves from 100% vapor to VLE, the dew curve defines the conditions for the formation of the first liquid dew. Second, the Figure 6a isochore labeled 19.66 kg/m³ encounters the dew curve at approximately −23 °C (point B). If the gas mixture is cooled below −23 °C, it will enter the VLE rather than strictly following the dew curve as would a pure substance. The consequences are that both the vapor phase density and composition of the gas mixture are changing as the gas mixture moves along path B-C. This is caused by condensation of C₄-FN, CO₂ and O₂ in proportions that are significantly different than the vapor phase mixture. For example, in Figure 6a, the liquid condensate mole fractions are approximately 50% C₄-FN and 50% CO₂ with negligible amounts of O₂. Therefore, if GIE is designed to operate within the VLE, thermodynamic behavior should be known in order to determine both the vapor phase density and composition since the vapor phase is the only phase participating in the insulation and possibly the interruption performance.

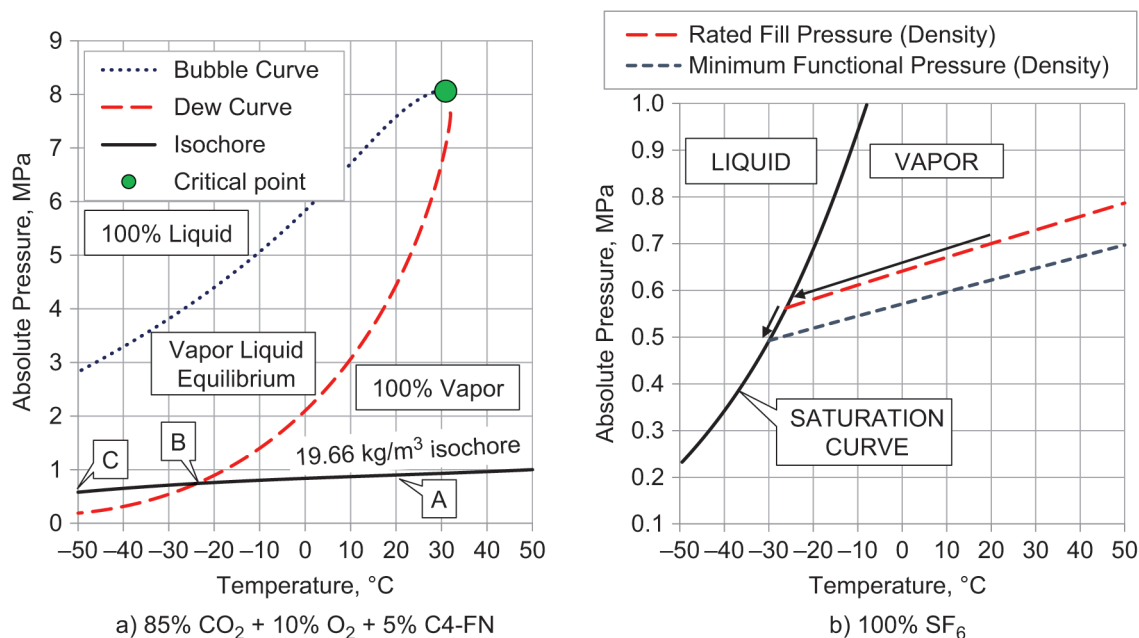


Figure 6—Pressure versus temperature phase plot for 5% C₄-FN, 10% O₂, 85% CO₂

If the gas mixture depicted in Figure 6a were applied at −30 °C service conditions, the thermodynamic behavior would no longer be strictly ideal due to partial condensation. Near the dew curve and within the VLE, the isochore is nonlinear. The same is true for pure gases near the saturation curve and when condensation occurs as shown in Figure 6b. Therefore, gases, and gas mixtures cannot be treated as ideal near the liquefaction conditions.

4.6 Gas composition and pressure for insulation and/or operation

Pure gases are completely defined by either their density or the pressure at a defined reference temperature (typically +20 °C). IEEE Std C37.100.1 [B56] uses terminology such as, “rated filling pressure (density) for insulation and/or operation” and “minimum functional pressure (density) for insulation and/or operation” as illustrated in Figure 7a. These terms are adequate for pure gases, but gas mixtures require a more complete description. Figure 7b and Figure 7c illustrate the equivalent proposed gas mixture terminology.

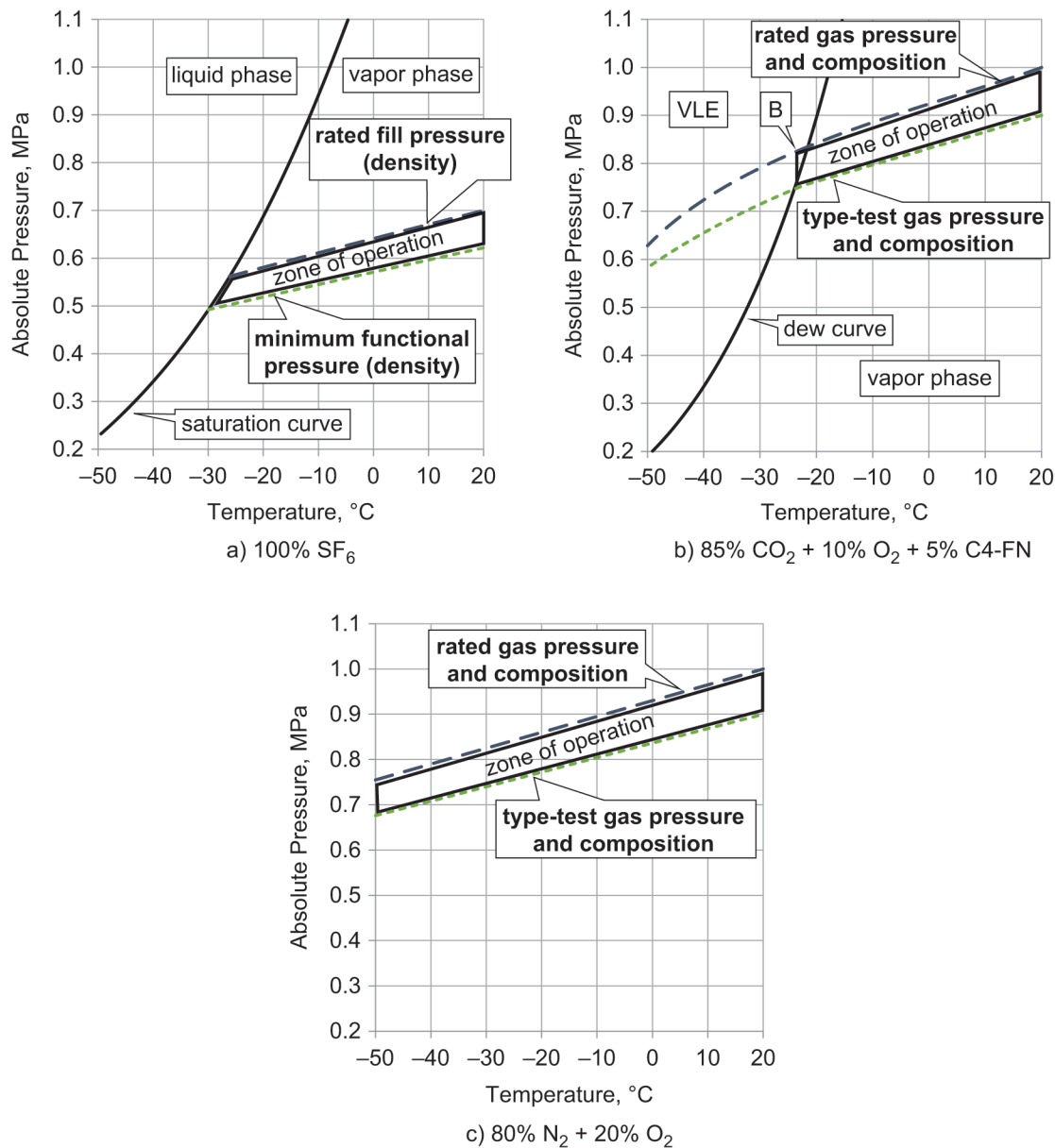


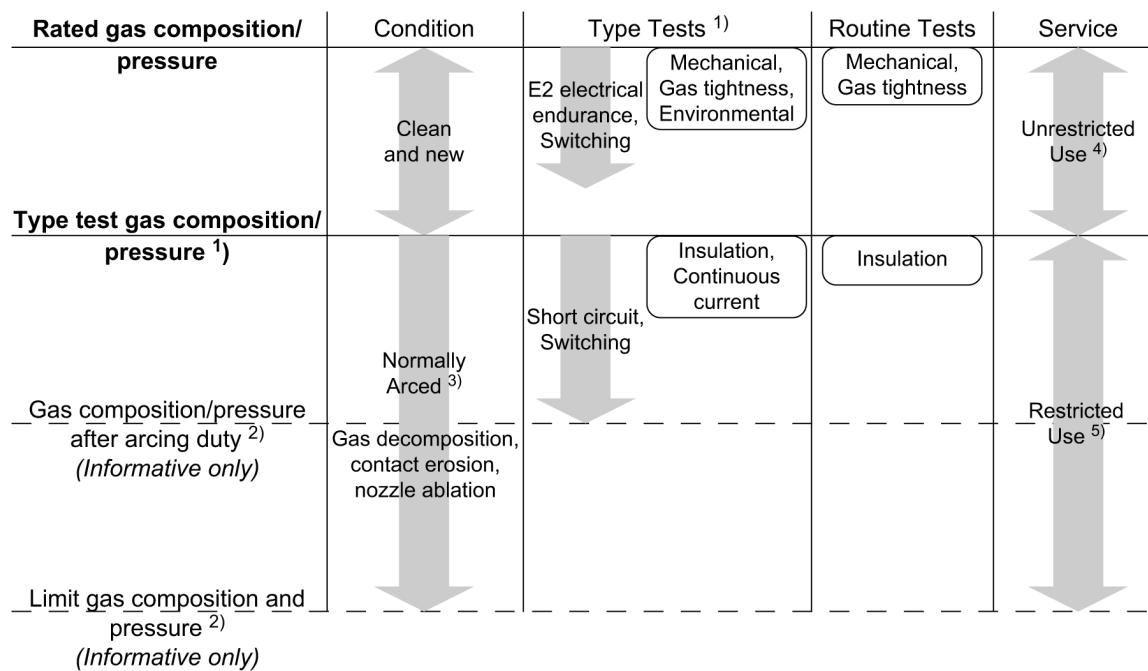
Figure 7—Pressure versus temperature phase plots

The terminology in Figure 7b and Figure 7c is adopted from CIGRÉ working group A3.41 (Technical Brochure 871 [B32]). It reflects the need to define both the pressure (at some reference temperature) and quantity of each component of the gas mixture. This can be done, for example, by defining the total pressure at +20 °C along with the mole fraction of each component. Alternatively, if the gas behavior is ideal, the mixture may be defined as the total pressure at +20 °C and each component partial pressure at +20 °C. In this way, the gas mixture definitions should specify both the quantity of each component and total pressure.

Note that in [Figure 7b](#) and [Figure 7c](#), the isochore defining the lower limit of the zone of operation no longer incorporates the phrase, “minimum functional” and is replaced by “type-test.” This was done to avoid the perception that the equipment ceases to function below the type test level. In fact, this isochore represents the clean and new condition at the start of most type test duties that demonstrate the rating.

[Figure 7b](#) illustrates another noteworthy aspect of gas mixtures. Point B represents the case in service where rated gas conditions exist (insignificant gas loss has occurred) and low temperature has caused the mixture to enter VLE. If this occurs, the vapor phase density and composition will change since some components will preferentially condense before others. Therefore, the manufacturer should confirm that the performance at point B is not limiting compared to that demonstrated by the type test composition and pressure at point A.

[Figure 7c](#) illustrates the case where the gas components and pressure scheme produce a mixture that never approaches the dew curve under any service condition. Liquefaction of the gas cannot occur in service. One unique aspect of this type of mixture is that if significant decomposition and non-uniform permeation are also absent in service (see [4.7](#) and [4.8](#)) then the mixture can be treated as a single gas during maintenance gas handling.



NOTE 1—Type tests normally begin at the “type test composition and pressure.” Duties that involve arcing then accumulate electrical wear concurrently as gas decomposition, contact erosion, and nozzle ablation.

NOTE 2—Gas composition at the conclusion and at the limit of an arcing duty are informative quantities that aid the manufacturer and user in the determination of electrical endurance in service.

NOTE 3—Normally arced equipment refers to short circuit and switching operations accumulated within the designated rating (excludes operations outside the rating and internal arc fault).

NOTE 4—Unrestricted use refers to the application of clean and new equipment within its rating and according to standards. Unrestricted application above the rated composition and pressure is also possible in accordance with the manufacturer’s instructions.

NOTE 5—Restricted use refers to the limited application of equipment after gas loss and/or electrical wear. Any equipment (SF₆ or non-SF₆) occupies this region after breaking operations leading to gas decomposition, contact erosion and nozzle ablation.

Figure 8—Overview of gas composition and pressure relative to test duties

Another way to view the proposed terminology is relative to test duties and the factors leading to changes in composition and/or pressure as illustrated in [Figure 8](#).

[Figure 8](#) only applies to gas interrupter technology. Sealed-for-life vacuum interrupters (VIs) do not incur gas decomposition during normal arcing, nor do they incorporate ablative nozzles. The terminology of gas composition and pressure at rated and type test levels, however, is still relevant if the insulation is composed of mixed gases.

In the case of a gas interrupter, [Figure 8](#) illustrates how gas composition and pressure relate to the condition of the equipment, type tests, routine tests, and operation in service. Most type tests start at the type test composition and pressure with equipment in the clean and new condition. Exceptions are some class C2 capacitive switching and class E2 electrical endurance test duties that start at the rated composition and pressure. Electrical wear that occurs during standard type tests and non-standard limit testing forms the basis for electrical wear limits in service. This is the case for SF₆ gas interrupter technology and continues to be the case for non-SF₆ gas interrupter technologies.

4.7 Electrical wear and gas decomposition

4.7.1 Gas decomposition overview

In the presence of an electrical arc, the molecules of gaseous dielectrics decompose and might not recombine to their original molecule, potentially leading to a reduction of performance. The rate of such decomposition is typically expressed in mol/MJ as shown in [Table 5](#).

Table 5—Decomposition rates of pure gases and gas mixtures

Gas	Decomposition rate (mol/MJ)	References
100% SF ₆	0.1 to 0.8	[B23]
100% CO ₂	0.80	[B110]
70% CO ₂ + 30% O ₂	0.01 to 0.03	[B110]
3%–5% C4-FN + 6%–13% O ₂ + 83%–89% CO ₂	0.24 to 0.42	[B22], [B39], [B93]
5.7% C5-FK + 11.4% O ₂ + 82.9% CO ₂	≤ 0.50	[B87]

Gas decomposition due to arcing is not a new phenomenon. [Table 5](#) indicates that SF₆ is known to decompose into, for example, lower fluoride compounds, metal fluorides, and other byproducts such as HF and SOF₂. However, even significant decomposition of SF₆ might have a negligible effect on performance characteristics, such as gaseous dielectric strength as shown in reference [B23].

Gas mixtures incorporating a relatively small mole fraction of C4-FN or C5-FK merit further consideration since, as the primary dielectric component, decomposition can have a large influence on performance characteristics. The range of decomposition rates reported for C4-FN and C5-FK in [Table 5](#) is due to the wide range of arc energy imposed upon the gas and the extent to which various designs permit decomposition.

Public data is available that illustrates how initial gas mixture composition, its subsequent decomposition and changes in pressure influence an important performance characteristic, such as dielectric strength. [Figure 9](#) is an example gas mixture of C4-FN in CO₂ and O₂, where points A and B are the mole fraction of C4-FN at the start of type tests and service respectively (both 3.5% in this case). The normalized dielectric performance data illustrated in [Figure 9](#) is based on uniform field 50 Hz power frequency tests reported in CIGRÉ technical brochure 849.

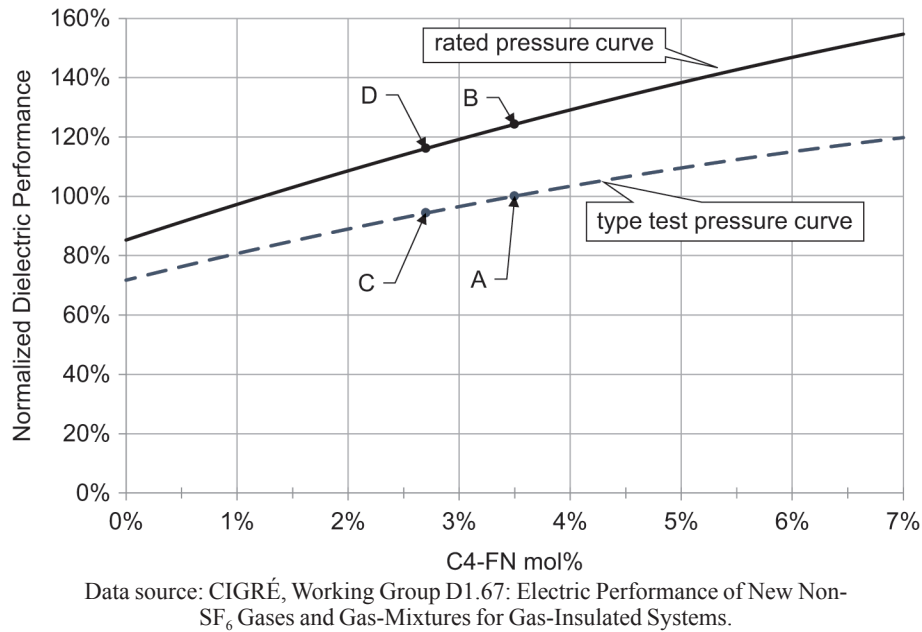


Figure 9—Normalized dielectric performance versus C4-FN mole fraction

With accumulated electrical wear during the type test, decomposition causes the gas mixture to move along the type test pressure curve from point A to point C. Similarly, accumulated electrical wear in service causes the gas mixture to move from point B to point D. On the other hand, gas loss via leakage would cause vertical movement to intermediate pressure curves between rated and type test. This behavior is especially important for decomposition of the primary dielectric component of a gas mixture where a relatively small mole fraction provides a large portion of the dielectric strength.

Therefore, power testing does induce electrical wear in the form of gas decomposition, contact erosion and nozzle ablation when the arc is quenched in the gas. [Clause 7](#) discusses decomposition and other SF₆-alternative phenomena in the context of both interruption and switching. Contact erosion and nozzle ablation are other modes of electrical wear which are heavily influenced by the circuit breaker design. An example is given below.

4.7.2 Gas interrupter electrical wear example

Consider a 63 kA test object with a 200 L or 400 L gas volume, a rated pressure of 1.0 MPa (absolute), and a starting mole fraction of 3.5% C4-FN. The duty under consideration is 90% short line fault (SLF L90, 57 kA) with average arcing time 14 ms. The goal is to consider each electrical wear mechanism encountered during successive L90 interruptions and quantify its influence on the remaining electrical life of the equipment. In doing so, the importance of test object volume as it relates to electrical life will be revealed.

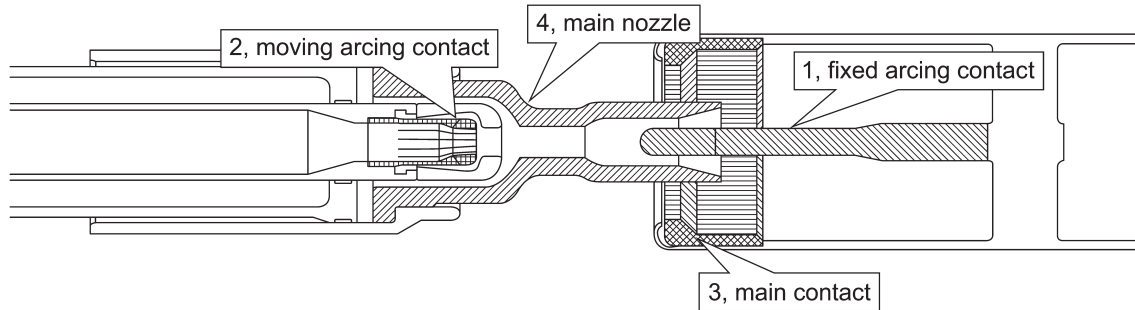


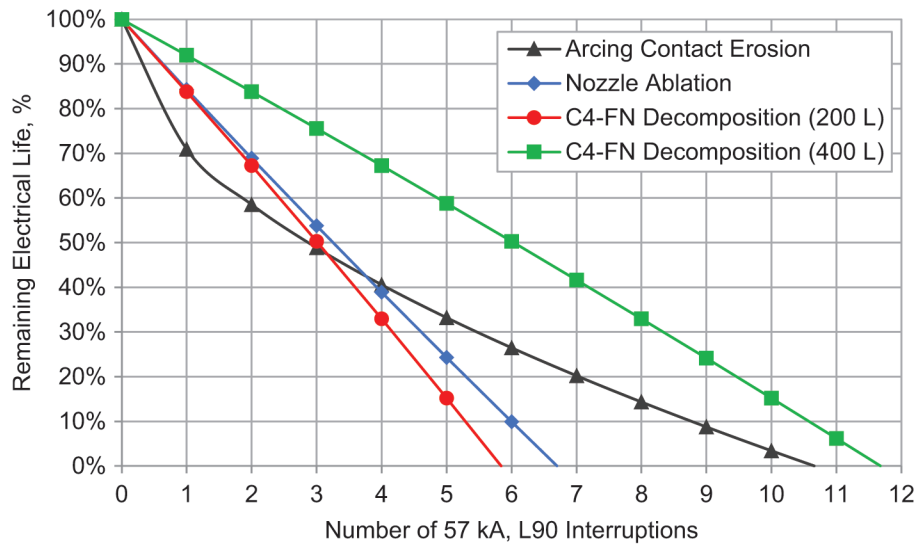
Figure 10—Gas circuit breaker interrupter (open position)

Gas circuit breaker arcing contact erosion is perhaps one of the original indicators of electrical wear as reported in reference [B101]. Despite the use of refractory metals such as tungsten combined with copper, the arcing contact will erode in the presence of a high temperature plasma arc. Figure 10 illustrates typical fixed and moving arcing contacts. For the purposes of this example, erosion of the fixed arcing contact is modeled as progressive flattening of an initially hemispherical tip. This model is slightly more conservative than uniform erosion because while the volumetric erosion rate is constant, first interruptions produce greater axial erosion due to the geometry of the tip. It is also a more accurate reflection of the actual behavior observed in service. The initial contact diameter is 25 mm, volumetric erosion rate is assumed to be $0.1 \text{ cm}^3/\text{kA-s}$ [B99] and the erosion limit is 5 mm in the axial direction. This erosion limit is a reasonable value based upon the need for both coordination of electrical stress between the fixed arcing and main contacts as well as sufficient time for the commutation of fault current from main to arcing contacts.

Nozzle ablation is a normal and necessary part of gas circuit breaker electrical wear. The PTFE vapor liberated by the arc from the solid nozzle is a significant contributor to pressure build up in the interrupter. However, as ablation increases the main nozzle throat diameter, thermal interruption performance will decrease until, eventually, the equipment is no longer able to meet its rating. In this example, the initial nozzle diameter is 29 mm, throat length 35 mm, and open gap length 150 mm. The PTFE density is 2.2 g/cm^3 and the ablation rate is assumed 17 g PTFE/MJ [B32]. The limit throat area is assumed to be 25% greater than the initial throat area, leading to a limit throat diameter of 32.4 mm.

Finally, decomposition of the low mole fraction, high dielectric strength component, C4-FN, is considered as the third mechanism of electrical wear. The decomposition rate is assumed to be 0.4 moles/MJ and the limit of dielectric strength reduction is assumed to be 10% for this example. A design with more or less dielectric margin would tolerate more or less C4-FN decomposition respectively.

The results are expressed graphically in Figure 11 as the remaining electrical life for each electrical wear mechanism. The clean and new condition is represented by zero interruptions and 100% remaining electrical life. As 90% short line fault interruptions are accumulated, the remaining electrical life of each wear mechanism decreases as shown in Figure 11. Arcing contact erosion and nozzle ablation occur independently of the volume of gas. However, recognize that in this example the test object gas volume will determine whether decomposition of C4-FN is the limiting mechanism of electrical wear. The test object with a 200-L gas volume will first reach the end of its electrical life by gas decomposition whereas the 400-L test object is limited by nozzle ablation. Therefore, type test objects should have the minimum gas volume of any design variant used in service.



NOTE—This example illustrates the influence of gas volume on the electrical life of the equipment. It is not intended to reflect expected, required, or recommended electrical life when non-SF₆ gas mixtures are used for interruption and insulation.

Figure 11—Remaining electrical life versus number of 90% SLF interruptions

4.8 Gas tightness testing

Gas tightness is a generalized term used to encompass the effects of both gas leakage and gas permeation from equipment to the atmosphere. No enclosure is perfectly gas tight if there exists a pressure or concentration gradient across the enclosure envelope. Therefore, the goal of the equipment supplier is to produce an acceptable level of gas tightness for the applicable service conditions, and to be able to validate the gas tightness by design and routine tests.

Gas leakage mainly refers to the viscous flow of gas through small pathways in the equipment envelope. While small, these pathways are large compared to the mean free path of the molecules that make up the gas or gas mixture. Therefore, for major leaks and viscous flows, negligible change in the composition of a gas mixture occurs—only a reduction of pressure. Leakage is influenced mainly by the viscosity and density of the gas, the pressure across the enclosure, and the size of the leak pathway(s). Some common examples of leak pathways are imperfections in a metal enclosure such as interconnected porosity, weld defects and imperfections in sealing surfaces such as scratches and foreign objects. In addition to viscous gas flow leaks, depending upon density, molecular gas flow can also exist. However, this type of gas leak normally exhibits leakage rates far below the levels of interest and therefore may be neglected.

Permeation is the diffusion of molecules across a solid barrier, driven by a concentration gradient. Permeation of a gas mixture can lead to an inhomogeneous or non-uniform change in composition over time. A typical example is the permeation of an insulating gas from inside the equipment, across a solid elastomeric seal and into the environment. Another is the permeation of water vapor from the environment, across the seal and into the equipment. Permeation is dependent upon several factors, including the permeability of the gas molecule in the solid, the concentration gradient of the gas across the solid, the temperature of the system and other design factors such as seal dimension and compression. Some gases exhibit higher permeability rates than others. Therefore, over time, the composition of a gas mixture might change when there is a significant difference in the permeation rates of its components.

The purpose of this subclause is to consider leakage and permeation of SF₆-alternatives compared to SF₆. Test methods for gas tightness are reviewed and finally an example is presented to quantify the influence of non-uniform permeation on gas tightness in service.

4.8.1 Vacuum integrity

Vacuum interrupters are sealed-for-life devices. Including accessories for the direct measurement of vacuum level can significantly reduce the overall reliability of the vacuum interrupter. Therefore, vacuum integrity is not practical to determine by direct measurement. Instead, vacuum integrity can be determined indirectly with some caveats depending upon the test situation.

The validity of vacuum integrity tests comes into question when a vacuum interrupter is applied within a gaseous dielectric other than ambient air. The integrity test can be defeated, for example, if a gaseous dielectric were to leak into the vacuum interrupter and enable a compromised test object to pass a voltage withstand test. To address this possibility, short circuit interruption tests that require a post-test condition check incorporate a 10% breaking test into the duty sequence. However, this is not practical for tests performed outside the high-power laboratory such as mechanical endurance and environmental type tests. Instead, the following options are proposed:

- a) After mechanical endurance and environmental tests, 80% of the rated power frequency voltage is applied as a condition check. A reduced contact gap is proposed to eliminate the possibility of a gaseous dielectric contaminant. A vacuum contact gap not more than 25% of the normal open gap has been proposed in CIGRÉ technical brochure 589 [B28].
- b) In addition to the power frequency voltage condition check, the vacuum interrupter contact force is measured before and after both mechanical endurance and environmental tests and compared to the contact force limit criteria defined by the VI manufacturer. This option requires removal of the VI from the assembly after all other tests, checks, and inspections are completed.
- c) In addition to the power frequency voltage condition check, the vacuum interrupter arc voltage is measured and compared before (baseline) and after both mechanical endurance and environmental tests. In this option, the VI interrupts approximately tens of amperes at hundreds of volts being provided by an ac power supply. The VI manufacturer defines the arc voltage limit criteria.

For any of the proposed options, the results of vacuum integrity checks should be part of the type test report.

4.8.2 Gas tightness development tests, step 1: material suitability

Material permeation tests exist to determine the permeation behavior of a material and gas system. Standardized material tests such as ASTM E2945–14 [B16] and DIN 53536 [B34] employ sheet stock samples and apply a concentration difference of the test gas across the specimen to measure the permeability over time. Testing with different gases, starting concentrations and temperatures characterizes the permeation for a wide range of conditions. These tests are a first step to determine the permeation behavior of a system composed of insulating gas, gas mixture and seal material. Systems that exhibit acceptable permeation behavior in these tests are candidates to move to step 2 development tests.

4.8.3 Gas tightness development tests, step 2: application suitability

Standardized permeation tests using sheet stock specimens might not correlate directly to the performance of o-ring seals in GIE service because of differences in geometry, compression, etc. In this case, a second type of development test using the actual seal system geometry can be designed. All material, geometry and assembly parameters are incorporated into a subscale test along with variables such as temperature and pressure. Another benefit of the step 2 permeation test is the establishment of a diffusion time constant specifically for the sealing system. The time constant is used to determine the time required to reach steady state permeation and therefore the time required for preconditioning of the actual test object during subsequent gas tightness type tests.

4.8.4 Gas tightness type tests

The purpose of the gas tightness type test is to validate the actual equipment design relative to the prescribed tightness limits. IEEE Std C37.20.9 [B61], IEEE Std C37.100.1 [B56], and IEEE Std C37.09 [B55] refer to IEC 60068-2-17 [B45] for gas tightness test methods. Of these, the tracer gas sealing test (test Q_m) might be the most appropriate to determine the gas tightness of switching equipment designs. With a few accommodations, test Q_m is applicable to both SF₆ and SF₆-alternative equipment.

In test Q_m , the test object is filled with a test gas at test pressure, allowed to stabilize for a time and then placed in a sealed enclosure where the increased concentration of the test gas is measured over a time interval. An advantage of this test procedure is flexibility. For example, variations in test gas, tracer gas and test pressure can be accounted for and converted to a leak rate in service. The procedure can also be applied over a range of temperatures, open and closed contact positions and with operations. This test quantifies overall gas tightness for the equipment including permeation if the test duration is sufficient for permeation to reach steady state at the test temperature. However, it does not locate or quantify individual leaks and it does not distinguish between leakage and permeation.

During test Q_m , leaked SF₆ concentration in an air-filled test enclosure is easily measured and converted to a leak rate if the initial background concentration of SF₆ in the test enclosure is negligible. The same is true for alternative mixtures that incorporate a fluorinated component, such as C4-FN or C5-FK. Natural origin mixtures of CO₂ and O₂ can use CO₂ as the tracer gas. In this case, the background concentration of CO₂ in ambient air (approximately 400 ppmv) should be accounted for when establishing the baseline measurement at the start of testing. Natural origin mixtures of N₂ and O₂ (technical air) require an added tracer gas since the test enclosure is also air-filled. Appropriate tracer gas options are helium, CO₂, and ozone [B85]. The influence on measured gas tightness by the addition of any tracer gas should be considered relative to the actual gas in service.

4.8.5 Gas tightness routine (production) tests

The purpose of the routine gas tightness test is to validate a production unit relative to the prescribed tightness limits. It should filter out manufacturing and assembly errors leading to unacceptable gas tightness. The routine tightness test is not intended to quantify permeation since this is already done during type tests. Therefore, routine tightness tests can have significantly shorter duration than type tests. IEC 60068-2-17 test method Q_m , with accommodations for the different tracer gases as mentioned in 4.8.4, is still applicable for routine tightness tests. Alternatively, test method Q_k can be applied to further reduce the test time. Test method Q_k is identical to test method Q_m except that the surrounding enclosure is evacuated, leading to a reduction in the time required to establish a stable tightness value. In either case, accommodations for background CO₂ concentration and/or added tracer gases can be used with existing test procedures to quantify the gas tightness of alternative gas mixtures.

4.8.6 Non-uniform gas permeation example

The following example illustrates how differences in permeation behavior can affect a gas mixture over time. Ideal gas behavior is assumed along with a constant temperature of +20 °C. Gas mixture one has 1.0 MPa absolute pressure and 90% CO₂, 5% O₂ and 5% C4-FN rated mole fractions, respectively. Gas mixture two has the same total pressure with 80% CO₂ and 20% O₂. A butyl seal compound is assumed where CO₂ permeates 21 times faster than C4-FN and O₂ permeates 4.2 times faster than C4-FN [B32]. All mass lost from a 100-L gas volume is conservatively assumed to be due to only permeation at a rate of 0.5% per year. An alarm occurs at 9.5 MPa-abs, +20 °C and type test pressure is reached at 9.0 MPa-abs, +20 °C.

Table 6—Example of gas composition evolution due to non-uniform permeation only

Pressure	Gas mixture 1 mole fraction (%)			Gas mixture 2 mole fraction (%)	
	CO ₂	O ₂	C4-FN	CO ₂	O ₂
Rated	80.0	16.5	3.5	80.0	20.0
Alarm	79.1	17.2	3.7	79.1	20.9
Type test	78.2	17.9	3.9	78.1	21.9

The results shown in Table 6 are produced by an extreme model where all gas mass lost from the equipment is by non-uniform permeation and none by uniform leakage. Additionally, although non-uniform permeation is considered, decomposition of the primary insulating component is excluded from this model. Clause 7 explores this more fully. This example shows gas mixture composition changes if pressure were to decrease to the type test pressure by permeation alone. For gas mixture one, since the primary dielectric component has the lowest permeation rate in this example, the mole fraction of C4-FN increases over time as pressure decreases. The net effect of this type of behavior is shown in Figure 12a where the type test pressure is reached via path A. C4-FN concentration has increased and the remaining gas mixture has greater dielectric strength than was demonstrated during type tests. Gas mixture two exhibits similar behavior, but to a lesser degree than gas mixture one. The other limiting case is when all mass is lost by uniform leakage, Figure 12a and Figure 12b, vertical path B. When this occurs, the gas composition does not change, and the gas mixture lands on the type test pressure curve at the same composition as the starting point. The reality of actual mass loss in service would lie somewhere between the path A and B extremes (combination of leakage and permeation).

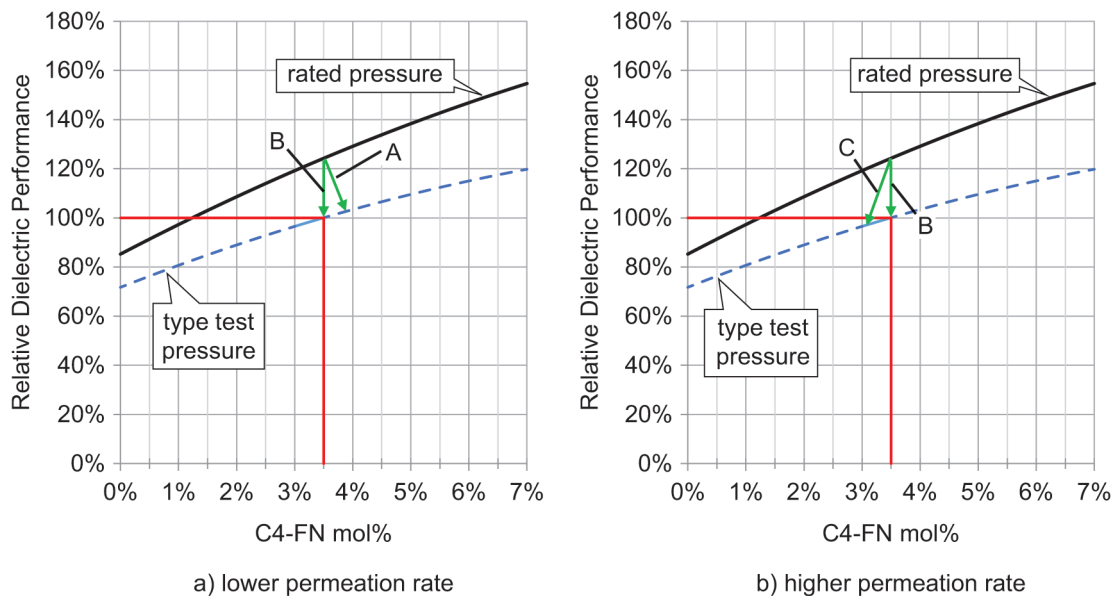


Figure 12—Influence of relative permeation rate of the primary dielectric component in a gas mixture

Figure 12b illustrates the potentially undesirable case where permeation of the primary dielectric component is higher than the other components, leading to path C. This type of behavior requires the OEM to decrease the type test composition to account for such non-uniform permeation in service.

In summary, management of non-uniform permeation in service is possible when the OEM has determined the permeation behavior of the seal system by material development tests over the range of service conditions.

Special attention should be given to seal replacement in service since only the use of qualified materials and sources lead to predictable permeation behavior.

5. Environmental performance

5.1 Introduction and guidance

Table 7 summarizes the guidance related to environmental performance.

Table 7—Summary of guidance related to environmental performance

Item	Guidance
General	Throughout ongoing efforts to reduce or replace SF ₆ gas, emissions reduction of high GWP gases should continue for the entire life cycle of the equipment.
Global Warming Potential	The environmental assessment of electrical equipment can be done by calculating the Global Warming Potential (GWP), calculating the carbon footprint, and conducting an environmental life cycle assessment (LCA).
	GWP of the insulating gas is a convenient and popular indicator of environmental performance. However, as a single parameter, GWP alone is insufficient to quantify total environmental performance of a design over its lifetime. Refer to 5.2 for details.
Carbon footprint	Carbon footprint as an intermediate methodology between GWP and life cycle assessment (LCA) is discussed in 5.3. A carbon footprint evaluation considers the life cycle environmental impact but only relative to carbon equivalency. The results are dependent upon evolving inputs that should be updated periodically and clearly reported along with the results.
Environmental Life Cycle Assessment	Environmental LCA is the most comprehensive study of the entire life cycle of the equipment. In addition to the effects of carbon emissions, several other environmental performance indicators are evaluated as shown in 5.4. As with any life cycle approach, the possibility of evolving inputs should be addressed by reporting those inputs along with the results and providing periodic updates as required.
	IEC TS 62271-320, High-voltage switchgear and controlgear—Part 320: Environmental aspects and life cycle assessment rules is currently under development and expected to be published in 2024. This technical specification is intended to provide guidance for the standardized execution of environmental LCA calculations on high voltage switchgear and controlgear.
	Today, multi-criteria LCA results do not have agreed upon weighting for the individual criteria. This is an opportunity for future improvement with potential benefits for all stakeholders. See 5.4.

SF₆ has been an essential part of Transmission and Distribution equipment, including switchgear for system voltages of 800 kV or higher.

SF₆ has a proven track record in the electric power industry dating to the 1960s. Its advantages are well understood and documented both in industry and academia. Its excellent dielectric, heat transfer, and arc quenching properties contribute to making switchgear smaller, lighter, more cost effective, and more reliable. Its nontoxic (in a pure state), nonflammable and noncorrosive properties allow for ease of installation and ease of handling. Being chemically stable with high breakdown strengths, SF₆ molecules provide excellent arc extinction which reduces contact wear and switchgear maintenance. Also, it is chemically inert up to 150 °C and will not react with metals, plastics, gaskets, and other materials which are commonly used in switchgear.

Despite the technical advantages of SF₆ there is one major shortcoming—its high global warming potential and subsequent environmental impact. The awareness of environmental aspects has been significantly increasing in the last two decades, especially after the Kyoto Protocol identified SF₆ as one of six greenhouse gases in 1997. Some of the same properties that make SF₆ a great gas for the electrical industry also contribute to its extremely high Global Warming Potential (GWP)—namely its long atmospheric lifetime and high absorption potential.

The electrical industry has been attempting to decrease SF₆ emissions for decades, even before the Kyoto protocol. Initially the effort was on reducing emissions from SF₆ switchgear through the whole lifecycle of the product. Later the focus has shifted to searching for alternative solutions to SF₆.

5.2 Global warming potential

5.2.1 Global warming potential of pure substances

The global warming potential (GWP) is an index that provides a relative measure of the possible climate impact due to the presence of a compound that acts as a greenhouse gas in the atmosphere. Greenhouse gases are those compounds that have measurable atmospheric lifetimes and absorb infrared radiation (IR), particularly within the range of wavelengths that are transparent in the natural atmosphere (around 8 to 14 μm). The GWP for a compound has been defined by the Intergovernmental Panel on Climate Change (IPCC, [B66]). It is calculated as the integrated change in energy flux through the earth's atmosphere due to the release of a mass of that compound relative to the change due to an equal mass of CO₂ over a specified time period as shown in Equation (10).

$$GWP_x = \frac{\int_0^{ITH} RF_x(t) dt}{\int_0^{ITH} RF_{CO_2}(t) dt} \quad (10)$$

where

ITH is the integrated time horizon

RF is the radiative forcing per unit mass of a compound (the change in the flux of radiation through the atmosphere due to the infra-red absorbance of the compound)

t is time

x is the compound of interest

The commonly accepted integrated time horizon (ITH) is 100 years representing a compromise between short-term effects (20 years) and longer-term effects (500 years or longer). As a result, GWP values reported in the literature can assume to be calculated using a 100-year ITH unless stated otherwise. The concentration of most compounds emitted to the atmosphere follows pseudo first order kinetics (i.e., exponential decay). The concentration of CO₂ over that same time interval incorporates a more complex model for the exchange and removal of CO₂ from the atmosphere via the carbon cycle.

A GWP value of 10 indicates that the compound has 10 times the impact of CO₂ over that time horizon. A physical interpretation of this is that a release of 1 kg of that compound has an impact equivalent to 10 kg of CO₂.

The GWP values calculated by the method outlined in IPCC assessment reports for SF₆ and several pure alternative gases are given in Table 8.

Table 8—Atmospheric lifetime and 100-year GWP of several relevant pure substances

Compound	Atmospheric lifetime (years)	100-year GWP (See NOTE 1)
SF ₆	3200	22 200 to 25 200
C4-FN	30	2090 to 2750
CO ₂	-	1
O ₂	-	-
N ₂	-	-
CF ₃ CH = CHF (HFO-1234zeE)	0.04	< 1

Table continues