IEEE Std C37.122.1-1993(R2002)
(Revision of IEEE Std C37.122-1983)

IEEE Guide for Gas-Insulated Substations

Sponsor
Substations Committee
of the
IEEE Power Engineering Society

Reaffirmed June 12, 2002
Approved December 2, 1993
IEEE Standards Board

Abstract: The technical requirements for the design, fabrication, testing, and installation of a gas-insulated substation (GIS) are covered. Parameters to be supplied by the purchaser are suggested, and technical requirements for the design, fabrication, testing, and installation to be furnished by the manufacturer are established.
Keywords: gas-insulated substation, GIS, GIS design, GIS equipment, GIS installation, GIS testing, SF_6, sulfur hexafluoride

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA.

ISBN 1-55937-402-0

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

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. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, 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.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

IEEE standards documents may involve the use of patented technology. Their approval by the Institute of Electrical and Electronics Engineers does not mean that using such technology for the purpose of conforming to such standards is authorized by the patent owner. It is the obligation of the user of such technology to obtain all necessary permissions.

Introduction

(This introduction is not a part of IEEE Std C37.122.1-1993, IEEE Guide for Gas-Insulated Substations.)

IEEE Std C37.122-1983 was initiated in the early 1970s when the first gas-insulated substations (GIS) were introduced. Approved in 1983, it contains standards, recommended practices, and guides. Circumstances beyond the control of the responsible Technical Committees delayed its availability to users until late 1988. Simultaneous to its publication, the Gas-Insulated Substations Subcommittee of the IEEE Power Engineering Society (PES) Substations Committee began work on the necessary update, revision, and expansion of the document.

The reliability of GIS has improved greatly since the first installation in the late 1960s. Utilities have taken advantage of the greater flexibility offered by GIS to locate substations closer to load centers with considerable savings in subtransmission systems. In addition, GIS typically offers 20 years or more of operation before major overhaul is required.

During the Working Group and Subcommittee deliberations on the update, it was recognized that users would be better served if the original document were divided in two, becoming IEEE Std C37.122-1993 (a standard) and IEEE Std C37.122.1-1993 (a guide). The two documents can be referred to individually or jointly depending on the purpose of the referral.

Although all Working Groups of the Gas-Insulated Substations Subcommittee contributed to this revision, the prime responsibility belonged to Working Group K2, Revision of IEEE Std C37.122-1983 , which approved this guide. At the time this guide was completed, Working Group K2 had the following membership:

A. A. Leibold, *Chair*

B. Becer	J. E. Holladay	P. R. Nannery
H. D. Bennett	C. Hurty	J. Nash
S. Boggs	R. A. Jones	K. Pettersson
P. C. Bolin	E. B. Khalafalla	J. F. Quinata
R. E. Carberry	L. M. Laskowski	J. Sabath
D. Charbonnet	R. Matulic	B. Sojka
J. M. Delcoustal	A. Mickevicius	H. Thakar
E. I. Hahn	K. B. Miners	N. G. Trinh

The Gas-Insulated Substations Subcommittee of the IEEE PES Substations Committee that reviewed and approved this guide had the following membership:

R. Matulic, *Chair*
J. F. Quinata, *Vice Chair*

A. Arora	J. Grzan	P. R. Nannery
B. Becer	E. I. Hahn	J. Nash
H. D. Bennett	J. E. Holladay	E. V. Olavarria
S. Boggs	C. Hurty	K. Pettersson
P. C. Bolin	G. M. Ihle	D. J. Poole
J. Buchsbaum	R. Jones	M. W. Randall
R. E. Carberry	E. B. Khalafalla	J. Sabath
D. Charbonnet	L. M. Laskowski	B. Sojka
J. L. Charney	A. A. Leibold	R. C. St. Clair
F. Y. Chu	K. E. Lewis	H. Thakar
T. F. Clark	J. Luiz	N. G. Trinh
J. M. Delcoustal	A. Mickevicius	R. Verma
H. R. Gilden	C. S. Miller	J. A. Yoder
	K. B. Miners	

The following persons were on the Substations Committee of the IEEE Power Engineering Society that approved this guide for submission to the IEEE Standards Board:

M. L. Holm, *Chair*
J. B. Cannon, *Vice Chair*
A. E. Kollar, *Secretary*

W. J. Ackerman
B. Y. Afshar
S. J. Arnot
A. C. Baker
N. Barbeito
G. J. Bartok
B. Becer
K. M. Bevins
M. J. Bio
K. L. Black
C. J. Blattner
W. R. Block
S. Boggs
P. C. Bolin
S. D. Brown
J. C. Burke
R. E. Carberry
D. Charbonnet
F. Y. Chu
J. R. Clayton
R. G. Cottrell
E. F. Counsel
W. K. Daily
F. A. Denbrock
C. C. Diemond
W. B. Dietzman
T. L. Doern
C. Durand
L. N. Ferguson
G. G. Flaig
D. L. Garrett
J. Grzan
D. L. Harris
J. E. Holladay
Z. Kapelina
R. P. Keil
F. F. Kluge
D. F. Koenig
T. J. Kolenda
T. L. Krummrey
L. W. Kurtz, Jr.
D. N. Laird
L. M. Laskowski
A. A. Leibold
C. T. Lindeberg
H. P. Lips
R. Matulic
J. D. McDonald
T. S. McLenahan
A. P. S. Meliopoulos
P. R. Nannery
R. S. Nowell
E. V. Olavarria
J. T. Orrell
J. Oswald
S. G. Patel
R. J. Perina
K. Pettersson
J. F. Quinata
D. G. Rishworth
B. D. Russell
J. Sabath
F. C. Shainauskas
B. Sojka
R. C. St. Clair
W. K. Switzer
E. R. Taylor
H. Thakar
C. F. Todd
D. R. Torgerson
L. F. Volf
R. J. Wehling
R. M. Youngs

The accredited Standards Committee on Power Switchgear, C37, that reviewed and approved this guide had the following members at the time of approval:

E. Byron, *Chair*
M. Williams, *Secretary*
M. Calwise *(Program Administrator)*
A. K. McCabe *(Executive Vice-Chair of High-Voltage Switchgear Standards)*
(vacant) *(Executive Vice-Chair of Low-Voltage Switchgear Standards)*
D. L. Swindler *(Executive Vice-Chair of IEC Activities)*

Organization Represented	***Name of Representative***
Association of Iron and Steel Engineers	(vacant)
Electric Light and Power Group	M. C. Mingoia D. J. Borchart T. E. Bruck J. H. Provanzana J. D. Stewart G. R. Brandenberger (*Alt.*) A. K. McCabe (*Alt.*)
Institute of Electrical and Electronics Engineers	D. F. Peelo L. B. Beard H. L. Bowles P. W. Dwyer D. Signon S. C. Atkinson (*Alt.*) D. G. Kumbera (*Alt.*) L. V. McCall (*Alt.*)
Laubach Associates	W. Laubach
National Electrical Manufacturers Association	R. Garzon G. Haynes W. Kracht H. L. Miller T. Olson E. Byron (*Alt.*) G. T. Jones (*Alt.*) G. Sakats (*Alt.*) S. Stone (*Alt.*) D. L. Swindler (*Alt.*)
Tennessee Valley Authority	D. N. Reynolds
Testing Laboratory Group	L. Frier W. T. O'Grady
U.S. Department of the Army, Office of the Chief of Engineers	J. A. Gilson
U.S. Department of the Interior, Bureau of Reclamation	R. Arnold
U.S. Department of the Navy, Naval Construction Battalion Center	R. L. Clark
Western Area Power Administration	G. D. Birney

The following persons were on the balloting committee:

A. Arora	E. I. Hahn	K. B. Miners
B. Becer	J. E. Holladay	P. R. Nannery
M. D. Bennett	C. Hurty	J. Nash
S. A. Boggs	R. Janezic	E. V. Olavarria
P. C. Bolin	R. Jones	K. G. Petterson
J. A. Buchsbaum	Z. Kapelina	D. J. Poole
J. C. Burke	E. B. Khalafalla	J. Quinata
R. E. Carberry	L. M. Laskowski	M. W. Randall
D. Charbonnet	A. A. Leibold	J. Sabath
F. Y. Chu	K. E. Lewis	B. Sojka
T. F. Clark	H. P. Lips	R. C. St. Clair
R. Cottrell	J. Luiz	H. Thakar
W. B. Dietzman	R. Matulic	N. G. Trinh
H. R. Gilden	T. S. McLenahan	R. J. Wehling
J. Grzan	A. Mickevicius	J. A. Yoder
	C. S. Miller	

When the IEEE Standards Board approved this guide on December 2, 1993, it had the following membership:

Wallace S. Read, *Chair*
Donald C. Loughry, *Vice Chair*
Andrew G. Salem, *Secretary*

Gilles A. Baril	Jim Isaak	Don T. Michael*
José A. Berrios de la Paz	Ben C. Johnson	Marco W. Migliaro
Clyde R. Camp	Walter J. Karplus	L. John Rankine
Donald C. Fleckenstein	Lorraine C. Kevra	Arthur K. Reilly
Jay Forster*	E. G. “Al” Kiener	Ronald H. Reimer
David F. Franklin	Ivor N. Knight	Gary S. Robinson
Ramiro Garcia	Joseph L. Koepfinger*	Leonard L. Tripp
Donald N. Heirman	D. N. “Jim” Logothetis	Donald W. Zipse

*Member Emeritus

Also included are the following nonvoting IEEE Standards Board liaisons:

Satish K. Aggarwal	Richard B. Engelman	Stanley I. Warshaw
James Beall	David E. Soffrin	

Valerie E. Zelenty, *IEEE Standards Project Editor*

IEEE Guide for Gas-Insulated Substations

1. Overview

This guide provides information of special relevance to the planning, design, testing, installation, operation, and maintenance of gas-insulated substations (GIS) and equipment. This guide is intended to supplement IEEE Std C37.122-1993 .[1]

In general, this guide is applicable to all ac GIS from 72.5–800 kV However, the importance of the topics covered varies with circumstances. For example, issues related to advanced field test techniques and very fast transients (VFT) are of particular interest for extra-high-voltage (EHV) GIS (345 kV and above), and are of lesser importance at lower voltage levels.

2. References

This guide shall be used in conjunction with the following references.

AA ACM 1-1986 The Aluminum Construction Manual.[2]

AISC S335-89, Specifications for Design, Fabrication, and Erection of Structural Steel for Buildings.[3]

ANSI/ASME 1992 Boiler and Pressure Vessel Code—Section VIII: Pressure Vessels, Division 1.[4]

IEC Draft 17A-339 (SECRETARIAT) [IEC Draft 17C-102 (SECRETARIAT)], Electromagnetic Compatibility (EMC) for Secondary Systems in Gas-Insulated Metal-Enclosed Switchgear for Rated Voltages of 72.5 kV and Above.[5]

IEC68-1 (1988), Environmental Testing—Part 1: General and guidance.

IEC68-2-6 (1982), Test Fc and guidance: Vibration (sinusoidal).

---

[1]Information on references can be found in clause 2.
[2]AA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (http://global.ihs.com/).
[3]AISC publications are available from the American Institute of Steel Construction, 400 N. Michigan Avenue, 8th Floor, Chicago, IL 60611, USA.
[4]ASME publications are available from the American Society of Mechanical Engineers, 22 Law Drive, Fairfield, NJ 07007, USA.
[5]IEC publications are available from IEC Sales Department, Case Postale 131, 3 rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse. IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

IEC 68-2-47 (1982), Mounting of components, equipment and other articles for dynamic tests including shock (Ea), bump (Eb), vibration (Fc and Fd) and steady-state acceleration (Ga) and guidance.

IEC 68-2-57 (1989), Test Ff: Vibration. Time-history method.

IEC 68-2-64 (1993), Part 2: Test methods—Test Fh: Vibration, broad-band random (digital control) and guidance.

IEC 68-3-3 (1991), Part 3: Guidance. Seismic test methods for equipments.

IEC 1166 (1993), High-voltage alternating current circuit-breakers—Guide for seismic qualification of high-voltage alternating current circuit-breakers.

IEEE Std 80-1986 (Reaff 1991), IEEE Guide for Safety in AC Substation Grounding (ANSI).[5]

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

IEEE Std 344-1987, IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations (ANSI).

IEEE Std 693-1984 (Reaff 1991), IEEE Recommended Practices for Seismic Design of Substations (ANSI).

IEEE Std C37.98-1987 (Reaff 1991), IEEE Standard for Seismic Testing of Relays (ANSI).

IEEE Std C37.122-1993, IEEE Standard for Gas-Insulated Substations.

IEEE Std 1125-1993, IEEE Guide for Moisture Measurements and Control in SF[6] Gas-Insulated Equipment.

NEMA CC 1-1993, Electric Power Connectors Substations[7]

Uniform Building Code™, 1991 ed., and 1993 Accumulative Supplement, International Conference of Building Officials (ICBO).[8]

Additional references on gas-insulated substations may be found in the bibliography in clause 5.

3. Definitions

The following definitions are applicable only to the subject treated in this guide. At the time this guide was approved there were no corresponding definitions in IEEE Std 100-1992 .

3.1 acting stress (working stress): The maximum applied or expected mechanical stress in a material during operation of the apparatus of which it is a part and including the stresses caused by seismic and other loading, acting independently or simultaneously as determined by the user.

3.2 allowable stress: The maximum stress permitted by applicable standards or codes, or both.

3.3 amplification (mechanical): The relationship between response acceleration and ground acceleration.

---

[5]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.
[6]As this standard goes to press, IEEE Std 1125-1993 is not yet published. It is, however, available in manuscript form from the IEEE Standards Department, (908) 562-3800. Anticipated publication date is Fall 1994, at which point IEEE Std 1125-1993 will be available from the IEEE Service Center, 1-800-678-4333.
[7]NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street NW, Washington, DC 20037, USA.
[8]Available from the International Conference of Building Officials (ICBO), 5360 S. Workman Mill Road, Whittier, CA 90601, USA.

3.4 assembly (GIS): A collection of GIS components that are interconnected and ready for insertion as a subassembly in a GIS, such as a breaker bay shipping assembly. The term is also used to describe a complete GIS.

3.5 auxiliary circuits: All control, indicating, and measuring circuits.

3.6 Class A seismic component: A component or system whose failure, malfunction, or need for repair prevents the proper operation of the gas-insulated substation during or after the design earthquake.

3.7 Class B seismic component: A component or system whose failure, malfunction, or need for repair does not prevent the proper operation of the gas-insulated substation during or after the design earthquake. Class B components are designed to meet either normal building codes and national standards in force at the site or another lower-level design earthquake. Application of further design requirements is left to the discretion of the user.

3.8 compartment (GIS): Any gas section of the gas-insulated substation assembly that provides gas isolation.

3.9 continuous enclosure: A bus enclosure in which the consecutive sections of the enclosure are electrically bonded together to provide a continuous current path through the entire enclosure length.

3.10 continuous monitoring: The process of sampling the state of some phenomenon at a time interval shorter than the time constant of the phenomenon.

3.11 damping (mechanical): A dynamic property that indicates the ability of a structure to dissipate energy.

NOTE — The phenomenon of damping is represented by the damping ratio, a percentage of critical damping. After being forced to deflect and allowed to vibrate freely, structures with zero damping vibrate indefinitely. Structures with critical damping return to their static or neutral position in the shortest time without oscillation.

3.12 design earthquake: The greatest earthquake postulated during the life of the gas-insulated substation that the user wishes the gas-insulated substation to survive in operating condition.

3.13 design pressure (working pressure): The maximum steady-state gas pressure to which a gas-insulated substation enclosure is subjected under normal operating conditions.

3.14 enclosure currents: Currents that result from the voltages induced in the metallic enclosure by effects of currents flowing in the enclosed conductors.

3.15 gas barrier insulator: A spacer insulator specifically designed to prevent passage of gas from one gas compartment to another.

3.16 gas density, minimum: The minimum operating gas density at which the gas-insulated substation and its components are certified to meet their assigned electrical ratings.

3.17 gas density, nominal: The manufacturer’s recommended operating gas density (usually expressed as a pressure at 20 °C).

3.18 gas-insulated substation (GIS): A compact, multicomponent assembly, enclosed in a grounded metallic housing in which the primary insulating medium is a compressed gas, and that normally consists of buses, switchgear, and associated equipment.

3.19 gas-insulated surge arrester: A metal-enclosed surge arrester specifically designed for use in a gas-insulated substation.

3.20 gas leakage: Loss of insulating gas from the pressurized compartment.

3.21 high-level testing (mechanical): Testing performed to determine a damping of complete assemblies, subassemblies, or components.

3.22 low-level testing (mechanical): Testing performed to determine natural frequencies of complete assemblies, subassemblies, or components.

3.23 main circuit: All the conducting parts of the gas-insulated substation assembly included in or connected to the circuits that its switching devices are designed to close or open.

3.24 malfunction: The loss of capability to initiate or sustain a required function, often a protective action, or the initiation of undesired spurious action.

NOTE — A certain degree of equipment degradation may be acceptable in one system and not in another. In such cases, an evaluation of the equipment or device application should include a determination that the degree of relay contact bounce, changes in device calibration, or degradation of pressure-retaining boundaries are within acceptable limits.

3.25 maximum ground acceleration: The maximum value of acceleration input to the equipment during a given earthquake for a particular site.

3.26 metallic enclosure: A grounded, leak-tight enclosure that contains the compressed insulating gas and associated electrical equipment.

3.27 mode shape (mechanical): A plot that shows displacements of various points in the vibrating structure at a particular instant in time. There is a characteristic mode shape associated with each natural frequency of a vibrating structure.

3.28 moisture content: The amount of water in parts per million by volume (ppmv) that is in the gaseous state and mixed with the insulating gas.

3.29 natural frequency (mechanical): The frequency (ies) at which a body vibrates due to its own physical characteristics (mass, shape, boundary conditions, and elastic forces brought into play) when the body is distorted and then released, while restrained or supported at specific points.

3.30 noncontinuous enclosure: A bus enclosure in which the consecutive sections of the enclosure are electrically insulated from each other, though each section is connected to ground.

NOTE — This construction prevents longitudinal currents from flowing beyond each enclosure section. This design is no longer in common usage.

3.31 periodic monitoring: The process of sampling the state of some phenomenon at a sample interval greater than 1 s.

3.32 qualification testing (mechanical): Testing of the complete assembly or subassemblies to determine acceptability by applying an actual input that has a test response spectrum (either ground- or floor-response spectrum) equal to or larger than the design earthquake response spectrum.

3.33 resonance (mechanical): A dynamic condition that occurs when any forcing frequency of mechanical vibration coincides with one of the natural frequencies of the structure.

NOTE — In a plot of the response of the structure (acceleration, velocity, and displacement) vs. forcing frequency for a constant forcing input, as the forcing frequency approaches one of the natural frequencies of the structure, the response increases to a maximum at the natural frequency if damping is less than critical. The response of the stricture at resonance may be much greater than the input, depending on the damping.

3.34 response spectrum (mechanical): A plot of the maximum response of single-degree-of-freedom bodies at a damping value expressed as a percentage of critical damping of different natural frequencies when these bodies are rigidly mounted on the surface of interest (i.e., on the ground for a ground-response spectrum or on the floor for a floor-response spectrum) when that surface is subjected to a given earthquake's motion as modified by intervening structures.

3.35 single-phase enclosure: A metallic enclosure containing the buses and/or devices associated with one phase of a multiple-phase system. *Syn:* Iso-Phase GIS.

NOTE — A single gas-insulated substation need not be composed of all single-phase or all three-phase enclosures. A common compromise is to use buses in three-phase enclosures mated with equipment in single-phase enclosures.

3.36 soil structure interaction (SSI): A general concept for effects caused by the influence of the soil dynamic behavior on the response of a structure.

3.37 spacer (insulator): An insulator used to support the inner conductor in the enclosure.

3.38 station ground: A ground grid or any equivalent system of grounding electrodes buried beneath or adjacent to the gas-insulated substation that determines the rise of ground voltage level relative to remote earth and controls the distribution of voltage gradients within the gas-insulated substation area during a fault.

3.39 sulfur hexafluoride (SF_6): A gaseous dielectric for high-voltage power applications having characteristics as specified in ASTM D2472-92 [B9][9].

3.40 three-phase enclosure: A metallic enclosure containing the buses and/or devices of all phases of a three-phase system. *Syn:* 3-in-1 GIS.

3.41 threshold limit value—short term exposure limit (TLV-STEL), as defined by the American Conference of Governmental Industrial Hygienists: The maximum concentration to which workers can be exposed for a period of up to 15 min continuously without suffering adverse effects, or materially reduced work efficiency, provided that no more than four 15 min excursions per day are permitted with at least 60 min between exposure periods, and provided that the TLV-TWA is not exceeded. (In most jurisdictions in North America, the TLVs are legislated limits to exposure.)

3.42 threshold limit value—time weighted average (TLV-TWA), as defined by the American Conference of Governmental Industrial Hygienists: The time-weighted average concentration for a normal 8 h work day and 40 h work week to which nearly all workers may be exposed repeatedly, day after day, without adverse effect.

3.43 time history (mechanical): The record of acceleration, velocity, or displacement as a function of time which the floor of a building or the ground experiences due to an earthquake.

3.44 transition compartment: The compartment specifically designed for joining gas-insulated substation equipment of different design or manufacture. This compartment provides the necessary transition for the current-carrying conductor and the enclosure.

3.45 type tests: Tests made on representative samples that are intended to be used as part of routine production. The applicable portions of these type tests may also be used to evaluate modifications of a previous design and to ensure that performance has not been adversely affected.

3.46 very fast transients (VFT): Switching- or breakdown-induced transients with rise times of 3–10 ns that propagate as traveling waves throughout the GIS and cause overvoltage waveforms that vary as a function of position throughout a substation, and that couple to the external enclosure of SF_6-to-air terminations and can thereby cause external sparking between the enclosure and the support structure.

3.47 zero period acceleration: The peak time history acceleration that can be determined by the merging of response spectra, for all damping values, in the high-frequency range (usually above 30 Hz), in which no change in acceleration occurs with frequency.

4. Guidelines for GIS

4.1 GIS arrangement

4.1.1 Bus schemes

The bus schemes illustrated in figure 1 are those most commonly applied by the industry.

4.1.2 Arrangement constraints

The GIS arrangement is influenced by a number of important constraints. Certain of these are of more interest to the manufacturer while the others are of more interest to the user. The constraints are as follows:

a) *Area*. The required area for the GIS will be influenced by the selected clearance between breaker poles, by the mode of the circuit-breaker mounting (i.e., vertical or horizontal), and by the need for adequate maintenance clearances.
b) *Height*. For an outdoor installation, the GIS height may have important aesthetic considerations. For an indoor installation, the required headroom may be a factor determining the mode of the circuit-breaker mounting.

[9]The numbers in brackets correspond to the bibliographical entries in clause 5.

c) *Bus and junctions*. The arrangement may influence the length of the bus and the number of junctions required.
d) *Line exits*. The overall GIS dimensions will be influenced by the type of line exit selected. For EHV substations in particular, overhead exits require spreading the GIS arrangement to meet minimum phase-to-phase clearances in air.
e) *Position indicators*. The arrangement should afford a clear view of as many mechanical position indicators for disconnecting and grounding switches, from as few locations as practical. All position indicators should be visible from the floor or a readily accessible platform.
f) *Expansion*. If expansion is foreseen, the arrangement should be such that expansion of the original installation can be accomplished with minimum GIS downtime.
g) *Auxiliary connections*. The length and the number of terminal points of control wiring, hydraulic, and SF_6 gas connections should be minimized.
h) *Control cabinets*. The number and the location of control cabinets may be influenced by the arrangement.
i) *Shipping units*. It is essential to minimize the number of shipping splits in order to keep the installation time of GIS to a minimum.
j) *Maintenance*. The arrangement should afford maximum flexibility for routine maintenance. Equipment removal and SF_6 gas handling should be accomplished with ease.

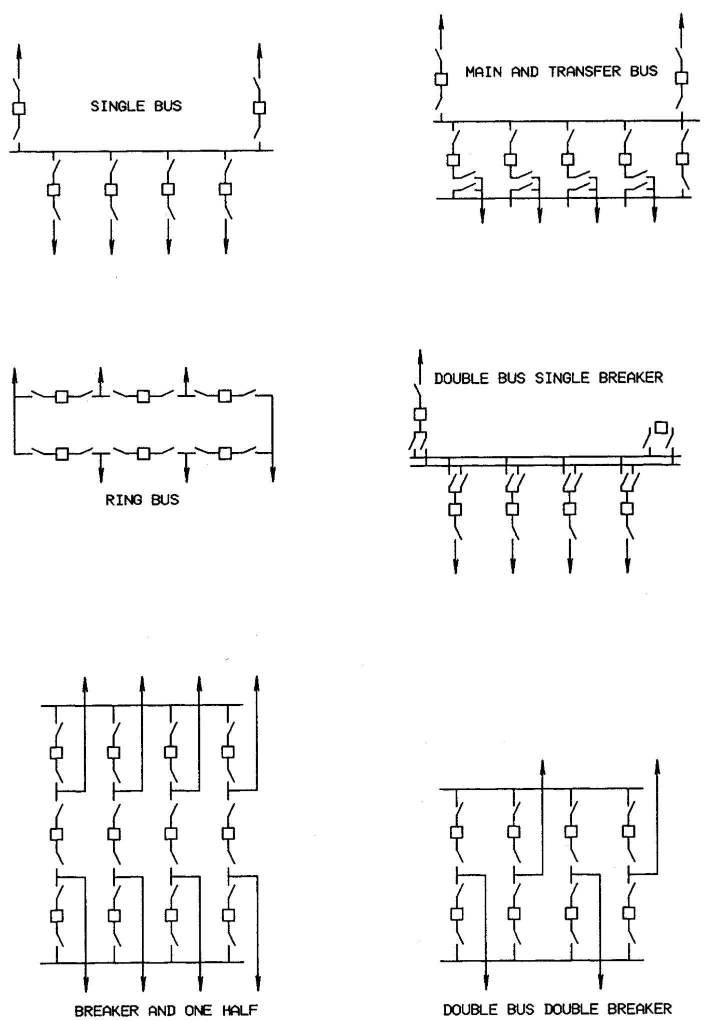


Figure 1— Common one-line schemes

k) *Operation*. The ease of operation should be ensured. Operating handles should be accessible and grouped. All indicating devices and gauges should be clearly visible and easily accessible. Access to viewports should be convenient.
l) *Power transformer*. Location and type of electrical connection for the power transformers will affect arrangement (SF_6-oil, SF_6-air, or through an SF_6-cable bushing).
m) *Cable connections*. Location and type of electrical connection for cables will affect arrangement (SF_6-oil, SF_6 to solid dielectric cable, or through an SF_6-air bushing).
n) *Surge arresters*. The arrangement, and particularly the length, of bus connections may dictate whether surge arresters are required inside the GIS.
o) *Layout*. The modular design of GIS components offers a high degree of flexibility for any single-line diagram specified. Considering the high reliability of today’s GIS components, with over 2000 operations before maintenance, simplified arrangements with less redundancy could be a way to reduce costs, particularly in stations with limited outage cost. A ring bus arrangement instead of a one-and-a-half breaker scheme, or a single instead of a double bus bar, can considerably reduce the total cost of a GIS. Using cable connections to overhead lines and/or transformers, especially at voltage levels up to 242 kV, may considerably reduce the total space required for an installation without limiting the access for ease of maintenance. As illustrated in figure 2, many different physical arrangements are possible for the same single-line diagram, balancing the shortest connection to adjacent equipment with the best fit to a particular site.

4.1.3 Three-phase or single-phase enclosure

A user should consider a number of factors in selecting between a three-phase enclosure design and a single-phase enclosure design, including the following:

a) The initial cost of a three-phase design is generally less for the lower voltage ratings.
b) Installation costs may differ depending on the amount of factory preassembly or on the overall size or weight of shipping sections.
c) Three-phase enclosure designs may be smaller and consequently occupy less land or require a smaller building.
d) When a fault occurs in a three-phase enclosure design, it rapidly evolves into a three-phase fault. This may be less tolerable than a single-phase fault from the point of view of system stability. However, in a three-phase enclosure design, the possibility of a burn-through is less. Venting of the pressure relief ports is less likely because the enclosure volumes tend to be larger.
e) Some users require circuit breakers with independent pole operation. This may be more readily available with a single-phase design than a three-phase design.
f) Hybrid designs employing single-phase and three-phase enclosure elements are both available and practical.

4.2 Installation and equipment handling

The following subclauses contain recommended procedures for installation and maintenance of gas-insulated substations.

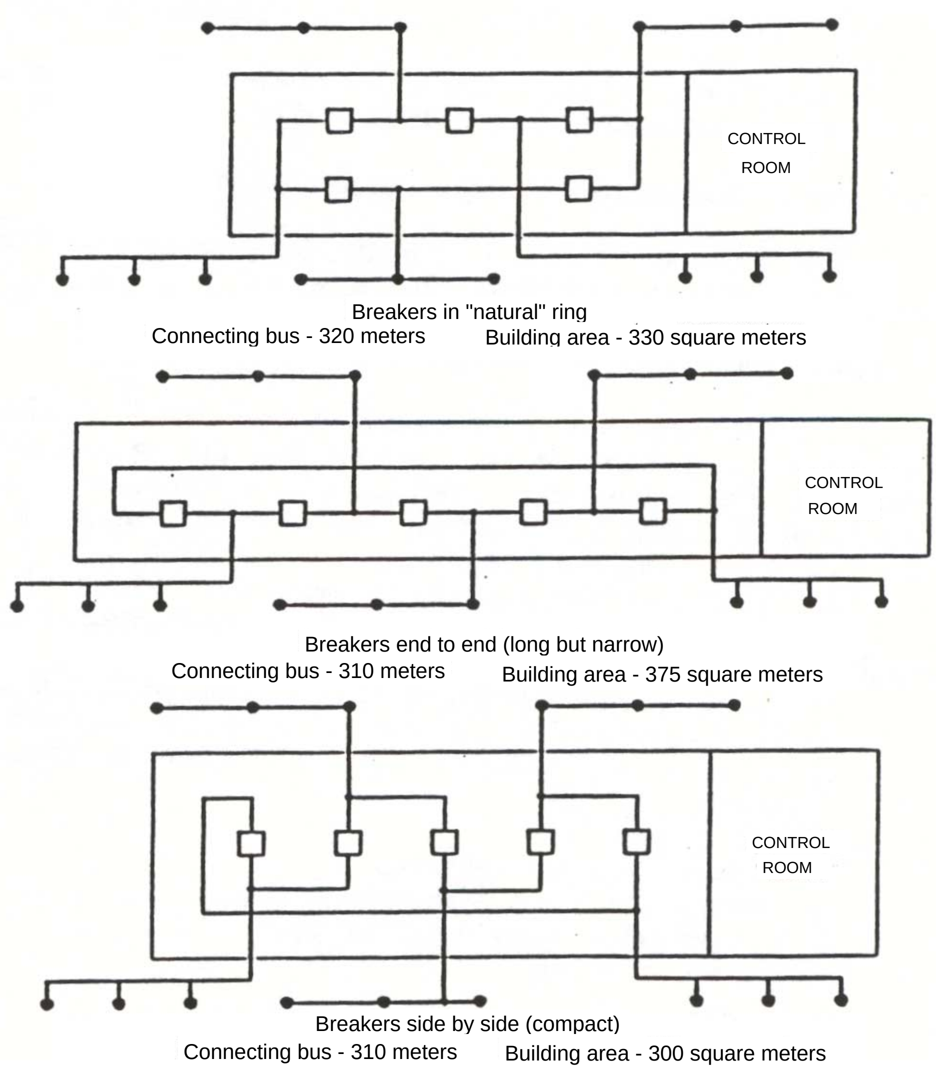


Figure 2—Comparison of physical arrangements for five-circuit ring bus requiring a building and SF_6 air bushings to overhead lines

4.2.1 Planning the installation

A deliberate and complete installation plan, including the future addition of similar equipment, is essential so that all aspects of construction can be reviewed. The preassembled sections of the equipment and the manufacturer's instructions dictate the assembly sequence and, in most instances, follow a series of steps categorized as follows:

a) Preconstruction meeting between the user and the manufacturer
b) Site preparation including grading; installation of drainage, foundations, and grounding mats; access roads; and auxiliary power
c) Staging of construction equipment required during the installation
d) Final alignment and leveling of foundation supports
e) Receiving, unloading, and storing GIS equipment

f) On-site assembly
g) Leak testing
h) Connection of control wires
i) Purging and filling with insulating gas
j) Mechanical or operational testing
k) Dielectric testing
l) Cleanup in accordance with applicable regulations
m) Energization

Other planning considerations are as follows:

- A schedule for work crews should be prepared to provide for more economical use of manpower and to minimize conflicts caused by limited space. Scheduling may also result in the release of specialized skills in the shortest possible time.
- On-site or nearby preassembly areas should be planned when practical so that specialized equipment can be set up and repetitive assembly tasks can be performed under controlled conditions.
- A site layout designating erection equipment locations should be prepared to allow maximum use of the equipment with minimum movement. The layout should include details for each phase of installation so that orderly movement of the equipment can be maintained.
- The capacity of cranes, hoists, gas-handling equipment, welding equipment, etc., should be considered to ensure that the proper size equipment is available for the job.
- Electric power, heat, water, etc., should be available at the appropriate time in the installation sequence.
- The suitability of the site for each phase of construction and installation should be planned in advance (e.g., to move about the work area requires proper ground preparation).
- Cleanliness, in accordance with manufacturer's instructions, should be observed at all times.
- Material safety data sheets and other health and safety information should be readily available to the work crews.

4.2.2 Installation crew

The training of crews or the selection of individuals having the proper skills should be planned well in advance. The timing of the training should be integrated into the overall project plan.

A factory service technician is recommended for the installation of this equipment. Most manufacturers will train the user's personnel to ensure proper installation and equipment operation.

4.2.3 Equipment access

Structural supports, access platforms, ladders, stairs, cable raceway, conduit, and other auxiliary equipment required for operation and maintenance, as furnished by the manufacturer, should be incorporated, if practical, into the design.

4.2.4 Temporary protective covers

Covers and other suitable provisions for protecting the equipment from damage or contamination during shipping and installation should be furnished. Necessary quantities should be retained for future use.

4.2.5 Equipment and tool requirements

Cranes or hoists having adequate lifting capacities should be available for handling material during installation. Nylon web slings provide an ideal means for lifting equipment without damaging it.

Gas is handled through commercially available gas-processing trailers that contain vacuum pumping equipment, gas storage tanks, compressors, filters, and dryers. The size of the individual gas compartments and the evacuating and storage capacity of the gas-handling equipment is especially important in large stations. Suitable evacuating equipment and a heat source to counteract the chilling effect of the expanding gas may permit filling directly from gas cylinders or gas-handling equipment. Filling procedures for GIS apparatus are covered in 4.4.4.

High-voltage test equipment is required for checking the quality of the insulation after installation. Adapters for high-voltage testing may be required. These include a suitable entrance bushing for connecting the high voltage to the gas-insulated conductor and a termination for closing off the end of the equipment when the entire assembly has not been completed. In many cases, it may be possible to use an entrance bushing that is a part of the installation. Field testing is covered in 4.10.

When tools and alignment templates not readily available on the open market are required for installation and maintenance of the equipment, one set should be furnished, by the supplier, with the equipment when it is delivered.

The following materials should be on hand before the bus is opened:

a) Gas-processing equipment with adequate storage capacity
b) Electrolytic or electronic hygrometer or comparable equipment for measuring moisture levels
c) Insulating gas leak detector (Where double “O” rings are used, a manometer can sometimes be connected at the sensing hole to measure any increase in pressure between the “O” rings. Commercial high-viscosity, noncorrosive solutions may be used to locate larger leaks at a sensing hole, at welds, or at bolted flanges.)
d) Dry air
e) Clean plastic gloves and work uniforms
f) Lint-free cloths and manufacturer-recommended solvents
g) Temporary plastic bags or covers for sealing openings after components have been removed
h) Commercial-type vacuum cleaner with high efficiency particulate air (HEPA) filters and nonmetallic accessories
i) Tools supplied and recommended by the manufacturer
j) Ventilating equipment
k) Handling and lifting equipment
l) Maintenance manual and erection drawings
m) Ladders and platforms as required

4.2.6 Drawings and instructions

Installation drawings, instructions, and data should be furnished by the supplier. This should include but not be limited to the information listed below. Dimensions and weights should be in English or in metric, or both, as specified by the user.

a) Instruction and procedures sequenced for storage, assembly, maintenance, and disassembly
b) General arrangement and shipping assembly
c) Assembly and maintenance clearance requirements
d) Component outline dimensions and weights
e) Method of lifting components
f) Item or subassembly identification, or both
g) Torque specifications
h) Equipment adjustment and preparation
i) Calculated point-to-point resistance for each assembled shipping component or shipping section, or both
j) Gas system installation procedures, gas handling procedures, and schematic diagrams
k) Specifications and procedures for cleanliness
l) Foundation and anchor bolt requirements
m) Grounding requirements
n) Logic, control, flow, and wiring diagrams
o) Operating instructions and procedures
p) Nameplate(s) indicating equipment ratings
q) Identification of component and assembly thermal expansion limits

r) List of recommended spare parts
s) List of components that may require replacement during a major overhaul
t) Resistance values referred to in item i) above

4.2.7 Environmental considerations

All work should be done in a clean, dry environment. For outdoor work during inclement weather, a temporary protective shelter should be provided with adequate room (and heat when necessary). Moisture infiltration should be minimized.

4.2.8 Work procedures

4.2.8.1 Opening the equipment

Great care should be taken when opening GIS in order to avoid introduction of impurities in the apparatus. To this end, the following procedures are recommended.

a) All safety precautions in 4.5 should be followed.
b) The area around the junction to be opened, including supporting steel and other parts from which dirt or contaminants could fall or be blown into the enclosures, should be vacuumed and wiped with lint-free cloths.
c) Evacuate the gas from the section on which work is to be performed to at least 670 Pa; then fill with dry air to a pressure of 100 kPa.
d) Open the junction between components or sections in accordance with the manufacturer's recommendations, using temporary caps or covers as required. In some circumstances, it may be advantageous while working on the equipment to maintain a slight flow of dry, clean air across the area being maintained so that the probability of dirt or moisture entering the equipment will be minimized. When a compartment containing sulfur hexafluoride (SF_6) gas arc byproducts is opened, the byproducts, which are usually in the form of a white-to-tan powder, should be removed at once in accordance with 4.4.1.5.2.
e) All work should be completed as quickly as possible. When delays are encountered, any open sections should be covered with temporary shipping covers or other suitable seals. It may also be necessary to add heat to prevent condensation. When any section is left overnight or longer, it should be pressurized with dry air to a pressure of approximately 136 kPa to avoid condensation or entrance of moist air.

4.2.8.2 Closing the equipment

The following procedures are to be followed:

a) Inspect the conductor and sheath for nicks, burrs, or scratches and repair according to the manufacturer's instructions. Re-clean as required.
b) Clean the enclosure thoroughly. Vacuum the inside of the enclosure and wipe the conductor and then the inside of the enclosure with a lint-free cloth. Insulators within easy reach should be cleaned according to the manufacturer's instructions.
c) Reassemble the equipment and ensure that no foreign particles are introduced. Dry air flow should be continued until this step is completed. However, it will be necessary to discontinue air flow during welding to prevent the inert shielding gas from being blown away.
d) Refill with dry air to a pressure suitable for preliminary leak checking and/or to a slightly positive pressure to maintain the interior clean and dry. Evacuate to the level agreed to between the manufacturer and the user and hold for the specified period of time. Perform a vacuum pressure rise test. Fill the enclosure with insulating gas to the specified pressure at ambient temperature and check for leaks. Check the water vapor (moisture) content immediately, and several days later recheck the pressure and moisture content. See 4.4.4 for further filling requirements. When major repairs or modifications have been made, it may be necessary to perform a dielectric test on the equipment to verify the insulation integrity. This decision should be made by the user, in consultation with the manufacturer. See 4.10 for recommended procedures on field testing.

4.3 Control wiring—Practices in GIS

IEEE standards cover qualification of substation control apparatus for immunity to damage from control wiring transients and electromagnetic interference (EMI). The standards developed for conventional substations are inadequate for GIS; however, the required standards for GIS are a straightforward extension of the existing standards and are already in draft form within the IEC. IEC Draft 17A-339 [IEC Draft 17C-102] introduces the principles that apply to control wiring practice in GIS.

Both conventional substations and GIS generate transients during switching. The transients generated in GIS have rise times roughly an order of magnitude shorter than those generated by conventional substations, which results in a frequency bandwidth roughly an order of magnitude greater. This causes increased coupling of interference into the control wiring, with the result that control wiring practice which has provedadequate for conventional substations may not be adequate for GIS. However, control wiring practice for GIS has been brought to the state which permits reliable operation of programmable controllers and computers within GIS. For a more detailed discussion of very fast transients (VFT) in GIS, see 4.9.

4.3.1 Background

Control wiring in early GIS was often implemented using well-shielded control cables (solid copper shields) that were installed with one end of the shield floating to eliminate unpredictable circulating currents in the cable shield. The grounded end of the shield was often connected to ground using a pigtail, which could vary in length from a few centimeters to 1 m. Where a cable entered a control cabinet, the cable and shield were often brought into the cabinet, and a pigtail was pulled from the cable shield to the cabinet ground within the cabinet. Control wiring systems installed in this manner often caused damage to electromechanical relays, especially as a result of flashovers during testing, as such flashovers cause the largest transients to which the control system is likely to be subjected. Even after the ungrounded end of the control cable shield was grounded (usually through another pigtail), routine switching operations sometimes caused incorrect operation of computers within GIS. For the very short rise time transients that occur in GIS, a pigtail represents a transmission line of significant impedance rather than a ground.

As a result of grounding the cable shield through a pigtail, significant lengths of control wiring conductors are likely to be left unshielded near the cable termination. Exposure of 15 cm of control wiring conductor can result in the coupling of transient voltages of up to 15 kV during a breakdown at a line-to-ground voltage of about 350 kV when the unshielded control wiring is located near a gas-to-air termination [B42]. The voltage generated during disconnector operation would be less than half this value, in both cases with frequencies in the range of 1–30 MHz. A 30 cm (1 ft) pigtail can generate in the range of 1000 V on the shield as a result of the inductive voltage drop across the pigtail at 20 MHz [B42]. These problems were addressed and solved when utilities started to install computer-controlled GIS.

4.3.2 Appropriate control wiring practices

Transient generation and propagation within and along the GIS enclosure are covered in 4.9. Such transients generate substantial radiated energy, electric and magnetic fields, and transient currents within the substation grounds. Any of these phenomena can couple into poorly executed control wiring systems, but none of them can couple to an appreciable degree into well-executed control wiring systems. The obvious and correct approach to GIS control wiring is to enclose the entire control system in a Faraday cage, i.e., within a metal enclosure. This is much simpler than it sounds, as will be described below.

A Faraday cage is a metal enclosure that fully surrounds the system, offering protection from EMI. In the case of control wiring, the system is typically a sensor (e.g., a gas density relay), the attached control wiring, the local control wiring cabinet in which the control wiring is terminated, the control wiring from the local cabinet to the substation control room, and the relay or computer racks in the control room. Each of these elements is usually well shielded. The sensor is usually housed in a metal case that sits on the GIS. The control wiring is usually shielded by a solid copper shield or several layers of braid. The local control cabinet is metal and well shielded, as are the computers or relay racks in the substation control room. The problem, therefore, is not to shield the individual elements, which are all usually well shielded, but to ensure the continuity of the shield from one element to the next. To this end, it is necessary to understand something about the flow of high-frequency currents in metals.

From 1 MHz to 100 MHz, the skin depth of current in copper varies from about 70 μm to 7 μm, respectively, so that almost no current flows in the conductor more than 0.25 mm below its surface. Since the copper cable shield, sensor enclosure, and local cabinet are all thick compared to the skin depth in this frequency range, independent currents can flow on the inner and outer surfaces of the cable shield. A large switching-induced transient current could be flowing on the outside surface of the shield with negligible current flowing on the inside surface. No coupling will occur to the sensor or control wiring within the shield so long as the current is not allowed to cross over from the outside of the shield to the inside. The key to proper control wiring practice for GIS is effecting connections between shielding elements that provide shield continuity and avoid such crossover.

When a cable enters a control cabinet, the cable shield should be terminated immediately on the control cabinet enclosure as the cable conductors enter the cabinet. A long pigtail termination of the cable shield after the cable has entered the cabinet is poor practice, as this brings the transient on the control cable shield within the control cabinet where it can couple to all of the conductors therein. Coaxial termination of the cable shield on the cabinet forces the shield currents to flow on the outside of the metal cabinet, which shields the conductors within from the shield currents. A range of connectors and cables is suitable for coaxial termination of cable shields. Cable with a solid copper shield offers best performance, and such cables do not necessarily cost more than cable with a less effective braided shield.

Some components in GIS require careful design to avoid the coupling of transients into the control wiring system. Voltage transformers (VT) are of special concern, as they effect a connection between the high-voltage conductor and the control wiring system. The interwinding capacitance in a magnetic VT can result in unacceptable coupling of transients from the GIS conductor to the low side of the VT unless an electrostatic shield is employed between the windings.

4.4 Gas handling—SF_6 and GIS

The purpose of the following subclauses is to familiarize the substation engineer, operator, maintenance worker, and industrial safety personnel with the nature of SF_6, SF_6 decomposition byproducts, and safety issues associated therewith as they relate to the maintenance and repair of GIS. The following subclauses reflect the consensus of GIS user practice and expert opinion. They do not prescribe work practices or required safety apparatus. Rather, they identify the issues that should be addressed in a document that specifies safe work practices, and provide some suggested guidelines for incorporation in such a document.

4.4.1 Pure SF_6

4.4.1.1 Physical and chemical properties

SF_6 is a heavy, nontoxic gas consisting of one sulfur atom surrounded by six fluorine atoms. As fluorine is the strongest of oxidizers, the fluorine atoms of SF_6 are tightly bound to the sulfur atom, resulting in a highly stable molecule. As a result of its symmetry, the intermolecular forces between SF_6 molecules are very low, resulting in a very low liquefaction temperature for its relatively high molecular weight of 146. Most materials of similar molecular weight are liquids or solids at room temperature.

As SF_6 is much heavier than air, it can “fall” into low places and displace the air, which can result in suffocation. However, once mixed with air, SF_6 will not separate and collect in low places. Although SF_6 is not toxic, a TLV-TWA of 1000 ppmv has been assigned for exposure to SF_6 in a working environment.

SF_6 is thermally very stable. However, in the presence of certain metals, it starts to decompose (0.2% per year) at temperatures as low as 200 °C, reaching a decomposition rate in the range of 2% per year at 250 °C. Above 600 °C, SF_6 degrades rapidly. Self-sustaining chemical reactions (burning) are possible between certain materials and SF_6.

Finely divided aluminum will burn in SF_6 if heated to a sufficiently high temperature. However, bulk aluminum will not burn, as the material carries heat away too rapidly for a self-sustaining reaction. Some molecular sieves and desiccants will go into a self-sustaining reaction with SF_6 at temperatures slightly above 100 °C.

4.4.1.2 Electrical properties

SF_6 is a highly electronegative gas, which means that it readily absorbs electrons to form negative ions. This gives it a very high dielectric strength of about 89 kV/cm-bar (225 kV/in-bar) in a uniform field. The dielectric properties of SF_6 vary greatly with electric field inhomogeneity, so that while SF_6 is an excellent dielectric for relatively uniform fields, its dielectric strength is reduced in the presence of stress-enhancement-causing defects. While the dielectric performance of SF_6 increases with pressure for uniform fields, it can decrease with pressure for nonuniform fields. Thus if the performance of an SF_6-insulated system is limited by defects that cause substantial electric field inhomogeneity, increasing the pressure of a system will not necessarily improve its dielectric performance.

SF_6 is useful as an insulating and arc interrupting medium as a result of the following properties:

a) SF_6 liquefies at a sufficiently low temperature for a wide range of power engineering applications.
b) SF_6 is electronegative, making it an excellent arc-quenching medium.
c) SF_6 has a high dielectric strength.
d) When SF_6 is decomposed as in an electrical arc, no solid conducting compounds are formed and the dielectric strength of the resulting mixture of gaseous decomposition byproducts and SF_6 is not degraded relative to that of pure SF_6.

4.4.1.3 Sources of SF_6 decomposition

SF_6 can be decomposed as a result of the following:

a) *Excessive heating*. Excessive heating is most likely to occur as a result of improperly formed, high-current electrical contacts in switchgear.
b) *Electric sparks*. Electrical sparking occurs routinely in some devices such as GIS disconnectors. The amount of SF_6 decomposition will vary widely with disconnector design and operating conditions. However, disconnector operation can generate as much as 1 ppmv of SF_6 decomposition byproducts within the switch compartment per operation.
c) *Power arcs.* The temperature at the core of a power arc is about 20,000 °C, which results in a fully ionized plasma. After a power arc in pure SF_6, the recombination of the plasma into SF_6 is highly efficient, which results in small amounts of decomposition byproducts. As impurities in the plasma increase (e.g., H_2O, metal vapor, etc.), the amount of byproducts formed increases. Power arcs occur routinely in circuit breakers. However, circuit breakers are designed to minimize the amount of SF_6 decomposition through the following means:
    1) The arcing contacts are designed to react with the decomposed SF_6 in the arc at a very low rate. Also, the materials in the arcing contacts generally form gases (WF_6 or CF_4) rather than solids when reacting with SF_6.
    2) The moisture level in SF_6 circuit breakers is very low as a result of desiccant installed within the breaker; this reduces the formation of gaseous byproducts.
    3) Circuit breakers typically interrupt within three cycles to minimize the arc duration. Circuit breakers always include an adsorbent to remove arcing byproducts (as well as moisture) from the SF_6 within the breaker.
    4) An in-service fault in GIS also results in a power arc, usually between aluminum electrodes. Because aluminum is easily melted and vaporized, because the reaction between aluminum and an SF_6 plasma is highly exothermic (gives off a great deal of heat as the aluminum “burns” in the SF_6), and because a fault arc generally lasts much longer than the arc during breaker operation, a great deal more solid and gaseous arcing byproducts are formed during a fault than during breaker operation. A fault can result in up to 20% decomposition of SF_6 within a relatively small GIS gas compartment and the generation of several hundred grams (0.5 lb) of solid arcing byproducts. For an arc between aluminum electrodes, the

solid arcing byproducts are dominated by extremely fine (micron size) aluminum tetrafluoride (AlF_3) powder. This powder has a very large surface area and tends to adsorb large amounts of gaseous arcing byproducts on its surface. These byproducts will react with moisture in air to give off noxious and toxic fumes. In the process, the byproducts become sticky and much more difficult to remove. AlF_3 should be considered toxic.

d) *Partial discharge.* Continuous partial discharge within SF_6-insulated apparatus generally causes dielectric failure as a result of the SF_6 decomposition byproducts [such as hydrogen fluoride (HF)] attacking dielectric surfaces within the apparatus. However, failure can take months or years in the case of relatively low-level discharge within a large gas compartment such as a long bus duct.

4.4.1.4 Decomposition byproducts

4.4.1.4.1 Major gaseous byproducts

The five major gaseous byproducts can be characterized as follows:

a) *Thionyl fluoride (SOF_2):* TWA = 1.6 ppmv. Colorless gas with a suffocating rotten-egg odor. It reacts with water to form SO_2 and HF, both toxic gases. In view of the high toxicity of this gas and its dominance as a byproduct of SF_6 power arcs, the concentration of this gas will usually determine protection requirements.
b) *Sulfuric oxyfluoride, "Vikane" (SO_2F_2):* TWA = 5 ppmv, STEL = 10 ppmv. Colorless, odorless gas used as a commercial fumigant. SO_2F_2 does not react with water except in aqueous solutions of strong bases such as sodium hydroxide. This gas has never been observed in SF_6 decomposition byproducts without substantial quantities of SOF_2, which has a strong odor. SO_2F_2 is generally considered to be one of the least toxic byproducts.
c) *Sulfur tetrafluoride (SF_4):* TLV-C = 0.1 ppmv. Highly toxic, colorless gas with an acrid odor. It reacts rapidly with water, vapor, or liquid to form SO_2 and HF, both highly toxic gases. Formed in high concentrations by arcs, SF_4 will react with available moisture in SF_6-insulated equipment, so that the main byproduct remaining is usually just SOF_2.
d) *Sulfur dioxide (SO_2):* TWA = 2 ppmv, STEL = 5 ppmv. Highly toxic, colorless gas with a suffocating, acrid odor. SO_2 is corrosive and affects mainly the upper respiratory tract and the bronchi. It is also an eye irritant. Excessive exposures to high enough concentrations can be fatal by inhalation, but concentrations below fatal levels can be tolerated for some time with no apparent permanent damage. SO_2 is easily sensed. At 0.3 ppmv, it is detectable by taste and at 3 ppmv it is detectable by odor. Immediate irritation of the nose and throat occurs at 6–12 ppmv.
e) *Hydrogen fluoride (HF):* TLV-C = 3 ppmv. Highly toxic, colorless liquid or gas. Inhaling HF gas may cause ulcers of the upper respiratory tract. HF produces severe skin burns that are slow to heal. HF is so highly reactive that its life within a GIS compartment is very limited. As noted above, however, HF is formed in the reaction of several other byproducts with moisture.

4.4.1.4.2 Solid arcing byproducts

As mentioned above, the danger from solid arcing byproducts comes more from the gases adsorbed on the large surface area of the finely divided powder than from the toxicity of the base material. However, the finely divided AlF_3 powder that normally dominates solid arcing byproducts is so fine that it is not easily expelled by the lungs. This, combined with the toxic gases that are generally adsorbed on the surface of solid arcing byproducts and reactions which take place between these adsorbed gases and moisture, implies that the solid arcing byproducts should be considered toxic.

4.4.1.4.3 Minor gaseous byproducts

Disulfur decafluoride, S_2F_{10}, usually listed as sulfur pentafluoride, may be the most important minor gaseous byproduct. It is highly toxic with a TLV-C of 0.01 ppmv. Odorless and colorless, and insoluble in water, it decomposes rapidly above 200 °C. It has been detected in partial discharges, sparks, and power arcs. For a review of properties and production of S_2F_{10}, see [B61].

4.4.1.5 Considerations in maintaining GIS

A clear distinction should be made between routine maintenance and repair after a fault. As a result, the two subjects will be discussed separately.

4.4.1.5.1 Routine maintenance

Very little gaseous or solid arcing byproducts should be encountered during routine maintenance. If the condition of the GIS is suspect, a simple field test can be carried out using a chemical sensing tube to determine the concentration of SOF_2 and SO_2 in the GIS. Commercial apparatus is available for this purpose. The byproduct concentration in normally operating GIS should be only a few parts per million by volume. In the case of a circuit breaker, the concentration will depend on the time since the last operation, especially the last fault clearing operation, and could range to several hundred parts per million by volume.

Before entering an SF_6 gas compartment for routine maintenance, the SF_6 gas should be removed from the apparatus (normally using a gas cart), and the compartment should be evacuated to about 130 Pa. The compartment should then be backfilled with dry air. This procedure should reduce the concentration of gaseous SF_6 byproducts in the backfilled air by a factor of about 1000 from that in the SF_6. Thus if the SF_6 initially contained 100 ppmv, well above the toxic limit in the range of 2 ppmv, after backfilling, the concentration will be in the range of 0.2 ppmv, well below the toxic limit.

For initial inspection in a confined space within a gas compartment, a half-face respirator with acid gas, organic solvent, and particulate filters is advisable. Although the concentration of SF_6 byproducts should be well below toxic values, if cleaning is undertaken with an organic solvent in a confined space, the concentration of solvent vapor is likely to exceed toxic limits.

For inspection and work in open space around the switchgear, such as refurbishing the operating components of a circuit breaker after it has been removed from the breaker housing, no protection should be necessary although eye protection and plastic gloves are advisable both to limit skin exposure to organic solvents and to protect the switchgear from fingerprints.

If appreciable quantities of solid arcing byproducts are present, these should be treated as toxic material and should be removed as quickly as possible using a vacuum cleaner with a HEPA filter, as is commonly used for asbestos.

4.4.1.5.2 Maintenance after an in-service fault

The gas involved in an in-service fault should be passed through an external filter (not an integral filter of a gas cart) designed to remove the toxic and corrosive byproducts immediately upon leaving the faulted compartment. Well-engineered filter units for this purpose are available from at least two commercial suppliers of SF_6 gas carts. The hose that connects the faulted compartment to the filter unit is likely to be contaminated with solid arcing byproducts and should not be reused prior to thorough cleaning. Such filter units theoretically clean even faulted gas to the point that it can be reused.

After use, the filter material should be handled and disposed of as toxic material. Under no circumstances should external filter material be regenerated by heating or other means, and under no circumstances should the desiccant in the gas cart be used to remove gaseous byproducts from SF_6 after an in-service fault, as this material is normally regenerated, rather than replaced, after use.

The gas should be evacuated from the faulted gas compartment (with the filter unit between the compartment and vacuum pump) to a pressure of about 130 Pa. The compartment should then be backfilled with dry air. Upon opening of the compartment, the exposure of the solid arcing byproducts to moist air will result in the evolution of toxic fumes with a strong rotten egg odor. Maintenance workers who conduct the initial opening of the faulted gas compartment and removal of the solid arcing byproducts should employ a supplied air respirator system operated in pressure demand or other positive pressure mode and should wear disposable protective clothing covering all garments, boots, hair, and hands. The compartment should not be opened until preparations have been completed for removal of the solid byproducts. Their removal should be the first priority, as they will become sticky and more difficult to remove with continued exposure to moist air.

After initial removal of the solid arcing byproducts using a vacuum cleaner with HEPA filter, the affected area should be wiped down using a solvent (typically ethyl alcohol denatured with 5% or 10% methyl alcohol) by workers wearing full protective clothing. This cleaning fluid contains about 3% water, which is desirable as some contaminants may be water soluble but not alcohol soluble. The wipes used to remove the remaining solid arcing byproducts should be treated as toxic waste.

After removal of the solid arcing byproducts, a full-face respirator should continue to be used in confined spaces. In well-ventilated open spaces, respiratory protection may not be necessary; however, if a rotten egg odor is noticed, a half-face cartridge filter mask with acid gas, particulate, and possibly organic vapor filters should be employed. Such protection is also adequate for short-term inspection of the faulted apparatus by engineering personnel. Full protective clothing should continue to be employed by personnel handling and cleaning components heavily contaminated by the fault.

Although the repair of faulted GIS requires careful attention to safety, several hundred faults in GIS have been repaired without incident. The few injuries that have occurred are generally the result of personnel untrained in the repair of faulted GIS coming into contact with the fault by accident, as, for example, when a cable repair crew was exposed to faulted SF_6 as a result of opening a pipe-type cable that was connected to a GIS that had suffered failure of the cable-to-GIS interface.

4.4.2 Gas handling

Gas handling relates to the storage, transfer, purification, and reclamation of the gas and also the evacuation and filling of the gas compartments of the GIS apparatus. Gas-insulated substations require substantial amounts of SF_6 gas for proper insulation and interrupting functions. Because the performance of the GIS apparatus is directly related to the quality of the SF_6 gas dielectric, appropriate attention is required in the handling and processing of the gas. The specific requirements for gas purity, handling, processing, filling, and refilling, which are provided by the equipment manufacturer, should be followed to ensure proper equipment operation.

4.4.2.1 Service conditions

It should be noted that manufacturer’s recommendations and handling equipment limitations may restrict gas handling to temperatures above the minimum operating temperatures for GIS apparatus.

4.4.2.2 SF_6 gas

4.4.2.2.1 Shipment

SF_6 is shipped as a liquefied gas in steel containers from the manufacturer. Bulk quantities are available in tube trailers for large installations.

4.4.2.2.2 Storage

SF_6 containers should be stored away from direct sunlight and sources of heat. The storage area should be free of explosives or flammable material.

Other storage considerations are as follows:

a) Cylinders should be secured so they will not fall and should be protected against physical damage.
b) Cylinders should not be stored on damp ground or in contact with moisture.
c) Valve caps should always be in place when cylinders are not in use or when they are being moved.

d) Cylinders should not be dropped, nor allowed to slam together.
e) Heat should not be applied to cylinders (see 4.4.2.2), nor should they be allowed to be chilled below –29 °C (–20 °F).
f) Gas should not be added to the cylinder, except as recommended by the gas supplier.
g) Valve or safety devices should not be tampered with.

4.4.2.2.3 Withdrawing the gas from gas cylinders

SF_6 gas can be withdrawn from the cylinder in either the gaseous or liquid state. When the cylinder is upright, the SF_6 will discharge as a gas. When the cylinder is inverted, the SF_6 will discharge as a liquid. Liquid SF_6 should be filtered to remove any contaminants.

Withdrawing SF_6 as a liquid when filling equipment requires less time, but it is not recommended. The SF_6 should be vaporized before it enters the equipment or the equipment may become overpressurized. Damage to gas compressors will occur if liquid SF_6 is drawn into the compressor.

For the initial filling of new equipment, it is recommended that new SF_6 be used and drawn directly from cylinders provided by the gas supplier. All hoses and fittings, as well as the GIS itself, should be evacuated prior to filling, and a filter should be used.

When filling directly from a gas cylinder into a GIS, the gas cylinders should always be in an upright position (to ensure withdrawal as a gas), well supported to prevent them from falling over, and equipped with an adjustable pressure reducer to avoid overfilling.

If SF_6 is withdrawn rapidly from a gas cylinder, a so-called “freezing effect” occurs, due to gas expansion and transition from liquid to gas, which will leave approximately 30% of the gas in the cylinder, causing the remaining gas to remain in the liquid state, even at atmospheric pressure. To avoid this freezing effect, a gas cylinder heater can be used to supply sufficient energy so that all gas can be released until pressure equalization occurs.

Such a heating device should be constructed to accommodate the following conditions:

a) It should not be possible to overheat a gas cylinder, causing its safety relief valve to release gas.
b) It should not be necessary to lift the heavy cylinders into such a device.

Direct gas withdrawals should generally be done at relatively slow gas flow rates (approximately 79 kg/h) to avoid liquid SF_6 from entering into the filling line or the gas compartment due to secondary expansion within the system.

If gas is taken from the top of a storage tank it will be taken in its gaseous form. As gas passes through the gas transfer systems, it will have to flow through several restrictions such as ball cocks, valves, etc. These devices reduce the flow diameter at a certain point followed by an increase in flow diameter leading to gas expansion within the gas flow system. This secondary expansion causes the gas temperature to drop low enough to liquefy the gas in that area.

In general, it takes longer to wait until the temperature of the gas has been equalized with the room temperature than to withdraw SF_6 at slower speeds. If gas filling speeds of more than 79 kg/h (175 lb/h) are desired, thermostatically controlled evaporators are required to keep the gas at approximately ambient temperature. This avoids the accidental condensation of gas during gas compartment filling.

In other cases, the SF_6 may be withdrawn from the cylinders into a gas transfer device, also referred to as a gas transfer cart, before it is used for filling GIS apparatus. The use of a transfer system facilitates the removal of SF_6 from the cylinders after the pressure has become equal to that within the GIS equipment. In such a procedure, caution should be used to avoid overfilling the GIS apparatus, and the manufacturer’s recommendations should be followed.

4.4.3 Gas-handling equipment

Due to the importance of having clean gas for proper operation and due to the cost of the SF_6 gas, it is essential that means be available to handle the gas properly for environmental reasons, to avoid loss and contamination during initial filling, and to permit the recovery of as much gas as possible from the GIS system during maintenance. For this purpose, a gas transfer cart is generally used for handling, storing, and processing the new or reclaimed gas.

4.4.3.1 Gas transfer cart

Gas transfer carts are available in a variety of sizes and models from a number of manufacturers. The carts generally consist of trailer-mounted storage tanks (approved by the ANSI/ASME 1992 Boiler and Pressure Vessel Code), electrically driven gas compressors and vacuum pumps, liquefaction equipment (refrigeration unit or other means), control valves, filters, dryers, electrical controls, and accessories such as appropriate gauges and indicators.

Gas transfer carts are widely used to fulfill the following functions:

a) Removing SF_6 from the GIS compartment and storing it in a storage tank or in SF_6 gas cylinders
b) Recharging the gas compartment with the stored gas
c) Drying, filtering, and purifying of the SF_6 gas
d) Evacuating moisture and air from the gas compartment prior to refilling

In selecting a transfer cart for use with GIS systems, it is important to note the capacity requirements of the installation and the capability of the available transfer carts. GIS systems are usually compartmentalized in such a way that, during maintenance, only a part of the total gas volume needs to be handled at one time. When large quantities of gas are to be withdrawn from the GIS apparatus, suitable storage facilities should be planned in advance to accommodate the gas which, even when liquefied, may exceed the capacity of the gas transfer cart.

The capacity of the vacuum pump should be evaluated when determining the size of the transfer cart to be used with a given GIS system. The time required for maintenance is directly related to the vacuum pump capacity and the volume of the GIS gas system since the vacuum pump is used for the recovery of SF_6 from the GIS apparatus and for removing air from the GIS prior to filling with SF_6. Appropriate bypass valves should be available on the gas transfer system to permit the recovery of gas from pressurized GIS apparatus without involving the vacuum pump in the system.

A scrubber-dryer with a molecular sieve that is capable of removing both moisture and trace amounts of arc decomposition products should be available in the gas transfer cart. To facilitate gas processing, it may be desirable that the dryer be of the regenerative type and that suitable valves be provided so that the moisture absorbed by the dryer can be removed by the vacuum pump. More than trace amounts of SF_6 decomposition byproducts should be removed using a commercial filter unit designed for this purpose; the filter materials from such a unit should not be regenerated.

Suitable precautions should be built into the gas transfer cart so that contamination of the SF_6 by the compressor lubricant is avoided. Additional precautions should be observed during any vacuum pump operating sequence to ensure that compressor lubricant is not inadvertently drawn into the SF_6 gas system. The design of the gas transfer system should be such as to avoid this possibility; however, the instructions of the equipment manufacturer should be closely followed.

4.4.3.2 Gas filter units

A gas transfer cart should have internal gas filters to accommodate the following specifications:

a) Removal of any solid products larger than 1 μm before the gas enters the pumps and the storage vessel
b) Removal of moisture from within the SF_6 to values less than 10 ppmv
c) Removal of gaseous decomposition products from the SF_6 such as HF, SO_2, SO_2F_2, SF_4, and WF_6

These internal gas filters will have to be maintained relatively frequently. Therefore, their construction should follow the following guidelines:

- They should be placed in an easily accessible location within a gas transfer system.
- The gas filters should use cartridges containing the actual filtering material to allow fast and easy on-site change of filters.
- It should be possible to replace internal cartridges without disconnection of any tubing within the gas circuit.

General considerations for SF_6 reclaiming are given in the following table.

To remove	Technique used
Moisture (H_2O)	Desiccant material such as Al_2O_3, also called drying agent. The recommended particle size is 2–5 mm.
Gaseous arc byproducts	Molecular sieve with a pore size of 4 Å can chemically absorb these gases into solid products. Material used for this purpose should not be regenerated.
Particles (generally dust residues) or solid arc byproducts	HEPA-type filter to remove particles with a size larger than 1 µm.

A gas transfer system should have two internal filtering sets, one within its gas input section and another one on the gas output section. This forces the SF_6 to be filtered twice during a complete gas transfer session. If solid arc byproducts are anticipated within a gas compartment, it is recommended to use an external hose and byproduct filter to avoid polluting the connection hoses and gas couplings with potentially toxic particles.

If a large quantity of molecular sieves is used, regeneration may be warranted. If not, replace the used agents with new material and dispose of the used material as toxic waste according to local regulations. Materials used as desiccants can be regenerated according to the gas cart manufacturer's instructions. The safest way to know if the filters used to reclaim the SF_6 are working according to specifications is to check the various conditions of the gas before and after having used the filters. This procedure should involve the following checkpoints:

- Moisture content of the gas before and after filtering
- Amount of decomposition byproducts before and after filtering
- Purity of the SF_6 gas by percentage of SF_6

SF_6 gas analyzers are commercially available and can be used for periodic checking on the above-mentioned criteria during standard GIS operation.

4.4.4 Filling with SF_6

The quality of the SF_6 dielectric is directly related to the performance of the GIS gas transfer cart; therefore, proper filling procedures should be observed during the charging of the GIS gas compartments both during initial installation and during maintenance. Although the details of the filling procedure may vary depending on the type and function of the gas transfer cart, the considerations in the following subclauses are generally applicable. In any case, the manufacturers' recommendations should be followed.

Pressure relief means should be provided at the GIS compartment to prevent overfilling of the compartment.

4.4.4.1 Evacuation sequence

A clean service hose is connected and sealed to the gas compartment and the air is evacuated from the gas compartment, service hose, and associated piping by the vacuum pump of the transfer cart. This vacuum, as recommended by apparatus manufacturers, will be maintained for several hours to ensure that the moisture level within the equipment is appropriately reduced (in some cases, it is appropriate that dry air be used to purge the gas compartment prior to evacuation). The vacuum pump system is then valved off. A vacuum gauge on the compartment side of the valve should be monitored for a number of hours. A constant rate of pressure increase indicates a leak. An initial rapid pressure rise, which then levels off, is indicative of moisture being driven off the interior surfaces of the compartment.

The time needed to evacuate a gas compartment from foreign gases and moisture is mainly affected by the amount of moisture that has to be vaporized and removed during the process as well as the volume of a gas compartment. A common misunderstanding is that the evacuation time decreases directly with the suctioning capacity of the vacuum pump. This correlation, however, applies only to the time needed to achieve a desired vacuum. The vacuum level should then be held constant to allow existing moisture to be vaporized and removed from the gas compartment. But this process does not differ with the capacity of the vacuum pump. The removal of the moisture vapor out of the gas compartment generally occurs through migration of the moisture to a drier spot (vacuum pump), not from actual gas flow (there is no gas left in a vacuum).

Experience shows that it is most efficient to use gas hoses that are as short as possible, and that it is of no practical value to use vacuum pumps that are larger than 17.5 L/s (37 ft^3/min). It has been found that the diameter of the hoses and the types of gas connections used do not influence the evacuation time as much as the distance between the vacuum pump and the gas compartment.

4.4.4.2 Filling sequence

The valves between the gas transfer cart and the GIS gas compartment are to be opened. The gas is then directed through the dryer and purifier elements prior to entering the GIS. The storage tank heater of the gas transfer cart is energized to raise the pressure within the storage tank and to vaporize the liquid SF_6. A considerable quantity of SF_6 is transferred during this equalization phase. When the storage tank contains a substantial amount of SF_6, it may be necessary to use heaters or pumps to complete the filling of the compartment.

To achieve the required fill density, the gas pressure and temperature curve from the manufacturer’s instruction book should be used. Sufficient time should be allowed for equalization of the gas temperature.

4.4.4.3 Moisture checks

It should be noted that a check of the moisture content of the gas within the GIS only at the time of filling can lead to a false conclusion regarding the true moisture content of the system. Several measurements should be taken hours, days, and even weeks after the filling process, to ensure that the moisture content of the SF_6 has remained acceptably low. The moisture adhering to the inner walls, buses, insulators, etc., of the compartment will tend to increase the moisture content of the gas over a period of time. Equipment that has internal surface paint, fiberglass insulation, etc., tends to absorb more moisture and hence should be monitored over longer periods to ensure that the gas remains acceptably dry. If the moisture content of the gas rises to an unacceptable level, the SF_6 should be circulated through the dehydration portion of the gas transfer cart to remove this excess moisture. The length of time required for this process depends on the amount of moisture absorbed by the gas. See also IEEE Std 1125-1993.

4.4.5 Removal of SF_6

The removal of SF_6 from the GIS apparatus should be undertaken in accordance with the recommended procedures specified by the equipment manufacturers. The following considerations are applicable:

- Before removal, gas sampling and analysis are to be performed.
- Care should be taken to avoid re-use of SF_6 that contains arc products or other contaminants unless such gas is properly purified, filtered, and tested.
- Unclaimed SF_6 should be disposed of in accordance with applicable ordinances and should not be released to the atmosphere.

The removal sequence is as follows:

a) A service hose is connected and sealed to the gas compartment from which the SF_6 is to be removed. The air is evacuated from the service hose and the associated piping by the vacuum pump of the transfer cart.
b) The pressure of the gas in the storage tank and the GIS compartment are compared. If the GIS pressure is higher, the first phase of the transfer is simply an equalization of pressure between the cart and the GIS. This phase of the transfer is generally rapid.
c) After equalization, or if the storage tank pressure is higher than the GIS compartment pressure, the compressor is utilized.
d) When a major portion of the SF_6 has been transferred, the GIS pressure is reduced to atmospheric pressure. At this point, the vacuum pump is utilized together with the SF_6 compressor to transfer the remaining gas, evacuating the compartment to approximately 133 Pa.
e) After isolating the transferred SF_6, air may be admitted into the GIS compartment. It is recommended that dry air be used to fill the GIS at this point. In some gas transfer systems, it is possible to pass air through the dehydration portion of the system before admitting it to the GIS. This procedure of using dry air will minimize the buildup of moisture in the GIS apparatus and thereby reduce the gas processing necessary when the equipment is being refilled with SF_6.

4.5 Safe operating procedures

The recommendations in this clause are not intended to replace or invalidate present applicable standards of safety, but rather to augment such standards with respect to the special factors involved in the installation, operation, and maintenance of gas-insulated substations.

The high degree of safety inherent in gas-insulated substations may tend to lure operating personnel into unsafe working habits. Care and vigilance are still necessary to avoid accidents.

The location of circuit-breaker current transformers should be considered when specifying gas-insulated substations. During maintenance of the circuit breaker with the isolating disconnect switches open, the ground switches closed, and the circuit breaker closed, a loop path is provided for the primary of the current transformer. When the current transformers are located between two grounding switches, this loop can disturb normal relay operation. This problem can be avoided by electrically locating the current transformers between the isolating disconnect switch and the grounding switch, or by the use of current transformer test switches that short-circuit the current transformer's secondary leads and open the circuit to the relays during breaker maintenance.

All switches, including disconnecting and grounding switches, should be provided with some means of switch contact position indication.

NOTE — If the user selects viewports as the means of switch contact position indication, a weatherproof sign (green or white background with black lettering) should be installed near each viewport to warn of possible danger when viewing the interior during switch operation. The suggested wording is as follows:

WARNING
Do not look into the viewport during switch operation. Arcing may damage your eyes.

The area around the viewport should be painted a distinctive color as a warning (orange or yellow). Facilities should be provided to allow safe access to viewports as specified by the user.

4.6 GIS grounding

4.6.1 User responsibilities

The user should furnish information to the GIS supplier on locally installed ground sources and the expected magnitude of ground current. Also, the user should review the substation grounding provisions with the manufacturer. The user should furnish materials for the grounding system that will:

a) Provide for connections to the pads and/or connectors furnished by the manufacturer
b) Comply with the grounding specifications mutually agreed to by the manufacturer and the user
c) Ensure safe step-and-touch voltage gradients under normal and abnormal operating conditions external to the GIS assembly
d) Be capable of dissipating surges caused by lightning and switching
e) Provide for the neutral currents of grounded circuits and apparatus
f) Provide for the requirements of protective relaying
g) Provide for ground connection of all platforms and structures, metallic sheaths, and shielding for cable terminations where applicable
h) Provide for the requirements of telephone and other communication facilities
i) Provide grounding of the reinforcing steel of the foundation and support structures of the GIS building, if applicable

4.6.2 Manufacturer responsibilities

The manufacturer has the following responsibilities:

a) Provide the subassembly-to-subassembly ground connectors to ensure safe voltage gradients between all intentionally grounded parts of the GIS assembly, between all parts of the GIS assembly, and between all parts and the main ground bus of the GIS.
b) Specify clearly what constitutes the main ground bus of the GIS, and reach agreement with the user on requirements for connecting the GIS assembly to the station ground.
c) Furnish documentation to ensure that any recommended connections from the main ground bus to the station ground will not interfere with required enclosure current paths or any operational feature of the GIS design. This may be especially pertinent if the main ground bus consists of a system of interconnections between the GIS subassemblies and no separate continuous ground busbar is provided.
d) Provide ground pads and connectors (per NEMA CC 1-1993) for at least two paths from the main ground bus to the station ground, or alternatively, from each metal enclosure or auxiliary piece of equipment to the station ground.
e) Recommend proper procedures for connections between dissimilar metals, typically between a copper ground cable and aluminum enclosures.
f) Provide readily accessible connectors having sufficient strength to withstand electromagnetic forces and normal abuses at a point of application.
g) Provide surge arresters across the insulating joint of enclosures to eliminate VFT sparks due to switching or circuit-breaker operation.

4.7 Seismic requirements

The following subclauses contain procedures and guidelines for the seismic design, analysis, and acceptance of gas-insulated substations to ensure functional adequacy under seismic disturbances. General recommendations on seismic design of substations are provided in IEEE Std 693-1984 .

A brief introduction to seismic fundamentals is provided. Engineers familiar with general calculation methods and design and construction of supporting structures are the intended audience. Special knowledge of the GIS technique is not required. The intention is to provide a survey of the various aspects of seismic phenomena and approaches to meet the requirements in order to make GIS plants resistant to earthquakes. This survey does not relieve the reader from the necessity of accessing particular knowledge as appropriate, and as available in the literature on a broad scale.

Standard earthquake ground motion criteria are presented for equipment purchase specification. Delineation of performance requirements necessary to qualify equipment is provided. The various methods for qualifying or demonstrating the adequacy of the design of the equipment are listed, including analytical methods, testing methods, and a combination of both.

Finally, suggestions or thoughts on design philosophy including working stresses, failure modes, reserve strengths, recommended design, construction practices, and recommended installation practices are included.

4.7.1 GIS features

Several fundamental features distinguish seismic behavior of a GIS from a conventional air-insulated station (AIS). Among such considerations are:

a) A GIS is a compact, multicomponent system coupled together so that strong dynamic interaction occurs between adjoining components, walls, and foundation. The GIS is usually of a size that full-scale proof testing is not possible, except possibly to identify natural frequencies and damping factors.
b) The GIS is characterized by a large number of sealed joints. The integrity (structural and gas sea]) of these joints shall be retained.
c) High dielectric stress exists between closely spaced components that might exhibit relative motions, reducing the dielectric withstand during a seismic disturbance.
d) The thermal expansion of enclosures may call for flexible connection to the foundation to avoid excessive forces in enclosures and joints. On the other hand, a flexible design may result in unacceptably high displacements during a seismic event.

4.7.2 Criteria for seismic stresses

4.7.2.1 Seismic information user should provide to equipment manufacturer

The user should provide information to the manufacturer that will adequately describe the seismic environment which the equipment will be expected to withstand. The information should at least comprise the maximum acceleration and response spectra or time history (see 4.7.2.1.2 and 4.7.2.1.3). The maximum vertical ground acceleration should be selected as 67% of the maximum horizontal design acceleration.

4.7.2.1.1 Response at mounting location

If the equipment is not mounted on the ground, the response at the mounting location (e.g., floor response) should be used. The user should provide this information to the equipment manufacturer.

4.7.2.1.2 Time history

The time history is a way of describing a particular earthquake. A particular earthquake time history may not be truly representative of the earthquake the equipment may experience during its service life since characteristics of real earthquakes vary from one earthquake to another. The following earthquake characteristics are of major concern:

a) Maximum horizontal acceleration
b) Maximum vertical acceleration
c) Frequency content
d) Duration

To allow for the variables listed in a) through d) above, the worst possible earthquake ground accelerations can be incorporated into groups of ground motion earthquake time histories (ensembles) of different frequency content and duration. These individual time histories can then be used in conjunction with each other to simulate or represent the effect of the design earthquake.

To use the time history method, four of the eight ground motion acceleration time histories used to develop the response spectra of figure 3 can be obtained, in a form suitable for computer processing, from the California Institute of Technology in Pasadena, California.

The earthquake records that may be used in testing a mathematical model are as follows:

— The El Centro, California, 1940 NS (multiplied by a factor of 1.12)
— The Olympia, Washington 1949 N86E (multiplied by a factor of 1.96)
— The Helena, Montana, 1935 EW (multiplied by a factor of 3.03)
— The Pacoima Dam, California, 1971 S16E (multiplied by a factor of 0.46)

For other than Zone 4 users (figure 4), the above acceleration time histories should be scaled by the factors given in 4.7.2.2, item c). These earthquakes occurred in the western United States, and may not be representative of earthquakes in other parts of the United States or other regions of the world.

In lieu of recorded time histories, it may be more practical to use one or several artificial (synthetic) ground motion time histories with response spectra, frequency content, and duration consistent with the specified design response spectra (see 4.7.2.1.3) and the recorded time histories mentioned above.

The maximum ground acceleration is the maximum value of acceleration input to the equipment during a given earthquake for a particular site. Typical design values of maximum acceleration range from 0.1–0.5 g (g is the acceleration due to gravity), with values over 0.5 g being required in some special cases.

4.7.2.1.3 Response spectrum

Another description of an expected earthquake environment is a response spectrum. A response spectrum (see figure 3) is obtained utilizing a time history. The response spectra shown in figure 3 are smoothed response spectra representing the average response spectrum shapes calculated from eight time histories.

The maximum ground acceleration of the earthquake can be obtained by reading the zero period response acceleration (typically taken as the acceleration of bodies with frequencies over 30 Hz) at any damping. The required response spectra (RRS) in figure 3 can be extra-interpolated linearly to obtain a seismic intensity that deviates from 0.5 g. The frequency content of the ground motion is indicated by the shape of the response spectrum curve. Earthquake duration and mechanism cannot be determined from a response spectrum.

4.7.2.1.4 Other conditions

a) *Soil structure interaction (SSI)*. Amplification of a structure’s seismic response can result from interaction between the vibrational characteristics of the structure and those of the foundation and soil. This amplification can be dependent on the following:

1) The ratio between the effective soil plus the foundation mass and the equipment mass
2) The ratio between the effective soil stiffness and the effective equipment stiffness
3) The effective soil damping

To minimize possible deleterious effects of soil structure interaction, the GIS can be installed on a monolithic foundation, and/or custom-grade soil (selected fill) can be used, upon which the foundation will rest to increase its rigidity.

b) *Displacement limitations*. Restrictions that impose displacement limitations on equipment (see 4.7.5.1) are as follows:

1) Alignment of moving parts
2) Impact with adjacent equipment
3) Interconnections to equipment on separate foundations

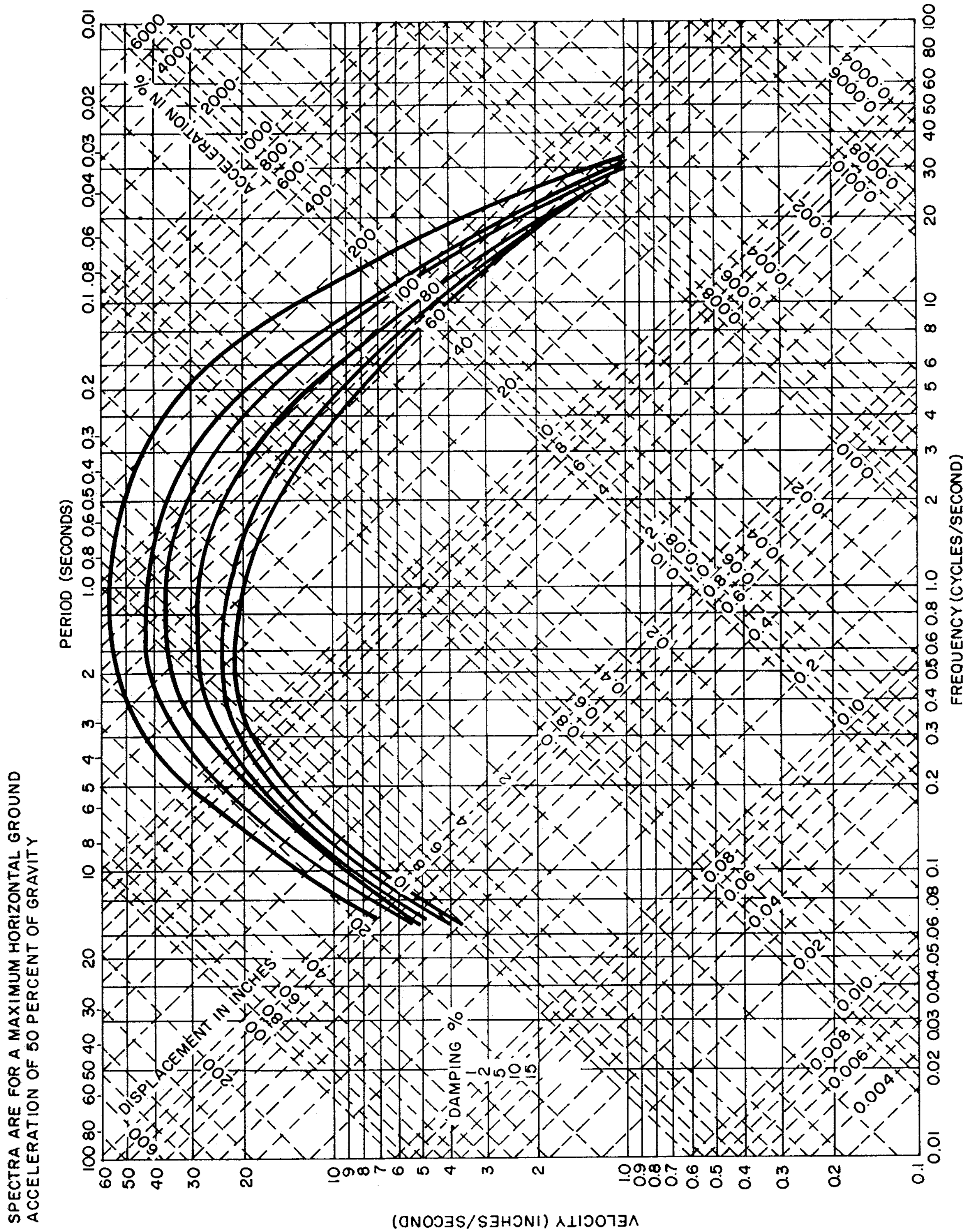
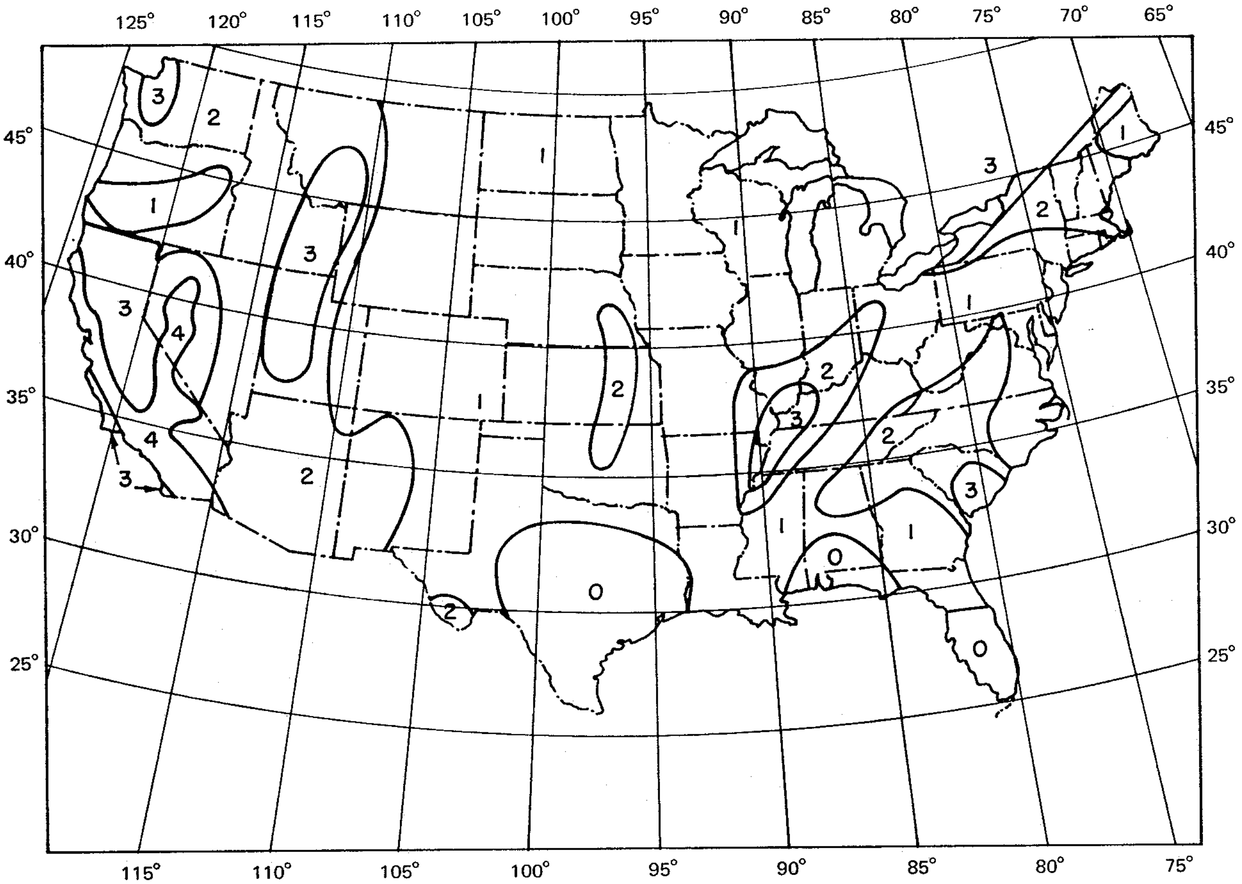


Figure 3— Seismic response spectra



ZONE 0 No damage.
ZONE 1 Minor damage, distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 second, corresponds to intensities V and VI of the M M* Scale
ZONE 2 Moderate damage, corresponds to intensity VII of the M M* Scale
ZONE 3 Major damage, corresponds to intensity VIII and higher of the M M* Scale
ZONE 4 Those areas within Zone No 3 determined by the proximity to certain major fault systems.

*Modified Mercalli Intensity Scale of 1931

Figure 4— Seismic zone map of the United States from the *Uniform Building Code*™, 1991

c) *Soil and foundation failures.* Soil failures that can be detrimental to equipment are as follows:

1) Fault rupture
2) Liquefaction of soil
3) Landslides
4) Foundation failures (such as foundation breaking or exceeding the bearing capacity of the soil)
5) Differential settlement

d) *Drawings.* Drawings of support structures and foundation(s) should be furnished by the equipment manufacturer as applicable.

4.7.2.2 Site evaluation for site-oriented equipment

When determining the maximum earthquake risk, the user should consider the adoption of earthquake criteria arrived at by any one of the following three methods. The results of a site-specific analysis (Method 1) should take priority over Methods 2 and 3. The results of a microzonation study (Method 2) should take priority over the results of a macrozonation study (Method 3).

a) *Method 1—site specific analysis.* A special seismic study for a particular site considering the local seismic history, geology, and dynamic properties of the soil.
b) *Method 2—Microzonation.* A seismic study that produces a seismic-relief map of the area (e.g., the size of a utility company's service area). Such a map should contain at least three to six values of known earthquake disturbances. The study should consist of a less intensive investigation of seismic history and geology than Method 1.
c) *Method 3—Macrozonation.* A seismic study, usually developed by a public agency, covering large areas, as is typically followed in building codes. The use of macrozone maps such as those included in the 1991 *Uniform Building Code*™ (see figure 4) or similar international documents is recommended. The response spectra should be applied as in table 1. For zones I through 3, a range of acceleration is given since there are no specific values for all applications. If very conservative values of acceleration are justified, the upper limit should be chosen. Otherwise, a mean value of the given range may be applied.
   The response spectra in figure 3 are from earthquakes in the western United States; they may not be representative of earthquakes in other regions of the world.

4.7.2.3 Differential motion in the ground

Seismic response spectra cannot be used to estimate actual motion in the ground, but only to assess the vibratory displacement and velocity response relative to the ground motion. In order to estimate the forced motion of the ground caused by seismic shear waves, information concerning effective shear wave propagation velocity is needed. This information may be obtained in a geological investigation of the site. Some typical values are given in table 2. Outgoing from the effective shear wave propagation velocity, the differential motion between two points (foundations) in the ground, and other types of motion, may be calculated using recorded or synthetic ground motion time histories. Alternatively, various types of motion in the ground may be estimated directly with formulas given in the literature using the maximum particle motion in the ground (for peak acceleration, velocity, and displacement, see table 3), together with the shear wave propagation velocity. The vertical ground motion may be selected as 67% of the horizontal ground motion. The ground particle motion may be assumed to be proportionate to the maximum acceleration (see table 1).

4.7.3 Performance requirements

Equipment seismic classifications and the criteria of adequacy that the GIS shall satisfy are described in the following subclauses. Adequacy means the capability of each critical component of the GIS to perform its principal functions during and after the design earthquake.

Table 1— Acceleration values

Zone	Acceleration
4	50
3	25–40
2	10–20
1	5–10
0	Local building code

Table 2— Typical effective shear wave propagation velocity for different soil types

Soil type	Shear wave propagation velocity
Compact granular soil	300 m/s (1000 ft/s)
Salty sand	150 m/s (500 ft/s)
Medium clay	75 m/s (250 ft/s)
NOTE — The given velocity corresponds to estimated effective strain level in soil during an earthquake with maximum ground acceleration of 0.5 g.	

Table 3— Maximum horizontal ground motion consistent with response spectra in figure 3

Frequency range	Amplitude
Above 1.6 Hz	Peak acceleration = 0.5 g
0.3–1.6 Hz	Peak velocity = 20 in/s (0.5 m/s)
Below 0.3 Hz	Peak displacement = 10 in (254 mm)

4.7.3.1 Component seismic classifications

Component seismic classifications may be different depending upon application. The two seismic classes discussed below are based on the importance of maintaining service. The following lists do not to cover all equipment in either the Class A or Class B category, but are merely a guide for the user considering components that may be unique to the user's system.

4.7.3.1.1 Class A components

Classification of components or systems in this category is determined on the basis that their failure, malfunction, or need for repair prevents the proper operation of the GIS during or after the design earthquake. The designs for installation of Class A components/systems should be in accordance with the recommended practices described herein.

The Class A components/systems are as follows:

a) Circuit breakers
b) Disconnecting switches

c) Gas supervision system
d) Current transformers
e) Potential devices
f) Internal surge arresters
g) Relay protection system
h) Enclosed bus
i) Grounding switches
j) Fast-acting grounding switches
k) Entrance bushings

4.7.3.1.2 Class B components

Classification of components or systems in this category is determined on the basis that their failure or need for repair does not prevent the proper operation of the GIS during or after the design earthquake. The user should evaluate the cost of adequate seismic withstand designs against the cost of possible repairs. Thus Class B components/systems may be designed to meet either a lower-level design earthquake or the seismic standards in IEEE Std 693-1984.

The Class B components/systems are as follows:

a) Metering not associated with the relaying protection system
b) Catwalks and ladders
c) GIS lighting
d) External surge arresters

4.7.3.2 Criteria of adequacy

The GIS has survived the design earthquake if, during and for 72 h immediately following the design earthquake, all Class A components and systems continue to operate properly and if the proper operation of connected systems, assemblies, subassemblies, and components is not disturbed.

Failure of Class B components and systems, though not desirable, may be tolerated insofar as such failure would not affect the proper operation of Class A components and systems. Deformation, gas leakage rate in excess of normal, and minor reduction of dielectric strength (but not below that necessary for normal switching surge voltage) may be tolerated as long as there is no detrimental effect on proper operation of Class A components and systems.

The seismic adequacy of individual components is a necessary, but possibly not a sufficient, criterion for the seismic adequacy of a GIS. System behavior will play a major role in defining the required performance of an individual component. Thus the response characteristics for adjoining components to which the component is coupled are required. Therefore, a complete definition of the response characteristics for a system of individual components will require an interactive combination procedure involving close interaction between the systems engineer and the component manufacturer.

Because of the large size and unique character of the intercoupling between the components of a GIS, full-scale proof-tests, as normally conceived, may be impractical, and special considerations become necessary to fully ensure the adequacy of the system. Methods of piece-wise analysis and testing with special accommodations to properly match boundary conditions are required. A proper definition of the boundary conditions for each component will require a full system analysis or, alternatively, scale-model tests. In either case, such studies should include sufficient precision to ensure that the component evaluation is based on a reasonable worst-case limit.

The criteria of adequacy are as follows:

a) *Permanent deformation/misalignment.* Permanent deformation of GIS components will be acceptable provided that no impairment of essential function results. Thus all switches, breakers, and metal components should be operable.

b) *Motion limitations.* Relative motion should be limited so that it does not cause any impairment of essential functions. In particular, special attention should be given to the following different kinds of relative motions for power, control, and protective circuitry:
   1) Coupling between components mounted on a common monolithic slab
   2) Coupling between components mounted on adjoining foundation slabs so that relative motion can occur at the foundation line
   3) Connection between a GIS and an overhead line (this is principally a question of ensuring adequate line slack, basically decoupling the overhead line from the GIS)
   4) Getaway connections from a foundation slab to an underground bus run
   5) Connections to an underground cable run
   6) Extended underground bus runs interacting with the surrounding soil

c) *Gas leakage.* Leakage should not prevent the operational capabilities of the GIS, including the ability to withstand minimum dielectric requirements, the ability to interrupt the maximum specified fault, and the normal ability to switch, isolate, and protect.

d) *Dielectric strength.* Dielectric strength should not be reduced below rated switching surge voltage due to design earthquake. Degradation of dielectric strength could arise from displacements between closely spaced components of different potential, spalling of insulators, or abrading of moving parts that produce floating particles.

e) *Superimposed loads.* Conditions that could reasonably be expected to occur simultaneously with the design earthquake should not cause impairment of essential functions. Possible conditions are identified in 4.7.5.3.

4.7.4 Qualification methods

The use of the methods and procedures described in IEEE Std 344-1987 is acceptable and satisfies the requirements of this guide. Alternately, the following methods will also serve to demonstrate the adequacy of the GIS.

4.7.4.1 Methods for demonstration of adequacy

The adequacy of the GIS can be demonstrated by one or a combination of analytical methods (see 4.7.4.3) and seismic proof-testing (see 4.7.4.4).

4.7.4.2 General qualification procedures

4.7.4.2.1 Modeling procedure

This method comprises modeling of each major component of the GIS by mathematical means. A dynamic analysis should be performed if the assembly cannot be considered a rigid body. The resulting subassemblies should be analyzed using the response spectrum method or the time history method, described in 4.7.4.3.3.

a) *Natural frequency.* The number of elements and degrees-of-freedom should be sufficient to adequately represent the important modes of vibration with resonant frequencies below 30 Hz, and account for the rigid elements (resonant frequencies greater than 30 Hz) in the system. In some applications it may not be practical to assess all natural frequencies below 30 Hz (this may involve more than 100 vibration modes), which may be acceptable if it is demonstrated that the modes that were considered properly account for the significant response of the GIS structure.

Calculated frequencies may be verified by measurement on the actual assembly. Normally, the measured values are smaller than the calculated values. The verification can be omitted if modeling of the plant is carefully done, based on experience.

b) *Damping.* Damping is the generic name ascribed to complex energy dissipation mechanisms in a system. Damping depends on many parameters such as structural system, mode of vibration, strain, stress, velocity, and materials. For assemblies with many components, there is usually no single value of damping. Damping is associated with every part of the equipment, ranging from bolted construction to uniform material. When a value of damping is ascribed to equipment, it is common to give a range of typical values. A useful practice is to associate a value of damping to each mode of vibration in the frequency range of interest.

Without any detailed measurements to the contrary, the damping associated with any joint should not exceed the percentages of critical damping given in table 4. These levels may be assumed as a basis for computations without further justification. Claims of greater damping levels should be justified by documented tests (see 4.7.4.5).

For a typical GIS structure with numerous welded and bolted joints, a damping factor of 5% may be used for major vibration modes (in which a major part of the structure is participating in the response).

Table 4— Damping factors

Type of construction	(% critical damping*)		
	Below 1/4 yield	At 1/2 yield	At full yield
Welded joints	0.5–1.0	2.0	5.0
Torqued bolted joints	0.5–1.0	5.0–7.0	10.0–15.0
Reinforced concrete with cracking	0.5–1.0	3.0–5.0	7.0–10.0
Prestressed concrete	0.1–1.0	2.0	5.0–7.0
Brittle components (failing at yield)	0.5–1.0	0.5–1.0	7.0–10.0

*See [B19].

4.7.4.2.2 Adjacent equipment

In testing and analysis, adequate consideration should be made of the effects of any adjacent equipment coupled to the GIS structure (subassembly).

4.7.4.2.3 Dynamic response

Determine the dynamic response of subassemblies in sufficient detail to assess the maximum loading on each component (where particular relative motions are significant, these should also be determined). The design earthquake seismic excitation already includes the vector addition of the two horizontal components of the disturbance. Hence, although it is necessary to consider two mutually perpendicular horizontal directions, it is not necessary to combine the horizontal responses. This response should be suitably combined with the vertical response to determine the maximum loading. Refer to 4.7.4.3.3 item a), if modal analysis is used, or to 4.7.4.3.3 item b), if time history analyses are used.

4.7.4.2.4 Component load strength capability

Establish the capability of each component to accommodate the most severe loading condition resulting from the performance criteria described in 4.7.3.2 without loss of critical function.

4.7.4.3 Analytical methods

The generally large size of GIS installations may make full-scale proof-testing qualification impractical. The difficulties of such testing, therefore, underscore the need for analytical qualification.

4.7.4.3.1 Static analysis method for rigid equipment

An assembly may be considered rigid if it is completely self-contained on a single monolithic foundation corresponding to the following conditions:

a) Effectively decoupled mechanically from adjoining structures
b) Found by test or acceptable analysis to have all significant resonant frequencies of vibration greater than 30 Hz

In this case, the natural frequencies of the equipment (including its supports) are such that the applicable response spectrum gives no amplification of the maximum acceleration and the equipment should be analyzed statically. The vertical input should be 67% of the horizontal input. The horizontal and vertical response should be considered to occur simultaneously. If significant, the seismic stress should be added to the equipment’s operating stresses, and determination should then be made of the adequacy of the strength of the equipment. The means used to establish the resonant frequencies should be documented.

When the assembly is mounted on more than one monolithic foundation, or when the assembly is not effectively decoupled mechanically from the adjoining structure, it should be proven that the coupling can accommodate the maximum relative motion with respect to the adjoining equipment without imposing loading in excess of the limits specified in 4.7.5. The user is responsible for defining the maximum relative motion of equipment on adjoining foundations that interface with the equipment being qualified.

4.7.4.3.2 Static coefficient analysis method for all equipment

Regardless of the natural frequencies of the equipment, the analysis may be performed by applying a static coefficient of 1.5 times the maximum peak of the applicable response spectrum in order to account for multimode response. Proper damping values may be used. The vertical response spectrum should be selected as 67% of the horizontal. The horizontal and vertical responses should be considered to occur simultaneously. A stress analysis is then performed with these calculated seismic forces.

NOTE — Caution should be taken in using this method for complex structures since it may yield nonconservative results, even with a static coefficient of 1.5.

4.7.4.3.3 Dynamic analysis method

In this case it is necessary to develop an adequate dynamic model of the equipment, representing the natural frequencies and the damping associated with each significant mode of vibration. The model can be used with either of the following two methods to determine the equipment’s response to the design earthquake.

a) *Response spectrum method.* A suitable method for dynamic analysis is the modal superposition procedure, the so-called response spectrum method (analysis), as described in Chapter 27 of [B26]. The maximum modal response is determined using the horizontal response spectrum shown in figure 3 or other applicable response spectra as directed by the user.

The vertical response spectrum is selected as 67% of the horizontal. Preferably, all modes up to 30 Hz should be considered, but if justified, a lower number of modes may be used. If necessary, the residual mass should be included in a static analysis and added to the other loads on an absolute sum basis.

The codirectional responses resulting from three orthogonal components of earthquake ground motion should be calculated (two in the horizontal and one in the vertical direction). The resultant seismic response should be the one due to the vertical and the most unfavorable horizontal direction combined using the square root of the sum-of-the-squares-procedure (SRSS).

b) *Time history method.* Apparatus modeled as a subassembly (see 4.7.4.2.1) may be analyzed by the time history method. This means that any three of the four horizontal design time histories as described in 4.7.2.1.2 should be used to compute the response of this structure. While the time histories for the horizontal response should be used as they are, they may be scaled to 67% of their value to compute the vertical response. The vertical response should be considered to act simultaneously and will be combined algebraically at each instant in time with the horizontal response. Each of the two perpendicular horizontal directions may be analyzed this way. The results of the two analyses need not be combined. Different time histories may be used for each horizontal direction and the vertical direction may be analyzed with an ensemble of at least three of the time histories of 4.7.2.1.2.

Alternatively it may be more practical to use a synthetic (artificial) ground motion consistent with the specified seismic ground motion (e.g., the seismic response spectrum according to figure 3).

4.7.4.4 Seismic testing

There are many procedures for seismic vibrational testing of equipment. In the following subclauses, some acceptable methods are briefly identified, with special emphasis on proof-test of comparatively light control equipment (relays, gauges, etc.) since this type of equipment is the most likely to be verified with tests. In general, all test methods and procedures directed in IEEE Std 344-1987 , IEC 68-1 (1988), IEC 68-2-6 (1982), IEC 68-2-47 (1982), IEC 68-2-57 (1989), IEC 68-2-64 (1993), IEC 68-3-3 (1991), and IEC 1166 (1993) are acceptable and satisfy the requirements of this guide.

4.7.4.4.1 General testing requirements

There are several general requirements to observe when performing a proof-test, e.g., equipment mounting and orientation, the input levels required for single-frequency and multiple-frequency proof-testing, and single- or multiple-axis proof-testing.

a) *Mounting.* The component or subassembly being tested should be mounted in a manner that actually, or as closely as possible, simulates the intended service mounting. The method of mounting the equipment should be documented, including a description of any interposing fixtures. The effect of such fixtures has to be evaluated if they are only used during qualification and not for in-service mounting.
b) *Orientation.* Tests should be performed in the vertical and in the mutually perpendicular horizontal directions, which should either be the principal axes of the equipment or other directions that produce the worst condition. The orientation should be documented and is the only orientation for which the equipment is qualified unless adequate justification can be made to extend the qualification to an untested orientation. However, if the equipment is proof-tested in the orientation that produces the worst condition, it should be considered to be adequately qualified for all orientations.

4.7.4.4.2 Proof-testing of subassembly

Seismic proof-testing may be substituted for part or all of the analysis. However, in the case of the GIS, it is unlikely that a complete, interconnected system, including foundation effects, can be tested to the required limits of seismic proof-testing. Shake tests on components for subassemblies should be supplemented by sufficient evidence that the total assembly is also adequate. This proof may take the following forms:

a) Provide proof by test or analysis that coupling between the components or subassemblies is sufficiently flexible, compared to other structural bracing to the foundation, so that no significant interaction can occur over the maximum anticipated excursion. This may be satisfied by showing that:
    1) The coupling can accommodate the sum of the relative motions to ground of the two components. If the coupled components do not share a common monolithic foundation, the contribution from this source should also be included.
    2) The natural frequencies of the components or subassemblies are substantially unaffected by the presence or absence of the coupling.
    3) The forces generated by the coupling in accommodating these relative motions are within the strength capabilities of both the coupling and the coupled subassemblies. Such capability can be demonstrated by static test.

b) In the more general situation, the coupling will affect behavior. For this case, analysis will be used to supplement proof-testing. The general procedures of 4.7.4.2 can be followed.

The testing, in accordance with a) and b) above, consists of the following three phases:

— *Phase I—Resonance search before proof-testing.* This phase consists of a low-amplitude, slowly changing frequency search to determine the resonant frequencies. The search is conducted over the frequency range of 0.5–30 Hz, unless a lesser range can be justified. This test is performed separately in the horizontal and vertical directions for which the proof-testing will be performed.
— *Phase II—Proof-testing.* For a subassembly positioned on a foundation directly on the ground, the seismic input motion is likely to have a broad-banded, multifrequency content with a response spectrum similar to the one defined in figure 1. Consequently, the preferable test method is a biaxial multiple-frequency test in one vertical direction and one horizontal direction at a time. The test is performed in two perpendicular horizontal directions. The required response spectrum (RRS) may be defined for a damping factor of 5%. The minimum duration of the test is 20 s. The shake table should produce a motion with a test response spectrum that envelopes the RRS at all frequencies relevant for the dynamic response of the subassembly. Other input signals of the shake table such as single frequency, sine-sweep, and sine beat may alternatively be used if shown to produce conservative response of the subassembly.
— *Phase III—Resonance search after proof-testing.* The frequency search of Phase I is repeated. Structural integrity is indicated if no changes in natural frequencies (resonance peaks) have occurred. If frequencies of resonance peaks have been changed, the reason for this should be investigated and documented in the test report. Possible effect on the function of the tested subassembly should also be evaluated.

To demonstrate the ability of the subassembly to withstand the shake table motion, function testing may be performed before, during, and/or after the test as found suitable and relevant.

4.7.4.4.3 Proof-testing of control equipment

Typical lightweight control equipment and components (relays, contacts, pressure gauges, etc.) mounted on the GIS structure are well suited to be verified by seismic proof-testing since such equipment may be considered as a seismic unit that does not interact significantly with adjoining equipment. Furthermore, the ground motion (horizontal and vertical) may be filtered and amplified by intervening GIS structures to produce fluctuating, sinusoidal motions. The dynamic response of GIS-mounted equipment may reach an acceleration many times that of the maximum ground acceleration, depending upon GIS structure damping and natural frequencies of vibration. The typical narrow-band response spectra that describe a GIS structure motion indicate that single-frequency excitation and quasi-resonance of equipment components can predominate. The magnification and bandwidth depend upon the dynamic response characteristics of each GIS and equipment structure. The seismic environment for lightweight equipment in a building structure is commonly defined by a narrow-band, so-called floor-response spectrum.

The sine-sweep test, as defined in items a) and b) below, is an acceptable and simple method for proof-testing lightweight equipment. For practical reasons, a single-axis test is acceptable. A sine-sweep signal will produce an input signal fairly similar to one expected at the actual mounting on the GIS structure. Furthermore, by performing the test with a continuously changing quasi-resonance frequency, the test will cover many possible applications. It will ensure that the equipment will be subjected to the worst-case exciting frequency that may be produced by a seismic motion.

The test procedures are as follows:

a) *Input signal for sine-sweep test.* Standardized acceleration input levels (see table 5) may be used for equipment mounted on a GIS structure without significant amplification of seismic input at the base due to soil-to-structure interaction or structure-to-structure interaction (e.g., due to a GIS positioned indoors). Two test severity classes are recommended: Class I for application in zones 1 and 2, and Class 2 for zones 3 and 4, as defined by response spectra in figure 1 and with maximum acceleration according to table 1. Alternatively, the acceleration level may be selected as the maximum acceleration assessed in analysis or in tests of the GIS structure, multiplied by a factor of 1.5 to consider uncertainties in analysis and the simplification when using the single-axis test.

b) *Performance of sine-sweep testing.* A single-axis sine-sweep proof-test should be performed in the frequency range of 2 to 35 to 2 Hz with the vibration amplitude as defined in item a) above and a sweep rate of 1 octave per min or less. A more narrow frequency range according to item a) above may be used if properly justified. The test should be performed in the vertical direction and in two perpendicular horizontal directions. If relevant, a function test should be performed during testing as directed by the manufacturer.

c) *Selection of frequency range.* Since many shake tables cannot uphold the specified acceleration level below 5–10 Hz due to limitations in their maximum displacement capacity, a crossover frequency between 8–9 Hz may be used. Below this frequency, a constant displacement amplitude as defined in table 5 should be used for the sine-sweep signal. This practical adjustment is justified since lightweight control equipment, including its mounting fixture, very seldom has any natural frequency below 10 Hz. If the equipment is judged to be comparatively flexible, its lowest natural frequency should be assessed in a resonance search before sine-sweep proof-testing. Any natural frequencies found below the crossover frequency should be documented in the test report. Special precautions should be taken to ensure that the equipment will be subjected to a conservative input test level.

Table 5— Single-axis sine-sweep seismic test parameters for different severity classes

Class	Peak displacement below the crossover frequency (mm)		Peak acceleration above the crossover frequency (g)		Number of sweep cycles in each axis
	x*	y†	x*	y†	
1 (zone 1–2)	5.0	3.5	1.5	1.0	1
2 (zone 3–4)	10.0	7.5	3.0	2.0	1
NOTE — For the frequency range of 1–35 Hz and a sweep rate of 1 octave per min, 1 sweep cycle corresponds to a test time of about 10 min.					

*x = horizontal axis of vibration
†y = vertical axis of vibration

Any tests that conform to the multiple-frequency proof-testing requirements of IEEE Std 344-1987 and IEEE Std C37.98-1987 are acceptable.

4.7.4.5 Supplemental testing to confirm mathematical modeling

High and low levels of excitation tests can be made to substantiate and supplement the seismic design analysis. The primary objectives of such testing are as follows:

a) To establish all important modes of vibration with frequencies below 30 Hz.
b) To confirm critical damping values associated with each important vibration mode when claimed damping levels exceed the values suggested in 4.7.4.2.1 item b). The following methods for evaluating the damping coefficient are frequently used:
    1) *Damping by measuring the decay rate.* It is assumed that a pure mode of vibration can be excited in the equipment and that motion transducers are mounted at positions other than at a point of zero motion. The equivalent linear damping can be calculated by recording the decay rate of the particular mode of vibration.
    2) *Damping by measuring resonance peaks (bandwidth method).* For excitation in a single-frequency test such as a slow sine-sweep test, the response at any desired location in the equipment is measured and plotted as a function of frequency. The damping associated with that equipment location can be calculated by measurements on the width of the resonance peaks obtained for the different modes of vibration.

Where possible and practical, such tests may be made to confirm the mode shapes predicted by analysis. Acceptable methods include the following:

- Shake-table tests
- Eccentric weight excitation
- Ambient vibration survey
- Explosive charge excitation in the earth surrounding the structure

Initial displacement, Snap-back, and Twang tests, or similar tests where the structure is statistically loaded and instantaneously released, tend to excite the lower natural frequencies. Such tests may prove the lowest natural frequencies and damping.

4.7.4.6 Simplified seismic verification procedure

For GIS to be located in seismic zones 0 to 2 (see table 1), simplifications in the verification procedure may be agreed upon between the manufacturer and the user. This is justified since the GIS being designed as a pressure vessel has an inherent ability to withstand these moderate seismic loads. Further, the probability of a severe earthquake may be very low.

Examples of simplification include the following:

a) Using the static coefficient analysis method (4.7.4.3.2) with a static coefficient of 1.0–1.5 for strength analysis of anchorages
b) Eliminating verification of control equipment

4.7.4.7 Documentation

Documentation should demonstrate that the equipment meets its performance requirements when subjected to the seismic motions for which it is to be qualified.

4.7.4.7.1 Analytical data

If proof of performance is obtained by analytical means, it should be presented in a step-by-step form that can be readily audited. The data should include a listing of the potential failure modes considered in the analysis.

4.7.4.7.2 Test data

If proof of performance is obtained by testing, the test data should contain the following items:

a) Equipment identification
b) Equipment specification
c) Test facility
d) Test method
e) Test data
f) Results and conclusions
g) Approval signature and date

4.7.5 Design philosophy

4.7.5.1 General considerations

Major natural frequencies in the most unfavorable frequency range of the response spectra [see amplification in required response spectrum (RRS), figure 3] should be avoided. If this is done by means of a flexible design, the higher displacement response associated with the flexibility can be further reduced by the use of additional damping devices in the connection to the foundation.

The following aspects should be considered:

a) *Center of gravity*. Low center of gravity is generally favorable, especially for heavy sections of a GIS assembly.
b) *Reserve strength*. It is good engineering practice, and also recommended, that whenever possible, reserve strength and reserve operation limits of the equipment should be provided by one, or both, of the following methods:
   1) Provide elements such that the mode of structural failure due to a response greater than the design response is ductile. Care should be exercised to ensure that brittle components are protected by yielding elements.
   2) Provide structural redundancy such that failure of any one element does not cause failure of the entire apparatus.
c) *Component ratings*. If possible, each component should be rated by the manufacturer as to the load (strength) capability of the various joints and connection points to each component in response to torques, moments, and forces. An estimate of the stiffness characteristics of the structure to such torques, moments, and forces at each of the points, plus the effective mass of the components, should also be given. Such data can then be utilized in the system analysis.
d) *Relative motion*. Means for accommodating relative motions should not impose abrupt shock-type loads by earthquakes (see 4.7.3.2).
e) *Equipment failure modes*. Equipment failure modes, due to the dynamic response of the apparatus to seismic motion, should be considered in the equipment design.

The criteria of adequacy identified in 4.7.3.2 should be fulfilled in GIS design. Switches, sealed joints, and damage tolerances should receive particular attention.

4.7.5.2 Maximum working stresses

Components of the GIS that do not fall under the jurisdiction of local building codes should be designed according to the considerations outlined below. The criteria for survival as defined in 4.7.3 should be the paramount considerations when determining proper design procedures and operating stress magnitudes.

The following criteria are recommended for structural members:

a) *Steel members*. AISC S335-89, or the equivalent, applies to steel structural members.
b) *Aluminum members*. AA Std ACM-1-1986, or the equivalent, applies to aluminum structural members.
c) *Nonmetallic materials*. The maximum acting stress of nonmetallic materials should be within a range between 0.25–0.5 times the average breaking strength (stress). For porcelain insulators and other brittle materials, a minimum safety factor of 1.5–2.0 to rated minimum strength, according to the supplier, should be satisfied.

While urging compliance with these criteria, it is recognized that the design earthquake is a dynamic phenomenon of limited duration. This factor leads to certain special considerations not included in the general references cited in clause 4.. Because of the limited duration of the design earthquake, low-cycle fatigue concepts may be of considerable importance in determining effective design procedures and material selections. For example, the very significant energy-absorbing capacity of materials stressed cyclically into the plastic zone has important implications in damping under vibratory conditions. Such damping has important influences upon the magnitude of the dynamic, seismic response of the GIS subject to the design earthquake.

4.7.5.3 Combination of seismic load with other loads

Seismic load is an irregular and short-term load. It should be combined with the following regular service loads (main loads):

a) Dead load
b) Temperature rise due to current and ambient influence
c) In-service gas pressure

Moreover, it may be combined with the following regular and irregular short-term stresses:

— Short-circuit current
— Wind pressure
— Mechanical operation impact, etc.

Simultaneous effects of different stresses on a combination of loads should be taken into account by reducing the single loads or the security factors.

4.7.5.4 Failure modes

The design of the apparatus should include an analysis of the probable modes of failure that will cause loss of function (see 4.7.3.2). Such modes of failure and the maximum values of the working parameters used in the analysis should be described. Failure modes that should be considered include the following:

a) Overstressed displacement failures that depend on the strength of materials used in equipment (allowable stress, loads, etc.)
b) Understressed displacement failures including the following:
    1) Alignment (configuration requirements of equipment needed to ensure predictable operation)
    2) Impact (collision of equipment components or subassemblies)
c) Leakage (rate of leakage at which system function is jeopardized)
d) Dielectric (electrical function integrity)
e) Fatigue (breakdown of material integrity due to load repetition)
f) Exposure and aging [breakdown of material integrity due to natural elements (sand, wind, sun, freeze-thaw, etc.) and time]

4.7.6 Recommended installation practices

4.7.6.1 Foundations

It is recommended that, as much as practical, all interconnected equipment be placed on a monolithic foundation to reduce differential movement due to the design earthquake. If interconnected equipment is not on the same foundation, then means to cope with expected differential motions of equipment due to foundation motion should be provided for. Foundations shall withstand all loads due to the design earthquake with simultaneous application of both the vertical and the horizontal earthquake motion.

A soil survey is recommended to determine if any unusual conditions exist at the site that would warrant special design considerations for the GIS foundation. Soil interaction on underground conduits entering and leaving through the foundations should be considered. If equipment is rigidly coupled to structural elements, such as walls or adjacent floors, the element response and relative motion should be taken into account.

4.7.6.2 Anchoring foundation equipment

Two methods of anchoring foundation equipment are as follows:

a) *Welding to embedded members.* It is recommended that equipment with large dimensions between anchor locations be anchored by welding the base to steel members (such as I-beams) embedded in and firmly attached (possibly welded) to structural elements (reinforcing steel) in the concrete. Size, location, and type of welds should be shown on the manufacturer's drawing. All welds should be adequate for forces due to the design earthquake.
b) *Bolting to foundations.* Bolts used to anchor equipment should either be cast in fresh concrete or fixed by means of well-tested chemical anchor for drilled holes in hardened concrete. Bolts of mild, ductile steel are preferred. Consideration should be given to any unequal distribution of dynamic earthquake loads on the anchor bolts (due to bolt hole tolerance, torquing, or noncontact of nut). The torque value (to which the anchor bolts are torqued), size, strength, location, and material should be shown on the construction drawings. Anchor systems should be designed to accommodate the tensile, shear, moment, and axial loads and any combination thereof that might be experienced during the design earthquake. Shear and tensile strength of that portion of the anchor system within the foundation should be used, rather than the strength of the bolt attached to the equipment.

4.7.6.3 Interconnection to adjacent equipment

Interconnections between items of equipment should accommodate large relative, axial, lateral, moment, and torsional motions. Structurally and dynamically dissimilar structures experience large relative displacements. Leads and interconnections should be long and flexible enough to allow these displacements to occur without causing damage. Particular attention should be paid to brittle, nonductile parts such as ceramic bushings and insulators. In no circumstances should electrical or structural interconnections abruptly stiffen with increasing motion or strain. Such nonlinearities develop large impact forces. Consideration should be given to the resultant change in dynamic characteristics of the equipment as a result of any bus being used to make interconnections between equipment.

4.7.6.4 Use of bracing on GIS structure

Stiffening the equipment may raise some of its natural frequencies and may raise these frequencies out of the critical range of earthquake energy. Diagonal cross-bracing members carrying axial load could be used to stiffen or strengthen equipment. Bolted joints are recommended throughout the structure to increase the effective damping at high force levels. Information on the proper bolt torque should be supplied by the manufacturer, ensuring the assembly will behave dynamically as intended. If part of the structure is to be supplied by the user, the manufacturer and/or user should supply the necessary information so that the static and dynamic characteristics and foundation requirements can be determined.

Bracing requirements to be considered are as follows:

a) The bracing should be substantially stiffer than the structure it reinforces in order to be effective.
b) The bracing should not buckle or exhibit a sharply nonlinear behavior. In particular, any abrupt stiffening under any circumstance is to be avoided.
c) Permanent deformation in the bracing after the design earthquake is acceptable, provided it does not impair normal functioning of the GIS.
d) Grounding implications of the bracing should be reviewed with the user. If required, the bracing should be insulated from either ground or the ground enclosure of the GIS.

4.8 Partial discharge (PD) testing

Partial discharge is an electrical phenomenon in which local breakdown of gas within apparatus causes a short duration current to flow in the conductor. The current flowing through the characteristic impedance of the coaxial switchgear results in a voltage pulse on the conductor that propagates away from the source of discharge. This voltage pulse or current is sensed by electrical PD detection techniques. In GIS, the pulse is about 1.5 ns wide at the source and propagates with relatively little attenuation and distortion, although some broadening (to the range of 3–5 ns) may take place, depending on the details of the GIS design. The optimum detection bandwidth for such a pulse is in the range of 300–100 MHz [B20]. Commercial PD detection apparatus typically uses bandwidths below 100 kHz to ensure general applicability. When applied to GIS, such apparatus achieves a PD detection sensitivity and noise rejection substantially less than that achievable with PD detection apparatus custom designed for use with GIS.

Partial discharge in GIS can be the result of many types of defects, including voids in spacers, asperities on the conductor, floating components (components not bonded to ground or the conductor), particles, etc. As noted above, the charge transfer generally takes place over 1 ns or so, and the current that flows in the conductor to provide the charge causes an electrical pulse that propagates away from the defect position. Thus the magnitude of the electrical PD signal is roughly proportional to the severity of the phenomenon. However, the danger of PD to the system varies with defect type, so that no direct correlation can be made between the severity of the defect and the magnitude of the detected PD signal.

Some types of PD can be detected acoustically through the use of an ultrasonic sensor on the enclosure. At present, this may be the only widely applicable method of PD detection in the field; however, the magnitude of the acoustic signal detected at the enclosure depends strongly on the type and position of the defect and the nature of the enclosure [B66]. Also, other external noises can produce signals similar to some forms of PD. Thus the interpretation of acoustic PD detection is complicated. At present, selective measuring apparatus and an experienced or well-trained operator are necessary to apply acoustic PD detection to GIS under field conditions.

4.8.1 Type testing

Type testing covers tests intended to ensure that the GIS design, when properly manufactured, meets the standards referenced or set out in purchasing documents. Type testing is undertaken only once after the development of a new product. If the product evolves significantly as a result of a major change or a succession of minor changes, the type tests should be repeated.

Type testing, which includes lightning impulse, switching impulse, and ac withstand tests along with a PD test, is normally undertaken on a representative sample of each GIS device (breaker, disconnector, bus, etc.). PD tests are normally carried out during the ac withstand test.

The essence of the test is to ensure that the PD inception and, more importantly, extinction levels are well (50%) above the (peak) normal operating voltage. The definition of PD-free is usually taken to be about 5 pC apparent charge, as this is a reasonable and easily achieved upper limit to the noise floor in high-voltage test laboratories. Ideally, a GIS component should be PD-free immediately before breakdown. Increasing the margin between peak operating voltage and PD extinction is preferable to increasing the test time for a number of reasons primarily related to statistical time lag for initiation of discharge.

Recent theoretical investigations of PD have shown that the sensitivity with which PD can be detected is generally inversely proportional to the dimensions of the apparatus [B18], [B27], [B75], [B77]. Thus a defect that generates 10 pC of apparent PD in a 138 kV GIS (and would be classed as a test failure) would generate only about 4 pC apparent PD if the system were scaled to a 550 kV GIS and would be considered to pass the test. This is troubling because a defect is more dangerous in a 550 kV GIS than in a 138 kV GIS. In principle, the test criteria for allowable apparent PD should change with the voltage to keep the real sensitivity constant. This may become practical as more advanced PD detection techniques are introduced into industrial practice and ongoing research results in a better definition of tolerable PD levels as a function of operating conditions.

In addition to type testing of assembled GIS, some testing of critical solid dielectric components (operating rods, spacers, etc.) may be undertaken. The test criteria for such components tends to vary substantially from one manufacturer to another, based on experience and operating stresses. Components used at the highest stresses should be subjected to much more stringent testing.

4.8.2 Routine testing

The factory (pre-ship) high-voltage test of GIS normally involves only ac and PD tests. In this context, the PD factory test is essential, as many defect types will not cause breakdown during a 1 min withstand test but will cause PD during the test and eventual failure if placed in service.

PD routine testing is comprised of the following:

a) *PD tests on shipping sections*. The standards for the PD test should be similar to those suggested above for the type test, and standards should become more stringent as improved PD detection technology moves into industrial practice. Very few test sections should fail the factory test. As the factory test is not 100% effective, the manufacturer should track the factory test failure rate and examine the reason for test failures in real time. The occasional wrench left in a test section is much less worrisome than several unexplained but similar test failures, as the latter may indicate a serious design problem.
b) *PD tests on dielectric components*. Each highly stressed solid dielectric component in a GIS (e.g., spacers, operating rods, etc.) should pass a rigorous PD test. Standards are generally set by the manufacturer based on the past history of reliability and the stress at which the component is operated. The test protocol for highly stressed solid dielectric components tends to be more rigorous than for shipping sections. This is partly the result of the universality of metal-enclosed test apparatus with a lower noise floor, but also due to the realization that a solid dielectric component should have no detectable PD up to its highest test voltage. The problem in conducting such a PD test is in keeping the test apparatus PD-free up to the highest test voltage. For this reason, the requirements for PD initiation and extinction are generally somewhat less onerous, but should be well above (150% of) operating voltage. The PD test is among the most important quality control tools for solid dielectric components in GIS, but even the PD test, as presently conducted, will not detect all forms of defects that can cause failure in service. For this reason, a history of good service experience and tight manufacturing quality assurance provide the best assurance of in-service reliability. For moderately stressed components with a long history of reliable production and operation, some manufacturers have successfully dispensed with PD testing of individual castings. The shipping section test becomes the only PD test to which the component is subjected. For the highest voltage classes, where some sections are often assembled for the first time in the field, this practice can result in solid dielectric components being installed without a prior PD test.

4.8.3 Field PD testing

Some PD sources will not decrease the ac dielectric withstand but will cause eventual failure as a result of either surface corrosion from SF_6 decomposition byproducts or treeing within solid dielectric spacers. GIS placed in service in the presence of partial discharge can be expected to fail in minutes to months, depending on the nature of the PD source.

4.8.3.1 Electrical techniques

Field PD testing of GIS can take many forms. One available and applicable electrical field PD test technique employs a metal-enclosed test transformer, which allows the central part of the station to be tested free of external interference by opening the line disconnectors [B38]. Perhaps with great care, acceptable results can be obtained [B10], [B11], [B62]; however, the large and highly variable background noise levels at most industrial sites make effective conventional electrical PD tests very difficult at the site. Successful techniques that have been applied in the field require special capacitive couplers within the switchgear [B10], [B11], [B13], [B28], [B41], [B62].

4.8.3.2 Acoustic techniques

Acoustic techniques have been most successfully applied under field conditions. As noted above, acoustic techniques suffer from the fundamental limitation that PD is an electrical phenomenon that happens to generate an acoustic signal; however, the acoustic signal detectable at the enclosure is related to the original PD by a complex transfer function that involves many factors that are not known during the test [B66]. In spite of these fundamental disadvantages, acoustic

PD detection has the overwhelming advantage that common sources of acoustic noise outside the GIS do not cause appreciable acoustic interference with acoustic detection of PD sources within the GIS. Thus acoustic PD detection can be used under many field conditions that are too noisy for electrical PD detection. A great deal of literature has been generated concerning the relationship between various types of defects and the acoustic signatures that they generate in various types of GIS. The complexity of acoustic PD detection systems varies from the use of a simple hand-held ultrasonic metal contact probe, which can be used to scan a station in a matter of a few hours, to (temporarily) fixed sensors, which permit sophisticated signal processing for improved detection sensitivity and diagnostic selectivity but require 1–2 days of test time for a typical GIS.

4.8.3.2.1 Equipment for acoustic testing

The simplest form of acoustic testing, used successfully in North America since the early days of GIS, employs a hand-held metal contact ultrasonic probe to detect PD-induced sheath vibration (typically in the 20–40 kHz range) and translate this frequency range down to the audible, so that the user can hear an interpretable acoustic signal. A calibrated volume control and meter are usually provided in addition to the audible signal. The use of a metal contact probe that makes direct contact with the GIS enclosure is essential. Ultrasonic acoustic probes that detect in the frequency range above 20 kHz may be equally sensitive. Sophisticated, fixed-acoustic sensor PD-detection systems are commercially available. In addition, the services of test personnel from the manufacturers, utilities, and/or academic institutions that have developed such systems are available.

4.8.3.2.2 On-site acoustic PD testing

A simple, hand-held metal contact probe acoustic sensor can be very effective when used by a knowledgeable operator. Such an instrument has the advantage that it can simply be pressed to the GIS enclosure between each pair of spacers for a quick check of acoustic noise. A knowledgeable operator can readily differentiate between free-conducting particles and other forms of PD that are correlated with power frequency. As a result of the inevitable operator unsteadiness in holding the probe against the GIS enclosure, the detection sensitivity will be less than that for more sophisticated instrumentation, the use of which requires fixed sensors [B64], [B65], [B73], [B81], [B83]. Also, the option of conducting sophisticated signal processing as an aid to determining the location or nature of the PD source is not available with the hand-held probe.

The instrumentation should be checked before use. The ultrasonic noise that results from blowing (axially) on the end of the metal contact probe should be audible throughout the system. Alternatively, the probe can be applied to a metal surface, and the effect of rubbing a finger lightly across the metal surface should be audible. These tests are generally sufficient to indicate that the apparatus is in working order.

Acoustic PD testing can be undertaken during the conditioning sequence of the ac high-voltage test, once the voltage exceeds normal line-to-ground, which has the advantage of locating some of the defects likely to cause breakdown during the subsequent high-voltage test. However, a breakdown during testing will cause transient groundrise, which could cause a shock to a person using an ultrasonic detector. Available experience indicates that the danger is primarily one of being startled, for example, while on a ladder. When using a hand-held sensor, the risk of a shock can be reduced by waiting a few minutes at each conditioning voltage level prior to undertaking the ultrasonic test or by reducing the voltage from a previous conditioning voltage level during the acoustic testing. Fixed-sensor systems can be designed with fiber-optic connections between the sensors on the grounded enclosure and the analytical instrumentation, which eliminates any concern related to groundrise.

During an acoustic test using a hand-held probe, the probe should be applied to the enclosure between each pair of spacers to listen for acoustic activity. Free-conducting particles are a frequent source of acoustic signals that cause a distinctive random noise not correlated with the power frequency voltage. If a PD-related noise source other than particles is suspected, the variation in acoustic signal with voltage is often useful. Most PD sources will change tone as the source goes from one to two to three discharges per half cycle with increasing voltage. Although the transitions may not be distinct, the trend is usually clear and unlikely to be confused with a source of vibration. The activity of a particle with increasing voltage is also distinctive. Above the voltage at which it is lifted, a particle will bounce with high frequency and small amplitude. The frequency will decrease with increasing voltage, as the bounce amplitude increases. Of course, if many particles are present over a range of sizes, increasing numbers of particles may start bouncing as the voltage is raised.

If, through a design, manufacturing, or assembly error, a component such as a corona shield is not bonded to the conductor or ground, it will usually discharge to the electrode to which it should be bonded. Discharge to the conductor and ground can be distinguished during acoustic PD testing by the fact that PD from a floating component to the enclosure (ground) is generally well localized on the enclosure. The acoustic signal will rise rapidly as the PD source is approached, whereas for PD from the conductor, the signal is poorly localized and will be essentially the same (to within the typical short-term signal variation of the source) over the full length of the section between the two spacers.

Free-conducting particles are a common source of PD and acoustic noise in GIS. The presence of free-conducting particles is normally not considered cause for immediate opening of the GIS. Ironically, in a well-manufactured and well-assembled station with extremely few conducting particles (e.g., 1 audible particle between each 1000 spacer pairs), the enclosure could be opened to remove every audible particle, whereas in a poorly manufactured and assembled station (with audible particles between up to 10% of spacer pairs), this would require reassembling the station, which is impractical. As noted above, testing is no replacement for quality assurance during design, manufacture, and assembly both in the factory and at the site.

The danger from a particle depends very much on its shape and location. A spherical particle will bounce at low amplitude and pose very little danger, while a long, thin particle will bounce with rapidly increasing amplitude with voltage and can cause a breakdown (which may destroy the particle) or, in the worst case, may bounce onto a spacer surface. A long particle on a spacer surface will usually cause a breakdown during the test, which can be either self restoring or not, depending on the surface tracking resistance of the spacer material and the energy stored in the test section at the time of the breakdown. On rare occasions, a particle may bounce onto a spacer surface, where it will not cause immediate breakdown during the test but may cause eventual failure in service as a result of continued (low-level) PD or as a result of moving from a position in which it does not cause PD during the test to a position in which it does cause PD after the test. Detection of a conducting particle on a spacer surface is among the most difficult cases for acoustic PD. A simple, hand-held acoustic probe is not likely to detect such a defect, while more sophisticated fixed sensor systems have demonstrated good sensitivity to such defects.

In a well-assembled GIS, each particle could be characterized by varying the voltage and noting the (subjective) change in bounce frequency, which gives some indication of the nature and danger of the particle. If the bounce frequency decreases rapidly with increasing voltage, the particle is more dangerous than if it does not. In a poorly assembled GIS, such characterization would not be practical as a result of confusion from multiple particles and the excessive time required for this test. Action to be taken when a particle is detected will depend on the design of the switchgear and the position of the particle. Usually, the test will proceed; however, if the particle is characterized as dangerous and is near a spacer, then it should be removed before completing the test.

Floating components are the second most common PD source detected during the commissioning of a GIS. The high-voltage test can often be completed without incident in spite of a floating component; however, such a defect should be repaired prior to placing the GIS in service. Floating components can usually be distinguished by their very high acoustic intensity and distinct change in tone with voltage, as described above.

Voids in spacers are unlikely to be detected by any form of field PD test. Spacers should always undergo a rigorous factory PD test that is far more sensitive than any possible field test.

Particles on spacer surfaces may be detected under some circumstances by an acoustic test; however, the detection is less than certain. At present, little unbiased field experience is available. Unbiased field experience would be the detection of a particle on a spacer surface during testing of a large substation with no prior knowledge that a particle may reside on a spacer. Most cases of such detection have been staged for the purposes of determining acoustic PD signatures or demonstrating effectiveness.

Asperities on the conductor should be rare, but may not cause immediate breakdown during an ac voltage test, as a result of corona stabilization.

4.8.3.3 Chemical techniques

4.8.3.3.1 Applicability of chemical techniques

Under many circumstances, PD in operating GIS is intermittent; activity may depend on temperature, random vibrations, etc. Under these circumstances, electrical and acoustic tests are of limited value, as the PD source, even if suspected, may have a small duty cycle and is unlikely to be present during any scheduled field test. Such a problem may become known as a result of a PD-induced failure, which suggests that intermittent PD activity may be present in other similar locations. This situation can be approached in several ways. If the suspected sources are located in relatively small compartments that normally sustain no forms of arcing or sparking (e.g., an SF_6-insulated bushing), then periodic gas analysis may be applicable, as the SF_6 decomposition byproducts present in the compartment represent a rough measure of integrated PD activity in the gas compartment.

4.8.3.3.2 Field byproduct determination

Instrumentation has been developed and is commercially available that allows field personnel to detect SF_6 byproducts down to parts per million by volume levels in a few minutes using disposable color-changing indicators [B21], [B23]. Concentrations of a few parts per million by volume can be detected; however, field instrumentation does not determine the concentration of the various byproduct components (SO_2F_2, SOF_2, etc.), but rather provides a single measure that is sensitive primarily to the SOF_2 and SO_2 concentrations. The reproducibility is probably similar to laboratory instrumentation, such as gas chromatography (GC) or gas chromatography-mass spectrometry (GC-MS). The basic technique is probably less reproducible; however, the overall measurement suffers from fewer sources of error, in that the sample is taken directly from the GIS into the instrument, without sampling, storage, and transportation, all of which tend to introduce impurities and add variability to the measurement. In addition, the result is available immediately to field personnel, whereas laboratory results are usually not available for hours to days.

Using such instrumentation, the level of activity can be tracked through periodic measurements. Obviously, chemical techniques are not applicable to compartments that undergo frequent discharges (disconnectors, breakers, etc.). In extended compartments such as long buses, a significant byproduct concentration gradient can exist along the length of the bus, and the concentration at the filling port may not indicate a problem from a distant discharge source. Desiccants, present in some compartments or switchgear designs, may absorb SF_6 decomposition byproducts and reduce the sensitivity of chemical detection techniques.

4.9 Very fast transients in GIS

The purpose of the following subclauses is to familiarize the substation engineer with phenomena associated with fast transients in GIS, to outline the factors on which these phenomena depend and the means by which detrimental phenomena can be ameliorated, and to provide a guide to the relevant literature in which further technical detail can be found.

The topics covered include generation of fast transients, transient voltages within GIS, transient groundrise on the enclosure, transient-induced failure of GIS-to-cable interfaces, GIS-generated transients incident on external apparatus, and health and safety aspects of GIS transients. The transient voltage levels are a function of the system voltage and, therefore, need special consideration at EHV levels (345 kV and above).

4.9.1 Fundamental features

During normal operation, fast transients in GIS are generated by switching of disconnectors, breakers, etc., within the station. During testing, fast transients are generated by any dielectric breakdowns. The collapse of voltage across the contacts of a switching device (or to ground in the case of a dielectric breakdown) occurs in 3.–5. ns. This is sufficiently rapid to stimulate resonances within the GIS at frequencies up to about 100 MHz. Resonant frequencies within the GIS are determined by a number of phenomena. The highest frequencies, typically up to 20 MHz, result from reflections at impedance discontinuities within the GIS, such as at a “T.” The shorter the distance between discontinuities, the higher the resonant frequency. Lower frequency resonances are associated with longer distances between discontinuities, such as can occur for line exit buses. The lowest frequency resonances tend to be caused by the capacitance of the GIS and an inductance near the GIS, such as that of a transformer.

The higher frequency resonances are damped over a period of some tens of microseconds, primarily as a result of energy transfer from within GIS to the outside at GIS-to-air or other terminations. When the energy transfer takes place through GIS-to-air terminations, the transferred energy gives rise to the phenomenon of transient groundrise, which is the transient increase of the potential of the GIS enclosure relative to the substation ground. Thus switching of a GIS results in a complex waveform characterized by a very rapid initial rise (3–5 ns) followed by superimposed oscillations at several frequencies.

The propagation velocity for electromagnetic radiation in GIS is slightly less than the speed of light in vacuum, about 30 cm/ns (1 ft/ns). As the fast initial rise of a GIS transient takes place in 3.–5. ns, this corresponds to the voltage changing over a distance of 1–2 m (3–5 ft). This extremely rapid change in voltage with time or over distance gives rise to a number of phenomena that are uncommon in the normal realm of power engineering.

High-voltage switching in air generates transients; switching in SF_6 simply makes these phenomena more evident as a result of roughly an order of magnitude shorter rise time, which results in an order of magnitude higher frequencies. The reduction in rise time and increase in bandwidth may require small changes in control wiring practice and, in conjunction with the much more compact nature of GIS, can result in observable phenomena that may disturb inexperienced maintenance and operating staff.

4.9.2 Generation of transients

Transients in GIS are generated in one of two ways. Either the voltage at some point in the GIS collapses as a result of a dielectric failure to ground as in figure 5 (possibly during high-voltage field testing), or the voltage across a disconnector or circuit breaker, which connects two portions of the bus duct at different voltages, collapses, as shown in figure 6. In either case, a traveling wave transient propagates in both directions away from the source. Assuming that the load side of a disconnector has a trapped charge, V_1, and a characteristic (surge) impedance, Z_1, and that the source side of the disconnector has a characteristic impedance, Z_S, and is at a voltage, V_S, at the time of the intercontact breakdown, the voltage on the load side of the disconnector goes from

$$V_1 to V_1 + \{V_s - V_1\}\left\{\frac{Z_1}{Z_s + Z_1}\right\} \tag{1}$$

while the source side goes from

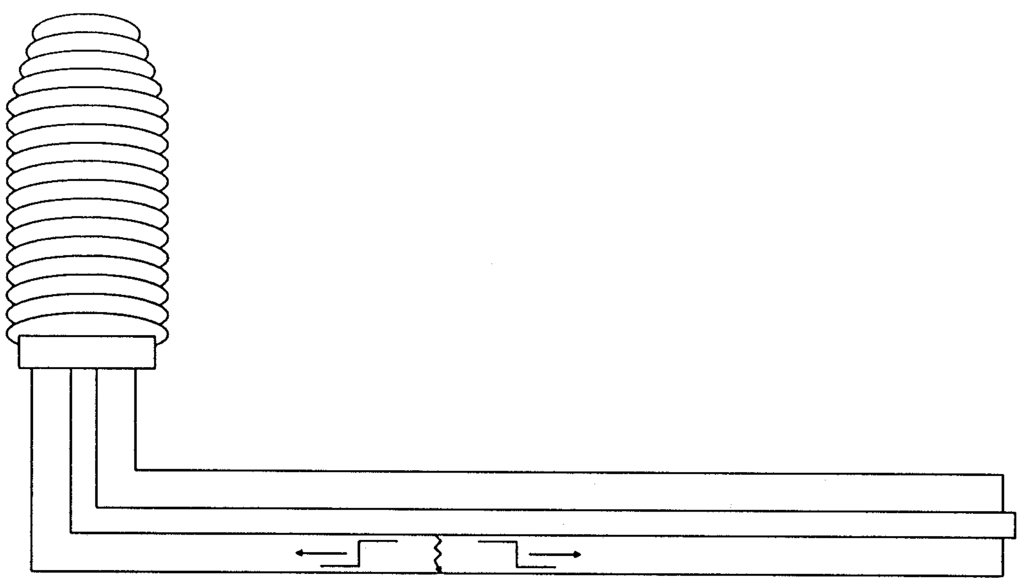
$$V_s to V_s - \{V_s - V_1\}\left\{\frac{Z_s}{Z_s + Z_1}\right\} \tag{2}$$

In the simplest and typical case of $Z_S = Z_1$, $V_S = 1$ pu, and $V_1 = 0$ (i.e., a previously grounded load and a disconnector closing slowly enough that the first pre-strike will occur at the peak of the ac waveform), V_S, will go from 1.0 pu to 0.5 pu in 3.–5. ns, while V_1 goes from 0.0 pu to 0.5 pu in about the same time. For 550 kV GIS operating at 520 kV, this implies a change of 210 kV in about 4 ns or a rate of change of about 50 MV/µs. In terms of spatial change (in the direction of propagation), the voltage changes by 210 kV over a distance of about 130 cm or by 1.6 kV/cm (4.1 V/in). As the 3–5 ns time for voltage collapse is fairly constant over all voltage classes, these numbers scale down with operating voltage. The transient magnitude on one side of the disconnector can increase if the impedances differ on the two sides of the disconnector. This can occur if a capacitive voltage transformer (CVT) is located close to one side of the disconnector or if the disconnector is near a “T.”

In the case that a breakdown occurs within the GIS, the transient magnitude is generally much greater than for a switching operation, as the voltage goes from the initial voltage *V* to 0, again in 3.–5. ns. Such breakdowns occur most often during testing, when the test potential can be 2.5 times the normal operating voltage. Transients generated by in-service failures are very rare, but when they do occur, they are often induced by a switching-induced transient or dynamic overvoltage, which again means that the voltage is elevated at the time of the breakdown. Thus most dielectric failures will generate a transient at least a factor of two greater than the typical disconnector transient characterized above, and as much as a factor of three or four greater in the case of failures during high-voltage testing.

The fast (3–5 ns) wavefront generated by the breakdown to ground or across switch contacts propagates away from its source. When the transient reaches an impedance discontinuity in the GIS, such as a “T,” it will reflect and refract according to standard transmission line theory. The multiple reflections and refractions result in a complex voltage waveform that varies as a function of time and position throughout the GIS. The waveform generated at a specified point within a GIS by the operation of a specified switch for a specified station configuration can be computed with reasonable accuracy [B37]. However, as the waveform will vary with position, station configuration, etc., the primary value of such computations is to ensure that the transient overvoltage within the GIS remains reasonable for anticipated worst-case conditions.

The above example of a disconnector-induced transient wavefront generation is based on the very simple assumption of breakdown from peak system voltage on the source side to ground on the load side. If the load side has no trapped charge at the time of disconnector closing, the above scenario correctly describes the transients that result from the first pre-strike. However, the situation can be complicated by many factors, including differing impedances on the two sides of the disconnectors (common for line entrance disconnectors), and the fact that the largest disconnector-induced transients are generated during opening rather than closing. Larger disconnector-induced transients occur during opening as a result of the statistical variation in the generally systematic nature of disconnector operation which is well described in the literature (see IEC Draft 17A-339 [IEC Draft 17C-102], IEEE Std 100-1992, and [B42]) and which, fortunately, facilitates statistical modeling of disconnector operation so that the worst-case statistical situation can generally be predicted analytically.

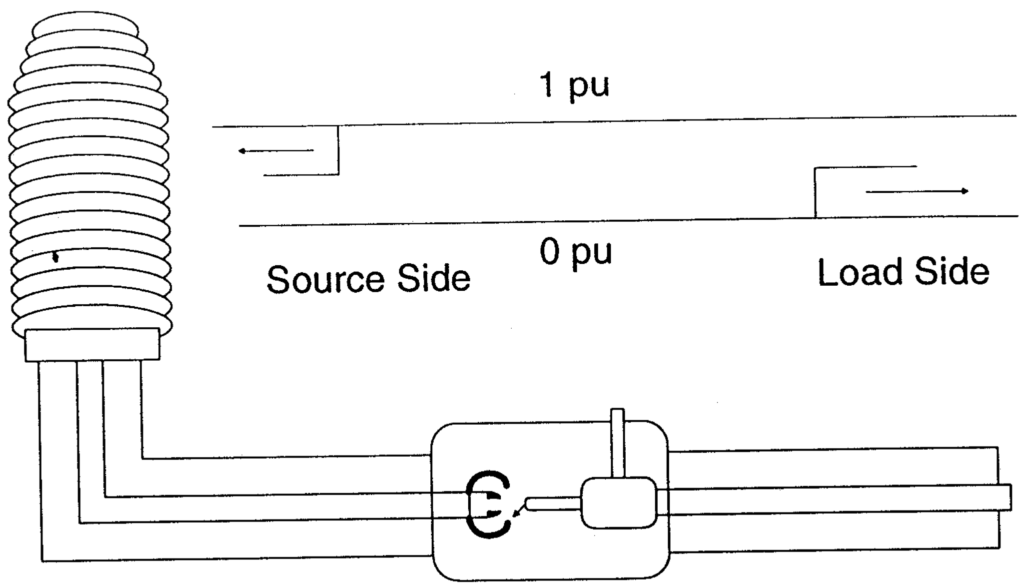


NOTE — A dielectric failure causes traveling wave transients to propagate away from the failure location. The transients have a magnitude equal to the voltage at the instant of failure. During testing, when most such breakdowns occur, the voltage at the instant of breakdown can be over twice the normal operating voltage, which can result in transients five times larger than typical during disconnector operation.

Figure 5— Propagation of transients from a dielectric failure

4.9.3 Transient voltages within GIS

As described above, the transient voltages generated by switching (and, under some circumstances, dielectric breakdown) in GIS have rise times in the range of 4 ns, which means that the voltage collapses over a distance in the range of 1.25 m (4 ft). The very rapid rise time transients propagate away from their source at approximately the speed of light, 30 cm (1 ft) per ns, reflecting and refracting at impedance mismatches (e.g., at a “T”) according to the standard transmission line theory. This results in a complex pattern of traveling waves within the substation that superimpose to generate greater voltages at some locations than at others. Thus the voltage stress to which the substation is subjected as a result of switching-induced (or breakdown-induced) transients is a function of the station configuration, the position of the operated switch, switch characteristics (which affect trapped charge during switching [B16]), and the position at which the voltage is measured.



NOTE — Disconnector operation induces traveling wave transients of opposite polarity on either side of the switch, as described by equations 1) through (3). Depending on the speed of operation, anywhere from a few to several hundred transients can be generated. In either case, only a few to a few tens of the transients are of relatively large magnitude. The magnitude of transients is correlated with both the speed of operation and the trapped charge left after opening [see IEC Draft 17A-339 (IEC Draft 17C-102)]. Faster disconnector operation reduces the number of transients per operation but generally increases the probability of large transients and large trapped charge after an opening operation. More slowly operating disconnectors can be designed so as to limit intercontact breakdowns to about 1.4 pu and to leave a trapped charge during opening of less than 0.4 pu.

Figure 6— Propagation of transients from a disconnector operation

For normal disconnector operation, the worst-case transient wavefront generation occurs for a breakdown from +1 pu on one side of the disconnector to -1 pu on the other side. In theory, the resulting 1 pu traveling wavefronts that propagate away from the disconnector can result in peak waveform amplitudes of 3 pu. Numerous studies indicate that theoretical worst-case conditions result in actual worst-case transientinduced voltages in the range of 2.8 pu (relative to the power frequency peak voltage), while in most GIS, a worst-case transient magnitude of a little over 2 pu is more typical (see IEC Draft 17A-339 [IEC Draft 17C-102], [B15], [B23], and [B42]). These magnitudes are low relative to the 4.56 pu BIL of a 242 kV GIS, but can become of concern relative to the 3.45 pu BIL of a 550 kV GIS.

Some components within the GIS have appreciable lumped capacitances. To obtain detailed agreement between measured and computed transient waveforms, moderately detailed models should be developed for such elements. Since most of the transient energy is lost through refraction to lines and cables connected to the substation, accurate modeling of these connections and the relationship between the enclosure and ground is necessary if detailed waveform agreement is desired [B17], [B37], [B84]. Other investigators have obtained reasonable agreement between measured and predicted peak voltages without modeling in the detail necessary to obtain accurate waveform agreement [B12], [B70]. Given that computing an accurate waveform at an interval of a few meters throughout a substation is impractical, an approximate approach is adequate so long as it has been verified against measurements or more accurate computations.

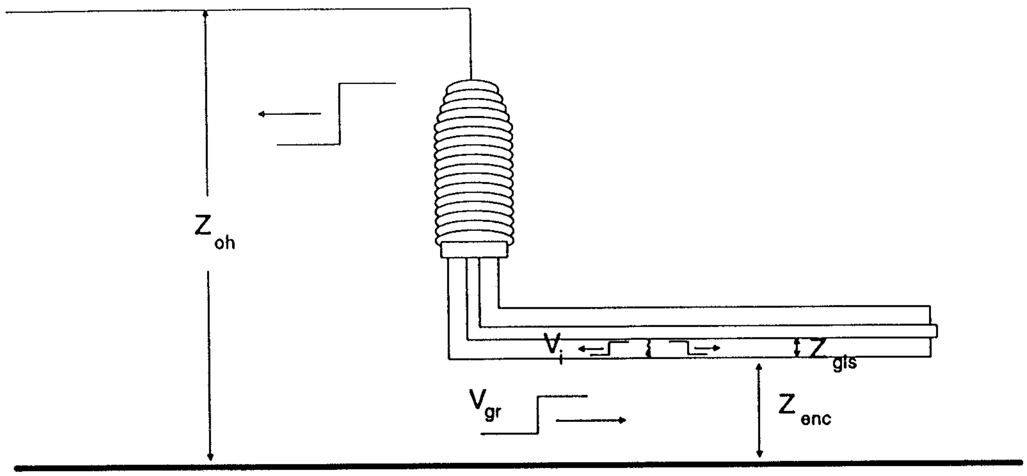
In the past, approximately 25% of GIS failures in 550 kV, 1550 kV BIL GIS have occurred during switching, even though switching should never produce transients above the BIL of 3.45 pu. Research has demonstrated that when a stress enhancement (defect) is present on the conductor of GIS, the withstand voltage can decrease by roughly a factor of 2 with a decrease of the surge waveform rise time from about 100 µs to about 10 µs [B30], [B69]. In the absence of other diagnostics, field testing with power frequency or a resonant switching surge does little to ensure integrity under switching-induced transients. One alternative is the combination of a power frequency test combined with sensitive partial discharge detection using high-frequency electrical or acoustic techniques [B2], [B3], [B10], [B11], [B31], [B39], [B40], [B60], [B67], [B68], [B76]. Testing with both power frequency and an oscillating lightning impulse with a rise time less than 10 µs is another alternative. Since overvoltages caused by refraction of the test waveform within the GIS should be avoided insofar as possible, a test waveform rise time of about 10 µs appears to be optimum for this purpose. Should a breakdown occur at the high voltages required during oscillating impulse testing, the transient overvoltages caused by such a breakdown can cause secondary flashovers within the GIS that may go undetected. Where possible, power frequency testing combined with sensitive partial discharge testing is generally the less risky and less expensive alternative. For partial discharge testing, see 4.8.

Since the magnitude of switching-induced transients is proportional to the operating voltage while the basic dimensioning of the GIS is roughly proportional to the BIL (at least through 550 kV GIS), the severity of switching-induced transients relative to the withstand of the GIS increases with increasing voltage class. For example, the ratio of BIL to service voltage for 550 kV, 1550 kV BIL GIS is 3.45, while that for 242 kV, 900 kV BIL GIS is about 4.56, and essentially all 230 kV GIS sold in North American are actually designed to 1050 kV BIL so that the real ratio is closer to 5.6.

The care with which GIS should be manufactured and assembled to avoid relatively minor defects that can cause switching-induced failures tends to increase with voltage class. The care taken and costs incurred during field testing should increase with the voltage class of the apparatus.

4.9.4 Transients on the enclosure

When a transient propagates to a GIS-to-air termination, part of the transient is refracted to the outside world. As mentioned above, this is the dominant mechanism for damping of transient energy after a switching operation. Assuming that the termination is connected to an overhead conductor, the connection results in the junction of three transmission lines, as shown in figure 7. The important characteristic of this configuration is that the GIS enclosure is ground for the GIS conductor but is a conductor relative to the station ground mat and earth. Thus part of the energy couples into the transmission line formed by the outside of the GIS enclosure relative to the earth and station ground, even if, as is often the case, a ground connection is made at the base of the GIS-to-air termination. The intricacies of this situation, along with an easy-to-understand explanation of transient groundrise, are provided in [B31] and [B32], while [B29] and [B36] provide a more complete technical explanation.



NOTE — Transient groundrise between the GIS enclosure and station ground mat (earth) is caused by the reflection and refraction of a transient generated within GIS by the junction of the three transmission lines formed by 1) an overhead line to earth, 2) the GIS enclosure to earth, and 3) the GIS conductor to GIS enclosure. A ground between the GIS enclosure and station ground mat (e.g., at the base of the GIS-to-air termination) generally has a greater effect on the duration of the transient overvoltage between the GIS enclosure and station ground mat than on the magnitude of the overvoltage.

Figure 7— Generation of transient groundrise

Two important and possibly counter-intuitive points should be appreciated. First, at high frequencies the GIS enclosure is really two distinct conducting surfaces, an interior surface and an exterior surface. At the frequencies relevant to transient groundrise, the currents flowing on these two surfaces are not coupled in any way. For example, a dielectric breakdown within a bus section could occur directly opposite a ground connection on the enclosure. That ground connection would have absolutely no effect on the transient generated by the breakdown, the transient magnitude at the GIS-to-air termination, or the transient groundrise generated. It would only have an effect when the transient groundrise, which originates as a result of the internal transient reaching the GIS-to-air termination, reaches the ground connection many nanoseconds after the initial breakdown. Second, the rise time of the wave which emerges from the GIS-to-air termination will be in the range of 10 ns (increased somewhat from 4 ns by the termination). The GIS enclosure is often about 1 m (4 ft) above ground. Thus the wave takes 4 ns to propagate from the GIS enclosure to ground, where it is reflected inverted and takes another 4 ns to return to the GIS enclosure, at which point it adds to the voltage and thereby cancels (grounds) the voltage on the enclosure [B32]. Since the rise time of the transient on the enclosure is comparable to the time required for the ground to become effective, the ground connection usually has more impact on the duration of the transient than on the peak magnitude. For rise times in the range of 10 ns, any connection longer than about 30 cm (1 ft) should be thought of as a transmission line with an impedance and a propagation time. The geometric scale of GIS permits no grounds where transients are concerned, only transmission lines between the GIS and ground. As will be shown below, connections as short as 1 cm (0.5 in) become relevant under some conditions.

The peak transient ground magnitude can be predicted reasonably well from transmission line theory and is given by

$$V_{gr} = -2V_i\left\{\frac{Z_{enc}}{Z_{enc}+Z_{oh}+Z_{gis}}\right\} \qquad (3)$$

where V_i is the voltage within the GIS incident on the termination, Z_{gis} is the GIS bus duct impedance (typically 60 Ω), Z_{oh} is the overhead line impedance (typically 300 Ω), and Z_{enc} is the impedance of the GIS enclosure relative to station ground (typically 150 Ω). Thus the maximum transient groundrise voltage at the base of the termination will typically be about 60% of the voltage incident on the GIS-to-air termination and will be of opposite polarity. The maximum transient likely to be incident on the termination is in the range of 1.3 pu, which could generate about 0.8 pu on the enclosure at the base of the termination. However, this voltage would last for only nanoseconds. If one were touching the enclosure, the potential would probably not be felt. However, if one were very close to the enclosure, one might feel a spark, much as one feels a spark from static electricity after walking across a carpet in very low humidity. One measurement of the attenuation of transient groundrise as a function of distance away from the termination indicated about 0.3 db/m [B32], [B36].

Transient groundrise caused by dielectric breakdown of the GIS, especially during testing, is of much larger magnitude than that caused by normal switching, as the transients incident on the termination are much larger for the reasons discussed above.

Transient groundrise of the enclosure can cause sparks across electrical discontinuities in the enclosure that occur in some GIS designs and between the enclosure and metal support members if they are separated by an insulator as was typical in some early GIS designs. Transient groundrise can induce transients on the conductors of poorly configured control cables and thereby cause incorrect operation or failure of electrical and electronic equipment. It can also destroy high-voltage test apparatus by inducing flashovers between high-voltage elements and ground in the test set. This can be avoided by isolating (floating) the power to the test set with an isolating transformer of at least 100 kV BIL.

Transient groundrise within an indoor GIS can be greatly reduced (essentially eliminated) through the use of a metal building with a coaxial connection between the metal wall and the bus enclosure. In this situation, the interior of the building becomes a Faraday cage and reflects transients that propagate from the external GIS-to-air terminations back toward the building. In a properly executed design, any transients within the building will be the result of electrical discontinuities in the enclosure within the building. In some designs, these occur at current transformers (CTs) and enclosure joints. In other designs, the enclosure is electrically continuous, which is clearly preferable to reduce EMI. In nonmetallic but steel reinforced buildings, use of the reinforcing steel in place of the metal shell of the building can effect substantial reductions in the transient groundrise within the building.

Transient groundrise can be alarming, and it can be a nuisance. However, it causes no insurmountable problems in properly designed GIS. Computers are operating within recent generations of GIS without difficulty.

4.9.5 Damage to cable-to-GIS interface

This subtle but important problem has been described in some detail in the literature [B35]. When a GIS is connected directly to a high-pressure, fluid-filled cable, the enclosures of the two systems are usually isolated with an insulator that is bypassed with a polarization cell so that cathodic protection can be applied to the cable pipe. If a failure occurs within the GIS, the transient generated by the failure can cause flashover of the insulation between the GIS enclosure and the cable pipe. In principle, the fault current is supposed to flow through the polarization cell; however, the leads on the polarization cell are often fairly long so that the fault-current-induced voltage drop across the inductance of the polarization cell circuit can be hundreds or even thousands of volts. The insulation will have been designed to withstand this voltage; however, once the insulation is flashed over by the transient, only hundreds of volts are necessary to maintain the arc, so the fault current will return through the much lower inductance path of the arc across the insulator rather than through the polarization cell. This may damage the cable-GIS interface and release cable fluid.

This problem can be eliminated by extending the insulator to the point that it does not flash over, or protecting it with a surge arrester with as short a lead length as possible, so that the voltage across it never reaches the insulator breakdown voltage. Using as short a lead as practical, the clamping voltage of the surge arrester array should be such that it suppresses breakdown across the isolating flange but does not conduct power frequency current. Careful coordination of this interface should be established between applicable interface components. A more complete treatment of the problem is provided in [B35].

4.9.6 Effect on external apparatus

Part of the very fast transient is refracted out of the GIS termination to any connected apparatus. The magnitude of this transient will depend on the magnitude of the transient incident on the termination, which, in turn, depends on the disconnector operating characteristics and the position of the disconnector relative to the termination. For example, each “T” between the disconnector and the termination will reduce the transient wavefront magnitude by 33% as a result of the transmission line division at the “T.” The GIS termination will generally increase the rise time of the transient, although the magnitude of this effect depends on the design of the termination. Under no circumstances can a termination, even a capacitively graded or condenser bushing, be modeled as a lumped element capacitor. Given the very (physically) short rise time of the incident transient relative to the typical length of a GIS termination, the termination should be modeled as a transmission line or a collection of transmission lines, depending on its design [B34].

Numerous GIS are connected to transformers by short overhead lines, and no case has been made for an abnormal failure rate in such situations. Nevertheless, transformer manufacturers should be aware of the circumstances under which a transformer will operate. The switching-induced wavefront that emerges from a GIS termination has an initial voltage step of 10–20 ns rise time with a worst-case magnitude of about 1 pu, which could occur if a line disconnector located at a “T” with a bus suffered a 2 pu intercontact breakdown during opening. A 1.6 pu intercontact breakdown in a disconnector situated with equal bus impedances on either side might be more typical, and this would give rise to an initial step of about 0.6 pu with a rise time of 10–20 ns. In general, the initial step on the line side of a GIS termination appears to be in the range of 75% of the incident transient voltage with a rise time of 10–20 ns [B34]. This results in a rate of rise in the range of 40–10 MV/µs for a 550 kV GIS. This is comparable to the rate of rise for a transformer chopped wave test and gives some concern for the voltage distribution in any coils (e.g., transformer windings) closely coupled to the GIS busing.

Numerous transformers operate directly connected to GIS without an abnormal rate of problems, and again, transformer manufacturers should be made aware of the environment in which a transformer will operate at the tendering and design stages. Direct connections between GIS and apparatus such as transformers expose the connected apparatus to much greater stresses. For such a situation, the initial wavefront is likely to have a rise time in the range of 10 ns after passing through the GIS-to-oil connection, and the worst-case transient magnitude is likely to be in the range of 0.8–1.3 pu relative to the peak ac service voltage. This results in a worst-case rate of rise in the range of 35–55 MV/µs.

The initial wavefront, discussed above, is followed by a ringing waveform typical of that which occurs within the GIS (but slightly damped by passing through the GIS-to-air termination).

4.9.7 General precautions

Although the totally enclosed GIS provides a safer environment than an air-insulated substation, the sparks of transient groundrise, for example, between bus enclosure and support members, prompt the question of personnel safety. This question was first examined in [B36], which concluded that medical knowledge was inadequate to provide much guidance for the range of parameters (voltage and time) represented by transient groundrise in GIS. A great deal of circumstantial evidence, including the experience of numerous utility and manufacturer personnel who have been touching GIS bus ducts near gas-to-air terminations during disconnector switching, strongly suggests that the transients generated under those conditions do not present a shock hazard. The greatest hazard is probably that of being startled by an electrostatic spark while in a precarious position, such as on a ladder. Much less experience is available for transient groundrise surges generated as a result of test breakdowns, which can be nearly an order of magnitude larger than typical disconnector switching-induced transient groundrise. As a result, a reasonable degree of caution is appropriate during testing.

4.10 Field dielectric testing

The purpose of the dielectric tests is to detect any defects in the assembled equipment that may have been introduced during shipping or site assembly. The types of defect that may lead to in-service failures are macroscopic defects on the conductor or enclosure, defects in the solid insulation, contamination on the insulating spacers, or presence of free-conducting particles in the enclosure.

The presence of free-conducting particles is best detected by a power frequency voltage test, while stress enhancements on the conductors are best detected by an impulse voltage test. The application of a gradually increasing ac voltage for the purpose of conditioning is beneficial, especially when done in conjunction with partial discharge measurements for the detection of internal defects.

From a statistical point of view, it is expected that an assembly of tested components will have a lower withstand value than the individual components. Thus a lower withstand voltage is more acceptable in the field than for individual components tested in the factory.

The field testing philosophy and techniques applied to GIS continue to evolve. Although a simple ac test, in many cases, was the only test performed, recent understanding of failure mechanisms has resulted in a multitude of test waveforms, different voltage levels, and diagnostic techniques, and a loss of international consensus on the best approach to on-site testing. The following subclauses attempt to describe what individual tests can be performed and what these tests can achieve, based on presently available knowledge. In addition, the considerations necessary in defining an overall test procedure (consisting of one or more individual tests) are discussed.

4.10.1 Purpose of testing

The purpose of on-site testing is to ensure that the GIS equipment, as manufactured, shipped, and assembled, is free of defects that could cause problems under conditions encountered during normal operation. Normal operating conditions include stresses caused by VFT which are the 1 ns rise time transients caused by the operation of the GIS disconnectors and circuit breakers.

Dielectric on-site tests are normally performed as part of the commissioning procedure for a newly assembled GIS. However, similar defects could occur during major overhaul and/or equipment repair. Consequently, dielectric on-site tests are sometimes performed following major repair or overhaul. However, the choice of test method in these cases is often influenced by other considerations not present at commissioning, such as the practicality of testing, the extent of the repair, the age of the unaffected equipment, the cost of outages, and the availability of spare parts.

4.10.2 Defect types

Defects that can occur during GIS assembly and affect the dielectric performance fall into four broad categories:

a) *Assembly errors, such as loose parts, tools, or debris left after assembly*. These defects should be detected and dealt with in all cases. Fortunately, these defects are normally easily detected with almost any test voltage.

b) *Free-conducting particles*. These defects are probably the most common form of contaminant and one of the most dangerous defect types. Particles in the GIS acquire charge when high voltage is applied to the conductor and then move in a bouncing fashion under the influence of applied ac voltage. When the voltage is sufficient that a particle can cross the gap between the grounded enclosure and the central conductor, flashover is likely to occur. A second problem is that, although particle movement is largely random, the movement can result in a particle landing on the surface of a solid insulating component and adhering due to electrostatic or mechanical forces. Such particles behave as a fixed defect of category c) below.

Although cases of particle-free installations have been reported, the complete absence of all particles is nearly impossible in practical situations. On-site tests should therefore be designed only to detect those particles that cause problems in the operation of the GIS. Since the movement of particles in GIS depends on many factors, including the size, shape, and density of the particle and the electric field configuration within the GIS, the severity of the particle depends on many factors. For GIS designs and operating stresses in present use, long, thin particles with lengths in the millimeter range and larger can be harmful, although size alone is not necessarily the best indicator of danger.

c) *Fixed defects, such as metallic protrusions and particles, that adhere to spacer surfaces*. These defects are most sensitive to transient waveforms. Investigations have shown that fixed defects such as metallic burrs or protrusions on the conductor can withstand very high ac voltages (as a result of corona stabilization) but will cause flashover at lower voltage levels when subjected to transient voltages, such as lightening impulses and VFT generated by the operation of disconnectors and circuit breakers. VFT appear to generate the critical stress since lightening transients are less frequent and conventional switching surges are of longer rise time (and therefore less onerous). For typical VFT magnitudes and stress levels in present designs of EHV GIS, protrusions of about 1 mm length appear to be critical.

Fixed defects on the surface of insulators generally exhibit sensitivity to transient waveforms similar to protrusions. Given sufficient stress, these defects will generate some form of partial discharge that may be detectable by diagnostic methods. Such partial discharges can result in long-term degradation of the surface of the insulator and eventual failure.

d) *Poor or loose electrical contact of electrostatic shields (floating components)*. These defects are difficult to detect directly with high-voltage waveforms, as they do not reduce the breakdown voltage. Such defects normally generate partial discharges. The partial discharges or the decomposition byproducts from the partial discharges may cause long-term degradation of the insulator surface and eventual failure. Unfortunately, the mechanisms of how electrostatic contacts degrade and how a nondischarging, poor, or loose contact develops into the more severe case of a fully floating component is not well understood. Consequently, detectable signals from these defect types may not appear for many years and may not be detected during the on-site commissioning tests.

4.10.3 Individual test techniques

The following subclauses describe several test protocols that are commonly employed during on-site tests of GIS. A total test procedure will normally consist of one or more of the individual tests.

4.10.3.1 Low-frequency conditioning

Since the most common defect results from free-conducting particles, and these are able to move under low-frequency excitation, a conditioning procedure is often used during which low-frequency voltage is applied in gradually increasing levels. This promotes movement of particles into regions of low field where they become trapped and presumably harmless under normal operating voltages. In such a procedure, occasional testing flashovers occur, but every opportunity is given for particles to move to harmless locations without resulting in a flashover. Conditioning is somewhat dependent on the design of the GIS, especially the nature and location of low-field regions for trapping particles. Consequently, each manufacturer will normally specify an appropriate conditioning procedure.

4.10.3.2 Low-frequency withstand

On-site testing of GIS with low-frequency waveforms is most common, as conducting particulate contamination has been the most troublesome defect and is best addressed using low-frequency test voltages. A low-frequency withstand test normally follows a low-frequency conditioning period (described above) and consists of a 1 min application of test voltage (usually 80–100% of the low-frequency withstand voltage). The intent is to detect remaining particles that have eluded the particle traps and other low-field regions but remain potentially harmful, and to detect other defect types.

4.10.3.3 Impulse testing

Fixed defects, such as needle-like protrusions on conductors and particles adhering to insulator surfaces, are generally more likely to cause flashover during an impulse waveform. As a result, a test using fast-fronted lightening impulse or oscillating impulse of rise time < 10 μs can be performed. Longer rise time (~100 μs) switching or oscillating switching impulses are sometimes used but are less effective than the lightning impulses, although switching impulse shapes are sometimes used as a compromise between lightning impulse and low-frequency waveforms. Generally, switching impulse waveforms are not recommended if lightning impulse and low-frequency waveforms are available.

Investigations have demonstrated that the breakdown voltages for VFT waveforms and lightning or oscillating lightning waveforms are approximately equivalent in practical systems. This suggests that the required test level using lightning impulse waveforms should be related to the maximum anticipated VFT. VFT magnitudes are normally restricted to the 1.5–2.0 pu range, but values up to 2.7 pu are sometimes reported. In addition, the VFT occur normally and frequently in GIS (for instance, with each disconnector operation). To compensate (somewhat) for the low number of applications of impulse test voltage (normally 3–5 applications for each polarity), a higher test voltage is usually preferred. Therefore, impulse test levels in the range of 2.5 pu or more should be selected. In EHV equipment, this level corresponds to 60–80% of the BIL.

Although impulse testing may be prudent and necessary in some cases, impulse testing imposes permanent damage caused by testing flashovers and the resulting overvoltages. In addition, the transient overvoltages generated by a test flashover can sometimes result in secondary flashovers in other portions of the equipment, extending the possibility of further damage and need for repair. A test voltage of 70–80% of the BIL is generally considered a reasonable compromise between efficacy and waste.

4.10.3.4 Partial discharge testing

The benefit of field testing can be greatly enhanced by partial discharge detection, acoustic particle detection, and/or other diagnostic techniques. The most common techniques used include the following:

a) Electrical partial discharge measurements
b) Acoustic particle detection
c) Acoustic partial discharge detection
d) Partial discharge detection using ultra-high-frequency (UHF) detection

The specifics of each of these techniques are covered in 4.8.

4.10.4 Planning a test approach

As one of many steps in the overall quality assurance process, the extent to which testing is performed should be considered in view of the overall process, which includes the required reliability and degree of dielectric margin in the GIS design. For example, for GIS at a major generating station, where a failure can be very expensive, the most rigorous testing program might be justified. For less critical GIS, a reduced test procedure might be acceptable. Most EHV GIS have dielectric margins (for instance, as indicated by the ratio of BIL to operating voltage) that are comparatively less than those for lower voltage class equipment, and consequently operate at much higher stress. More highly stressed designs result in systems that are more sensitive to defects and that demand greater attention to quality assurance. EHV equipment, therefore, requires a more rigorous test procedure, possibly including impulse tests and/or partial discharge detection, as compared to the lower voltage equipment, for which simple low-frequency tests are often considered adequate.

The approach to testing should take equipment characteristics into account. For instance, a system that is prone to protrusion defects (i.e., as a result of the specific assembly process) should be tested more thoroughly with respect to that type of defect than equipment for which this type of defect is not likely. Some GIS include solid insulators with material formulations that make them very susceptible to damage by testing flashovers. In such systems, testing often includes extensive diagnostic techniques and avoids the use of high voltages so that defects are detected without flashover. On the other hand, systems that can easily withstand a number of testing flashovers without significant damage may be suited to a high-voltage test protocol.

4.10.5 Overall test procedures

The test program selected should be determined within the context of the above considerations and of the cost and availability of test equipment. The most common test procedures that can be recommended and the circumstances in which they are appropriate are as follows:

a) Low-frequency conditioning is carried out in conjunction with some form of PD detection to avoid flashovers. Maximum low-frequency voltage is usually in the range of 1.1–1.3 pu. As this voltage is only high enough to provide a cursory check on the assembly quality, PD detection techniques should be used for defect detection. This test is appropriate on GIS where testing flashovers should be avoided. Test benefits depend on the quality of the PD detection methods.
b) Experience demonstrates the adequacy of high-voltage, low-frequency testing, especially for equipment at voltages less than ~ 362 kV (i.e., voltages less than EHV levels), as a result of lower stresses and larger dielectric margins. Maximum ac voltages are usually in the range of 80–100% of the rated low-frequency withstand level. This test, without augmentation by PD detection or impulse, is not recommended for EHV installations requiring the highest reliability levels.
c) The inclusion of PD and/or particle detection enhances the quality of test procedure b) above and makes it more suitable for use on EHV-level GIS.
d) Lightning impulse or oscillating lightning impulse waveforms increase the ability to detect fixed defects. The impulse application addresses some of the concerns over VFT stress not addressed by low-frequency testing. However, higher-energy testing flashovers (and damage) are possible. This test is often performed for EHV-level GIS.
e) The PD detection can identify and minimize the probability of testing flashover during the application of impulse voltages. This test procedure is sometimes performed for the installations requiring the highest reliability and when testing cost is of lesser concern.

4.11 Maintenance and repair

It is desirable to be able to repair and maintain major elements (such as breakers and switches) without removing them from the system. However, this may not always be possible, and it is recommended that station components be installed and arranged so that devices that might have to be removed for repair or maintenance can be removed with a minimum amount of disturbance to other equipment in the system. This will require sectionalizing components or sections with gas barrier insulators. In some cases, specially designed temporary protective covers that can withstand the same electrical and mechanical stresses as the other GIS components may be required.

At points where disconnection or removal is likely, the following suggestions should be considered:

a) Suitable terminals should be provided for the connection of the control wiring.
b) Provisions for disconnecting gas pipelines should be incorporated.
c) Cutting of metal should be avoided if possible. Where it is required, design should be such that contaminants to the system are minimized. Particular attention should be given to vertical runs, where contamination could fall into the equipment.

A 100 µm or smaller particle filter suitable for pressures involved may be installed at the gas service connection. This filter does not replace the filters associated with the gas handling equipment system, but rather serves as an additional safety feature.

4.11.1 Removal of SF_6 byproducts

SF_6 gas that has been subjected to arcing contains harmful byproducts. These gases and any solid byproducts should be handled with care to avoid injury to personnel. Maintenance personnel should be advised to wear protective equipment and clothing to avoid contact with these byproducts.

All GIS equipment that may contain arc byproducts should be thoroughly cleaned prior to performing maintenance within the equipment.

4.11.2 Safety during maintenance and repair

Before maintenance work is performed on the gas-insulated substation, follow normal user safety precautions.

The components on which work is to be performed should be electrically isolated, de-energized, and grounded. Points of isolation should be locked or guaranteed safe. Precautions should be taken to provide adequate ventilation. Gas in the section where work will be performed should be reduced to atmospheric pressure before any bolts or other fasteners subject to internal pressure are loosened.

SF_6 gas is heavier than air and tends to collect in low places. While un-arced SF_6 gas is nontoxic, it can exclude oxygen and hence, could cause suffocation. Adequate ventilation should be provided and caution should be observed when working in circuit-breaker tanks or other confined areas where pockets of SF_6 gas can accumulate.

Arcing in SF_6 causes decomposition of the gas into other sulfur fluorides and, in the presence of moisture, hydrogen fluoride. These decomposition products may be toxic and are harmful to the eyes, nose, and lungs. If arcing has occurred, precautions should be taken to avoid breathing or touching any of the SF_6 byproducts.

The recommended procedures before entering any gas-insulated compartment in which arcing has taken place are as follows:

a) Evacuate to 133 Pa all gas from the compartment and pass it through a filter capable of removing arc decomposition products. Allow air to enter and fill the compartment to atmospheric pressure before opening the access port.
b) Before entering the compartment, it should be well ventilated with dry air. The oxygen content should be measured, and if the oxygen content is less than 18%, breathing air should be supplied to the person entering the compartment. Continuous circulation of dry air should be provided, or if not objectionable, continuous circulation of fresh air may be provided by the use of an air blower. It is advisable that protective clothing and equipment be supplied to persons required to come in contact with the arc solid byproducts.
c) A commercial-type vacuum cleaner with HEPA filters and nonmetallic accessories should be used to remove the arc solid byproducts. Precautions should be taken to avoid breathing the exhaust air from the vacuum cleaner since dust particles will go through the collection system.

Instruction books furnished with gas-insulated substations should be readily accessible to operating and maintenance personnel. This instructional literature should include information pertaining to safe operating and maintenance procedures.

The following instructions are of special concern and should be emphasized. They are not implied to be a final or complete listing, but should be augmented as necessary by the supplier or the user, or both.

- Energized equipment should never be depressurized until it is de-energized and grounded.
- Gas-insulated equipment should not be opened, entered, or touched before making sure the equipment is grounded.
- Do not stand or step on small piping or connections.

5. Bibliography

[B1] AA Std ACM-1-1986, Aluminum Construction Manual—Section 1: Specifications for Aluminum Structures.

[B2] Albiez, M., "Preventatives Messen in Elektrischer Anlagen," ETG Tagung: "TE-Messungen in GIS-AnLagen," Zurich, Sept. 14, 1989. *Elektrishchen Schweizerischer Elektrotechnischer Verein*, Reihe ETG: Band 8d, p. 131.

[B3] Albiez, M.; Zaengl, W.; Diederich, K.; and Meppelink, J.; "Design and calibration of a universal sensor for the measurement of very fast transients and partial discharges in GIS," *Sixth International Symposium on High-Voltage Engineering (ISH)*, Paper 42.48, 1989.

[B4] ANSI C37.06-1987, American National Standard Preferred Ratings and Related Required Capabilities for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

[B5] ANSI C63.2-1987, American National Standard Specifications for Electromagnetic Noise and Field-Strength Instrumentation, 10 kHz to 40 GHz.

[B6] ANSI MC96.1-1982, American National Standard Thermocouples Temperature Measurements.[10]

[B7] ANSI/ASME B31.1-1992, Power Piping.

[B8] ANSI/NFPA 70-1993, National Electrical Code.

[B9] ASTM D2472-92, Specification for Sulfur Hexafluoride.

[B10] Baumgartner, R.; Fruth, B.; Lanz, W.; and Pettersson, K.; "Partial discharge—Part X: PD in gas-insulated substations—Measurements and practical considerations," *IEEE Electrical Insulation Magazine*, vol. 7, no. 6, Nov./ Dec. 1992, p. 5.

[B11] Baumgartner, R.; Fruth, B.; Lanz, W.; and Pettersson, K.; "Partial discharge—Part XI: PD in gas-insulated substations—Measurements and practical considerations," *IEEE Electrical Insulation Magazine*, vol. 8, no. 1, Jan./ Feb. 1992, p. 16.

[B12] Boeck, W., and Witzmann, R., "Main influence of the fast transient development in gas-insulated substations (GIS)," *Fifth International Symposium on High-Voltage Engineering (ISH)*, Paper 33–87, 1987.

[B13] Boggs, S. A., "Electromagnetic techniques for fault and partial discharge location in gas-insulated cables and substations," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 7, July 1982, pp. 1935–1941.

[B14] Boggs, S. A., "Sulphur hexafluoride—A complex dielectric," *IEEE Electrical Insulation Magazine*, vol. 5, no. 6, Nov./Dec. 1989, p. 16.

[B15] Boggs, S. A., "Sulphur hexafluoride—Introduction to the material and dielectric," *IEEE Electrical Insulation Magazine*, vol. 5, no. 5, Sept./Oct. 1989, p. 18.

[B16] Boggs, S. A.; Chu, F. Y.; Fujimoto, N.; Krenicky, A.; Plessel, A.; and Schlicht, D.; "Disconnect switch-induced transients and trapped charge in gas-insulated substations," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 5, Oct. 1982.

[10] ANSI MC96.1-1982 has been withdrawn; however, copies can be obtained from Global Engineering, 1990 M Street NW, Suite 400, Washington, DC, 20036, USA.

[B17] Boggs, S. A.; Fujimoto, N.; Collod, M.; and Thuries, E.; “The modeling of statistical operating parameters and the computation of operation-induced waveforms for GIS disconnectors,” *CIGRE*, Paper 13–15, 1984.

[B18] Boggs, S. A.; Pecena, D. D.; Rizzetto, S.; and Stone, G. C. “Limits to Partial Discharge Detection—Effects of Sample and Defect Geometry.” In *Gaseous Dielectrics V*, edited by L. G. Christophorou and D. W. Bouldin. New York: Pergamon Press, 1987.

[B19] Boggs, S. A., and Schram, H. H., “Current interruption and switching in sulphur hexafluoride,” *IEEE Electrical Insulation Magazine*, vol. 6, no. 1, Jan./Feb. 1990, p. 12.

[B20] Boggs, S. A., and Stone, G. C., “Fundamental limitations in the measurement of corona and partial discharge,” *IEEE Transactions on Electrical Insulation*, vol. EI-17, 1982, p. 143.

[B21] Chu, F. Y, “Novel low-cost SF_6 arcing byproduct detectors for field use in gas-insulated switchgear,” *IEEE Transactions on Power Delivery*, vol. PWRD-1, no. 2, Apr. 1986, p. 81.

[B22] Chu, F. Y, “Procedures for dealing with solid arcing byproducts from gas-insulated substations,” *Canadian Electrical Association*, Report 128-T-289, Apr. 1985.

[B23] Chu, F. Y, “SF_6 decomposition in gas-insulated equipment,” *IEEE Transactions on Electrical Insulation*, vol. EI-21, no. 5, Oct. 1986, p. 693.

[B24] CIGRE WG 23.03, “Handling of SF_6 and its decomposition products in gas-insulated switchgear (GIS)—Part I,” *Electra*, no. 136, June 1991.

[B25] CIGRE WG 23.03, “Handling of SF_6 and its decomposition products in gas-insulated switchgear (GIS)—Part II,” *Electra*, no. 137, Aug. 1991.

[B26] Clough, R. W., and Penzien, J., *Dynamics of Structures*. New York: McGraw Hill, 1975.

[B27] Crichton, G. C.; Karlsson, P. W.; and Pedersen, A.; “Partial discharges in ellipsoidal and spheroidal voids,” *IEEE Transactions on Electrical Insulation*, vol. EI-24, no. 2, Apr. 1989, p. 335.

[B28] “Detectors spot incipient failure,” *Electrical World*, Nov. 1986, p. 37.

[B29] Dick, E. P.; Fujimoto, N.; Ford, G. L.; and Harvey, S.; “Transient ground potential rise in gas-insulated substations—Problem identification and mitigation,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 4, Oct. 1982.

[B30] Diessner, A.; Luxa, G. F.; Mosca, W.; and Pigini, A.; “High-voltage testing of SF_6-insulated substations on site,” *CIGRE*, Paper 33-06, 1988.

[B31] Ford, G. L.; Boggs, S. A.; and Chu, F. Y; “Transient groundrise in SF_6 substations investigated,” *Transmission and Distribution*, vol. 31, no. 8, Aug. 1979.

[B32] Ford, G. L.; Boggs, S. A.; and Fujimoto, N.; “Transient groundrise in GIS,” *Transmission and Distribution*, vol. 34, no. 4, Apr. 1982.

[B33] Ford, G. L., and Geddes, L. A., “Transient ground potential rise in gas-insulated substations—Assessment of shock hazard,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 4, Oct. 1982.

[B34] Fujimoto, N., and Boggs, S. A., “Transients incident on externally-connected power system components,” *IEEE Transactions on Power Delivery*, vol. PWRD-3, no. 3, July 1988, p. 961.

[B35] Fujimoto, N.; Croall, S. J.; and Forty, S. M.; "Techniques for the protection of gas-insulated substation to cable interface," *IEEE Transactions on Power Delivery*, vol. PWRD-3, no. 4, Oct. 1988, p. 1650.

[B36] Fujimoto, N.; Dick, E. P.; Boggs, S. A.; and Ford, G. L.; "Transient ground potential rise in gas-insulated substations—Experimental studies," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 4, Oct. 1982.

[B37] Fujimoto, N.; Stuckless, H. A.; and Boggs, S. A. "Calculation of Disconnector-Induced Overvoltages in Gas-Insulated Substations." In *Gaseous Dielectrics IV*, edited by L. Christophorou, p. 473. New York: Pergamon Press, 1984.

[B38] Hadorn, P., "The advantages of a fully metal-enclosed test arrangement for ac field testing of SF_6-insulated substations," *Canadian Electrical Association*, Mar. 1981.

[B39] Hampton, B. F., "Update on UHF PD diagnostic methods," Paper presented at *IERE Workshop*, Toronto, Canada, Sept. 30-Oct. 4, 1990.

[B40] Hampton, B. F., and Meats, R. J., "Diagnostic measurement at UHF in gas-insulated substations," *IEEE Proceedings*, vol. 135, pt. C, no. 2, Mar. 1988.

[B41] Hampton, B. F.; Meats, R. J.; Pryor, B.; and Watson-Jones, B. "The Application of Partial Discharge Measurements to GIS." In *Gas-Insulated Substations—Technology and Practice*, edited by S. A. Boggs, F. Y. Chu, and N. Fujimoto, p. 313. New York: Pergamon Press, 1986.

[B42] Harvey, S. M., "Breakdown and switching-induced transients on control wiring of gas-insulated substations," *Canadian Electric Association*, Report 127-T-238.

[B43] Hicks, R. L., and Jones, D. E., "Transient voltages on power station wiring," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 1, 1971, pp. 261–269.

[B44] IEC 517-1990, Gas-insulated metal-enclosed switchgear for rated voltages of 72.5 kV and above.

[B45] IEEE Std 24-1984, IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings (ANSI).

[B46] IEEE Std 48-1990, IEEE Standard Test Procedures and Requirements for High-Voltage Alternating-Current Cable Terminations (ANSI).

[B47] IEEE Std 315-1975 (Reaff 1989), IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams (ANSI).

[B48] IEEE Std 367-1987, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault (ANSI).

[B49] IEEE Std C37.04-1979 (Reaff 1988), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

[B50] IEEE Std C37.09-1979 (Reaff 1988), IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

[B51] IEEE Std C37.010-1979 (Reaff 1988), IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

[B52] IEEE Std C37.24-1986 (Reaff 1991), IEEE Guide for Evaluating the Effect of Solar Radiation on Outdoor Metal-Enclosed Switchgear (ANSI).

[B53] IEEE Std C37.30-1992, IEEE Standard Definitions and Requirements for High Voltage Air Switches (ANSI).

[B54] IEEE Std C37.38-1989, IEEE Standard for Gas-Insulated Metal-Enclosed Disconnecting, interrupter, and Grounding Switches (ANSI).

[B55] IEEE Std C37.123-1991, IEEE Guide to Specification for Gas-Insulated Substation Equipment (ANSI).

[B56] IEEE Std C62.11-1987, IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (ANSI).

[B57] IEEE Committee Report, “Bibliography of gas-insulated substations,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 11, Nov. 1982, pp. 4289–4315.

[B58] IEEE Committee Report, “Bibliography of gas-insulated substations,” *IEEE Transactions on Power Delivery*, vol. PWRD-4, no. 2, Apr. 1989, pp. 1003–1020.

[B59] IEEE Committee Report, “Bibliography of gas-insulated substations,” *IEEE Transactions on Power Delivery*, vol. PWRD-8, no. 1, Jan. 1993, pp. 73–82.

[B60] IEEE Committee Report, “Partial discharge testing of gas-insulated substations,” *IEEE Transactions on Power Delivery*, vol. PWRD-7, no. 2, Apr. 1992, p. 499.

[B61] James, D. R., ed.; Sauers, I.; Griffin, G. D.; Van Brunt, R. J.; Olthoff, J. K.; Stricklett, K. L.; Chu, F. Y.; Robins, J. R.; and Morrison, H. D.; “Investigation of S_2F_{10} production and mitigation in compressed SF_6-insulated power systems,” *IEEE Electrical Insulation Magazine*, vol. 9, no. 3, May/June 1993.

[B62] Konig, D.; Neumann, C.; Suiter, H.; Lipken, H.; and Schmidhuber, P.; “Partial discharge measurements of SF_6-insulated high-voltage metal-enclosed switchgear on site—A study based on fundamentals and experiences available up to now,” *CIGRE*, Paper 23-09, 1980.

[B63] Kynast, E. E., and Luherman, H. M., “Switching of disconnectors in GIS-laboratory and field tests,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 11, Nov. 1985, pp. 3143–3150.

[B64] LaLot, J. “On-Site Acoustic Detection of Abnormalities in Metal-Clad Substations.” In *Gas-Insulated Substations—Technology and Practice*, edited by S. A. Boggs, F. Y. Chu, and N. Fujimoto, p. 322. New York: Pergamon Press, 1986.

[B65] Leijon, M. A. S., and Vlastos, A. E., “Pattern recognition of free-conducting particle motion modes in GIS,” *Proceedings of the IEEE International Symposium on Electrical Insulation*, Boston, Mass., June 5–8, 1988.

[B66] Lundgaard, L. E., “Partial discharge—Part XIII: Acoustic particle discharge detection—Fundamental considerations,” *IEEE Electrical Insulation Magazine*, vol. 8, no. 3, May/June 1992.

[B67] Lundgaard, L. E.; Runde, M.; and Skyberg, B.; “Acoustic diagnostics of gas-insulated substations—A theoretical and experimental basis,” *IEEE Transactions on Power Delivery*, vol. PWRD-5, no. 4, Oct. 1990, p. 1751.

[B68] Lundgaard, L. E.; Tangen, G.; Skyberg, B.; and Faugstad, K.; “Acoustic diagnosis of GIS—Field experiences and development of expert system,” *IEEE Transactions on Power Delivery*, vol. PWRD-7, no. 1, Jan. 1992, p. 287.

[B69] Luxa, G. E; Kynast, K.; Boeck, W.; Hiesinger, H.; Pigini, A.; Bargigia, A.; Schlicht, M. S.; Wiegart, N.; and Ullrich, L.; “Recent research activity on the dielectric performance of SF_6 with special reference to very fast transients,” *CIGRE*, Paper 15-06, 1988.

[B70] Narimatsu, S.; Yamaguchi, K.; Nakano, S.; and Maruyama, S.; "Interrupting performance of capacitative current by disconnector switching for gas-insulated switchgear," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-100, no. 6, June 1981, p. 2726.

[B71] Newmark, N. M., and Rosenblueth, E., *Fundamentals of Earthquake Engineering*. Englewood Cliffs, NJ: Prentice-Hall, 1971.

[B72] Niemeyer, L., and Chu, F. Y., "SF_6 and the atmosphere," *IEEE Transactions on Electrical Insulation*, vol. EI-27, no. 2, Feb. 1992, pp. 184–187.

[B73] Nitta, T.; Ibuki, K.; and Tada, S. "Application of On-line Diagnostic Techniques to GIS." In *Gas-Insulated Substations—Technology and Practice*, edited by S. A. Boggs, F. Y. Chu, and N. Fujimoto, p. 276. New York: Pergamon Press, 1986.

[B74] Ogawa, S.; Haginomori, E.; Nishikawa, S.; Yoshida, T.; and Teraska, K.; "Estimation of restriking transient overvoltage on disconnecting switch for GIS," *IEEE Transactions on Power Delivery*, vol. PWRD-1, no. 2, Apr. 1986, p. 95.

[B75] Pedersen, A. "Partial Discharge in Voids in Solid Dielectrics—An Alternate Approach." In *1987 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena*, IEEE Publication 87CH2462-0, p. 58.

[B76] Pryor, B. M., "UHF partial discharge detection in GIS," Paper presented at *IERE Workshop*, Toronto, Canada, Sept. 30-Oct. 4, 1990.

[B77] Rizzetto, S.; Stone, G. C.; and Boggs, S. A. "The Influence of X-rays on Partial Discharges in Voids." In *1987 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena*, IEEE Publication 87CH2462-0, p. 89.

[B78] Russel, B. D.; Harvey, S. M.; and Nilsson, S. L.; "Substation electromagnetic interference—Part I: Characterization and description of the transient EMI problem," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 7, July 1984, pp. 1863–1887.

[B79] Ryan, H. M., and Jones, G. R., SF_6 *Switchgear* London, UK: Institute of Electrical Engineers, 1989.

[B80] Smith, A. A. Jr., *Coupling of External Electromagnetic Fields to Transmission Lines*. New York: J. Wiley & Sons, 1977.

[B81] Spaeren, P. H.; Skyberg, B.; Hegerberg, R.; and Lundgaard, L. E. "On-Site Particle Detection in GIS by Acoustic Measurements." In *Gas-Insulated Substations—Technology and Practice*, edited by S. A. Boggs, F. Y. Chu, and N. Fujimoto, p. 33 1. New York: Pergamon Press, 1986.

[B82] Vlah, Z. J., and Harvey, S. M., "Multi-frequency surge withstand capability tests for protective relays," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-100, no. 3, Mar. 1981, pp 1065–1071.

[B83] Wahlstrom, B.; Lord, W.; Pettersson, K.; Alvinsson, R.; and Leijon, M. A. S.; "Experiences and considerations regarding erection, testing and operation availability of GIS in Sweden," *CIGRE*, Paper 23-07, 1988.

[B84] Witzmann, R., "Gas transients in gas-insulated substations (GIS)—Modeling of different GIS components," *Fifth International Symposium on High-Voltage Engineering (ISH)*, Paper 12.06, 1987.

