

**567**

**SF6 Analysis for AIS, GIS  
and MTS Condition  
Assessment**

**Working Group  
B3.25**

**February 2014**



# SF<sub>6</sub> ANALYSIS FOR AIS, GIS AND MTS CONDITION ASSESSMENT

WG B3.25

## Members

**Eamonn Duggan, Convener (IE), Ian Ring, Secretary (IE), Dieter Fücksle (DE), Falko Meyer (CH), Peter Sieber (DE), Dagmar Kopejtkova (CZ), Roland Kurte (DE), Lutz-Rüdiger Jänicke (DE), Peter Glaubitz (DE), Toshiyuki Saida (JP), Neil Kane (UK), Edgar Dullni (DE), Daniel Mutter (CH), Marie-Claude Lessard (CA), Bob Hardy (US), Thomas Schwarze (DE)**

## Copyright © 2013

“Ownership of a CIGRE publication, whether in paper form or on electronic support only infers right of use for personal purposes. Are prohibited, except if explicitly agreed by CIGRE, total or partial reproduction of the publication for use other than personal and transfer to a third party; hence circulation on any intranet or other company network is forbidden”.

## Disclaimer notice

“CIGRE gives no warranty or assurance about the contents of this publication, nor does it accept any responsibility, as to the accuracy or exhaustiveness of the information. All implied warranties and conditions are excluded to the maximum extent permitted by law”.



**ISBN : 978-2-85873-262-3**

# CONTENTS

---

1.	Scope .....	10
2.	Summary .....	11
3.	Definitions .....	12
4.	Standards & Guidelines.....	13
4.1.	IEC 60376 - New SF <sub>6</sub> gas.....	13
4.2.	IEC 60480 - Used SF <sub>6</sub> gas .....	14
4.3.	CIGRE SF <sub>6</sub> Recycling Guide .....	15
5.	Origin and Control of Contaminants .....	16
5.1.	External Sources.....	16
5.1.1.	Gas Handling.....	16
5.1.2.	Water .....	17
5.1.2.1.	Humidity from Exposure to Air .....	17
5.1.2.2.	Moisture in Insulators.....	17
5.1.2.3.	Moisture in Adsorber Material .....	17
5.1.3.	Dust and Metal Particles.....	17
5.2.	Internal Sources .....	18
5.3.	Academic Research .....	18
5.3.1.	Boudéne, Cluet, Keib and Wind.....	18
5.3.2.	Belmadani, Derdouri, Casanovas, Grob and Mathieu.....	18
5.3.3.	Heise, Kurte, Fischer and Klockow.....	19
5.3.4.	Piemontesi .....	19
5.4.	Formation of Decomposition Products.....	19
5.4.1.	SF <sub>6</sub> Decomposition Products from Electrical Discharges .....	19
5.4.1.1.	Burst of Decomposition Products produced during Switching Operation .....	20
5.4.1.2.	Stream of Decomposition Products produced by Corona Discharge .....	20
5.4.2.	Decomposition Product Reactions .....	21

5.4.2.1.	SOF <sub>2</sub> and SO <sub>2</sub> .....	23
5.4.2.2.	HF .....	23
5.4.2.3.	CF <sub>4</sub> .....	24
5.4.2.4.	Metal Fluorides .....	24
5.4.2.5.	Other Contaminants .....	25
5.5.	Control of Contaminants .....	26
6.	Gas Measurement and Analysis .....	27
6.1.	impact Equipment Design .....	27
6.1.1.	Switchgear .....	27
6.2.	Purpose of Gas Analysis .....	27
6.2.1.	Before Equipment Enters Service .....	28
6.2.2.	During Equipment Service .....	28
6.2.2.1.	Periodically (as part of a maintenance regime) .....	28
6.2.2.2.	Failure Investigation (after an event) .....	28
6.2.3.	Prior to Disposal of Equipment .....	29
6.3.	Most Appropriate on-Site Measurements .....	29
6.3.1.	On-Site Measurement Procedures .....	29
6.3.1.1.	Safety Precautions .....	29
6.3.1.2.	Measurement Procedure .....	29
6.3.1.3.	Detector Tubes .....	30
6.3.1.4.	Portable Analysers .....	30
6.4.	Site Trials .....	32
7.	Gas Quality .....	33
7.1.	Identification & Analysis of Abnormal Conditions .....	33
7.1.1.	Gas Compartments not containing Switching Equipment .....	35
7.1.2.	Gas Compartments containing Switching Equipment .....	35
8.	Review of Utility Gas Sampling Practices .....	36
8.1.	Survey of Utilities .....	36

9.	Case Studies .....	39
9.1.	Review of High Voltage Equipment Reliability .....	39
9.1.1.	International Surveys.....	39
9.1.2.	SF <sub>6</sub> Diagnostics .....	39
9.1.3.	GIS Failure Rates .....	41
9.2.	Specific Case studies .....	43
9.2.1.	Post Fault Gas Analysis.....	43
9.2.1.1.	Failure in 420kV GIS Disconnecter Compartment .....	43
9.2.1.2.	Failure in 420kV GIS Circuit Breaker .....	43
9.2.1.3.	SF <sub>6</sub> filled EHV Voltage Transformer .....	43
9.2.2.	Routine Gas Analysis .....	44
9.2.2.1.	SF <sub>6</sub> filled EHV Current Transformer .....	44
9.2.2.2.	EHV Circuit Breaker .....	44
9.2.3.	Site Trials .....	44
10.	Conclusions .....	45
11.	References .....	47
	Annexes .....	48
A.	Information sought when procuring SF <sub>6</sub> filled Equipment .....	49
B.	Instruments and Measurement Methodologies.....	50
B.1.	Introduction .....	50
B.2.	Measurement of SF <sub>6</sub> Content .....	51
B.2.1.	Sound Velocity .....	51
B.2.2.	Condensation Principle.....	51
B.2.3.	Thermal Conductivity Detector.....	51
B.3.	Humidity Measuring Devices.....	52
B.3.1.	Chilled Mirror Technology .....	52
B.3.2.	Capacitive Humidity Sensors .....	53
B.4.	Measurement of SF <sub>6</sub> contaminants and Decomposition Products.....	55

B.4.1.	Detector Tubes .....	55
B.4.2.	Electrochemical Measuring Cell (SO <sub>2</sub> and HF) .....	55
C.	Gas Density Measurement.....	61
C.1.	Introduction .....	61
C.2.	SF <sub>6</sub> Gas .....	61
C.3.	SF <sub>6</sub> Gas Density Instruments vs. Pressure Gauges.....	62
C.3.1.	General Principle of Temperature Compensation .....	62
C.3.2.	Indication of Gas Density .....	62
C.3.3.	Electronic Density Instruments for Direct Measurement – Density Sensor .....	63
C.3.5.	Mechanical Instruments for Direct Measurement – Reference Chamber .....	63
C.3.6.	Mechanical Instruments for Indirect Measurement - Temperature Compensated Pressure Gauges .....	64
D.	Diffusion and Kinetics.....	65
D.1.	Transport of Decomposition Products through SF <sub>6</sub> Gas .....	65
D.2.	Reaction Kinetics of SF <sub>6</sub> Decomposition Products on Wall Surfaces .....	66
D.2.1.	Unsaturated surface limit.....	66
D.2.2.	Saturated surface limit.....	67
D.3.	Removal of Decomposition Products and Moisture by Molecular Sieves.....	68
E.	Filter Material Characteristics .....	72
F.	Water in Sulfur Hexafluoride .....	76
F.1.	Water .....	76
F.2.	Water as a Contaminant in Sulfur Hexafluoride .....	76
F.3.	Definitions .....	77
F.3.1.	Moisture.....	77
F.3.2.	Humidity.....	77
F.4.	Pressure and Temperature Influences.....	78
F.4.1.	Pressure Dependence.....	78
F.4.2.	Temperature Related Pressure Dependence .....	79
F.4.3.	Temperature Influence .....	79

F.4.4.	IEC SF <sub>6</sub> Pressure and Temperature Specifications .....	79
F.4.5.	Water Content in ppm <sub>w</sub> in various Gas Mixtures .....	80
F.5.	Clarification of Units .....	81
F.5.1.	Dew or Frost Point .....	81
F.5.2.	Volume/Weight Ratio vs. Volume/Weight Fraction .....	81
F.6.	Calculations & Conversions .....	82
F.6.1.	Symbols, Units and Values .....	82
F.6.2.	Fundamental Formulas .....	83
F.6.3.	Humidity Conversions .....	89
G.	Gas Insulated Transformers and Reactors .....	92
G.1.	Introduction .....	92
G.2.	Structural Features of GIT .....	92
G.2.1.	Conductor Insulation .....	93
G.2.2.	On load tap changer .....	93
G.3.	Gas Insulated Transformers and Reactors - Contaminants .....	93
G.3.1.	Introduction .....	93
G.3.2.	Analysis of CO <sub>2</sub> /CO Concentration level .....	93
G.3.3.	SF <sub>6</sub> Decomposition Products .....	93

# LIST OF TABLES

---

Table 3-1: Definitions .....	12
Table 4-1: Maximum acceptable impurity levels (full details available in IEC 60376) .....	13
Table 4-2: Maximum acceptable impurity levels (full details available from IEC 60376).....	14
Table 4-3: SF <sub>6</sub> contaminants (reproduced from Table 1 in the CIGRE Brochure 234) .....	15
Table 8-1: Comparison of utility practices with regard to SF <sub>6</sub> gas sampling.....	37
Table 9-1: Application of diagnostic tests - number of responses within individual voltage classes .	39
Table 9-2: SF <sub>6</sub> quality checks periodicity – responses within individual voltage classes.....	40
Table 9-3: GIS HV parts dielectric major failure data .....	42
Table B-1: List of measurement and analysis methods.....	50
Table B-2: Description of a typical GC-TCD method [2].....	56
Table C-1: Measurement of gas density - electronic vs. mechanical device.....	62
Table F-1: Volume Ratio by Weight for various gases .....	80
Table F-2: Volume Ratio.....	81
Table F-3: Weight Ratio.....	81
Table F-4: Symbols, units and values .....	82



# LIST OF FIGURES

---

Figure 5-1: Schematics of hot plasma reactions (left side) and cold wall reactions (right side) .....	21
Figure 7-1: Decision making process for SF <sub>6</sub> gas analysis to identify decomposition products .....	33
Figure 7-2: Decision making process for SF <sub>6</sub> gas analysis to identify humidity content .....	34
Figure 7-3: Decision making process for SF <sub>6</sub> content analysis .....	34
Figure 9-1: SF <sub>6</sub> quality measurements .....	41
Figure 9-2: GIS HV dielectric major failure frequency versus year of manufacture .....	42
Figure B-1: Dew Point Mirror .....	52
Figure B-2: Structure of a Polymer Sensor .....	53
Figure B-3: Aluminum Oxide Sensor .....	54
Figure B-4: Detector tube and sampling arrangement .....	55
Figure B-5: Analysis of SF <sub>6</sub> and CF <sub>4</sub> in a SF <sub>6</sub> gas insulation sample .....	57
Figure B-6: Analysis of air (N <sub>2</sub> and O <sub>2</sub> ) as a contaminant in a SF <sub>6</sub> gas insulation sample .....	57
Figure B-7: Analysis of the major decomposition products in a SF <sub>6</sub> gas insulation sample .....	58
Figure B-8: SF <sub>6</sub> subtracted mid-infrared spectrum of a discharge sample and indication of the decomposition products .....	59
Figure C-1: SF <sub>6</sub> Properties – pressure/temperature .....	61
Figure C-2: Density sensor .....	63
Figure C-3: Reference chamber .....	63
Figure C-4: Mechanical pressure gauge .....	64

Figure D-1: Model to describe the diffusion of decomposition products to an adsorber surface.....	68
Figure E-1: Lattice structure of Faujasite [1] .....	72
Figure E-2: Adsorption isotherms measured at room temperature for molecular sieve 13X and activated alumina for H <sub>2</sub> O and SO <sub>2</sub> [5] .....	74
Figure G-1: Schematic structure of GIT.....	92
Figure G-2: Winding structure of GIT .....	92

# 1. SCOPE

Due to an exceptional combination of physical and chemical properties, SF<sub>6</sub> has become an indispensable insulation material for electric power transmission and distribution equipment. Its functional superiority has resulted in the replacement of older insulation and switching technologies to a large extent. In particular, high voltage transmission circuit breakers and gas insulated switchgears (GIS) are almost entirely based on SF<sub>6</sub> as a switching and insulation medium.

However, in order to ensure that the equipment performs in accordance with its functional purpose the quality of the gas must be maintained as contaminants will negatively impact the dielectric and arc quenching properties of the gas. It is well known that the gas contains contaminants, which arise from different sources. They may be introduced at the time of the initial filling with gas, they may desorb from the internal surfaces of the equipment or may arise as a result of electric activity, either by partial discharges or arcs. Therefore, ensuring that the gas does not contain inappropriate levels of impurities is an important consideration.

Furthermore, it has been suggested that from an understanding of SF<sub>6</sub> decomposition mechanism and an analysis of the decomposition products (or their evolution over time) it should be possible to identify the type of electrical discharge and estimate the condition of the equipment. Armed with this knowledge it should then be possible to judiciously plan maintenance work.

The objective of this brochure is to provide guidance to utility personnel in the use of gas analysis, or more strictly speaking, how to interpret the results of gas analysis and assess the condition of high voltage equipment. A further objective was to identify maximum permissible levels of decomposition products which have no diminishing effects on the dielectric performance of the equipment.

While the initial intent was to include the gas mixtures SF<sub>6</sub>/N<sub>2</sub> and SF<sub>6</sub>/CF<sub>4</sub>, in the scope of this work, it was subsequently rejected due to limited knowledge of the topic. However, the basic analysis processes outlined in this technical brochure are also valid for the analysis of gas mixtures.

During the preparation of this brochure an initial investigation of the failure mechanisms and consequential generation of contaminants within SF<sub>6</sub> gas insulated transformers and reactors was undertaken. However, as the failure mechanisms are significantly different to those found within switchgear, it was decided that this analysis warranted a dedicated work activity and a separate brochure. However some preliminary background information is included in Annex G.

## 2. SUMMARY

The brochure documents the current understanding of the types and sources of contaminants in SF<sub>6</sub> gas, the manner in which they migrate through a gas volume and how they may be controlled or removed. In exploring how contaminants can be produced it is evident that there are many parameters involved, potentially involved a variety of primary, secondary and even tertiary reactions. Hence the formation rates of SF<sub>6</sub> decomposition products depend on many parameters such as the type of discharge, the energy involved, the gas pressure, the electrode material, the presence of contaminants such as humidity and oxygen, the presence of adsorbers and the time between the event and the analysis.

Furthermore the paper presents information on the latest portable multi-analysers available in the market, including data obtained from mini-trials performed with these instruments. Additionally the paper contains a number of case studies on gas analysis and how it supported the process of identifying the location of internal failures.

Identifying a threshold for the permissible level of decomposition products without a reduction of the dielectric performance of the gas is very complex and has proven to be impossible in practice. However, a GIS compartment which contains no switching elements should have no decomposition products at all and therefore, if some are detected, intervention is warranted. Compartments with switching elements can contain decomposition products that may have been generated by normal switching activity but also by abnormal arcing or sparking. Unfortunately gas analysis, other than in controlled laboratory settings, cannot distinguish between the different sources of decomposition products. Other forms of analysis must be used to advance the investigation before deciding on the course of action.

One of the main conclusions from this investigation is that there are simple to use portable multi-analysers available to measure the most critical properties of the sampled gas, namely SF<sub>6</sub> content, humidity content and will also provide an assessment of decomposition products. The use of these instruments does not result in the release of SF<sub>6</sub> gas to atmosphere as they either pump it back into the switchgear compartment itself or into a dedicated cylinder.

### 3. DEFINITIONS

Table 3-1: Definitions

<b>Concentration:</b>	The amount of substances in a gas, measured either as volume or mass fraction of the main gas and expressed in % (per cent) or ppm (parts per million) related to volume (ppm <sub>v</sub> ) or mass (ppm <sub>w</sub> ).
<b>Contaminants:</b>	Foreign substances in SF <sub>6</sub> gas originating from the assembly, gas handling and operation of the electrical equipment.
<b>Decomposition Products:</b>	<p>Contaminants that are produced as a result of chemical reactions within the compartment.</p> <p>Some entities distinguish between contaminants produced from the dissociation of SF<sub>6</sub> and those produced from further reactions between these SF<sub>6</sub> fragments and other gases or solids within the compartment. They are referred to as decomposition products and decomposition by-products respectively.</p> <p>However, for simplicity the single term “decomposition products” is used exclusively in this document.</p>
<b>Dew Point and Frost Point:</b>	The temperature at which the water vapour in the gas begins to condense in liquid form or deposit in solid form. Historically these terms have been confused and are discussed in greater detail in Annex F.
<b>Failure:</b>	A failure of a piece of equipment is an event which causes the cessation of one or more of the fundamental functions of the equipment. It will result in the equipment being immediately removed from service or removal being mandatory within 30 minutes.
<b>Fault:</b>	A fault is synonymous with an internal arc in switchgear caused by a failure of the switchgear (dielectric failure, interruption failure etc.).
<b>Humidity:</b>	Water vapour in gaseous form.
<b>Impurities:</b>	Foreign substances in a technical grade gas originating from the gas production process.
<b>Moisture:</b>	Water on the surface or in the structure of solids.

## 4. STANDARDS & GUIDELINES

IEC provides standards for both new and used gas for the use in electrical equipment.

### 4.1. IEC 60376 - NEW SF<sub>6</sub> GAS

IEC 60376 - Specification of Technical Grade Sulphur Hexafluoride (SF<sub>6</sub>) for use in Electrical Equipment [1] defines the permitted levels of impurities for new gas. Some details are provided in the following table.

Table 4-1: Maximum acceptable impurity levels (full details available in IEC 60376)

Content	Specification	Analytical methods (for indication only, not exhaustive)	Precision
Air	2 g/kg	Infrared absorption method	35 mg/kg
		Gas-chromatographic method	3 – 10 mg/kg
		Density method	10 mg/kg
CF <sub>4</sub>	2400 mg/kg	Gas-chromatographic method	9 mg/kg
H <sub>2</sub> O	25 mg/kg	Gravimetric method	0.5 mg/kg
		Electrolytic method	2 – 15 mg/kg
		Dew point method	1 °C
Mineral oil	10 mg/kg	Photometric method	< 2 mg/kg
		Gravimetric method	0.5 mg/kg
Total acidity expressed in HF	1 mg/kg	Titration	0.2 mg/kg

## 4.2. IEC 60480 - USED SF<sub>6</sub> GAS

IEC 60480 - Guidelines for the Checking and Treatment of Sulphur Hexafluoride (SF<sub>6</sub>) taken from Electrical Equipment and Specification for its Re-use [2] defines the maximum impurity levels for re-used gas. The following table is taken from the standard.

Table 4-2: Maximum acceptable impurity levels (full details available from IEC 60376)

Impurity	Rated absolute pressure <200 kPa	Rated absolute pressure >200 kPa
Air and/or CF <sub>4</sub>	3 % volume	3 % volume
H <sub>2</sub> O	95 mg/kg	25 mg/kg
Mineral oil	10 mg/kg	
Total reactive gaseous decomposition products	50 µl/l total or 12 µl/l for (SO <sub>2</sub> +SOF <sub>2</sub> ) or 25 µl/l HF	

### 4.3. CIGRE SF<sub>6</sub> RECYCLING GUIDE

The CIGRE Brochure 234 - SF<sub>6</sub> Recycling Guide, Re-use of SF<sub>6</sub> Gas in Electrical Power Equipment and Final Disposal [3], provides guidance as to the levels of contaminants that can be permitted in equipment in services without a reduction in performance. The following table is taken from the brochure.

Table 4-3: SF<sub>6</sub> contaminants (reproduced from Table 1 in the CIGRE Brochure 234)

Contaminant	Main origin	Deteriorating effects	Maximum tolerable impurity levels in equipment	Proposed maximum tolerable impurity levels for re-use	Practical impurity detection sensitivity
Non-reactive gases:					
Air	Handling	Reduction of switching performance	3% vol.	3% vol. total	< 1% vol.
CF <sub>4</sub>	Switching	Reduction of insulation performance			
Reactive gases or vapours:					
SF <sub>4</sub> , WF <sub>6</sub>	Arcing	Toxicity	100 ppm <sub>v</sub>	50 ppm <sub>v</sub> total <sup>1)</sup>	~ 10 ppm <sub>v</sub> total
SOF <sub>4</sub> , SO <sub>2</sub> F <sub>2</sub>	Partial discharge	Surface insulation by corrosion	2000 ppm <sub>v</sub>		
SOF <sub>2</sub> , SO <sub>2</sub> , HF	Follow-up reactions				
Moisture	Desorption from surfaces and polymers	Surface insulation by liquid condensation	pH <sub>2</sub> O < 400Pa <sup>2)</sup>	pH <sub>2</sub> O< 150 Pa (Td < -15 °C) 750 ppm <sub>v</sub> for p < 200 kPa <sup>3)</sup> 200 ppm <sub>v</sub> for p < 850 kPa <sup>3)</sup>	< 10 Pa <sup>4)</sup>
Oil	Pumps, lubrication, bushings to oil insulated equipment	Surface insulation by carbonisation	Not quantified	10 mg/m3, <sup>5)</sup>	< 1 mg/m <sup>3</sup>
Dust Carbon	Arcing, partial discharges	Surface insulation by conducting deposits, gas and surface insulation	Not quantified	Should be removed by dust filter of pore size < 1 µm	
Dust/particles	Assembling, mechanical wear				
Switching dust: CuF <sub>2</sub> , WO <sub>x</sub> F <sub>y</sub> ,	Contact erosion by arcing				

1) or, equivalently, 12 ppm<sub>v</sub> SO<sub>2</sub> + SOF

2) Based on IEC 62271-1 and corresponding to a dew point of Td = -5°C

[Editorial Comment: This should be more correctly identified as frost point of T<sub>f</sub> = -5 °C]

3) Within the complete range of re-use pressures p < 850 kPa, covering all possible applications (both HV and MV insulation systems as well as all circuit breakers), the low re-use pressure range p < 200 kPa has been defined to highlight low pressure insulation systems (typically applied in MV distribution).

4) Corresponding to a dew point Td = -45 °C

[Editorial Comment: This should be more correctly identified as frost point of T<sub>f</sub> = -45 °C]

5) Corresponding to 0.3 ppm<sub>w</sub> in pure SF<sub>6</sub> at 500 kPa



## **5. ORIGIN AND CONTROL OF CONTAMINANTS**

### **5.1. EXTERNAL SOURCES**

External foreign substances for instance air or water vapour, in SF<sub>6</sub> can arise from several sources, namely:

- Gas handling
- Leakage
- Desorption from surfaces and bulk materials
- Desorption from adsorber materials (filters)
- External substances (permeation via sealing, flanges and enclosures)
- Leakage of insulation medium from neighbouring boundaries (e.g. oil from a bushing)

The levels at which these contaminants are present depend mainly on equipment design, manufacturing, assembly, gas handling procedures, condition of insulators, gas seals, flanges, enclosures, boundaries, cleanliness of surfaces and handling of adsorber materials.

The presence of water must be avoided as, if it condenses, it will form water droplets or film on the surface of insulators or enclosure housing resulting in the deterioration of insulation performance. In combination with some decomposition products it also creates hydrofluoric acid which is corrosive.

While these issues are considered in detail in the CIGRE Brochure 234 [3] and IEC Technical Report 62271-303 [4], some additional comments are given below for completeness.

#### **5.1.1. Gas Handling**

Before filling any compartment with SF<sub>6</sub> it is important that the compartment is first evacuated to remove air and moisture. Humidity and surface adsorbed moisture are readily removed under vacuum, typically within 24 hours or less. However it is very difficult to remove absorbed moisture from bulk materials such as insulators and support bushings.

Before commencing the filling procedure, special attention should be paid to:

- the condition of any vacuum pump that includes oil. If not correctly maintained oil can penetrate into the gas compartment.
- the cleanness, dryness, evacuation and tightness of all interconnected pipes and hoses.

All new bottles of gas shall be certificated or gas quality analysis shall be made on-site. Only approved gas handling carts shall be used for gas filling and all gas lines shall be filled using filters to prevent dust or metallic particles from entering the gas compartments.

### **5.1.2. Water**

#### **5.1.2.1. Humidity from Exposure to Air**

Humidity from the ambient air can diffuse into the interior of the compartment through seals such as O-rings and gaskets. When the rate of diffusion is known, the increase of partial pressure of water vapour inside the compartment can be calculated as a function of time. Under normal conditions, this effect is negligible.

#### **5.1.2.2. Moisture in Insulators**

Water contained in the bulk of insulators may amount to several 0.1% of the mass of the insulator material depending on its condition and if released into the switchgear compartment, it can easily amount to several 10 g of water. Thus the humidity in a compartment is increased above the permitted level ( $<-5^{\circ}\text{C}$  frost point at rated filling pressure) [11]. In order to remove water vapour contained in insulating material, adsorber materials are placed into the compartments.

#### **5.1.2.3. Moisture in Adsorber Material**

Commercial adsorber materials are molecular sieves type material or activated alumina. They are available in either pressed cylindrical or spherical pellets of millimetre size, which are contained in a bag and are placed in every switchgear compartment. The mass of the adsorber material is calculated by the switchgear manufacturer based on the amount of water vapour expected to be produced during the life of the equipment. Typically the weight of applied adsorbers ranges from 100 g to several kg.

These adsorber pellets are stored in sealed containers or bags before use. This prevents humidity from the ambient air penetrating into the adsorber material. Usually the adsorber pellets have an expiry date. If not handled correctly the adsorber pellets can become saturated with water vapour and introduce humidity into the compartment negating the desired effect. When installing new adsorber bags, they should only be taken out of their containers shortly before placement into the compartment. Subsequent closure and evacuation of the compartment should be done immediately.

### **5.1.3. Dust and Metal Particles**

External dust and metal particles originate either from poor manufacturing or from poor assembly processes. Though high voltage equipment is designed to tolerate particles to a certain extent, they should be avoided. If particles are detected during routine and on-site dielectric tests e.g. by partial discharge measurements, they shall be removed from the equipment before energising. Experience has shown that opening a gas compartment on-site for cleaning may result in an increased amount of particles. Good practice is to wait after gas filling to give the particles enough time to migrate to lower parts of the equipment.

## 5.2. INTERNAL SOURCES

Substances generated during the lifetime of the equipment, can arise from several internal sources, namely:

- Decomposition of SF<sub>6</sub> by electrical discharges and reaction with other materials inside the electrical equipment e.g. contact materials and contaminants.
- Mechanical abrasion from the operation of the electric device resulting in the production of dust and metal particles.
- Ablation of nozzles and contacts.

## 5.3. ACADEMIC RESEARCH

There is a considerable body of academic research dealing with the formation of decomposition products arising from various types of electrical discharges in SF<sub>6</sub>. This research has examined the impact of different discharge energies, contaminants present in the gas (humidity and air) and electrode material on the decomposition products generated. The experiments were conducted using a tightly controlled cell/vessel. This allowed the impact of changing one specific parameter to be isolated and measure.

While there is general agreement between the various pieces of research, there are some discrepancies and in many cases these discrepancies have not been fully explained. What this body of work highlights is that the formation of decomposition products is very complex including many interacting variables.

### 5.3.1. Boudéne, Cluet, Keib and Wind

Some of the earliest comprehensive work was done in the 1970's by Boudéne et al [12]. The motivation for this early work was to examine the toxicological impacts of SF<sub>6</sub> decomposition products. A series of electrical arc discharges was undertaken and the resulting gaseous decomposition products were analysed using gas chromatography and infrared spectroscopy. The conclusion from the study was that toxicity levels were low and that toxic gaseous decomposition products could be efficiently eliminated with adsorbers.

### 5.3.2. Belmadani, Derdouri, Casanovas, Casanovas, Grob and Mathieu

These researchers have published a significant body of work examining the SF<sub>6</sub> decomposition products under different conditions. A lot of the work has focused on the different types of electrical activity, partial discharges, sparks and arcs, but was extended to examine the impact of humidity in the gas and different types of electrodes [7], [13] and [14]. Much of this work was published in the late 1980's and early 1990's.

### 5.3.3. Heise, Kurte, Fischer and Klockow

Some of the earlier work was repeated and expanded upon by these researchers. The analysis of the decomposition products was undertaken using infrared spectroscopy which offered the opportunity of direct and in-situ detection of intermediate decomposition products [15].

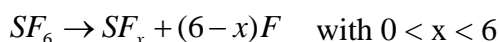
### 5.3.4. Piemontesi

In a custom made stainless steel cell mounted in the light path of a Fourier Transform Infrared (FTIR) spectrometer the concentration of SF<sub>6</sub> decomposition products was measured. The production rates of decomposition products generated by negative point to plane corona and sparks was significantly influence by the presence of water and oxygen, and the type of cell surface, namely stainless steel, aluminium and glass. Whereas some decomposition products, such as CF<sub>4</sub>, SO<sub>2</sub> and SO<sub>2</sub>F<sub>2</sub> were found to be rather long-lived, other products, such as SF<sub>4</sub>, SOF<sub>2</sub>, SOF<sub>4</sub> and HF were observed to decay rapidly. The decay time depends on the material of the enclosure, the presence of H<sub>2</sub>O and its surface state, and the presence of contaminants in the gas phase. Also, the specific sorption efficiency of several adsorber substances, namely activated alumina and molecular sieve type 13X, was determined for different decomposition products [6].

## 5.4. FORMATION OF DECOMPOSITION PRODUCTS

### 5.4.1. SF<sub>6</sub> Decomposition Products from Electrical Discharges

During normal load or short-circuit current switching, SF<sub>6</sub> molecules are ionized and fragmented by the arc. While the majority of the molecules will recombine a number of the ionized and fragmented molecules will react to form decomposition products. A number of intermediate products are created depending on the type of excitation and intensity of arc energy according to [3], [5].



SF<sub>6</sub> decomposition products created in an arc will react with the materials of the electrical contacts such as aluminium, copper, and tungsten. This reaction generates metal fluorides. In the presence of carbon, which may originate from the nozzle material (PTFE) or other insulating materials, CF<sub>4</sub> is formed. Inside the arc channel, further chemical reactions of fragmented SF<sub>6</sub> are possible with contaminants H<sub>2</sub>O, N<sub>2</sub> and O<sub>2</sub>. The resulting decomposition products will often contain oxygen, e.g. SO<sub>2</sub>F<sub>2</sub>.

At the boundary of the discharge channel or after cessation of the arc, most of the fragments, molecules and ions recombine to SF<sub>6</sub>. However, some decomposition products, in particular SF<sub>4</sub> and HF, are quite stable. Whilst stable in an SF<sub>6</sub> environment they become extremely reactive in the presence of oxygen or humidity, the latter much more abundant on the inner surface of the compartment compared to the gas volume. Therefore SF<sub>4</sub> will react with water molecules and create decomposition products. In the same way, HF will react with metal oxides and form metal fluorides.

#### 5.4.1.1. Burst of Decomposition Products produced during Switching Operation

The total number of SF<sub>6</sub> molecules decomposed and ionised during a switching operation is proportional to the interrupted current and arcing time. From measurements, a relationship between arc energy and the decomposition product SOF<sub>2</sub> was derived [5], [7], which is representative of the total decomposition products produced by a discharge in SF<sub>6</sub> (see Figure 5-1). The production rate of decomposition products can be determined by assuming that all SF<sub>6</sub> molecules in the arc nozzle of a circuit-breaker are dissociated and some fraction of the dissociated molecules end up in decomposition products. The order of magnitude of the number of decomposition molecules originating from one switching operation can be calculated by:

$$N_0 = N_L r \cdot I U_{arc} t_{arc} n \quad (5.1)$$

Where:

$N_L$	number of molecules in one litre at 100 kPa and 21°C i.e. $2.462 \times 10^{22}/l$
$r$	formation rate of decomposition products in relation to the arc energy given in [l/kJ]
$I$	interrupted current in [kA]
$U_{arc}$	arc voltage typically 200 V for medium voltage switchgear and 800 V for HV
$t_{arc}$	duration of arc, typically 0.015 s
$n$	number of poles in the interrupter chamber

In IEC 62271-303, the production rate of the decomposition product SOF<sub>2</sub> – resulting mainly from SF<sub>4</sub> - is given by  $3.7 \times 10^{-3}$  l/kJ [4]. So assuming a single phase interruption at 31.5 kA and corresponding arc energy of 95 kJ, this would provide 0.35 litres of decomposition product gas or  $8.5 \times 10^{21}$  molecules. Distributed into a circuit-breaker volume of 0.3 m<sup>3</sup> filled with 600 kPa of SF<sub>6</sub>, the concentration of decomposition products would be 192 ppm<sub>v</sub>. For load current switching, the arc current is accordingly smaller, resulting in a much smaller amount of decomposition products.

#### 5.4.1.2. Stream of Decomposition Products produced by Corona Discharge

The number of ions produced per second,  $S$ , by a corona discharge are estimated from the corona current:

$$S = \alpha \frac{I}{e} \quad (5.2)$$

With the following parameters:

$I$	Corona current
$e$	electron charge i.e. $1.6 \times 10^{-19}$ As
$\alpha$	multiplication factor for decomposition products (>1)

This would typically produce a flux of  $6.25 \times 10^{13} \text{ s}^{-1}$  of charged ions and an equivalent flux of decomposition products, if  $\alpha=1$ . From experiments [5], a formation rate of approximately 50 µmole/C is derived with reference to the emitted charges instead of the discharge energy. This would result in a flux of decomposition products of  $3 \times 10^{14} \text{ s}^{-1}$  assuming a continuous corona current of 10 µA. This is consistent with the estimate according to (Equation 5.2) proposing that one electron is able to create more than five SF<sub>6</sub> fragments and associated decomposition products. Because of the high energy of the electrons this is reasonable. In a

volume of 0.3 m<sup>3</sup> filled with 4 bar of SF<sub>6</sub>, a flux of  $3 \times 10^{14} \text{ s}^{-1}$  continuing over one week would give a concentration of 6 ppm<sub>v</sub>, if no decomposition products are removed from the volume by adsorber material.

#### 5.4.2. Decomposition Product Reactions

The probability of reaction of SF<sub>4</sub> or SF<sub>2</sub> with other gaseous contaminants inside the arc channel or corona discharge region is high due to the availability of H<sub>2</sub>O or O<sub>2</sub> molecules or substances with chemically bonded hydrogen or oxygen. However, in the general gas volume the probability of a reaction is low, since both reaction partners are minor constituents of the gas and must collide with sufficient energy to trigger a reaction.

Supposing that the main transport process inside the volume is provided by convection and not by the much slower diffusion, SF<sub>4</sub> reaches the walls of the container in a relatively short time (typically hours) so that the surface reaction starts relatively quickly after the occurrence of an arc. On metallic walls, moisture is readily available to react with impinging SF<sub>4</sub>. A lot of experiments recognize little change in the concentrations of SOF<sub>2</sub>, when the humidity concentration is changed by even an order of magnitude, which can be explained by the dominance of surface reactions [6], [7]. It has to be remarked that even 1 ppm<sub>v</sub> of humidity in a volume of 0.3 m<sup>3</sup> filled with SF<sub>6</sub> at 600 kPa contains sufficient water to cover a surface of 3 m<sup>2</sup> with a monolayer of H<sub>2</sub>O molecules (surface density for a monolayer is  $1.5 \times 10^{19}/\text{m}^2$ ). Oxygen is available in insulating material and on metal surfaces.

Figure 5-1: Schematics of hot plasma reactions (left side) and cold wall reactions (right side)

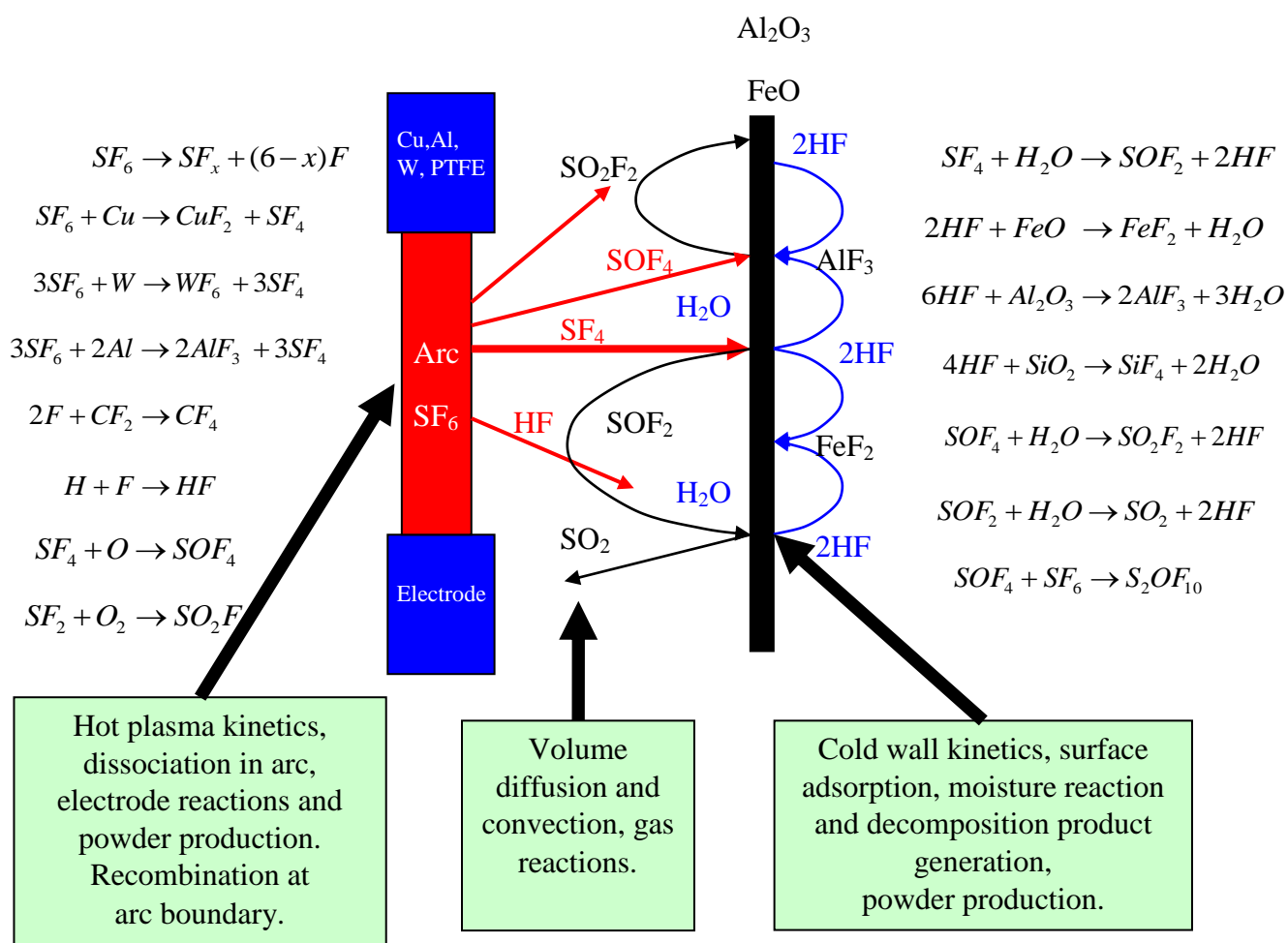


Figure 5-1 depicts the main reaction processes and where each is likely to occur.  $SF_4$ , as the main decomposition product from the electric discharge, first reacts with  $H_2O$  on the inner wall surface resulting in  $SOF_2$ . This process is called hydrolysis. The resulting  $HF$  mostly remains on the surface and rapidly reacts with the metal oxides on the surface material making it short lived compared to other decomposition products. The metal fluorides remain as powder or dust on the surface.  $H_2O$  is released in this reaction and therefore available for further reactions with  $SF_4$  or for the much slower conversion of  $SOF_2$  to  $SO_2$  [9]. Since in this process,  $H_2O$  is in fact not consumed but plays the role of a catalyst [6].

The probability of detecting decomposition products is determined by several physical processes which are considered in detail in Annex D. The factors involved are:

- Formation rate of decomposition products as a function of the arc or discharge energy.
- Transport speed (diffusion or convection) of decomposition products from the arc or discharge location to the walls of the compartment.
- Gas mixing of decomposition products created at surfaces (diffusion or convection).
- Reaction rate of decomposition products at wall surfaces.

- Adsorption rate of decomposition products in adsorber materials depending on the properties and the location of the adsorber material.

#### 5.4.2.1. SOF<sub>2</sub> and SO<sub>2</sub>

The two decomposition products SOF<sub>2</sub> and SO<sub>2</sub> are the most abundant substances detected after electric arcs, sparks or corona discharges. SOF<sub>2</sub> is not produced by the discharge itself, but originates from secondary reactions of SF<sub>4</sub> with H<sub>2</sub>O on the walls as described above with a reaction rate of  $k = 1.8 \pm 0.9 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$ . Because of the hydrolysis of SOF<sub>2</sub> this gas is converted to SO<sub>2</sub> depending again on the availability of water molecules on surfaces but with a slower reaction rate of  $k = 1.2 \pm 0.3 \times 10^{-23} \text{ cm}^3 \text{ s}^{-1}$ . These reaction times are in the order of 10 to 100 days [7] so that the concentration of SO<sub>2</sub> might even rise in time after an event producing decomposition products. At the moment SOF<sub>2</sub> cannot be detected with sufficient sensitivity by portable devices in the field and the decomposition product detection is mainly based on SO<sub>2</sub>.

SOF<sub>2</sub> and SO<sub>2</sub> are very rapidly adsorbed by adsorbents like zeolite 13X molecular sieves. It was observed that both substances disappeared within 48h from a small volume of a couple of litres containing some zeolite 13X [7], whereas they stayed in the volume for more than 100 days, when no adsorber material was present. Therefore, the ability to detect these decomposition products very much depends on the presence of adsorbents and the time span between generation and measurement.

SO<sub>2</sub>F<sub>2</sub> and SOF<sub>4</sub> are also sometimes observed in GIS equipment but in concentrations much smaller than SOF<sub>2</sub>. These decomposition products are most probably directly produced in the arc or discharge channel. Their abundance being directly proportional to the level of humidity in the switchgear [10].

#### 5.4.2.2. HF

In cases where hydrogen in a bounded form like H<sub>2</sub>O is available in the gas in considerable amounts, HF may be produced by a direct reaction between fluoride and hydrogen in the arc discharge. As soon as HF reaches the walls by diffusion or convection, HF rapidly reacts with surface oxides like Al<sub>2</sub>O<sub>3</sub>, FeO or SiO<sub>2</sub>. HF is quickly converted into a solid fluoride, which sticks to the surfaces in the form of powder, and therefore disappears from the volume. In addition HF is produced in the hydrolytic surface reaction of SF<sub>4</sub> with water molecules as well as in the subsequent decomposition of SOF<sub>2</sub> with moisture, thereby producing SO<sub>2</sub> as a final stable by-product. Moisture is a pre-requisite for this decomposition process, however, in practice it is always available on the surfaces.

In fact HF is mainly observed, in those cases, where a high concentration of SF<sub>4</sub> itself is detected e.g. shortly after a short-circuit interruption. High concentrations of SF<sub>4</sub> (in the range of 1000 ppm<sub>v</sub> and higher) may remain in a large compartment for several hours or even days after a switching event. In-situ gas analysis, if done during this time, may detect HF. As the SF<sub>4</sub> is eliminated, so also is the HF.

The relative abundance of HF is difficult to determine since the reaction speeds /or rates of formation of the three decomposition products SF<sub>4</sub> i.e. HF, SOF<sub>2</sub> and SO<sub>2</sub> are very dissimilar. Although the decomposition of SF<sub>4</sub> into SOF<sub>2</sub> and HF should deliver 1 part of SOF<sub>2</sub> and 2 parts of HF, the concentration of both parts in the gas volume does not obey a



ratio of 1:2. Since the subsequent reaction of  $\text{SOF}_2$  with water into  $\text{SO}_2$  takes much longer than the subsequent reaction of HF with metal oxides,  $\text{SOF}_2$  will accumulate in the volume whereas HF will diminish. Therefore, the concentration of  $\text{SOF}_2$  in the gas will be much higher than that of HF. The amount of HF produced by the conversion of  $\text{SOF}_2$  into  $\text{SO}_2$  is even lower, since the reaction speed of this process is low compared to that of  $\text{SF}_4$ .

One consequence of the high reactivity of HF is that, on its own, it is not a good indication of the volume of decomposition products created. Considering the reaction schemes other decomposition products provide more reliable indication, e.g.  $\text{SO}_2$ . If a suitable method for measuring HF is available, this test might add value to the diagnosis.

#### 5.4.2.3. $\text{CF}_4$

Most of the  $\text{SF}_6$  insulated circuit breakers and load switches use nozzles made out of PTFE for current interruption or breaking. Its main decomposition product, when in contact with an  $\text{SF}_6$  arc, is  $\text{CF}_4$  (see Figure 5-1). These nozzles serve to shape the flow of cold gas and hot arc plasma so as to cool the arc by heat removal while increasing the gas pressure and facilitate arc extinction. With each current interruption ablation of nozzle material occurs with the result that the nozzle diameter increases and its performance deteriorates over time. Therefore, a method to indicate the degree of nozzle wear is important and the monitoring of the amount of  $\text{CF}_4$  has a potential application in this regard.

In several publications [7], [8] it was shown that the amount of  $\text{CF}_4$  is proportional to the arc energy. Absolute values, however, depend on the specific nozzle geometry as well as on the design of the circuit-breaker. Adsorber material placed inside the device does not seem to be effective in adsorbing  $\text{CF}_4$  no matter which adsorbent is used. The molecular sieve 13X was shown not to trap  $\text{CF}_4$  over a period of 47 days [7].

Considerable amounts of  $\text{CF}_4$  have been measured during consecutive interruptions of currents up to 8.3 kA [7]. These production rates depend on the circuit-breaker design principle and the interrupted current as explained above. A failure within the circuit breaker will produce a somewhat higher concentration of  $\text{CF}_4$  than measured during normal operation. However, the increase might not be significant. The detected  $\text{CF}_4$  levels are proportional to the accumulated arc energy. Because of the dependence on design, only the manufacturer is able to provide benchmark values indicating the wear of a nozzle. Nozzle wear will increase the arc time but is generally not the limiting factor in the life of  $\text{SF}_6$  circuit breakers, particularly above 72.5kV.

Another difficulty arises with the permissible  $\text{CF}_4$  contamination level of new  $\text{SF}_6$  gas. According to IEC 60376 [1], levels of up to 4000  $\mu\text{l/l}$  (2400 mg/kg or 830 ppm<sub>v</sub> at 100 kPa) are permissible. However this has little relevance from an equipment performance perspective as 50:50  $\text{SF}_6/\text{CF}_4$  gas mixtures are used for equipment that is required to operate at very low ambient temperature.

#### 5.4.2.4. Metal Fluorides

Solid decomposition products (mainly metal fluorides and metal oxide fluorides) may be produced directly by the interaction of an arc with metal parts or by the reaction of decomposition products of  $\text{SF}_6$  with metals or metal oxides. The main decomposition products are  $\text{AlF}_3$ ,  $\text{CuF}_2$  and  $\text{WF}_6$ .

$\text{AlF}_3$  is produced by the interaction of an arc with aluminium or by the reaction of HF with  $\text{Al}_2\text{O}_3$  e.g. at the inner wall of a compartment. This white powder is usually the main solid product found after electrical activity in a compartment.  $\text{CuF}_2$ , which is also a white powder, is produced by the interaction of an arc with copper or components containing copper.  $\text{WF}_6$  is produced by the interaction of an arc with the material of the main contact. It is very toxic and has special physical properties. Above  $17^\circ\text{C}$  it exists in the form of a colourless gas, between  $2^\circ\text{C}$  and  $17^\circ\text{C}$  it is a pale yellow liquid and below  $2^\circ\text{C}$  it freezes into a white solid.  $\text{WF}_6$  reacts instantaneously with water to form  $\text{H}_2\text{WO}_4$  and HF.

The amount of metal fluorides produced by an arc cannot be determined quantitatively. Metal fluorides and their further reaction products are non-conductive and therefore do not reduce the dielectric insulation levels.

For removal, the compartment has to be opened and partly disassembled and all surfaces have to be cleaned carefully. Metal fluorides cannot be detected by gas analysis.

#### 5.4.2.5. Other Contaminants

Abnormal heating of polymeric materials like epoxy insulators or cellulose insulating material, as used in instrument transformer windings, may produce CO or  $\text{CO}_2$ . Similarly COS may be produced by corona discharge involving polymer material [10].

## 5.5. CONTROL OF CONTAMINANTS

An effective method for the control of contaminants is the use of adsorber materials. Molecular sieves or activated alumina have large surfaces of up to 600 m<sup>2</sup>/g made up of pores and cavities inside the material. These internal cavities are linked with each other by channels, the diameter of which is determined by the molecular structure of the adsorber material. The channel diameters are typically available in sizes of 0.3, 0.4, 0.5 or 1 nm. This is just sufficient to let all molecules with smaller diameter pass through the channels and be trapped. Molecules with larger diameter are blocked. Adsorber materials with smaller channels are generally used for the removal of water vapour, while those of larger diameter are effective for the removal of decomposition products as well as moisture.

The adsorber will continue to adsorb decomposition products and contaminants until it is saturated. Normally the quantity of the adsorber material is calculated in such a way that saturation is not reached during the life of the equipment.

Adsorber materials are very effective in removing decomposition products from the volume. This, coupled with limited information on the amount of products generated means that only a qualitative evaluation of the concentration of the decomposition products is possible. This is further explained in Annex B. The omission of adsorbents, however, is not an alternative for switchgear, since decomposition products may react with insulating surfaces and degrade their voltage withstand capability [1]. Additional details on adsorber materials are available in Annex E.

## **6. GAS MEASUREMENT AND ANALYSIS**

### **6.1. IMPACT EQUIPMENT DESIGN**

The type and design of the equipment influences the creation and effects of decomposition products, thus these factors must be considered in the analysis and interpretation of results.

#### **6.1.1. Switchgear**

In the case of switchgear filled with SF<sub>6</sub> as an interrupting medium and/or insulation, the compartments can be grouped into three classes:

- Switchgear, with high energy arc (circuit breakers and load switchers - either AIS or GIS)
- Switchgear, with low energy arc (disconnectors and earthing switches - GIS)
- Static components, without switching arcs (busbar compartments, VT's – GIS)

### **6.2. PURPOSE OF GAS ANALYSIS**

SF<sub>6</sub> analysis can help at all stages of the equipment lifecycle, before the equipment is commissioned, during service and when it is to be decommissioned.

SF<sub>6</sub> analysis thus serves three main purposes:

- To ensure that the initial quality of the gas at the time the equipment is commissioned (or subsequent to any gas handling) fulfils the requirements.
- To identify and diagnose deterioration of the equipment when in-service.
- To ensure the proper handling of SF<sub>6</sub> gas at the time the equipment is removed from service.

All three are very important, however, the second purpose is critical when deciding if remedial measures are required to ensure satisfactory performance of the equipment or indeed to prevent catastrophic failure. Similarly it can avoid unnecessary opening of the equipment and the resulting outages and costs. This aspect is of increasing importance as Utilities are under pressure to reduce maintenance costs. Condition Based Maintenance (CBM) can provide optimum solutions and is therefore being adopted by many Utilities as their preferred maintenance strategy.

### **6.2.1. Before Equipment Enters Service**

At the time of installation of the equipment gas analysis can be used:

- To verify the quality and condition of the gas in the equipment prior to the latter being put into service; typically SF<sub>6</sub> percentage and humidity are measured,
- To determine if SF<sub>6</sub> decomposition products are present, though normally the result should always be below the permitted levels for re-used gas.

The same measurements may also be made of the gas in each cylinder before filling the equipment.

### **6.2.2. During Equipment Service**

#### **6.2.2.1. Periodically (as part of a maintenance regime)**

During the service life of the equipment SF<sub>6</sub> gas analysis may be undertaken as part of a maintenance regime. Typically SF<sub>6</sub> percentage, decomposition products and humidity are measured. Depending on the type of equipment involved (arcing or non-arcing) these tests can identify potential problems such as:

- Dielectric activities (partial discharge, corona).
- Nozzle wear.
- Hot spots (high contact resistance).
- Non-standard switching conditions (heavy duty switching operations).
- Sealing problems (humidity, air).
- Improper gas handling (humidity, air, oil).

#### **6.2.2.2. Failure Investigation (after an event)**

Following a failure or suspected failure, analysis of the SF<sub>6</sub> gas may be used as part of the investigation process:

- To identify the compartment following internal flash over.
- To identify the level of decomposition products and hence the necessary gas handling procedures prior to opening a compartment.
- To investigate an abnormal behaviour highlighted by other factors, i.e. to identify if the problem is within a gas compartment.
- To correlate results obtained from other condition assessment techniques, e. g. partial discharge measurements.

Initial measurement of the decomposition products should be made using simple detector tubes to prevent damage to sensitive detection equipment.

### **6.2.3. Prior to Disposal of Equipment**

Before evacuating a compartment of SF<sub>6</sub>, the condition of the gas has to be checked so that the necessary handling/recycling procedures can be identified e.g. whether the removed gas can be re-used or whether it has to be returned for recycling or even disposed.

## **6.3. MOST APPROPRIATE ON-SITE MEASUREMENTS**

While it is possible to measure a wide variety of SF<sub>6</sub> decomposition products using portable gas chromatography instruments, they are complex to use and hence not practicable as part of a condition based maintenance strategy. However recently a number of manufacturers have developed multi-analysers that allow three or four parameters of the gas to be measured easily and quickly, thus overcoming the issues with gas chromatography devices. The traditional detector tubes continue to play a role in the high level screening for decomposition products.

From an equipment performance perspective the most critical element is SF<sub>6</sub> content (clearly coupled with SF<sub>6</sub> density), the next being humidity and finally decomposition products. As discussed in an earlier section, the two products SOF<sub>2</sub> and SO<sub>2</sub> are the most abundant substances detected after electric discharge activity. Because of the hydrolysis of SOF<sub>2</sub> it degrades over time leaving SO<sub>2</sub> as a stable decomposition product. HF is also present but it reacts with surface oxides producing solid metal fluorides and is removed from the gas volume.

The most appropriate decomposition product to measure is SO<sub>2</sub> as it is a stable decomposition product. The measurement of HF may also be undertaken if the capability is available.

### **6.3.1. On-Site Measurement Procedures**

#### **6.3.1.1. Safety Precautions**

Before conducting a measurement, care must be taken to ensure that a gas-tight connection has been established between the gas compartment and the measuring device.

Where possible it is recommended that gas sampling is carried out on an apparatus that has been switched out of service. If this is not possible the operating instruction manual from the equipment manufacturer shall be strictly observed when taking samples from energized equipment.

Only properly trained personnel should handle SF<sub>6</sub>.

#### **6.3.1.2. Measurement Procedure**

Two separate and distinct scenarios require the performance of on-site gas analysis. The first is following a known or suspected internal failure. The objective of the measurement is to identify the compartment or phase within which the failure has occurred, the severity of the contamination and the necessary precautions to be taken by maintenance personnel.

The second scenario is where measurements are carried out as part of condition assessment. This requires a much higher level of measurement precision.

#### 6.3.1.3. Detector Tubes

Simple easy to use detector tubes, e.g. for SO<sub>2</sub> and other acidic compounds like HF and SO<sub>2</sub>F<sub>2</sub>, are available for the detection of decomposition products and can be used to identify a faulted gas compartment. A small amount of gas is taken from a compartment and passed through the tube which changes colour in the presence of decomposition products. It is suggested that a detector tube with a sensitivity of 1 – 25ppm<sub>v</sub> is used initially and if this range is exceeded then a tube with a sensitivity of 20 – 200ppm<sub>v</sub> should be used.

Detector tubes sensitive to one specific decomposition product are available, however, they tend to be cross-sensitive to other decomposition products. Typical accuracy range is 10 – 30%.

#### 6.3.1.4. Portable Analysers

A number of single and multi- measurement devices are available for on-site measurements. Typically they can measure humidity, percentage SF<sub>6</sub> and decomposition products. Some devices may also be capable of measuring CF<sub>4</sub>. The advantage of a multi-measurement device is that it is capable of simultaneously measuring three or four parameters and thus vastly reducing the time and effort required. Most modern devices capture the sampled gas, with some injecting the gas back into the compartment. They generally include a safety feature which shuts the measurement down in the presence of high levels of decomposition products.

Each analyser should have a detailed operation instruction manual. The user should strictly follow the instructions.

The following principles and recommendations should be followed:

- The sampled gas has to be in a closed circle, i.e. not vented into atmosphere. Recovery of sampled gas is now easily achieved either by using gas collection devices or by returning it to the apparatus under test. It is strongly recommended that this procedure be followed to ensure minimal loss of gas.
- Corruption of the measurement result has to be avoided. A suitable hose should be selected for the measurement. Ideally, a PTFE / PFA bend-proof (metal-jacketed) hose should be used. Rubber hoses should not be used due to their hygroscopic nature and permeability.
- The hose used should be flushed with the SF<sub>6</sub> sample gas to ensure that the measuring device measures the gas from the compartment and not the gas from the hose or an SF<sub>6</sub>-air mixture. Measuring hoses with self-sealing couplings on both ends are recommended.
- When connecting the measuring device, it is important to establish whether the measurement must be started manually, i.e. by opening an internal inlet valve in the measuring device, or the measuring device works as a "display device" and the SF<sub>6</sub>

from the compartment flows through the measuring device as soon as the measuring hose is connected.

- If a high concentration of decomposition products is suspected, this should be determined before any other measuring devices are used. Polymer or aluminium oxide sensors of electronic humidity measuring devices are easily damaged by decomposition products due to corrosion of their thin surface layers. On the other hand, dew point mirror measuring devices are more robust because their surfaces have a protective coating.
- Each recorded sample should contain information about the ambient temperature and the measurement pressure.
- The measurement results may be documented either electronically or manually. In this context, it is important to ensure the traceability of the measurement results by specifying the location (compartment/system), time and date. If the data is stored electronically, the data must be downloaded from the measuring device and archived appropriately.
- Depending on the measuring device in use, either the results are interpreted automatically (and displayed on the device's screen) or the operator makes a decision regarding the quality of the SF<sub>6</sub>. For devices with automatic data interpretation, the threshold values for the individual sensors can be adjusted via the settings menus of the devices.
- After a measurement, particularly after the identification of decomposition products, it is recommended to purge all measuring devices either with pure SF<sub>6</sub>, air or nitrogen,
- If the instrument is to be regularly re-calibrated, the manufacturers recommendations for the re-calibration period should be followed.



## **6.4. SITE TRIALS**

In preparing the previous sections, information was gathered from the measurement experience of the organizations represented by the authors. In addition a dedicated series of on-site trials was undertaken to assess the performance of some recently introduced gas analysers and gain an understanding of the latest testing technologies.

The on-site trials also included gas testing at two laboratories. While the test techniques available in laboratories are far more sophisticated than those available on-site, there are issues with the sampling and preserving of the gas samples. The latter is due to the reactive nature of some of the decomposition products. There are also some very practical issues such as the time and cost involved with laboratory testing. It is difficult to envisage laboratory testing of SF<sub>6</sub> gas to form part of regular condition assessment.

## 7. GAS QUALITY

### 7.1. IDENTIFICATION & ANALYSIS OF ABNORMAL CONDITIONS

When interpreting the results of gas analysis it is important to be cognizant of the function of the equipment and to distinguish between gas compartments with and without switching/interrupting functions.

The following flowcharts identify the steps in SF<sub>6</sub> decomposition product analysis, humidity measurement and percentage SF<sub>6</sub> content. Where individual instruments are being used it is recommended that this order be followed to avoid inadvertent damage to the instruments due to high levels of decomposition products. When multi-measurement devices are used, all parameters are clearly measured simultaneously.

The following flowcharts provide a pictorial view of the analysis and decision-making process.

Figure 7-1: Decision making process for SF<sub>6</sub> gas analysis to identify decomposition products

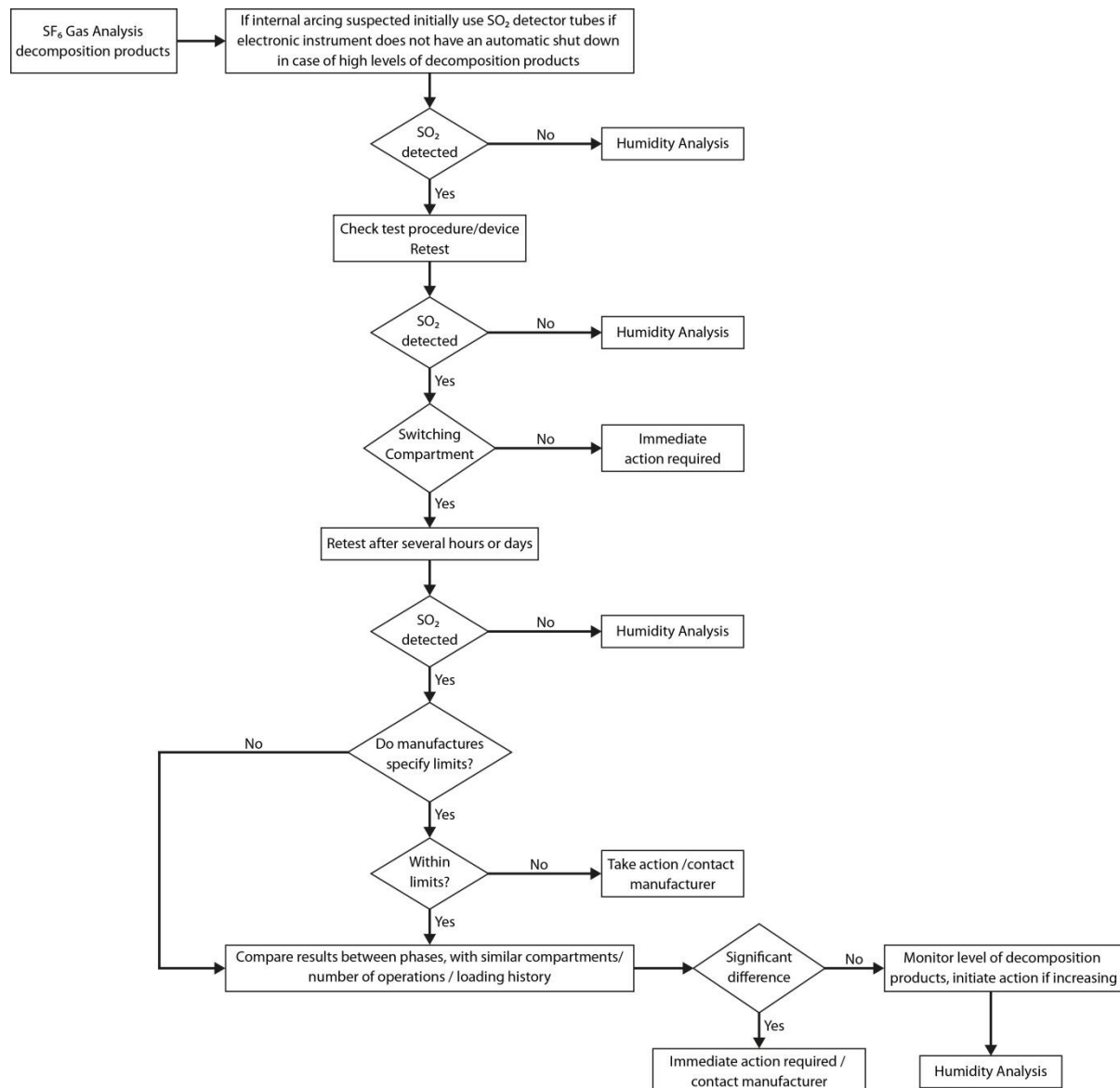


Figure 7-2: Decision making process for SF<sub>6</sub> gas analysis to identify humidity content

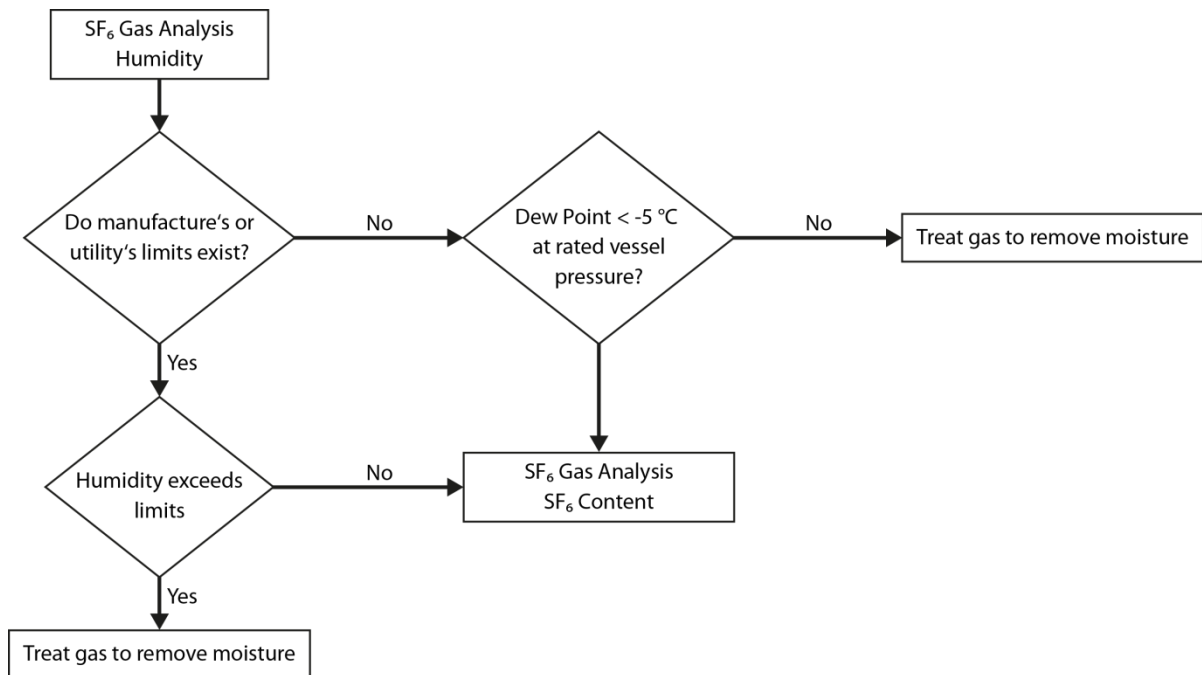
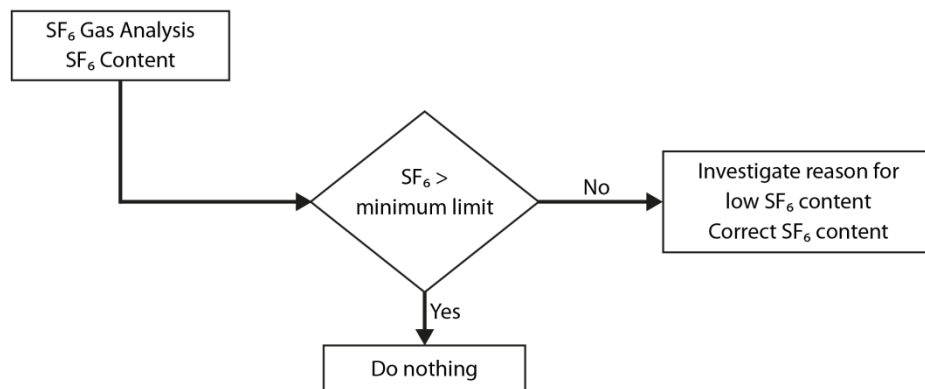


Figure 7-3: Decision making process for SF<sub>6</sub> content analysis



Note: The permissible humidity value can be expressed in different units. Details on how to convert between units is given in Annex F.

### **7.1.1. Gas Compartments not containing Switching Equipment**

In gas compartments which do not contain load switching equipment, such as busbar and busduct sections, bushings, maintenance earthing switches and instrument transformers (GIS or AIS) any level of decomposition products would be a cause for concern independently of whether the compartment includes adsorbers or not. Any measured value should trigger further investigation so as to identify the origin of the decomposition products.

### **7.1.2. Gas Compartments containing Switching Equipment**

In gas compartments which contain switching equipment, the decision process is much more complicated than in a compartment which normally does not contain any switching activity. When evaluating the measured level of SF<sub>6</sub> decomposition products it is necessary to consider the following aspects before any conclusion is made:

- a) The presence and type of adsorber material inside the gas compartment. If the adsorber material traps only water, the stable SF<sub>6</sub> decomposition products remain and accumulate in the gas compartment.
- b) The loading history, i.e. number and magnitude of switching currents (e.g. currents during normal switching operations, fault clearance, disconnecter busbar transfer current). The loading history of circuit breaker phases can be different if there is single-phase auto-reclosing function.
- c) Any abnormal operating conditions (e.g. asynchronous switching, re-strikes, and any voltages exceeding rated parameters).
- d) Whether there are differences in the level of decomposition products between individual phases of the equipment or similar equipment. In the case of three-phase encapsulated equipment, or interconnected gas compartments, comparison between phases is not possible.
- e) The time delay between the last switching operation and the analysis or gas sampling. In compartments fitted with adsorbers capable of trapping SF<sub>6</sub> decomposition products, the level of decomposition products will reduce over time. If the level does not decrease then it might indicate internal partial discharge (PD) activity, overheating problems, or that the adsorber has ceased to function correctly.
- f) The results of other diagnostic measurements, such as PD measurements, main contacts static resistance measurement, CB contacts dynamic resistance measurement, CB re-strikes and re-ignitions monitoring.

As the evaluation is a process, it is not possible to identify an absolute limit of SF<sub>6</sub> decomposition products for indication of ‘concern’ or dangerous conditions. For instance during the type testing of circuit breakers, large amounts of decomposition products are produced without negatively impacting the performance of the circuit breaker. However, when in service, should decomposition products be found in a circuit breaker that has not operated for several weeks or found in one phase and not in the others, then this is a cause for concern and further investigation is required. In any case where there are doubts it is always recommended that the manufacturer be contacted for advice.

## **8. REVIEW OF UTILITY GAS SAMPLING PRACTICES**

### **8.1. SURVEY OF UTILITIES**

A number of utilities were surveyed to determine their practices in relation to the sampling and analysis of SF<sub>6</sub> in various types of equipment. The following table summarises the results of this survey. Some of the finer details have been removed to facilitate the tabulation of the results. All dew point references in the following table are meant to include all types of humidity measurements including dew point, frost point, ppm<sub>v</sub> and ppm<sub>w</sub>.

Table 8-1: Comparison of utility practices with regard to SF<sub>6</sub> gas sampling

	<b>Commissioning Tests (applied to SF<sub>6</sub> gas)</b>	<b>Monthly/ Continuous</b>	<b>1 Year</b>	<b>4/6 Year</b>	<b>8/10 Year</b>	<b>20 Years</b>	<b>24/25 Years</b>	<b>As Required</b>
<b>GIS/MTS Company 1</b>	Measurements of %SF <sub>6</sub> , dew point and SO <sub>2</sub> /HF decomposition products	Record gas density values	Dew point measurements (outdoor GIS) Gas leak detection survey (if leak suspected)		Measurements of %SF <sub>6</sub> , dew point and SO <sub>2</sub> /HF decomposition products	Change SF <sub>6</sub> desiccant in CB's, CB compartments	SF <sub>6</sub> gas analysis (as part of major overhaul)	Special/fault investigation
<b>GIS/MTS Company 2</b>	Measurements of %SF <sub>6</sub> , dew point and SO <sub>2</sub> /HF decomposition products			Measurements of %SF <sub>6</sub> , dew point and SO <sub>2</sub> /HF decomposition products	Measurements of %SF <sub>6</sub> , dew point and SO <sub>2</sub> /HF decomposition products			Special/fault investigation
<b>GIS/MTS Company 3</b>		Record gas density values	Test SF <sub>6</sub> pressure/density devices	Measurements of %SF <sub>6</sub> , dew point and SO <sub>2</sub> /HF decomposition products (outdoor GIS)	Testing of SF <sub>6</sub> gas monitoring system Measurements of %SF <sub>6</sub> , dew point and SO <sub>2</sub> /HF decomposition products		SF <sub>6</sub> gas analysis (as part of plant condition assessment)	
<b>GIS/MTS/CB's Company 4</b>				Measurements of %SF <sub>6</sub> , dew point and decomposition products				Measurement of decomposition products after a short circuit
<b>GIS/CB's Company 5</b>	Measurements of %SF <sub>6</sub> , dew point and decomposition products		Measurements of %SF <sub>6</sub> , dew point and decomposition products	Measurements of %SF <sub>6</sub> , dew point and decomposition products				After 2-3 short line faults - measurements of %SF <sub>6</sub> , dew point and decomposition products
<b>CT/VT's Company 5</b>	Measurements of %SF <sub>6</sub> , dew point and decomposition products				Measurements of %SF <sub>6</sub> , dew point and decomposition products	Measurements of %SF <sub>6</sub> , dew point and decomposition products		After 2 – 3 short line faults - measurements of %SF <sub>6</sub> , dew point and decomposition products

<b>GIS/MTS Company 6</b>	Measurements of %SF <sub>6</sub> , dew point and decomposition products			Measurements of %SF <sub>6</sub> , dew point and decomposition products	Measurements of %SF <sub>6</sub> , dew point and decomposition products	Measurements of %SF <sub>6</sub> , dew point and decomposition products	Measurements of %SF <sub>6</sub> , dew point and decomposition products	
<b>CB CT/VT's Company 6</b>	Measurements of %SF <sub>6</sub> , dew point				Measurements of %SF <sub>6</sub> , dew point and decomposition products	Measurements of %SF <sub>6</sub> , dew point and decomposition products		Special/fault investigation
<b>GIS Company 7</b>	Measurement of %SF <sub>6</sub> , dew point			Measurement of dew point				Special/fault investigation
<b>CB's Company 7</b>	Measurement of %SF <sub>6</sub> , dew point							Special/fault investigation
<b>CB's Company 8</b>					Measurements of %SF <sub>6</sub>			
<b>GIS Company 8</b>					Measurements of %SF <sub>6</sub> , dew point and decomposition products using tubes and portable analysers			

Notes: The time intervals 4/6 and 8/10 years – the shorted time interval applies to critical installations.

## 9. CASE STUDIES

### 9.1. REVIEW OF HIGH VOLTAGE EQUIPMENT RELIABILITY

#### 9.1.1. International Surveys

CIGRE undertakes periodic international surveys amongst its members of high voltage equipment reliability. It examines equipment performance, failure rates and modes, and the maintenance policies and procedures applied to the equipment. The results are collated and then shared with the broader electricity industry.

The most recent survey was initiated in 2003 and covered the years 2004 – 2007. Data for the survey was gathered from over 80 utilities in 30 different countries and the results are available in a series of CIGRE brochures [15]. The survey included some specific questions in relation to gas insulated switchgears which have some relevance for the topic of this brochure.

#### 9.1.2. SF<sub>6</sub> Diagnostics

The survey asked a number of questions in relation to GIS diagnostic testing, namely:

- a) Do you specify diagnostic tests for your existing GIS? If yes, which ones?
- b) Do you specify diagnostic tests for your future GIS? If yes, which ones?
- c) In your opinion, has the application of diagnostic tests already avoided an internal breakdown?
- d) How often do you perform SF<sub>6</sub> quality check (humidity, decomposition products, % of SF<sub>6</sub> content)? At period ≤5 years, >5 and ≤10 years, >10 years?

The results for Questions a), b) and c) are shown in Table 9-1 and are based on six defined voltage classes.

Table 9-1: Application of diagnostic tests - number of responses within individual voltage classes  
(in %, only positive answers)

Voltage class		Do you specify diagnostic tests for your existing GIS?	Do you specify diagnostic tests for your future GIS?	Has the application of diagnostic tests avoided an internal breakdown?
		% of Yes from all responses	% of Yes from all responses	% of Yes from answers indicated present application of diagnostics
1	60≤ U<100 kV	100,0	66,7	26,7
2	100≤ U<200 kV	75,0	60,0	30,0
3	200≤ U<300 kV	87,5	62,5	12,5
4	300≤ U<500 kV	100,0	58,8	47,1
5	500≤ U<700 kV	100,0	72,7	27,3
6	≥ 700 kV	100,0	100,0	100,0
Total		91,3	63,8	30,0



In Questions a) and b), the respondents were asked to identify what kind of diagnostics they currently apply or are planning to apply. The following tests were identified: PD (mainly acoustic), primary resistance, timing, contact movement curve and speed and operation mechanism (at minimum supply voltage and minimum SF<sub>6</sub> pressure incl.) characteristics of circuit breakers and disconnectors, **SF<sub>6</sub> gas quality (humidity, SF<sub>6</sub> content, decomposition products content and density)**, thermal image scan (IR) and X-ray checks of enclosure. There was no difference between the list of tests currently applied and those planned for the future.

In response to Question c), 30% of the respondents (excluding Class 6 as it represents only 1% of the total population of GIS installed) identified that the use of diagnostics tests has prevented a major failure.

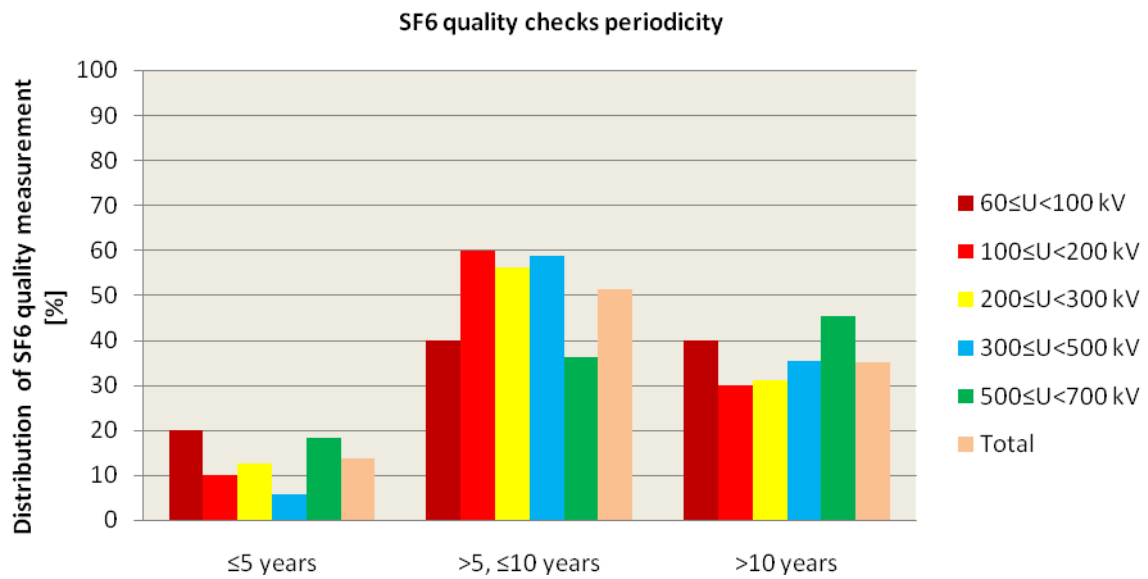
Question d) asked about the time interval between SF<sub>6</sub> quality checks (humidity, decomposition products, % of SF<sub>6</sub> contents). Three options were identified: periods ≤5 years, >5 and ≤10 years, >10 years. The responses are given in Table 9-2 below.

Table 9-2: SF<sub>6</sub> quality checks periodicity – responses within individual voltage classes

GIS voltage class		Period for SF <sub>6</sub> quality checks (% of positive of answers)		
		≤5 years	>5, ≤10 years	>10 years
1	60≤U<100 kV	20,0	40,0	40,0
2	100≤U<200 kV	10,0	60,0	30,0
3	200≤U<300 kV	12,5	56,3	31,3
4	300≤U<500 kV	5,9	58,8	35,3
5	500≤U<700 kV	18,2	36,4	45,5
6	≥700 kV	100,0	0,0	0,0
Total		13,8	51,3	35,0

The same information is shown graphically below.

Figure 9-1: SF<sub>6</sub> quality measurements



With exception of voltage class 5, the majority of utilities perform SF<sub>6</sub> quality checks at intervals ranging from between 5 to 10 years (50% in total). More frequent quality checks are performed by about 14% of the respondents; longer intervals (10 years or more) were performed by 35% of the respondents. In class 5 the longest interval is the most frequent (45% of answers).

### 9.1.3. GIS Failure Rates

Some of the most pertinent information relates to the number of dielectric failure and failure rates. The survey sought to correlate dielectric failure and equipment age. The following table shows the number of Major Failures<sup>1</sup> for GIS CB-bays<sup>2</sup> by year of manufacture.

---

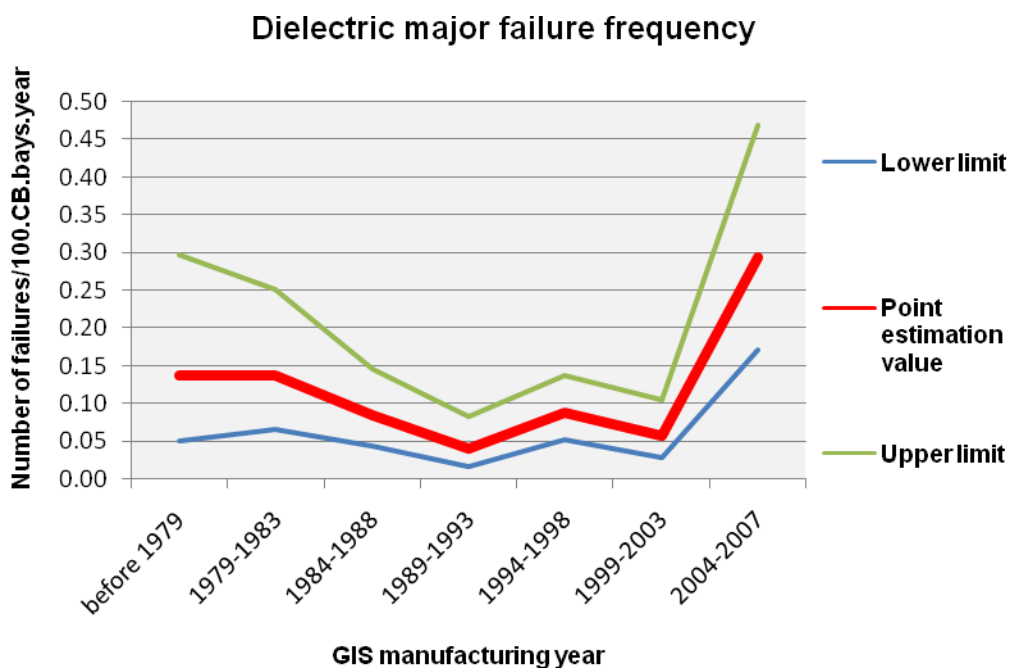
<sup>1</sup> A major failure is one which causes the cessation of one or more of the fundamental functions of the equipment. It will result in the equipment being immediately removed from service or removal being mandatory within 30 minutes

<sup>2</sup> A CB bay is a three phase assembly of one circuit breaker or switch, its associated disconnectors, instrument transformers, interconnecting busducts up to and including the line disconnect switch (if applicable) and the section of main busbar (if applicable).

Table 9-3: GIS HV parts dielectric major failure data

Manufacturing date	Number of collected GIS CB-bays service experience [CB-bays-years]	Number of collected HV parts dielectric MaF [-]	MaF frequency point estimation value [MaF/100 CB-bay-years]
before 1979	4391	6	0,14
1979-1983	7314	10	0,14
1984-1988	14407	12	0,08
1989-1993	17610	7	0,04
1994-1998	21778	19	0,09
1999-2003	17644	10	0,06
2004-2007	5804	17	0,29
Total	88948	81	0,09

Figure 9-2: GIS HV dielectric major failure frequency versus year of manufacture (95% confidence interval)



The data and the graph exhibit the traditional “bathtub” curve with higher failure rates in the initial years and near the end-of-life of the equipment. This would indicate that the interval between tests should be 3-5 years initially, but be extended to 8-10 years for the mid-life period, before being reduced again.

## **9.2. SPECIFIC CASE STUDIES**

Section 9.1 provides general information collected in an international survey. This section however, examines a number of specific cases where SF<sub>6</sub> analysis was used as part of, either a post fault analysis or routine testing. The following examples were provided by the Working Group members.

However at a global level it must be acknowledged that the vast number of results from SF<sub>6</sub> analysis do not identify any anomalies. Where an anomaly is identified it is usually a problem with the humidity level within the enclosure.

### **9.2.1. Post Fault Gas Analysis**

#### **9.2.1.1. Failure in 420kV GIS Disconnecter Compartment**

Following an internal arc, SF<sub>6</sub> gas analysis was used to identify the specific compartment where the arc occurred. Detector tubes were used to sample the gas in the various compartments. It was quickly identified that the fault had occurred in a disconnector compartment. The gas in the compartment caused the colour of the tubes to change within 2-3 seconds. Subsequent examination of the compartment identified a defect with a support insulator as the cause of the failure.

The use of gas analysis allowed the faulted compartment to be quickly identified and repair works to commence.

#### **9.2.1.2. Failure in 420kV GIS Circuit Breaker**

A 420kV circuit breaker was subject to a single phase reclosing and an immediate three phase lockout. The circuit breaker was then manually reclosed, but tripped instantaneously. The protection indicated that a close-in fault had occurred. When a line inspection failed to identify any problems, SF<sub>6</sub> gas analysis was undertaken to determine whether the fault was within the GIS.

This analysis identified that the fault had occurred within the circuit breaker compartment itself, but the particular phase could not be identified directly as there was a common gas system. Using the protection records, the phase that had tripped and reclosed was identified and opened. On dismantling the compartment clear evidence of an internal arc was found, with significant damage to various components. The origin of the failure was identified as a poorly fitted filter housing.

#### **9.2.1.3. SF<sub>6</sub> filled EHV Voltage Transformer**

The visual inspection of an AIS overhead line bay failed to identify the location of an earth fault. SF<sub>6</sub> gas analysis was then applied to the instrument transformers and two voltage transformers were found to have high readings of decomposition products; Phase A: 0 ppm<sub>v</sub>, Phase B: 15 ppm<sub>v</sub> and Phase C: > 300ppm<sub>v</sub>. The latter two VT's were opened and signs of partial discharge activity were evident in Phase B, while an internal discharge had clearly occurred in Phase C. The inherent source of the problem was identified as a manufacturing problem with an insulating spacer.

### **9.2.2. Routine Gas Analysis**

#### **9.2.2.1. SF<sub>6</sub> filled EHV Current Transformer**

Gas analysis was undertaken as part of a routine condition assessment of SF<sub>6</sub> filled current transformers. The analysis of one phase identified an SF<sub>6</sub> decomposition product content of greater than 200 ppm<sub>v</sub> (the range of the detector tubes was 0-200 ppm<sub>v</sub>), with zero readings from the other two phases. Upon opening the CT a large amount of metallic fluoride dust was found inside as well as evidence of discharge activity. While the source of the problem was not conclusive, it appeared that the underlying problem was one of poor bonding between components. The CT was replaced. In this case gas analysis had identified a problem and allowed the component to be removed from service in a controlled manner.

#### **9.2.2.2. EHV Circuit Breaker**

During routine gas analysis one pole of an EHV breaker was found to have a much higher content of decomposition products, 150 versus 40 ppm<sub>v</sub>, than the other poles. Upon opening this pole some signs of arcing were observed on the arcing contacts and PTFE nozzle as well as erosion of the arcing contacts. After discussing the case with the manufacturer it was agreed that this was a normal level of wear and that no remedial action was required. Further investigation identified that this specific pole had operated more frequently than the other poles as part of a single phase reclosing scheme.

In this instance gas analysis was not beneficial in the assessment of the condition of the equipment as the decomposition products were produced by normal switching behaviour.

### **9.2.3. Site Trials**

Part of the background work for this brochure involved a series of site trials with four multi-analysers. While these trials were far from exhaustive, they provided some details on the types of instrument currently available and their practical use on-site. They all measured SF<sub>6</sub> content, humidity and one or two decomposition products.

About 50 gas compartments were analysed with these instruments. In all cases the SF<sub>6</sub> content was 97% or higher, a small number of compartments were found to have high humidity levels (frost point in the range -8 to -12 °C). No verifiable decomposition products were identified in this limited sample.

In addition, samples from two compartments were sent to two different laboratories for analysis. One laboratory used FT-IR spectroscopy while the second used gas chromatography analysis methods. These laboratory tests confirmed the results obtained on-site with the multi-analyser instruments.

## 10. CONCLUSIONS

The motivation for preparing this brochure was the desire among utilities to assess the condition of the increasing quantities of SF<sub>6</sub> insulated equipment deployed in electrical networks around the world, while reducing the need for invasive testing and inspection. The latter would reduce maintenance costs as well as the potential for SF<sub>6</sub> gas to be released to the atmosphere. Although electrical equipment is highly reliable, breakdowns of gaseous insulation or mal-operation of components can occur on occasion. These incidents can be preceded by some form of electrical activity, either sparking or partial discharge (PD) in the gas. This electrical activity results in the formation of SF<sub>6</sub> decomposition products, which can be detected by gas analysis and hence give an indication of the type and intensity of the electrical activity. Armed with this information an assessment can be made as to the likelihood of an arc and the appropriate action to be taken. Thus SF<sub>6</sub> gas analysis is another tool available to utility personnel in assessing the condition of the equipment.

The primary objective of the brochure was to provide guidance to utility personnel in the use of gas analysis, or more strictly speaking, how to interpret the results of gas analysis in assessing the condition of high voltage equipment. This assessment would be an addition to the well-established practice of monitoring SF<sub>6</sub> content and humidity. A further objective was to identify the type of electrical activity that is or has occurred in a gas compartment by comparing the relative quantities of different decomposition products. The final objective was to identify absolute values of decomposition products that could be tolerated without degrading the dielectric withstand value of the compartment. These objectives were framed within the context of what is practicable on-site, but with the option for more detailed off-site laboratory analysis for limited and specific cases.

An analogy can be made with dissolved gas analysis (DGA) which is used as one element in the assessment of the condition of oil immersed transformers. Developing an equivalent process or system for SF<sub>6</sub> analysis would be a significant achievement and must be viewed as a long-term objective.

The formation of decomposition products arising from various types of electrical discharges in SF<sub>6</sub> has been the subject of much laboratory based investigation. These investigations were undertaken in tightly controlled environments with small volumes of gas, a repeatable source of electrical activity and with a direct connection to a gas analysis system, such as gas chromatography, infrared spectroscopy or mass spectrometry. These investigations illustrated that, under these conditions, it is possible to identify the decomposition products and their ratios resulting from different types of electrical discharges. However, it also identified that the formation rates of SF<sub>6</sub> decomposition products depends on many parameters such as the type of discharge, the energy involved, the gas pressure, the electrode material, the presence of contaminants such as humidity and oxygen, the presence of adsorbers, the time between the event and the analysis and indeed the sampling technique used for the analysis. This insight highlights the challenges of using SF<sub>6</sub> analysis for assessing the condition of electrical equipment.

By highlighting the various difficulties, this paper has confirmed the complexity of SF<sub>6</sub> decomposition analysis.

Identifying permissible levels of decomposition products is paradoxically very simple and very difficult.

- a) For non-switching compartments it is very simple, any level of decomposition products is a cause for concern and needs immediate intervention.
- b) In switching compartments it is a much more complex matter. While high levels of decomposition products are tolerable without negatively impacting the performance of the device, it is important to identify the source of the decomposition products. If they arise from switching operations there is no cause for concern, however, if they are produced by partial discharge or spark activity there is. Consequently, further investigation will be required before determining the appropriate action. The flowchart in Chapter 7 provides guidance in this regard.

One of the most important conclusions from this investigation is that simple to use portable multi-analysers are available to measure the most critical parameters of the gas. The most important one is the SF<sub>6</sub> content as it is essential for correct operation of the equipment. Second is humidity as it is important to avoid condensation and limit the formation of decomposition products and finally an assessment of decomposition products can be used as a diagnostic tool.

## 11. REFERENCES

- [1] IEC 60376, "Specification of technical grade sulphur hexafluoride (SF<sub>6</sub>) for use in electrical equipment", 2<sup>nd</sup> Edition 2005.
- [2] IEC 60480, "Guidelines for the checking and treatment of sulphur hexafluoride (SF<sub>6</sub>) taken from electrical equipment and specification for its re-use", 2<sup>nd</sup> Edition 2004.
- [3] CIGRE Brochure 234, "SF<sub>6</sub> Recycling Guide, Re-use of SF<sub>6</sub> Gas in Electrical Power Equipment and Final Disposal Revision 2003".
- [4] IEC 62271-303, "High-voltage switchgear and controlgear – Part 303: Use and handling of sulphur hexafluoride (SF<sub>6</sub>)" Technical Report Ed. 1.0, 2008.
- [5] F. Y. Chu, "SF<sub>6</sub> decomposition in gas-insulated equipment", IEEE Trans. On Electrical Insulation, Vol.21, 1986.
- [6] M. Piemontesi, "Basic studies on SF<sub>6</sub> decomposition", dissertation ETH Zürich no. 12786, 1998.
- [7] B. Belmadani, J. Casanovas, A.M. Casanovas, R. Grob, J. Mathieu, "SF<sub>6</sub> decomposition under power arcs - Physical Aspects", IEEE Trans. On Electrical Insulation Vol 26, No. 6, pp 1163-1176 (1991).
- [8] I.Wylie, Ed Hall, "SF<sub>6</sub> gas analysis as a diagnostic technique for Teflon nozzle wear in circuit-breakers", Powertech Labs Inc. project report No. 15430-43-00, (2009).
- [9] R. J. Bruns, I. Sauer, "Gas-phase hydrolysis of SOF<sub>2</sub> and SOF<sub>4</sub>", J. Chem. Phys. Vol. 85, pp. 4377 – 4380, 1986.
- [10] J. Tang, F. Liu, X. Zhang, Q. Meng, J. Zhou, "Partial discharge recognition through an analysis of SF<sub>6</sub> decomposition products part 1", IEEE Trans. On Dielectric and Electrical Insulation, Vol. 19, no.1, pp. 29 – 36, 2012.
- [11] IEC 62271-101, "High-voltage switchgear and controlgear – Part 101: Synthetic testing", 2<sup>nd</sup> Edition 2012.
- [12] C. Boudéne, J-L. Cluet, G. Keib and G. Wind, "Identification and study of some properties of compounds resulting from the decomposition of SF<sub>6</sub> under the effect of electrical arcing in circuit-breakers", Revue Générale de l'Electricité, Special Issue, June 1974.
- [13] B. Belmadani, J. Casanovas, A.M. Casanovas, R. Grob, J. Mathieu, "SF<sub>6</sub> decomposition under power arcs - Chemical Aspects", IEEE Trans. On Electrical Insulation Vol 26, No. 6, pp. 1163-1176 (1991).
- [14] A. Derdouri, J. Casanovas, R. Grob and J. Mathieu, "Spark Decomposition of SF<sub>6</sub>/H<sub>2</sub>O Mixtures", IEEE Trans. On Electrical Insulation Vol 24, No. 6, pp. 1147-1157, December 1989.
- [15] CIGRE Brochures 509 – 514, "Final Report of the 2004 – 2007 International Enquiry on Reliability of High Voltage Equipment, Parts 1 – 6", 2012.
- [16] H.M. Heise, R. Kurte, P. Fischer, D. Klockow, "Gas analysis by infrared spectroscopy as a tool for electrical fault diagnostics in SF<sub>6</sub> insulated equipment", Fresenius Journal of Analytical Chemistry (1997) Volume 358, No 7: pages 793 – 799.



# **ANNEXES**

## **A. INFORMATION SOUGHT WHEN PROCURING SF<sub>6</sub> FILLED EQUIPMENT**

When procuring SF<sub>6</sub> filled equipment it is normal to obtain details as to the filling pressure, minimum SF<sub>6</sub> content, expected leakage rates and the alarm levels. However to have a better understanding of the performance of the gas in service it is appropriate to obtain additional information.

<b>Parameter</b>	<b>Value</b>
Max. permissible SF <sub>6</sub> humidity during service (at rated SF <sub>6</sub> pressure)	< ..... °C frost point (temperature to be specified)
Is adsorber fitted and if so, type of material	
Max permissible SF <sub>6</sub> decomposition products during service	SF <sub>6</sub> decomposition products < ..... ppm <sub>v</sub>

## B. INSTRUMENTS AND MEASUREMENT METHODOLOGIES

### B.1. INTRODUCTION

The following sections provide some detail on the available measurement techniques for the measurement of SF<sub>6</sub>, humidity and decomposition products. Further details are available in IEC 60480 [2] and the CIGRE Brochure 234, SF<sub>6</sub> Recycling Guide [3].

The following table lists the different measurement/analysis methods, the parameters that they can measure, the complexity involved, accuracy and time required for the analysis of gaseous substances.

Table B-1: List of measurement and analysis methods

Measurement Analysis/ Method	Parameters	Complexity of Measurement	Accuracy	Time Required
Measurement of sound velocity	Percentage SF <sub>6</sub>	Simple	High	2-5 minutes
Condensation Principle	Percentage SF <sub>6</sub>	Simple	High	2-5 minutes
Thermal Conductivity detector	Percentage SF <sub>6</sub>	Simple	Low	2-5 minutes
Chilled Mirror	Humidity	Simple	High	10-15 minutes
Hygroscopic polymer sensor	Humidity	Simple	Medium	5-10 minutes
Aluminium oxide sensor	Humidity	Simple	Medium	5-10 minutes
Detector tubes	Oil mist Acidic compounds (SO <sub>2</sub> , HF)	Simple	Low	3 minutes
Electrochemical Cell	SO <sub>2</sub> , HF	Simple	Medium	2-5 minutes
Gas Chromatography With different detectors (TCD, FID, ECD) laboratory	SF <sub>6</sub> , O <sub>2</sub> , N <sub>2</sub> , CF <sub>4</sub> , CO <sub>2</sub> , COS, SO <sub>2</sub> F <sub>2</sub> , SOF <sub>2</sub> , SO <sub>2</sub>	High	High (ppm <sub>v</sub> range)	30 -60 minutes
Infrared spectroscopy - laboratory	SF <sub>6</sub> , H <sub>2</sub> O, SO <sub>2</sub> , HF, COS, SF <sub>4</sub> , SO <sub>2</sub> F <sub>2</sub> , SOF <sub>2</sub> , S <sub>2</sub> F <sub>10</sub> , SOF <sub>4</sub> , SiF <sub>4</sub> , CF <sub>4</sub> , CO, CO <sub>2</sub>	High	High (ppm <sub>v</sub> up to percentage range)	4 minutes

The following sections provide details on the site and laboratory measurement techniques used in the trials undertaken for this brochure.

## **B.2. MEASUREMENT OF SF<sub>6</sub> CONTENT**

There are different measuring principles. The measurement of the velocity of sound and the thermal conductivity in the measuring medium are usual. But recently there have been devices which are operated by measurement of condensation points.

### **B.2.1. Sound Velocity**

This measurement principle works by evaluating the different sound velocities of gases. The sound velocity in nitrogen is normally around 337 m/s and for SF<sub>6</sub> around 130 m/s. The sound velocity measured in the measurement cell is temperature-compensated and is converted into the percentage SF<sub>6</sub> volume assuming that the mixture is composed only of SF<sub>6</sub> and nitrogen. Since the velocity of sound in oxygen is similar to that in nitrogen the results are applicable for an SF<sub>6</sub>/air mixture. The accuracy of such devices is +/-1 % SF<sub>6</sub> content.

### **B.2.2. Condensation Principle**

The same condensation technique employed by a chilled mirror to measure the water vapour in SF<sub>6</sub> can be used to determine the purity of the SF<sub>6</sub> gas. Since the condensation point of pure SF<sub>6</sub> at a given pressure is a known value on the SF<sub>6</sub> vapour pressure curve, the % Vol SF<sub>6</sub> can be calculated based on the difference between the SF<sub>6</sub> partial pressure and the measured total pressure. This is a selective measuring method directly detecting the actual SF<sub>6</sub> content in a gas compartment.

### **B.2.3. Thermal Conductivity Detector**

Thermal conductivity detectors (TCDs) continually measure the thermal conductivity of the SF<sub>6</sub> using the heated-filament method. The accuracy of TCDs is typically lower than those instruments based on sound velocity.

## B.3. HUMIDITY MEASURING DEVICES

### B.3.1. Chilled Mirror Technology

Chilled mirror hygrometers measure the dew or frost point of a gas using the following principles. Light shines onto a polished mirror surface, the temperature of which is controlled by a thermoelectric heat-pump known as a Peltier element. A light-sensitive receiver measures the intensity of the direct reflection. When the mirror is clean and dry, the intensity of the reflected light is at its maximum. Conversely, a cold mirror with water vapour condensed on its surface scatters the light, resulting in less directly reflected light and in reduced signal intensity. Using this received light signal as feedback in a closed loop control system, the mirror is cooled to the temperature at which the thickness of the condensed layer, detected through the intensity of the received light, remains constant. A condensate layer of constant thickness, with no further net increase or decrease in condensation, is in dynamic equilibrium with the gas flowing over the mirror surface. In this equilibrium condition, the dew or frost point temperature of the gas is determined by measuring the temperature of the mirror. This mirror temperature is physically linked to the corresponding vapour pressure via the saturation vapour pressure functions.

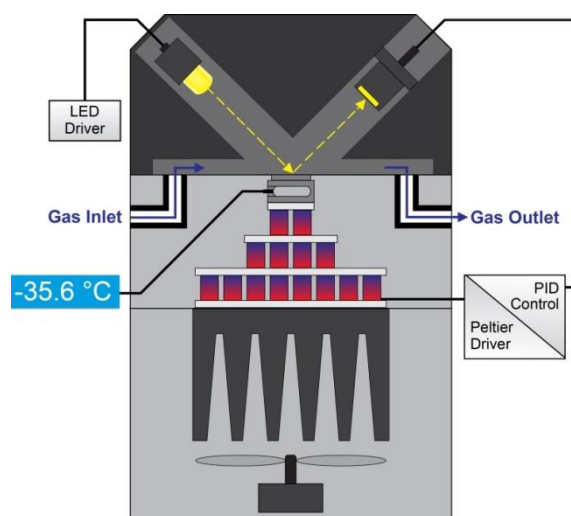


Figure B-1: Dew Point Mirror

If the condensate is known to be in liquid form, even for temperatures below freezing, then the measured mirror temperature is taken as the dew point. If the condensate is known to be in a solid form as ice, then the measured mirror temperature is taken as the frost point. The measuring range of a chilled mirror in this application is limited by the condensation point of  $\text{SF}_6$  which is about  $-65\text{ }^{\circ}\text{C}$  at 100 kPa. This does not present a problem since the lowest expected frost point in a gas-filled compartment is generally above  $-60\text{ }^{\circ}\text{C}$  frost point at 100 kPa, equivalent to about 10 ppm<sub>v</sub>. If measurements are taken at system pressures, the  $\text{SF}_6$  condensation point is higher and can become a limiting factor in the measurement of the frost point temperature with a chilled mirror. Advanced instruments take these factors into

account, ensuring correct indications. When measuring new SF<sub>6</sub> directly from a cylinder it is likely that the water content is below this limit and the measurement result of the chilled mirror may be a quality indication ( ‘<-65 °C FP’ meaning dryer than -65 °C frost point) rather than an absolute number.

Historically, chilled mirror hygrometers, when operating at mirror temperatures below 0 °C, encountered problems due to their inability to differentiate between dew and frost. Advanced chilled mirror hygrometers have the capability to properly distinguish between dew and frost by forcing all super-cooled water condensation into a solid state in the form of ice or frost. Once in this state, the condensed layer remains in a solid form and frost point temperature is accurately measured.

### B.3.2. Capacitive Humidity Sensors

#### B.3.2.1. Polymer

These sensors use a hygroscopic polymer film which changes the capacitance of the sensor depending on the relative humidity. Instruments using Capacitive Polymer sensors are the most commonly used hygrometers. These hygrometers usually measure the humidity at atmospheric pressure, with the inlet connected to the gas compartment being sampled. Depending on the instrument design, flow rates are maintained either automatically or by manual adjustment of a needle valve. When a measurement is started, polymer sensors begin with a high indication and dry down during measurement. As they dry down below some desired threshold limit, the measurement can be terminated and no additional time is required waiting for a stable indication.

Polymer sensors measure relative humidity (RH) and recalculate to other units for indication. Because the conversion from RH to frost/dew point or ppm is a very non-linear function, there is a significant loss of resolution at low humidity. In addition, because of its temperature dependence, the RH value decreases if the temperature increases at stable absolute humidity (constant vapour pressure and constant frost/dew point). High temperatures and low humidity, compound the resolution problem of RH measurement. The typical specified measuring range of a polymer sensor is limited by a maximum temperature difference ( $\Delta T$ ) of 80 K between the frost/dew point and the temperature. This results in a lower limit of -60 °C frost point (10 ppm<sub>v</sub>) at 20°C and -40 °C frost point (129 ppm<sub>v</sub>) at 40 °C at 100 kPa standard absolute pressure.

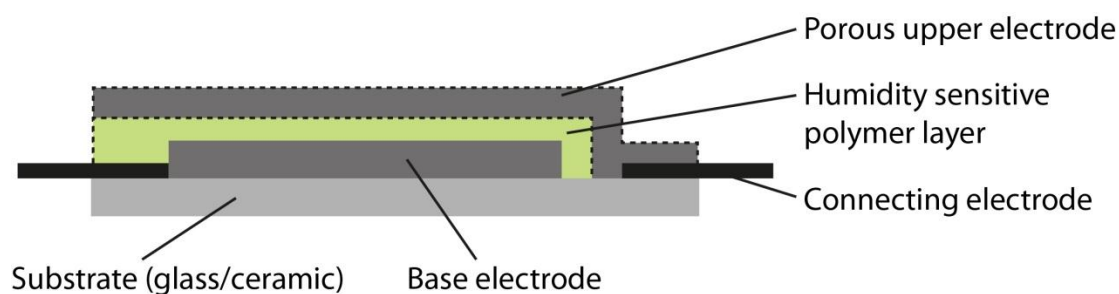


Figure B-2: Structure of a Polymer Sensor

### B.3.2.2. Aluminium Oxide

Aluminium Oxide sensors work on a principle similar to the Capacitive Polymer type. The sensor uses an oxide layer ( $\text{Al}_2\text{O}_3$ ) allowing water molecules to migrate in and out of the porous structure changing the capacitance with water vapour content. Flow rates are maintained until the indicated reading stabilizes. Typical indications are in frost/dew point. Most Aluminium Oxide sensors are maintained dry within a desiccant chamber between measurements, and when not in use. This means that these instruments start with a dry indication and rise during the measurement process to a higher value.

Since the aim is to remain below a specified threshold limit, it is difficult to determine when the instrument has reached its final stable value. Some Aluminium Oxide sensor instruments indicate dew point below 0 °C although frost point is the correct term.



Figure B-3: Aluminum Oxide Sensor

## B.4. MEASUREMENT OF SF<sub>6</sub> CONTAMINANTS AND DECOMPOSITION PRODUCTS

### B.4.1. Detector Tubes

These measuring devices make use of the chemical reaction in a special test tube, with the reaction identified by a change in colour. Such test tubes are available for different gases, such as SO<sub>2</sub>, HF and oil mist. A defined quantity of measuring medium is fed through the test tube within a set period of time. The discolouration of the test tube scale indicates the gaseous decomposition product of the SF<sub>6</sub> present in quantitative terms.

Tubes that are calibrated for SO<sub>2</sub> are also sensitive to other decomposition products like SOF<sub>2</sub> and SO<sub>2</sub>F<sub>2</sub> etc. which can influence the reaction time to SO<sub>2</sub>. Hence any measurement is an estimate of the decomposition product.

The gas should be collected after flowing through the test tube either in a dedicated collecting vessel or flexible plastic bags. Various measuring ranges are available and the measurement time varies from several seconds to minutes for the more sensitive ranges. No calibration is required but the expiry date of the test tubes must be observed. Typically 1 – 2 l of gas are required for a measurement.



Figure B-4: Detector tube and sampling arrangement

### B.4.2. Electrochemical Measuring Cell (SO<sub>2</sub> and HF)

An electrochemical sensor is based on an electrode system and an electrolyte calibrated to detect the substance being measured. The SO<sub>2</sub> or HF will react with the electrode changing its potential, which can be equated to a concentration in ppm<sub>v</sub>.

### B.4.3. Gas Chromatography

The gas chromatography is a common type of chromatography used on a gas mixture for separating and analysing compounds that can be vaporised without decomposition. It can be used to verify the quality of a new insulating gas, the integrity of in-service or used insulating gas. It is composed of a mobile phase (moving phase) – a carrier gas, usually an inert gas such as helium, and a stationary phase which is a microscopic layer of an inert solid support called a column. It is possible to have 2 or more columns in order to analyse different type of compounds. Each different compound requires a different time to traverse the column. The result is a chromatogram. The area of the peaks is proportional to the



quantity of the component. In order to achieve a high degree of precision the instruments must be calibrated before use with reference gases for each substance you intend to measure.

Different columns coupled with different detectors can be used to analyse SF<sub>6</sub>, N<sub>2</sub>, O<sub>2</sub>, CF<sub>4</sub>, HF and oil mist, and the stable decomposition products [1].

#### B.4.3.1. Thermal Conductivity Detection

The thermal conductivity detector is one of the most frequently used methods to analyse SF<sub>6</sub> and its stable decomposition products. A typical method recently developed with a thermal conductivity detector (GC-TCD) is presented in Table B-1. The chromatograms produced with this method are presented respectively in Figure B-5, Figure B-6 and Figure B-7.

Table B-2: Description of a typical GC-TCD method [2]

	Contaminants	Insulating gas	Decomposition products
<b>Analytical conditions</b>	O <sub>2</sub> , N <sub>2</sub>	SF <sub>6</sub> , CF <sub>4</sub>	CF <sub>4</sub> , SOF <sub>2</sub> , SO <sub>2</sub> F <sub>2</sub> , SO <sub>2</sub> , COS
<b>Column</b>	Restek Molesieve 5A 80/100 2 m x 1 mm	Restek Hayesep Q 100/200 2 m x 1 mm	Restek Hayesep Q 100/200 2 m x 1 mm
<b>Injection port</b>			
- Volume	50 µL		2000 µL
- Temperature	150 °C		150 °C
- Flow Helium (carrier)	30 mL/min		15 mL/min
<b>Oven</b>	35 °C hold for 2 min Heat to 65 °C (10 °C/min) hold 5 min Heat to 175 °C (25 °C/min) hold 0.6 min Total time : 10 minutes		35 °C hold for 12 min Heat to 155 °C (10 °C/min) hold 0 min Total time : 24 minutes
<b>Detector (TCD)</b>			
- Temperature	225 °C		225 °C
- Helium Flow (reference)	45 mL/min		30 mL/min
- Helium Flow (makeup)	2 mL/min		2 mL/min

All laboratory techniques require the use of a gas sampling protocol. Passivated or PTFE coated stainless steel cylinders of 500 ml capacity are typically required [2].

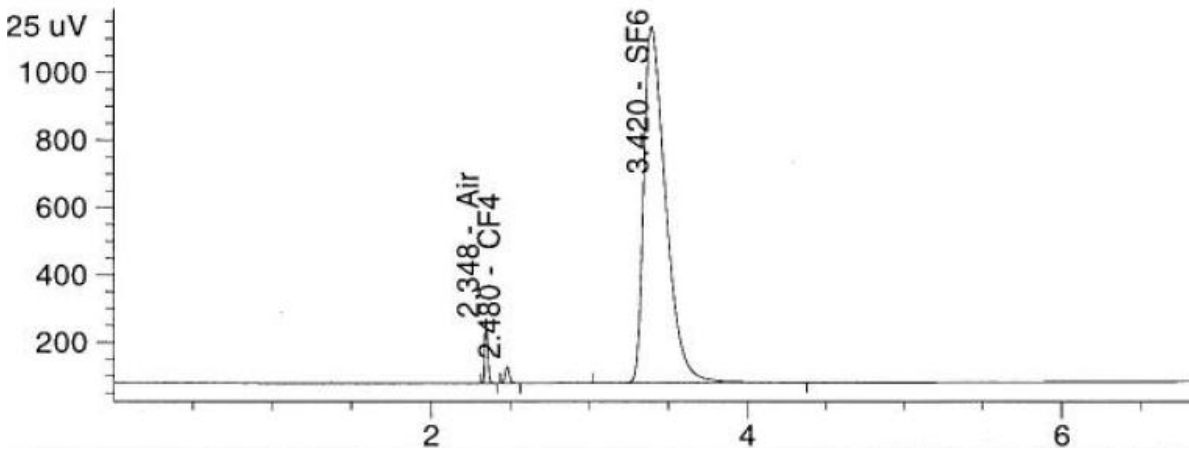


Figure B-5: Analysis of SF<sub>6</sub> and CF<sub>4</sub> in a SF<sub>6</sub> gas insulation sample

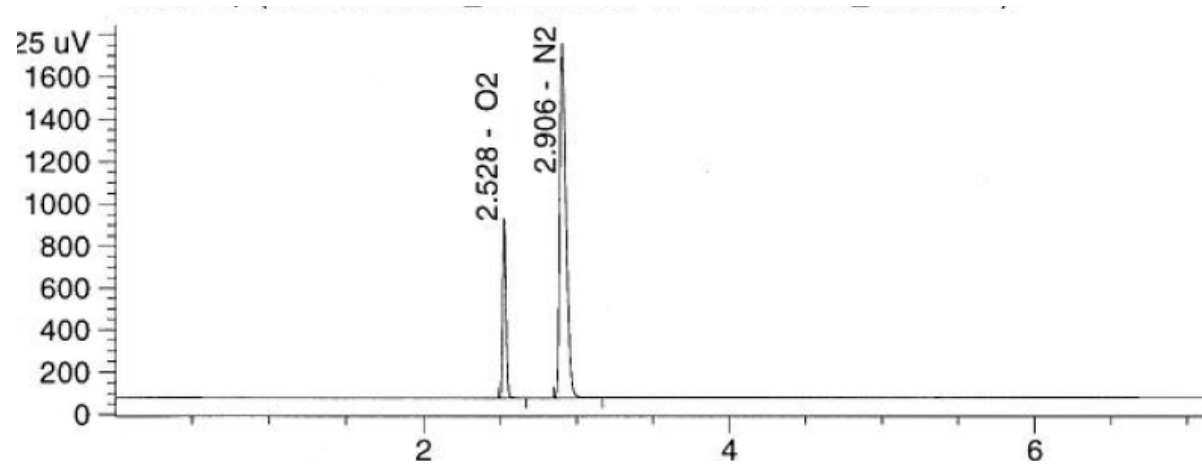


Figure B-6: Analysis of air (N<sub>2</sub> and O<sub>2</sub>) as a contaminant in a SF<sub>6</sub> gas insulation sample

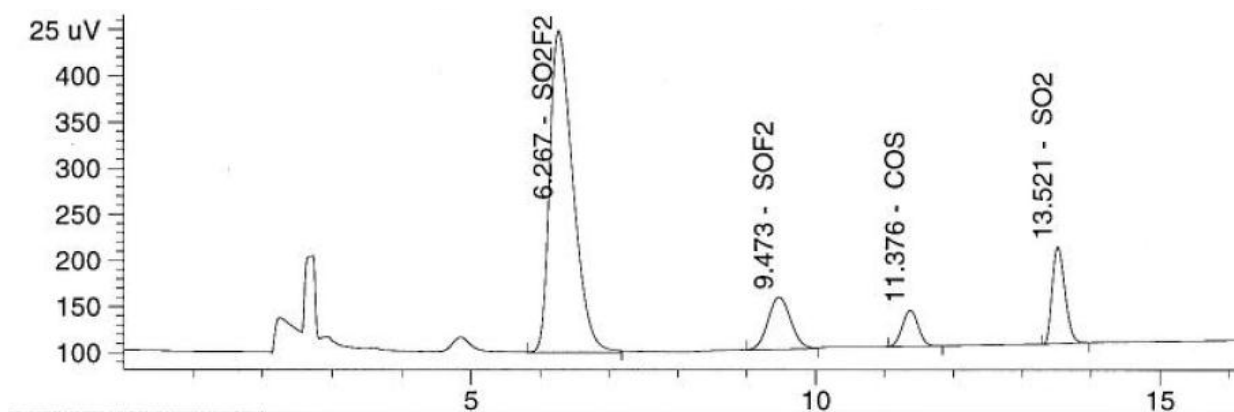


Figure B-7: Analysis of the major decomposition products in a SF<sub>6</sub> gas insulation sample

#### B.4.3.2. Flame ionization detection

The use of a gas chromatograph coupled with a flame ionization detector (FID) can allow the determination of the oil content in SF<sub>6</sub>. Typical analytical conditions applicable to the analysis of C10 to C50 petroleum hydrocarbons have already been presented in the IEC 60480 standard [2].

#### B.4.3.3. On-site gas chromatography

It is possible to use on-site a portable Gas Chromatography having also a TCD (thermal conductivity detector) which can precisely measure the levels of Air, CF<sub>4</sub>, SO<sub>2</sub>, SOF<sub>2</sub> and SO<sub>2</sub>F<sub>2</sub> in SF<sub>6</sub>. However, high levels of skills are required to operate these instruments and therefore they do not offer a practicable option.

### B.4.4. Infrared spectroscopy

#### B.4.4.1. Fourier Transform -IR

Infrared spectroscopy can be used to verify the quality of new gas, used gas and the cleaning and recycling process of contaminated SF<sub>6</sub>. Infrared spectroscopy is a common type of spectroscopy used on a gas mixture for all decomposition products including the reactive substances e.g. HF, SF<sub>4</sub>, SOF<sub>4</sub>, SiF<sub>4</sub> and S<sub>2</sub>F<sub>10</sub>.

It consists of an optical cell connected to a vacuum system. The vacuum system can also be used to prepare the sample cylinder. The result is a spectrum and the absorption of infrared light in the spectrum is directly proportional to the quantity of a component from low ppm values up to percentages. The measurement time for one sample is normally around 4 minutes for the complete measurement of the impurities and the main decomposition products [3].

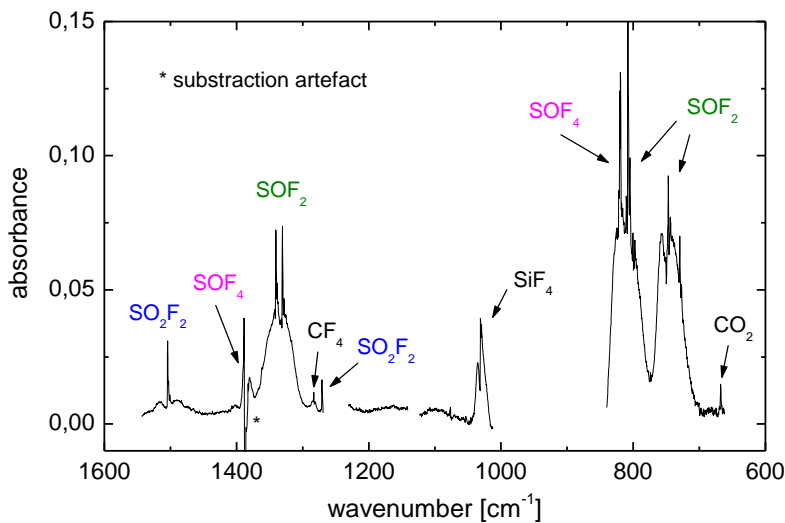


Figure B-8: SF<sub>6</sub> subtracted mid-infrared spectrum of a discharge sample and indication of the decomposition products

#### B.4.4.2. Non-dispersive IR

A non-dispersive infrared sensor (or NDIR) is a spectroscopic device often used as a gas detector. The main components are an infrared source, a sample chamber or light tube, a wavelength filter, and an infrared detector.

The SF<sub>6</sub> gas is pumped into the sample chamber and gas concentration is measured electro-optically by its absorption at a specific wavelength in the infrared (IR) range. The IR light is directed through the sample chamber towards the detector. The detector has optical filters in front of it that eliminate all light except a wavelength range that the selected gas molecules can absorb (i.e. SF<sub>6</sub>/ H<sub>2</sub>O). Other gas molecules that do not absorb light at this wavelength range do not affect the amount of light reaching the detector.

This technique enables NDIR sensors to achieve high level of selectivity. Potential cross interference between gases with overlapping IR absorption patterns can be minimized in various ways such as careful selection of the optical components, measuring and compensation for the interfering gas and filtering out the interfering gas either optically or physically.

In terms of response time, an NDIR sensor typically takes one or more new readings every second. However, digital filtering, data processing, time needed to purge the sensor and flow enough gas to obtain a representative sample can increase the total measurement cycle to 3-5 minutes.

The amount of gas required by an NDIR sensor depends mainly on the volume of the sample chamber and the chosen gas flow rate. The gas flow rate need to be adequate to purge the sample chamber a few times.

## B.5. MULTIPLE MEASURING DEVICES

Multi-measuring devices are created by combining a number of sensors in series and housing them in the same case. Typically they will measure SF<sub>6</sub> content, humidity and either SO<sub>2</sub> or HF. Generally SF<sub>6</sub> decomposition products are measured first and the instrument will automatically shut down in the event of high concentration levels.

They have the advantage that only a single instrument is required, they reduce the quantity of gas needed and the time required to complete the measurements. Furthermore, most of the manufacturers now offer systems which can pump the gas samples back into the equipment after the analysis is completed, eliminating the potential for release of SF<sub>6</sub> to atmosphere.

### References

- [1] Lessard M.C., Larocque G., Vienneau M., private correspondence.
- [2] IEC 60480 “Guidelines for the checking and treatment of sulphur hexafluoride (SF<sub>6</sub>) taken from electrical equipment and specification for its re-use”, 2<sup>nd</sup> Edition 2004.
- [3] R. Kurte, C. Beyer, · H. M. Heise, D. Klockow, “Application of infrared spectroscopy to monitoring gas insulated high-voltage equipment: electrode material-dependent SF<sub>6</sub> decomposition”, Anal Bioanal Chem (2002) 373 : 639–646.

## C. GAS DENSITY MEASUREMENT

### C.1. INTRODUCTION

The performance of electrical equipment is critically dependent on the gas pressure and therefore important that it is constantly monitored. Since pressure is temperature dependent, density is the parameter that must be measured.

### C.2. SF<sub>6</sub> GAS

The properties of SF<sub>6</sub> gas in the 3-dimensions of pressure, density, and temperature are not directly proportional. SF<sub>6</sub> is a “real gas” and therefore complex equations are required to get an accurate picture of its behaviour. Simplification using “ideal gas” equations, while convenient, would neglect crucial factors. .

SF<sub>6</sub> density can be measured either directly with electronic density sensors or reference chambers, or indirectly with temperature compensated pressure gauges or sensors. Indirect measurement always requires accurate temperature information besides the pressure measurement.

When monitoring SF<sub>6</sub> density with a direct or indirect method monitored volume, 1 °C difference can result in a deviation of 3 kPa SF<sub>6</sub> pressure at 20 °C.

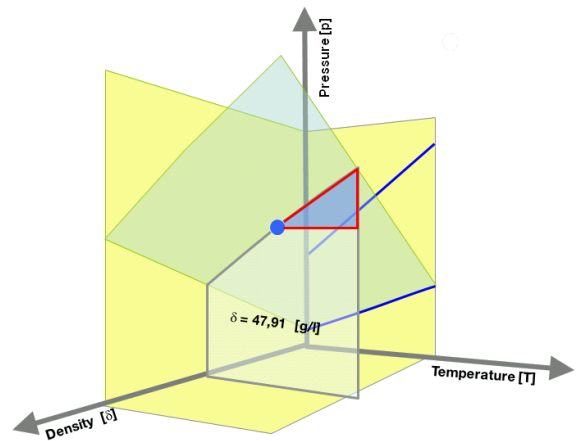


Figure C-1: SF<sub>6</sub> Properties – pressure/temperature

### C.3. SF<sub>6</sub> GAS DENSITY INSTRUMENTS VS. PRESSURE GAUGES

Pressure and temperature may change over time, either 24-hours or 12-months. If the pressure is not compensated automatically in the instrument, it must be calculated afterwards by using the associated measured temperatures in order to get an accurate reading of the density.

#### C.3.1. General Principle of Temperature Compensation

A gas density instrument consists of a media (pressure) connection, a sensing element with electronics or mechanical parts, an electrical connection and a case to protect the inner elements against environmental influences.

Table C-1: Measurement of gas density - electronic vs. mechanical device

	<b>Indirect measurement (through pressure)</b>	<b>Direct measurement</b>
<b>Electronic devices</b>	An electronic pressure sensor signal and a temperature sensor signal are combined. A microprocessor calculates the density.	The frequency of a quartz tuning fork in the SF <sub>6</sub> is compared with one in vacuum. The frequency difference equals the gas density.
<b>Mechanical devices</b>	A pressure gauge (Bourdon tube or bellows type) is equipped with mechanical temperature compensation. The compensation is calibrated for the condition at the alarm density level.	A reference chamber filled with SF <sub>6</sub> according at alarm level density is mechanically compared with the actual SF <sub>6</sub> density in the system.

#### C.3.2. Indication of Gas Density

Electronic devices rarely have any indicator or display, the density signal is processed in a host controller. Mechanical devices can have either an indicator showing normalized pressure at 20 °C or a simple three-color-indicator (green=OK, Yellow=low, red=critical). To allow indicator reading, the density monitor is often installed remote of the gas tank, with a gas pipe connection. This type of installation causes more temperature compensation issues than installing the measuring devices with good thermal contact directly on the SF<sub>6</sub> compartments.

### C.3.3. Electronic Density Instruments for Direct Measurement – Density Sensor

The constant resonant frequency of a quartz oscillator under vacuum is compared with the resonant frequency of an identical quartz situated in the sample gas. The difference in the resonant frequency is proportional to the density of the sample gas. This difference is processed into an analogue or digital output signal.

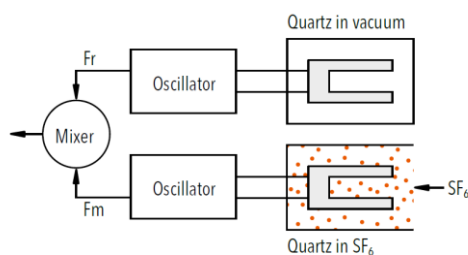


Figure C-2: Density sensor

### C.3.4. Electronic Density Instruments for Indirect Measurement – Temp. Compensated Pressure Sensor

Indirect measuring gas density transmitters are technically based on pressure measurement constructions. They consist of an electronic pressure sensor, a temperature sensor for temperature compensation purpose and electronics to process the signals. The density output signal is generated based on both the pressure and temperature that is measured locally inside the transmitter.

### C.3.5. Mechanical Instruments for Direct Measurement – Reference Chamber

The gas density of  $SF_6$  compartments is compared via a bellows system with the gas density in a reference gas chamber in the monitor. If the density of the gas alters, the bellows system actuates one or more micro switches. If the gas temperature and therefore its pressure changes, the same pressure difference occurs also in the reference chamber. No false alarm is triggered due to temperature induced pressure changes. Up to four galvanically isolated micro switches actuate different alarm signals. An  $SF_6$  indicator allows reading the  $SF_6$  gas density as gas pressure at 20 °C.

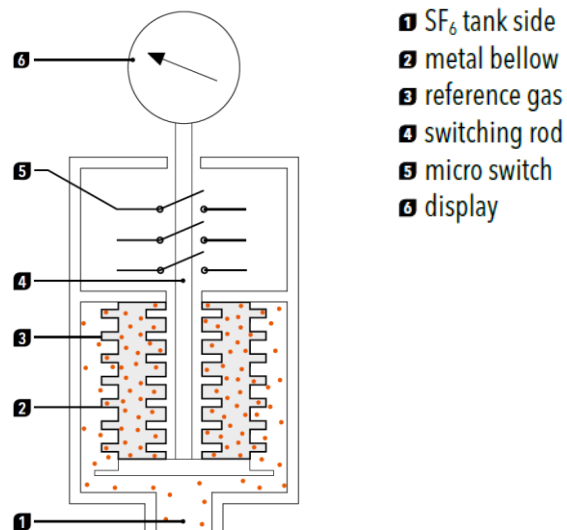


Figure C-3: Reference chamber



### **C.3.6. Mechanical Instruments for Indirect Measurement - Temperature Compensated Pressure Gauges**

A mechanical pressure gauge based on Bourdon pipe principle is equipped with a bimetal lever for temperature compensation. The bimetal lever is calibrated for the alarm density to allow optimal accuracy.



Figure C-4: Mechanical pressure gauge

## D. DIFFUSION AND KINETICS

### D.1. TRANSPORT OF DECOMPOSITION PRODUCTS THROUGH SF<sub>6</sub> GAS

After a gaseous substance is produced at a particular location in a compartment e.g. at the contacts of a circuit-breaker or at an insulator junction exposed to a high electric field, it will effuse into the whole compartment. The time it takes to be detected elsewhere depends on the conditions inside the compartment and the location of the detector. If the gas is totally at rest, only gas diffusion is active, which is a rather slow transportation process. Due to the high pressure of SF<sub>6</sub>, the “random walk” path of the substance is very short namely in the range of 10 nm. Consequently, the diffusion of the substance may take hours or even days in typical switchgear compartments. The decomposition by-product concentration will be very non-uniform.

Diffusion is determined by concentration or pressure gradients in proportion to the diffusion coefficient  $D$ , which is linked to the mean free walk path  $\lambda$  and mean thermal speed  $v_{th}$  of the gas, which can finally be expressed as function of gas pressure and temperature:

$$D = 0.376 \frac{(RT)^{3/2}}{p \sigma \sqrt{\mu}} \quad (1)$$

Where:

D	diffusion coefficient in m <sup>2</sup> /s
R	universal gas constant of 8314.4 J/K/kmole
T	Temperature in K
p	background gas pressure in N/m <sup>2</sup>
$\sigma$	effective collision cross-section of the substance in SF <sub>6</sub>
$\mu$	effective mass number of the substance A in gas B: $\mu = M_A / (M_A + M_B)$ .

The collision cross-section  $\sigma$  can be determined from the diameter of the molecules, which is 0.56 nm for SF<sub>6</sub> and 0.36 nm for SO<sub>2</sub>. From these values, a diffusion coefficient of  $D = 0.018$  cm<sup>2</sup>/s results, which has been confirmed by measurements of the diffusion of SOF<sub>2</sub> in 400 kPa of SF<sub>6</sub>. In [1], a value of 0.02 cm<sup>2</sup>/s is given. The diffusion of gases in air at a pressure of 100 kPa would be almost one order of magnitude faster. A useful measure is the time  $t$  needed for a molecule to cross a distance  $L$ . Assuming a typical distance of 0.3 m, the resulting diffusion time would be 11 hours.

$$t = \frac{\pi L^2}{4D} \quad (2)$$

On the other hand, it is likely that not only diffusion, but also some convection of the gas is active due to temperature differences between inner conductors and outer walls of a compartment or due to forced gas flow induced by the switching process itself. Even speeds very much lower than the thermal speed of gas would mix the substances effectively. It can

therefore be assumed that a homogeneous distribution is achieved within a time much shorter than that solely due to diffusion (typically a couple of hours depending on the size of the volume).

## D.2. REACTION KINETICS OF SF<sub>6</sub> DECOMPOSITION PRODUCTS ON WALL SURFACES

The kinetics of surface reactions is determined by the flux of impinging molecules, their sticking probability, their momentary concentration on the surface and the concentration of reactants on the surface [1]. At the beginning every impinging molecule will find a free place on the surface as well as a reaction partner. When the maximum surface coverage of molecules is reached, which is usually one complete monolayer of molecules, the sticking probability goes to zero and no more molecules will find a free place on the surface. The two extremes of this process are therefore called the unsaturated and the saturated surface limit [1].

### D.2.1. Unsaturated surface limit

The molecules impinging on the wall surface immediately find an empty site on the surface and a reaction partner. The surface density  $N^*$  of the reacting molecules is then proportional to the flux density of arriving molecules.

$$\frac{dN^*(t)}{dt} = -k_{unsat} A_{ads} \gamma \frac{1}{4} v \cdot n = -\delta_s \cdot n \cdot A_{ads} \quad (3)$$

With the designations:

- $n$ : Density of decomposition products in front of the surface in  $m^{-3}$
- $A_{ads}$ : Surface area in  $m^2$
- $v$ : Thermal speed of decomposition products impinging onto the surface
- $\gamma$ : Sticking probability of decomposition products on the surface (0 ... 1)
- $\delta_s$ : Unsaturated surface decomposition coefficient [1]

The total number  $N^*$  of reactant molecules available in the volume  $V$  is given by the product of  $n$  and  $V$ . The combination then gives:

$$\frac{1}{n} \frac{dn(t)}{dt} = -\delta_s \cdot \frac{A_{ads}}{V} \quad (4)$$

This equation has a solution with the initial density decreasing in time with an exponential decay time constant of:

$$\tau_s = \left[ \delta_s \cdot \frac{A_{ads}}{V} \right]^{-1} \quad (5)$$

In specially prepared stainless steel containers, the exponential decay of the by-product density could be proven for SF<sub>4</sub> and SOF<sub>4</sub> resulting in unsaturated surface decomposition coefficients of 1 to 5 x 10<sup>-5</sup> m/s for SF<sub>4</sub> and 2 to 10 x 10<sup>-7</sup> m/s for SOF<sub>4</sub>. According to equation (5), a smaller coefficient represents a longer by-product decay time. The decay to

half the initial value is achieved within less than 5 hours for an unprepared surface, whereas the time increases considerably for dried surfaces, which proves the importance of hydrolysis for these decomposition products i.e. the reaction with water molecules at the wall surface. Volume reaction normally does not play a role even at high water vapour concentrations up to 2000 ppm<sub>v</sub>.

#### D.2.2. Saturated surface limit

In the other extreme, the surface reaction is the slowest process, since the impinging molecules do not find a free site and a free reaction partner. In this case, the rate of reaction is independent of the density of molecules in front of the surface [1]:

$$\frac{dN^*(t)}{dt} = -k_{sat}N_{sat}^*A_{ads} = -C_{dec} \cdot A_{ads} \quad (6)$$

With

$k_{sat}$  saturated surface coefficient

$N_{sat}$  surface density of molecules at complete coverage

$C_{dec}$  saturated surface decomposition coefficient [1]

$A_{ads}$ : Surface area in m<sup>2</sup>

Inserting the density of molecules in the volume as above, the following equation results, which gives a linear decay of the decomposition product density:

$$\frac{dn(t)}{dt} = -C_{dec} \cdot \frac{A_{ads}}{V} \quad (7)$$

Again in [1], the decay of decomposition products in specially prepared stainless steel containers was measured for SOF<sub>2</sub>, which is known to have a slow reaction with water, giving a linear decay of the product density with a saturated surface decomposition coefficient of in the range of 1 to 3 x 10<sup>13</sup> m<sup>2</sup>/s. The decay to half the initial value occurs now in the order of 1000 h. When taking glass containers almost no decrease of the density was observed even with a background moisture concentration of 2000 ppm<sub>v</sub>, (which is equivalent to a frost point of -12.8 °C and a dew point of -14.3 °C) These experiments also showed the increase of volatile gases like SO<sub>2</sub> and SO<sub>2</sub>F<sub>2</sub> coming from secondary surface reactions with H<sub>2</sub>O. HF is seldom detected, since it rapidly reacts with metallic oxides to form metal fluorides, which are immediately bound to surfaces.

It is interesting to estimate the density of decomposition by-product molecules in the volume corresponding to one monolayer of molecules adsorbed on the inner surface of a GIS compartment. Knowing that the maximum number of molecules per m<sup>2</sup> is 1.5 x 10<sup>19</sup> and assuming an inner surface area of e.g. 3 m<sup>2</sup>, one could adsorb a total number of 4.5 x 10<sup>19</sup> in one monolayer, which equals to a concentration of 1 ppm<sub>v</sub> of decomposition products at 600 kPa SF<sub>6</sub>. Since 1 ppm<sub>v</sub> is a rather low value for the concentration after switching operations, it can be anticipated that the surface of the housing is saturated with decomposition products in a short time after a switching operation. In order to keep the

number of decomposition products low in the long term, adsorber material should be introduced into switchgear compartments, which not only absorbs water molecules but also decomposition products.

### D.3. REMOVAL OF DECOMPOSITION PRODUCTS AND MOISTURE BY MOLECULAR SIEVES

In most gas insulated electrical equipment, adsorber materials e.g. molecular sieves (see Annex E) are used to adsorb humidity arising from the moisture in insulators released over the life-time of the switchgear. Most of these adsorber materials also trap decomposition products. Because of inevitable temperature differences inside the switchgear – at least, if it is in service – it can be assumed that convective gas flow mixes the decomposition products effectively inside the volume in a short time. Therefore, all surface reactions between decomposition products and moisture take place shortly after a burst of decomposition products from the arc or continuously during the emission of decomposition products from a corona discharge.  $\text{SF}_4$  and  $\text{HF}$  (produced either in the arc or by subsequent reactions) are detected at the same time [2].  $\text{SO}_2$  normally occurs much later, since the corresponding reaction process is much slower.

However, the removal of decomposition products by molecular sieves present in the compartment will not always happen as fast as the decomposition products arrive in the vicinity of the adsorber material. The much slower diffusive transport in  $\text{SF}_6$  gas has to be considered, when the molecular sieve is positioned in niches of the compartment e.g. inside enforcing profiles. These locations are shielded from convection flows and the substances reach them only by random walk i.e. diffusion. Finally, the decomposition products have to be transported into the interior of the adsorbent, since otherwise the adsorption capability on the surface would be very soon exhausted. The time of penetration of decomposition products into the inside of the molecular sieve depends on the effective diffusivity of the gas molecules in the adsorber pores and channels (see Annex E).

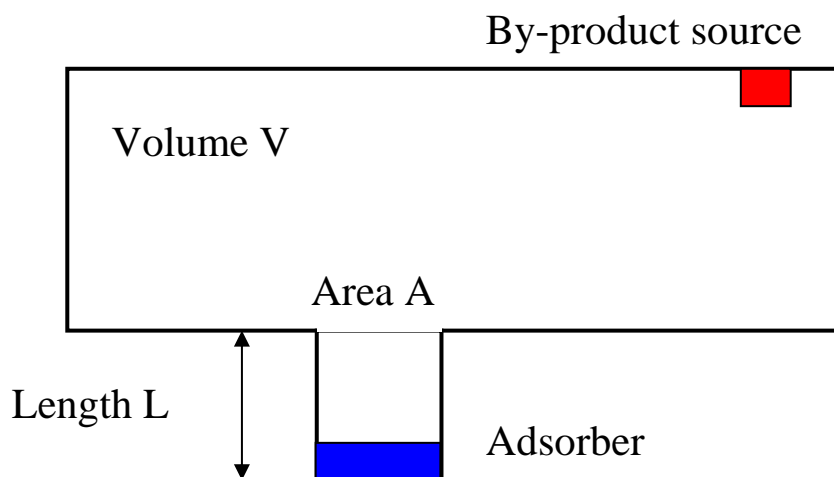


Figure D-1: Model to describe the diffusion of decomposition products to an adsorber surface

Piemontesi [1] has used an approach depicted in the figure above. The adsorber material is positioned in a separate channel providing an entrance area A, which can be equivalent to the external surface of a bag filled with molecular sieve pellets. Assuming that the density n of decomposition products is uniform in the volume up to this entrance and that all molecules impinging on the surface of the adsorber are trapped, the flux of decomposition products arriving at the adsorbent can be calculated in a first approximation by the diffusion equation in one dimension with the length L of the channel:

$$j_x = -D \frac{\partial n}{\partial x} \approx -D \cdot A \cdot \frac{n}{L} \quad (8)$$

The temporal development of the density of molecules in the large gas volume V i.e. the loss due to adsorption can then be determined by considering the particular kind of source S of decomposition products.

$$\frac{dn(t)}{dt} = S - D \cdot \frac{A}{L \cdot V} n \quad (9)$$

With the abbreviations:

- V: Inner gas volume of GIS compartment in m<sup>3</sup>
- n: Density of decomposition products in the compartment in m<sup>-3</sup>
- D: Diffusion coefficient of the molecule in gas in m<sup>2</sup>/s
- S: Flux from source of decomposition products in s<sup>-1</sup>
- A: Area of entrance of channel in m<sup>2</sup>
- L: Length of channel to adsorber in m

This equation can be solved analytically under the following two different initial conditions and the assumption that the molecular sieve has a low loading of decomposition products i.e. far from saturation:

- The source is a short burst of decomposition products e.g. generated by one switching operation
- The source is a steady, continuous stream of molecules e.g. generated by a corona discharge

### D.3.1. Burst of decomposition products

The general solution of equation (9) is obtained with S = 0 with an initial condition of N<sub>0</sub> molecules. The parameter τ is defined as:

$$\frac{1}{\tau} = D \cdot \frac{A}{L \cdot V} \quad (10)$$

Knowing the total initial number of decomposition products N<sub>0</sub> released in one switching operation, the resulting linear differential equation of first order has the solution:

$$n(t) = \frac{N_0}{V} \exp\left(-\frac{t}{\tau}\right) \quad (11)$$

This solution describes an exponential decrease of the initial density of decomposition products with a time constant determined by equation (10). If the sorption capability for the adsorbent is not saturated and if there is no other source of decomposition products inside the GIS besides the original burst, the by-product density should decay to zero after some time. Inserting typical values ( $D = 2 \cdot 10^{-6} \text{ m}^2/\text{s}$ ,  $L = 0.01 \text{ m}$ ,  $A = 20 \text{ cm}^2$ ,  $V = 0.3 \text{ m}^3$ ), a time constant of 140 h or 6 days results. If the adsorber is exposed directly to the convective fluxes inside the switchgear, time will be further reduced. The concentration of decomposition products produced by a switching operation would be reduced to 36% of its original value after this time. Taking the example for a 31kA current interruption, where a maximum concentration of 192 ppm<sub>v</sub> was calculated, the initial concentration would be reduced to 70 ppm<sub>v</sub> after 6 days and to 25 ppm<sub>v</sub> after 12 days.

### D.3.2. Continuous stream of decomposition products

When the source term  $S$  consists of a continuous flux of decomposition products, it has to be retained in equation (9). The differential equation then has a particular solution, which is calculated from the general solution by applying the concept of variation of coefficients. For a zero initial by-product density, the solution is:

$$n(t) = \frac{S}{V} \tau \left( 1 - \exp\left(-\frac{t}{\tau}\right) \right) \quad (12)$$

Now the density of decomposition products increases up to a saturation density  $n_s$ , which is given by:

$$n_s = \frac{S}{V} \tau = \frac{\alpha \cdot I \cdot L}{e \cdot D \cdot A} \quad (13)$$

With typical values such as  $D = 2 \times 10^{-6} \text{ m}^2/\text{s}$ ,  $L = 0.01 \text{ m}$ ,  $A = 20 \text{ cm}^2$ ,  $V = 0.3 \text{ m}^3$ , and a corona current of 10  $\mu\text{A}$ , a saturation density of decomposition products of  $7.8 \times 10^{20} \text{ m}^{-3}$  results assuming  $\alpha = 5$ . This is equivalent to a saturation concentration of 8 ppm<sub>v</sub> at 400 kPa SF<sub>6</sub> filling pressure, which will be achieved after more than 2 weeks.

These simple examples show that the detection of a concentration of decomposition products e.g. on the occasion of a scheduled maintenance does not give information about its origin, since irrespective of the kind of source, the same concentration may result after some time. Therefore, to be analytic, the switching history and temporal development of concentration has to be taken into account.

## References

- [1] M. Piemontesi, “Basic studies on SF<sub>6</sub> decomposition”, dissertation ETH Zürich no. 12786, 1998,
- [2] B. Belmadani, J. Casanovas, A.M. Casanovas, R. Grob, J. Mathieu, “SF<sub>6</sub> decomposition under power arcs- physical aspects”, IEEE Trans. On Electrical Insulation Vol 26, No. 6, pp 1163-1176 (1991).



## E. FILTER MATERIAL CHARACTERISTICS

There are two approaches adopted by manufacturers to adsorb moisture and decomposition products. While most seek to adsorb both moisture and decomposition products, others focus on the removal of moisture only. The latter approach is adopted where the equipment is required to operate at very low ambient temperatures where the adsorption of SF<sub>6</sub> in some adsorbers might reduce the filling pressure considerably.

There are two basic types of adsorber materials: molecular sieves and activated alumina. Molecular sieves are microporous solid materials that have the ability to trap molecules. They have a regular pore structure that allows molecules of a particular size to enter the pores and be adsorbed. Typical designations are 3A, 4A, 5A or 13X (pore size of 0.3, 0.4, 0.5 and 1.0 nm, respectively). The second type of filter material is activated alumina i.e. Al<sub>2</sub>O<sub>3</sub>. It is produced from aluminium hydroxide and is a very porous material. Its pore size is distributed over a larger range than for molecular sieves and may extend from 0.4 to 2.2 nm.

Molecular sieves are called zeolites and are in principle composed from different oxides according to the general formula:

$$M_{x/n}[(AlO_2)_x(SiO_2)_y] \cdot z H_2O$$

M is a cation (e.g. Na<sup>+</sup>) and determines some of the properties of the zeolite. The corresponding anion is part of the oxide lattice structure comparable to a salt. The pores and openings are composed by the lattice structure and form multi-dimensional straight or zig-zag like channels. The ratio of the number of Al- and Si-oxides determines whether a zeolite behaves hydrophilic or hydrophobic. Zeolites are found as natural minerals, but most often are produced synthetically, which allows choosing the size of pores and channels. Hundreds of zeolites with different properties are known and used in numerous applications.

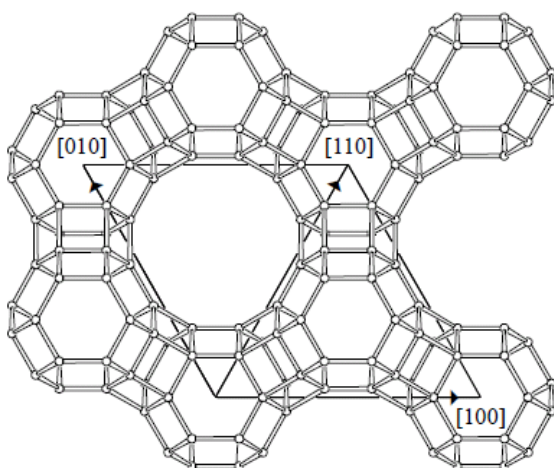


Figure E-1: Lattice structure of Faujasite [1]

Molecular sieves contain an extraordinary large inner surface of up to 600 m<sup>2</sup>/g, which results from the surface of all pores and cavities in the bulk material. The diameter of the channels can be adjusted in a very narrow range just to let all molecules with smaller diameter pass through the channels and being trapped. Molecules with larger diameter are blocked. These kind of molecular sieves are e.g. used for the purification or separation of mixed gases.

Water, which has a molecule diameter of 0.27 nm, can enter a molecular sieve with 0.3 nm channel size i.e. 3A-Zeolite. SF<sub>6</sub> molecules have a diameter of 0.55 nm and will not enter a molecular sieve with 0.3 or 0.5 nm channel dimension, but those with 1 nm i.e. 13X-zeolite. Therefore, the smaller size molecular sieves are chosen when a reduction of the SF<sub>6</sub> gas density at very low ambient temperatures needs to be avoided. The adsorption of SF<sub>6</sub> was first observed when equipment was operated at temperatures below -50°C. The by-product SO<sub>2</sub>, which has a molecule diameter of 0.36 nm, may not enter a 3A-zeolite, but would be adsorbed in every zeolite having a pore size of larger than 0.4 nm. CF<sub>4</sub> on the other hand is a gas, which is hardly adsorbed in 5A-zeolite or larger sieves, though its diameter of 0.47 nm would fit well.

Activated alumina also absorbs SF<sub>6</sub> at low temperatures similar to the large size molecular sieves. Its use should be avoided when equipment is required to operate at very low ambient temperatures.

Alumina and zeolites not only adsorb water molecules and SF<sub>6</sub>, but also the decomposition products created by the arc. According to the equations given in Figure 5-1 in chapter 5, substances such as SF<sub>4</sub>, SOF<sub>2</sub> and HF are chemisorbed i.e. react irreversibly with the adsorber material, whereas other substances such as H<sub>2</sub>O, SF<sub>6</sub> and SO<sub>2</sub> are physisorbed i.e. are bound to the pore surfaces only by polar forces and can be removed afterwards. Chemisorption is always accompanied by a strong exothermic reaction, which might even heat up the adsorbent considerably.

Inside the adsorber material, the adsorbed molecules are transported by surface diffusion, the speed of which depends on the ratio of pore to molecule diameter and on the residence time of a molecule on the pore surface. The residence time is inversely proportional to an exponential Boltzmann factor determined by the ratio of adsorption energy and adsorbent temperature. The transport time of a substance into the bulk adsorber material can be estimated from measured diffusion rates in molecular sieves. The effective diffusivity of H<sub>2</sub>O in 4A-Zeolite was determined to  $4 - 7.55 \times 10^{-11}$  m<sup>2</sup>/s at a temperature of 30°C [2]. This results in a transport time of almost 3 hours for a pellet size of 1 mm and correspondingly longer for larger pellets. On the other hand, the effective diffusivity of SO<sub>2</sub> in 4A-Zeolite was determined to  $3.85 \times 10^{-7}$  m<sup>2</sup>/s [3], which would result in a very short transport time of only 2s. The difference originates from the strong polar forces acting on water molecules, which obviously increase the residence time by orders of magnitude. Chemisorbed substances stay, where they have reacted with the surface. Further filling of the adsorber can only be achieved, when the gaseous molecules entering the outer surface of the adsorbent penetrate further into the interior, where they can react with fresh adsorber material.

For new adsorber material, it can be assumed that humidity and SF<sub>6</sub> decomposition products are rapidly removed from the gas volume, since every substance arriving at the surface of the adsorbent is trapped. This describes the situation of an unsaturated adsorber. When on the

other hand the surface is already covered by molecules, newly arriving molecules will not find a free place and might be reflected. This behaviour can be described by a sticking coefficient depending on the surface coverage. The balance of flux of molecules arriving at the surface - being proportional to the partial pressure of molecules in the gas volume - and the coverage of the surface is in the simplest case determined by the Langmuir isotherm [4]:

$$\frac{d\Theta(t)}{dt} = -k_{ads} \cdot p \cdot N(1 - \Theta) + k_{des} \cdot N \Theta \quad (1)$$

Where:

$k_{ads}$ : adsorption coefficient comprising the sticking coefficient

$k_{des}$ : desorption coefficient

$p$ : partial pressure of molecules in the volume in  $\text{m}^{-3}$

$N$ : maximum number of available absorption sites (normally  $1.5 \times 10^{19} \text{ m}^{-2}$ )

$\Theta$ : relative surface coverage

In equilibrium, the time derivative is equated to zero and gives the Langmuir isotherm:

$$\Theta = \frac{Kp}{1 + Kp} \quad (2)$$

with  $K = k_{ads}/k_{des}$ . Such isotherms mostly are applied to the equilibrium of humidity in the gas volume and moisture in the adsorbent, but are also valid for any other gas. The isotherms show a linearly increasing coverage or adsorber content at low partial pressure and the saturation of coverage or adsorber content at high partial pressures. Surely this adsorber equilibrium can only be established, when there is no other independent source of these molecules in the compartment. In that case, equation (1) has to be solved together with an equation for the partial pressure  $p$  including a source term due to by-product generation and a loss term due to adsorption.

Also, the simple Langmuir isotherm is only applicable in those cases, where only one monolayer of molecules can form on a surface. In much more cases and also for molecular sieves, several layers may form on top of each other at higher pressures with either reaching another saturation level or even no limit, when the gas starts to liquefy in pores. Adsorption isotherms for  $\text{H}_2\text{O}$  and  $\text{SO}_2$  have been measured for zeolite 13X and activated  $\text{Al}_2\text{O}_3$  [5].

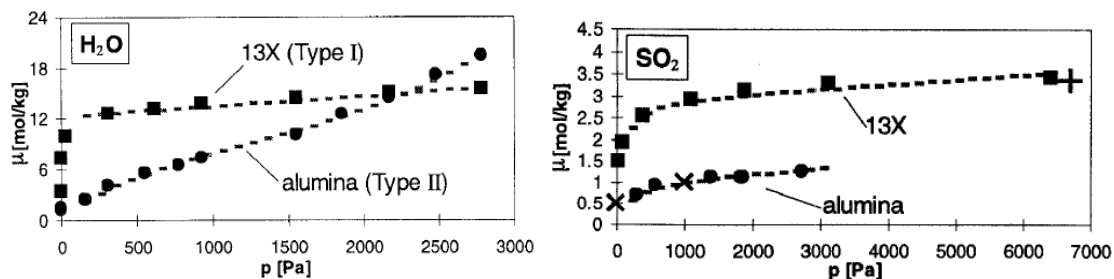


Figure E-2: Adsorption isotherms measured at room temperature for molecular sieve 13X and activated alumina for  $\text{H}_2\text{O}$  and  $\text{SO}_2$  [5]

It is noticed that for 13X-Zeolite the saturation of the adsorber is already obtained at a steady-state partial pressure of H<sub>2</sub>O of approximately 100 Pa, which is equivalent to a water vapour content in the volume of 250 ppm<sub>v</sub> with a filling pressure of 400 kPa of SF<sub>6</sub>. The isotherms change with temperature, since the adsorption and desorption processes are dependent on temperature.

In general, the adsorption capability is reduced with higher temperature for all physisorbed gases. One consequence is that a saturated adsorber releases gas at higher temperatures. This is utilized in order to remove adsorbed water and drying an adsorbent at 300 to 400 °C. It was shown that the pre-loading of 13X-zeolite or alumina by handling in humid air before posing it into a switchgear compartment might easily reach 2.2 mol/kg and 1.2 mol/kg, respectively [5], which is equivalent to approximately 20% of saturation by weight. A negative consequence of this effect is that for a saturated adsorber water might be released into a compartment during summer and adsorbed during winter.

The adsorption capability for decomposition products like SO<sub>2</sub> depends on the sorption of other substances in the same adsorber material. If e.g. a molecular sieve is already heavily loaded with moisture the adsorption capability for SO<sub>2</sub> might be decreased by 25 to 40% [5]. Whereas the parallel adsorption of SF<sub>6</sub> does hardly degrade the performance of zeolites and activated alumina, the chemisorption of considerable amounts of SF<sub>4</sub> or SOF<sub>2</sub> reduces the capability drastically by 50 to 70% [5]. Therefore, it is essential to put sufficient adsorber material into a compartment so that the anticipated quantities of moisture and decomposition products are well below the saturation limit of the adsorber material. Normally the mass of the adsorber material in gas insulated equipment is dimensioned in such a way that this limit is not reached during the life of the equipment.

## References

- [1] Database of International Zeolite Association
- [2] D. Bobok, E. Besedova, Petroleum and Coal, “Effective diffusivities of water vapours and heptane vapours in particles of molecular sieves 4A and 5A”, Vol.45, 19-24, 2003,
- [3] Yi Hua Ma, C. Mancel, “Diffusion studies of CO<sub>2</sub>, NO, NO<sub>2</sub>, and SO<sub>2</sub> on molecular sieve Zeolites by gas chromatography”, AIChE Journal, Vol.18, 1148-1153, 1972,
- [4] P.W.Atkins, “Physical Chemistry”, Chapter 294<sup>th</sup> edition, Oxford Univ. Press, 1990,
- [5] M. Piemontesi, L. Niemeyer, “Sorption of SF<sub>6</sub> and SF<sub>6</sub> decomposition products by activated alumina and molecular sieve 13X”, IEEE int. symposium on electrical insulation, Montreal, Canada, pp. 828-838, 1996.

## **F. WATER IN SULFUR HEXAFLUORIDE**

### **F.1. WATER**

Water is a substance with the chemical formula  $\text{H}_2\text{O}$ . A water molecule contains one oxygen and two hydrogen atoms. The term ‘Water’, as commonly used, refers to  $\text{H}_2\text{O}$  in liquid phase, but chemically its solid state ice, as well its gaseous state vapour are also water. Water in the atmosphere is actually the most effective greenhouse gas of all, but without it, we would not have the liveable environment on our planet as we know it.

### **F.2. WATER AS A CONTAMINANT IN SULFUR HEXAFLUORIDE**

Humidity measurement and moisture control are necessary in any effective maintenance program for  $\text{SF}_6$  insulated equipment. High levels of humidity can result in condensation of water into its liquid phase on the surface of insulators or enclosure housings resulting in the deterioration of insulation performance. To ensure that water vapour does not condense the maximum frost point temperature of the gas is kept below  $-5\text{ }^\circ\text{C}$ . If condensation does occur it will be in the form of ice and is much less likely to impact the insulation performance.

A second issue is the reaction of  $\text{SOF}_2$  with  $\text{H}_2\text{O}$  leading to the production of  $\text{HF}$  and  $\text{SO}_2$ . The  $\text{HF}$  generally interacts quickly with metal oxides of the enclosure to produce metal fluorides. As  $\text{HF}$  is corrosive it may also cause degradation of the insulators.

In an effort to prevent these two potential problems, most users periodically measure the humidity in their  $\text{SF}_6$  insulated equipment. However, utility engineers have experienced difficulties in carrying out humidity measurements and in the interpretation of the results.

Compounding the problem of humidity measurement in  $\text{SF}_6$  is the fact that water inside the  $\text{SF}_6$  insulated equipment can exist in the vapour phase in the  $\text{SF}_6$  gas, adsorbed on the surface of the enclosure, and absorbed within the polymeric materials such as epoxy insulators. The humidity measurement itself detects only the amount of water vapour in the  $\text{SF}_6$  gas and cannot determine the total water content within the system. Adsorption/desorption and absorption/desorption are temperature dependent effects which influence the distribution of water molecules within the compartment filled with  $\text{SF}_6$ , resulting in variations of the humidity measurements. Humidity measurements taken in the cool of winter tend to be lower than humidity measurements taken in the heat of summer. At higher temperatures, moisture on the surfaces and within the bulk material is released as water vapour into the  $\text{SF}_6$  gas.

## **F.3. DEFINITIONS**

### **F.3.1. Moisture**

Moisture is water in its molecular form bound on the surface or within the structure of solids.

- Adsorbed moisture is water in molecular form that adheres to and accumulates on the surfaces of solids.
- Absorbed moisture is water in molecular form that permeates into materials. The degree to which water permeates is dependent on the structure and type of the material.

### **F.3.2. Humidity**

Humidity is water in the gas phase (water vapour), within a gas mixture. Various terms are used to express Humidity.

- Water vapour partial pressure is the pressure that water vapour contributes to the total pressure, or the partial pressure exerted by the water vapour alone, generally expressed in Pascal (Pa).
- Saturation vapour pressure with respect to water is the maximum water vapour partial pressure that can exist at a given temperature with respect to liquid water. Any attempt to increase the water vapour partial pressure beyond the saturation vapour pressure results in condensation of liquid water. Saturation vapour pressure is generally expressed in Pascal (Pa).
- Saturation vapour pressure with respect to ice is the maximum water vapour partial pressure that can exist at a given temperature with respect to ice. Any attempt to increase the water vapour partial pressure beyond the saturation vapour pressure results in deposition (condensation in solid form) of ice. Saturation vapour pressure is generally expressed in Pascal (Pa).
- Dew point is the temperature to which a gas must be cooled to start condensing water vapour in liquid form. Dew point is pressure dependent and must be stated with its associated pressure. While not technically correct, it has been common practice to use dew point below 0 °C although frost point is the correct term. Dew point can exist below 0 °C in the form of liquid super-cooled water and is different in value from the equivalent frost point temperature. For the same vapour pressure, the super-cooled dew point is approximately 10% of reading below the corresponding frost point value (when expressed in °C). For example, a vapour pressure of 38 Pa corresponds to a dew point of –33 °C and a frost point of –30 °C. It is important to properly distinguish between the two.
- Frost point is the temperature to which a gas must be cooled to start deposition of water vapour in the form of ice. Frost point is pressure dependent and must be stated with its associated pressure. Frost point exists only below 0 °C.

- Relative humidity is the ratio between the water vapour partial pressure and the saturation vapour pressure at a given temperature, expressed in %RH.
- Volume ratio is the ratio of the water vapour volume to the total volume of the humid gas, generally expressed in parts per million by volume, ppm<sub>v</sub> or its numerically equivalent value µl/l. Once determined, ppm<sub>v</sub> has no further pressure dependence. It is also independent of the gas type or mixture.
- Weight ratio is the ratio of the mass of water vapour to the total mass of the humid gas, generally expressed in parts per million by weight, ppm<sub>w</sub> or its numerically equivalent value mg/kg. Once determined, ppm<sub>w</sub> has no further pressure dependence, but depends on the gas type and mixture through the molecular weight of the constituents.
- Volume fraction is the fraction of the water vapour volume to the volume of the dry gas, generally expressed in parts per million by volume, ppm<sub>v</sub> or its numerically equivalent value µl/l. Once determined, ppm<sub>v</sub> has no further pressure dependence. It is also independent of the gas type or mixture.
- Weight fraction is the fraction of the mass of water vapour to the mass of the dry gas, generally expressed in parts per million by weight, ppm<sub>w</sub> or its numerically equivalent value mg/kg. Once determined, ppm<sub>w</sub> has no further pressure dependence, but depends on the gas type and mixture through the molecular weight of the constituents
- Molecular weight is the mass of one mole of a specific substance. It is expressed in g/mol.

## **F.4. PRESSURE AND TEMPERATURE INFLUENCES**

### **F.4.1. Pressure Dependence**

Frost/dew point is pressure dependent and can be converted from frost/dew point at one pressure to the equivalent frost/dew point at another pressure. In order to obtain correct results, the following should be observed.

Frost/dew point temperature without a corresponding pressure is incomplete. Generally the frost/dew point is with respect to either gas compartment pressure or atmospheric/standard pressure (100 kPa). Hygrometers without a pressure sensor, but with ppm<sub>v</sub> or ppm<sub>w</sub> indication, are generally converting the frost/dew point to ppm under the assumption that measurements are carried out at 100 kPa absolute standard pressure. Atmospheric pressure, due to its dependence on altitude and weather related variability, is not necessarily 100 kPa.

Historically, due to lack of computational capability, dew point was used as the direct measurement and de-facto standard for reporting humidity data in SF<sub>6</sub> filled equipment. However, newer technology with built-in computing capability provides automatic conversion of pressure-dependent frost/dew point to pressure-independent ppm.

Consideration should be given to the use of ppm rather than frost/dew point for data reporting to avoid pressure dependent variation of the humidity values.

Various pressure units are used in the field of SF<sub>6</sub> due to geographical and historical reasons. Non SI units like bar and psi are still in use. Some pressure measurements are referenced to relative (gauge) pressure. The SI unit for pressure is Pascal (Pa = 1 N/m<sup>2</sup>). The pressure unit kilo Pascal (kPa) absolute is the standard unit in high voltage applications and is recommended to be used to ensure equivalence of pressure and pressure dependent humidity measuring results.

#### **F.4.2. Temperature Related Pressure Dependence**

Although frost/dew point is not temperature dependent by definition, the total pressure and the water vapour partial pressure within a closed vessel are temperature related. As temperature increases or decreases, the total pressure and water vapour partial pressure increase or decrease proportionately, resulting in a change of frost/dew point only due to the pressure variation. This effect only applies to frost/dew point measurements made at compartment pressure. However, this effect is negligible compared to temperature related adsorption, absorption and desorption effects.

#### **F.4.3. Temperature Influence**

The humidity measurement determines only the water vapour content in the SF<sub>6</sub> rather than the adsorbed and absorbed moisture. Therefore, the results show only a portion of the total water content in the system. When humidity measurements are taken in winter the results are always lower than in summer. This seasonal variation can create the impression of erratic measurements which can be confusing to utility engineers. If not well understood, this variability of the recorded values could lead to loss of confidence in the overall humidity measurement program. The influence of temperature also implies that measurements should be carried out in the summer months in order to establish the maximum humidity values in the system. This is a common practice among utilities since attempts to normalize all data to 20 °C, as recommended in other documents, proves difficult. Temperature dependent change of humidity in gas compartments is not a function of the gas properties in terms of water vapour but rather an effect of moisture adsorption/absorption and desorption from the materials within the gas compartment. There have been attempts to quantify this effect in order to derive empirical functions to normalize humidity data to 20 °C. However, this also proves to be complex and controversial since these empirical functions are highly dependent on the design, construction materials and condition of individual gas compartments making a universal normalization function difficult to define.

#### **F.4.4. IEC SF<sub>6</sub> Pressure and Temperature Specifications**

In the Standards IEC 60376 (for new SF<sub>6</sub>) and IEC 60480 (for used SF<sub>6</sub>), maximum acceptable impurity levels are defined. These maximum levels for humidity are referenced to a pressure of 100 kPa and temperature of 20 °C. With the referenced pressure, the pressure dependence of frost/dew point is properly accounted for. However, the specification of 20 °C is often misunderstood as a requirement to normalize data to that temperature. While



normalization to 20 °C has been implemented by some switchgear manufacturers and utility companies, no universal method is defined.

#### F.4.5. Water Content in ppm<sub>w</sub> in various Gas Mixtures

Humidity values expressed in ppm<sub>w</sub> depend on the molecular weight of the carrier gas. Parts per million by weight are usually used with respect to binary mixtures with water vapour in a specific gas or gas mixture. If the carrier gas mixture changes the different molecular weight needs to be taken into account. Not all gas-insulated installations are filled with pure SF<sub>6</sub>. For example in Gas Insulated Lines (GIL) SF<sub>6</sub> is typically mixed with 50 to 90% Nitrogen (N<sub>2</sub>). In low temperature applications SF<sub>6</sub> is mixed with up to 20% CF<sub>4</sub> (Fluor Methane) to avoid gas liquefaction when the compartment is at very low temperatures. Nitrogen or dry air is used to purge gas compartments. In these examples the measured ppm<sub>w</sub> with respect to the molecular weight of the carrier gas would be drastically different to the ppm<sub>w</sub> in pure SF<sub>6</sub>.

Table F-1 indicates the ppm<sub>w</sub> values of different gases and gas mixtures when the correct molecular weight is applied. It is recommended to always use ppm<sub>v</sub> rather than ppm<sub>w</sub> for all data reporting.

Table F-1: Volume Ratio by Weight for various gases

Gas Composition	mol. weight	Frost Point °C at 100 kPa	ppm <sub>v</sub>	ppm <sub>w</sub>
100% SF <sub>6</sub>	146.05	−42	100	12.34
95% SF <sub>6</sub> and 5% Air	140.18	−42	100	12.86
50% SF <sub>6</sub> and 50% Nitrogen	87.02	−42	100	20.71
10% SF <sub>6</sub> and 90% Nitrogen	39.80	−42	100	45.28
90% SF <sub>6</sub> and 10% CF <sub>4</sub>	140.25	−42	100	12.85
100% Air	28.97	−42	100	62.21
100% Nitrogen	28.01	−42	100	64.33
100% CF <sub>4</sub>	88.01	−42	100	20.48

## F.5. CLARIFICATION OF UNITS

### F.5.1. Dew or Frost Point

Historically, no distinction was made between dew and frost point. Dew point has been used for values below 0 °C although frost point is the correct term. Therefore, dew point values below 0 °C defined in standards and guidelines (IEC, CIGRÉ and IEEE) should always be interpreted as frost point. The use of the correct term is highly recommended in order to avoid ambiguities.

### F.5.2. Volume/Weight Ratio vs. Volume/Weight Fraction

Very often it is unclear whether the expressions ppm<sub>v</sub> and ppm<sub>w</sub> should be based on a volume/mass ratio referred to as the dry expression, or on a volume/mass fraction referred to as the wet expression. In the volume/mass fraction, the total volume is used as the divisor rather than the volume that would remain from the dry gas in that volume if the water vapour was removed. Although there are two competing methods for computing this value, the numeric difference is negligible in the range of interest for SF<sub>6</sub> as indicated in Table F-2 and Table F-3.

#### Volume Ratio

Table F-2: Volume Ratio

Volume Ratio ppm <sub>v</sub> $\frac{e}{p - e} * 10^6$	Volume Fraction ppm <sub>v</sub> $\frac{e}{p} * 10^6$	Frost/Dew Point °C at 100 kPa
10000	9900	6.8
1000	999.0	−20
100	99.99	−42
10	9.999	−60

#### Weight Ratio

Table F-3: Weight Ratio

Weight Ratio ppm <sub>w</sub> $\frac{e}{p - e} * 10^6$	Weight Fraction ppm <sub>w</sub> $\frac{e}{p} * 10^6$	Frost/Dew Point °C at 100 kPa
1000	999.0	3.7
100	99.99	−23
10	9.999	−44
1	0.9999	−62

## F.6. CALCULATIONS & CONVERSIONS

There are a range of measuring instruments available giving a variety of different parameters. In addition, manufacturers specify their acceptable limits in differing units. Formulas and conversion between these varying units and values are presented to ensure equivalency between measured and reported parameters.

### F.6.1. Symbols, Units and Values

Table F-4: Symbols, units and values

Description	Symbol	Units	Value
Total Pressure	$p$	Pa, kPa	—
Standard Pressure	$p$	kPa	100
Temperature	$t, T$	°C, K	—
Water Vapour Partial Pressure	$e$	Pa	—
Saturation Vapour Pressure with respect to Water	$e_w$	Pa	—
Saturation Vapour Pressure with respect to Ice	$e_i$	Pa	—
Dew Point Temperature	$t_d$	°C	—
Frost Point Temperature	$t_f$	°C	—
Relative Humidity	$RH$	%	—
Volume Ratio, Parts per Million by Volume	$ppm_v$	µl/l	—
Weight Ratio, Parts per Million by Weight	$ppm_w$	mg/kg	—
Molecular Weight of Carrier Gas (SF <sub>6</sub> )	$M_g$	g/mol	145.06
Molecular Weight of Water Vapour (H <sub>2</sub> O)	$M_v$	g/mol	18.02

## F.6.2. Fundamental Formulas

### F.6.2.1. Saturation Vapour Pressure with respect to Water

There are many different empirical equations to express the saturation vapour pressure with respect to water at a specific temperature. These equations have varying degrees of complexity. Some have large numbers of parameters and are not analytically reversible. For most technical applications, a less complex approximation formula is given by Magnus. This formula provides saturation vapour pressure with respect to water as a function of temperature and can be reversed to provide dew point temperature as a function of vapour pressure. This formula is valid with respect to water and super-cooled water in the range  $-45\dots+50\text{ }^{\circ}\text{C}$ .

$$e_w = 611.2 \cdot \exp\left(\frac{17.62 \cdot t}{243.12 + t}\right) \quad (1)$$

where  $e_w$  is the saturation vapour pressure with respect to water in Pa  
 $t$  is the temperature in  $^{\circ}\text{C}$

### F.6.2.2. Saturation Vapour Pressure with respect to Ice

There are many different empirical equations to express the saturation vapour pressure with respect to ice at a specific temperature. These equations have varying degrees of complexity. Some have large numbers of parameters and are not analytically reversible. For most technical applications, a less complex approximation formula is given by Magnus. This formula provides saturation vapour pressure with respect to ice as a function of temperature and can be reversed to provide frost point temperature as a function of vapour pressure. This formula is valid with respect to ice in the range  $-65\dots+0\text{ }^{\circ}\text{C}$ .

$$e_i = 611.2 \cdot \exp\left(\frac{22.46 \cdot t}{272.62 + t}\right) \quad (2)$$

where  $e_i$  is the saturation vapour pressure with respect to ice in Pa  
 $t$  is the temperature in  $^{\circ}\text{C}$

#### F.6.2.3. Dew Point Temperature

The Magnus formula for saturation vapour pressure with respect to water, equation 1, may be reversed to calculate dew point temperature given a known vapour pressure. The equation takes the following form which is valid over the temperature range of  $-45 \dots +50$  °C.

$$t_d = 243.12 \frac{\ln\left(\frac{e}{611.2}\right)}{17.62 - \ln\left(\frac{e}{611.2}\right)} \quad (3)$$

where  $e$  is the vapour pressure in Pa  
 $t_d$  is the dew point temperature in °C

To calculate the vapour pressure  $e$  from dew point temperature  $t_d$  equation 1 is used substituting the temperature  $t$  with the dew point temperature  $t_d$ .

$$e = 611.2 \cdot \exp\left(\frac{17.62 \cdot t_d}{243.12 + t_d}\right) \quad (4)$$

#### F.6.2.4. Frost Point Temperature

The Magnus formula for saturation vapour pressure with respect to ice, equation 2, may be reversed to calculate frost point temperature given a known vapour pressure. The equation takes the following form which is valid over the temperature range  $-65 \dots 0$  °C.

$$t_f = 272.62 \frac{\ln\left(\frac{e}{611.2}\right)}{22.46 - \ln\left(\frac{e}{611.2}\right)} \quad (5)$$

where  $e$  is the vapour pressure in Pa  
 $t_f$  is the frost point temperature in °C

To calculate the vapour pressure  $e$  from frost point temperature  $t_f$  equation 2 is used substituting the temperature  $t$  with the frost point temperature  $t_f$ .

$$e = 611.2 \cdot \exp\left(\frac{22.46 \cdot t_f}{272.62 + t_f}\right) \quad (6)$$

#### F.6.2.5. Relative Humidity (WMO definition)

Relative humidity, as defined by the World Meteorological Organization (WMO) is defined as the ratio of the vapour pressure that exists to the maximum vapour pressure with respect to water that could exist at a given temperature (saturation vapour pressure), even at temperatures below 0 °C. The equation is given as:

$$RH = \frac{e}{e_w} \cdot 100 \quad (7)$$

where  $e$  is the vapour pressure in Pa

$e_w$  is the saturation vapour pressure with respect to water at the given temperature  $t$

The inverse equation to calculate the vapour pressure  $e$  from  $RH$  is:

$$e = \frac{RH \cdot e_w}{100} \quad (8)$$

#### F.6.2.6. Relative Humidity (Technical Definition)

Relative humidity is defined as the ratio of the vapour pressure that exists to the maximum vapour pressure that could exist at a given temperature (saturation vapour pressure). When the temperature is above 0 °C, there is no difference between the technical and WMO definitions. Contrary to the WMO, for temperatures below 0 °C, saturation vapour pressure with respect to ice is used in the denominator. The equation is given as:

$$RH = \frac{e}{e_w} \cdot 100 \text{ for } t \geq 0 \quad (9)$$

$$RH = \frac{e}{e_i} \cdot 100 \text{ for } t < 0 \quad (10)$$

where  $e$  is the vapour pressure in Pa

$e_w$  is the saturation vapour pressure with respect to water at temperature  $t$  above 0 °C

$e_i$  is the saturation vapour pressure with respect to ice for a given temperature  $t$  below 0 °C

The inverse equation to calculate the vapour pressure  $e$  from  $RH$  is:

$$e = \frac{RH \cdot e_{w,i}}{100} \quad (11)$$

where  $e_{w,i}$  is  $e_w$  for temperature above 0 °C and  $e_i$  for temperature below 0 °C

#### F.6.2.7. Volume Ratio, Parts per Million by Volume

Volume ratio is defined as the ratio of the number of water molecules to the number of molecules of the carrier gas (SF<sub>6</sub>). It is most often expressed as parts per million by volume, ppm<sub>v</sub>, and given by the equation:

$$ppm_v = \frac{e}{p - e} \cdot 10^6 \quad (12)$$

where  $e$  is the vapour pressure in Pa

$p$  is the total pressure at which the vapour pressure  $e$  is measured

The inverse equation for calculating the vapour pressure  $e$  from ppm<sub>v</sub> and total pressure  $p$  is:

$$e = \frac{ppm_v \cdot p}{ppm_v + 10^6} \quad (13)$$

#### F.6.2.8. Weight Ratio, Parts per Million by Weight

Weight ratio is defined as the ratio of the mass of water to the mass of the carrier gas (SF<sub>6</sub>). It is most often expressed as parts per million by weight, ppm<sub>w</sub>, and given by the equation:

$$ppm_w = \frac{M_v}{M_g} \cdot \frac{e}{p - e} \cdot 10^6 \quad (14)$$

where  $e$  is the vapour pressure in Pa

$p$  is the total pressure at which the vapour pressure  $e$  is measured

$M_v$  is the molecular weight of water (H<sub>2</sub>O), 18.02

$M_g$  is the molecular weight of Sulfur Hexafluoride (SF<sub>6</sub>), 146.05

Using the molecular weights for water vapour and SF<sub>6</sub> the equation reduces to

$$ppm_w = \frac{18.02}{146.05} \cdot \frac{e}{p - e} \cdot 10^6 = 0.123 \frac{e}{p - e} \cdot 10^6 \quad (15)$$

The inverse equation for calculating the vapour pressure  $e$  from  $ppm_w$  and total pressure  $p$  is

$$e = 8.1 \frac{ppm_w \cdot p}{ppm_w + 10^6} \quad (16)$$



#### F.6.2.9. Volume Fraction, Parts per Million by Volume

Volume fraction is defined as the ratio of the number of water molecules to the total number of molecules. It is most often expressed as parts per million by volume,  $ppm_v$ , and given by the equation:

$$ppm_v = \frac{e}{p} \cdot 10^6 \quad (17)$$

where  $e$  is the vapour pressure in Pa

$p$  is the total pressure at which the vapour pressure  $e$  is measured

The inverse equation for calculating the vapour pressure  $e$  from  $ppm_v$  and total pressure  $p$  is:

$$e = \frac{ppm_v \cdot p}{10^6} \quad (18)$$

#### F.6.2.10. Weight Fraction, Parts per Million by Volume

Weight fraction is defined as the ratio of the mass of water to the mass of the total gas. It is most often expressed as parts per million by weight,  $ppm_w$ , and given by the equation:

$$ppm_w = \frac{M_v}{M_g} \cdot \frac{e}{p} \cdot 10^6 \quad (19)$$

where  $e$  is the vapour pressure in Pa

$p$  is the total pressure at which the vapour pressure  $e$  is measured

$M_v$  is the molecular weight of water ( $H_2O$ ), 18.02

$M_g$  is the molecular weight of Sulfur Hexafluoride ( $SF_6$ ), 146.05

Using the molecular weights for water vapour and  $SF_6$  the equation reduces to

$$ppm_w = \frac{18.02}{146.05} \cdot \frac{e}{p} \cdot 10^6 = 0.123 \frac{e}{p} \cdot 10^6 \quad (20)$$

The inverse equation for calculating the vapour pressure  $e$  from  $ppm_w$  and total pressure  $p$  is

$$e = 8.1 \frac{ppm_w \cdot p}{10^6} \quad (21)$$

### F.6.3. Humidity Conversions

#### F.6.3.1. Converting between ppmv and ppmw

The simplest of conversions is between  $ppm_v$  and  $ppm_w$ . These conversions are done with the following relationships if water content is measured in pure SF<sub>6</sub> with a molecular weight of 146.05 g/mol.

$$ppm_v = 8.1 ppm_w \quad (22)$$

$$ppm_w = 0.123 ppm_v \quad (23)$$

#### F.6.3.2. Frost/Dew Point Pressure Correction

Frost/dew point is a pressure dependent quantity and is usually measured at standard pressure (100 kPa) or system pressure (for example 450 kPa). To convert the frost/dew point from one pressure to another, use the following procedure.

*Convert Frost Point at Pressure  $p_1$  to the equivalent Frost Point at Pressure  $p_2$ :*

With equation 6, use frost point temperature  $t_1$  to calculate vapour pressure  $e_1$  with respect to total pressure  $p_1$ .

$$e_1 = 611.2 \cdot \exp\left(\frac{22.46 \cdot t_1}{272.62 + t_1}\right) \quad (24)$$

Convert vapour pressure  $e_1$  to vapour pressure  $e_2$  relative to total pressure  $p_2$

$$e_2 = \frac{p_2}{p_1} \cdot e_1 \quad (25)$$

With equation 5 and vapour pressure  $e_2$ , calculate frost point temperature  $t_2$  relative to pressure  $p_2$ .

$$t_2 = 272.62 \frac{\ln\left(\frac{e_2}{611.2}\right)}{22.46 - \ln\left(\frac{e_2}{611.2}\right)} \quad (26)$$

Following this procedure, convert  $-20\text{ }^{\circ}\text{C}$  frost point measured at 100 kPa to the equivalent frost point with respect to a system pressure of 450 kPa.

$$\begin{aligned}t_1 &= -20\text{ }^{\circ}\text{C} \\p_1 &= 100\text{ kPa} \\p_2 &= 450\text{ kPa}\end{aligned}$$

$$e_1 = 611.2 \cdot \exp\left(\frac{22.46 \cdot (-20)}{272.62 + (-20)}\right) = 103.26 \quad (27)$$

$$e_2 = \frac{450}{100} \cdot 103.26 = 464.67 \quad (28)$$

$$t_2 = 272.62 \frac{\ln\left(\frac{464.67}{611.2}\right)}{22.46 - \ln\left(\frac{464.67}{611.2}\right)} = -3.3\text{ }^{\circ}\text{C} \quad (29)$$

The frost point relative to system pressure  $p_2$  of 450 kPa is  $-3.3\text{ }^{\circ}\text{C}$ .

*Convert  $\text{ppm}_v$  to frost point  $t_f$  relative to pressure  $p$ :*

With equation 13, use the  $\text{ppm}_v$  to calculate vapour pressure  $e_i$  with respect to total pressure  $p$ .

$$e_i = \frac{\text{ppm}_v \cdot p}{\text{ppm}_v + 10^6} \quad (30)$$

With equation 5 and vapour pressure  $e_i$ , calculate frost point temperature  $t_f$  relative to pressure  $p$ .

$$t_f = 272.62 \frac{\ln\left(\frac{e_i}{611.2}\right)}{22.46 - \ln\left(\frac{e_i}{611.2}\right)} \quad (31)$$

Following this procedure, convert 150  $ppm_v$  to the equivalent frost point with respect to a standard pressure  $p$  of 100 kPa.

$$ppm_v = 150$$

$$p = 100 \text{ kPa} = 100000 \text{ Pa}$$

$$e_i = \frac{150 \cdot 100000}{150 + 10^6} = 14.998 \quad (32)$$

$$t_f = 272.62 \frac{\ln\left(\frac{14.998}{611.2}\right)}{22.46 - \ln\left(\frac{14.998}{611.2}\right)} = -38.6 \text{ }^\circ\text{C} \quad (33)$$

The frost point relative to standard pressure  $p$  of 100 kPa at 150  $ppm_v$  is  $-38.6 \text{ }^\circ\text{C}$ .

*Convert frost point  $t_f$  relative to pressure  $p$  to equivalent  $ppm_v$ :*

With equation 6, use frost point temperature  $t_f$  to calculate vapour pressure  $e$  with respect to measurement pressure  $p$ .

$$e = 611.2 \cdot \exp\left(\frac{22.46 \cdot t_f}{272.62 + t_f}\right) \quad (34)$$

With equation 12, use vapour pressure  $e$  and measurement pressure  $p$  to calculate  $ppm_v$ .

$$ppm_v = \frac{e}{p - e} \cdot 10^6 \quad (35)$$

Following this procedure, convert a frost point of  $-40 \text{ }^\circ\text{C}$  measured at standard pressure  $p$  of 100 kPa to the equivalent volume ratio in  $ppm_v$ .

$$t_f = -40 \text{ }^\circ\text{C}$$

$$p = 100 \text{ kPa} = 100'000 \text{ Pa}$$

$$e = 611.2 \cdot \exp\left(\frac{22.46 \cdot (-40)}{272.62 + (-40)}\right) = 12.850 \quad (36)$$

$$ppm_v = \frac{12.850}{100'000 - 12.850} \cdot 10^6 = 128.5 \quad (37)$$

The equivalent volume ratio to a frost point of  $-40 \text{ }^\circ\text{C}$  measured at a pressure of 100 kPa is 128.5  $ppm_v$ .

## G. GAS INSULATED TRANSFORMERS AND REACTORS

### G.1. INTRODUCTION

Gas insulated transformers (GIT) and reactor (GIR) have had limited application but the requirement to install substations in large urban areas is leading to an increase in their application. The larger size GIT's are now of the order of 400 MVA at 330 kV.

### G.2. STRUCTURAL FEATURES OF GIT

While there are several types of GIT the most common is the gas cooled and gas insulated type. The gas pressure increases with unit size being 0.12 MPa below 100 MVA and 0.43 MPa for the larger units. The higher pressure is required to improve insulation and cooling capacity.

Figure G-1 and Figure G-2 show an example of a high pressure GIT. The structure of the core and the winding is a simple structure similar to that used in conventional oil immersed transformers. The windings and the core are cooled and insulated by high pressure SF<sub>6</sub> gas. The SF<sub>6</sub> gas, which is taken from the lower side of the tank, cools the winding and the core, is collected in the upper part of the tank, returned to the radiator, and cooled. The transformer has a disc type winding and the internal gas flows in a zigzag path directed by the gas block collars.

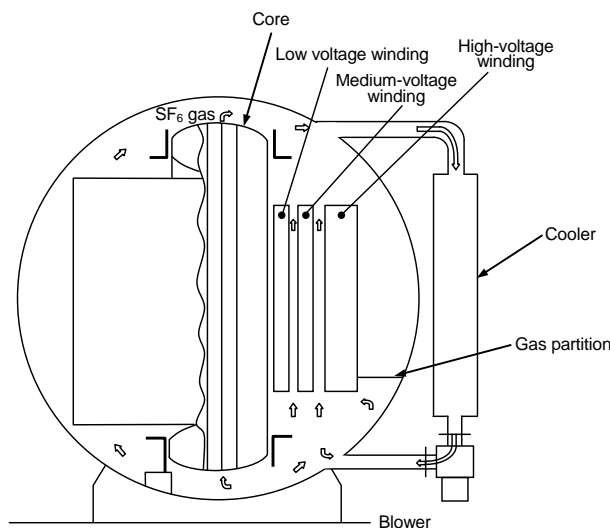


Figure G-1: Schematic structure of GIT

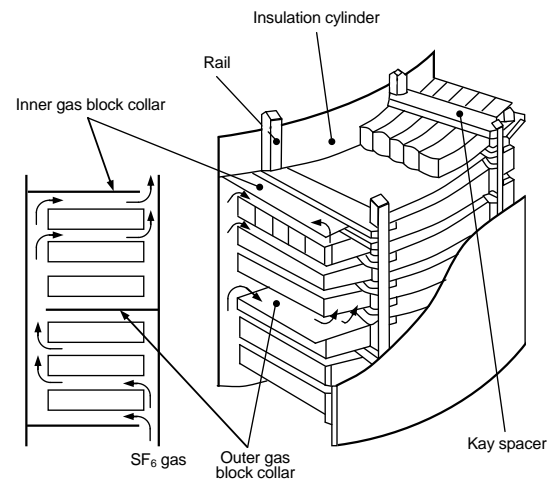


Figure G-2: Winding structure of GIT

The cooling capability of SF<sub>6</sub> gas is lower than that of insulation oil and therefore a large volume of SF<sub>6</sub> gas must be circulated to obtain the required cooling.

### **G.2.1. Conductor Insulation**

Plastic films or aramid papers are used for the conductor insulation instead of insulation papers as in oil insulated transformers. The most typical film is polyethylene terephthalate (PET). This film has high mechanical and dielectric strength, and also has high thermal resistant temperature.

### **G.2.2. On load tap changer**

Vacuum switches are used for the arcing contacts of the diverter switch. Interruption in SF<sub>6</sub> is not used in order to avoid the formation of decomposition products.

## **G.3. GAS INSULATED TRANSFORMERS AND REACTORS - CONTAMINANTS**

### **G.3.1. Introduction**

Gas analysis has been used since the inception of GIT's and GIR's to identify abnormalities within the unit. Since there is no switching within the unit any detectable level of SF<sub>6</sub> decomposition products is of concern. This analysis has progressed to the stage where it is possible to identify the abnormal condition by reference to the ratio of certain decomposition products.

### **G.3.2. Analysis of CO<sub>2</sub>/CO Concentration level**

The components CO<sub>2</sub> and CO are generated from cellulose material in GIT's and measuring their ratio is a useful diagnosis technique. The amount of CO<sub>2</sub> generated with the aging of the solid insulators is more than that of CO so monitoring their ratio will indicate if overheating of solid insulating materials is occurring. Typically if the ratio of CO<sub>2</sub>/CO is greater than 6 it indicates overheating. However the presence of adsorbers must be considered as CO<sub>2</sub> is adsorbed more quickly than CO.

### **G.3.3. SF<sub>6</sub> Decomposition Products**

Any level of decomposition products greater than that specified for new gas is a cause for concern and must be investigated further.

Research undertaken by ETRA [1] has indicated that it is possible to distinguish between electrical discharges and overheating by comparing the ratios of SOF<sub>2</sub>, SO<sub>2</sub>F<sub>2</sub> and SO<sub>2</sub>. If the quantities of SOF<sub>2</sub> or SO<sub>2</sub>F<sub>2</sub> are much greater than SO<sub>2</sub> this indicates electrical discharges, while if the quantity of SO<sub>2</sub> is greater than SOF<sub>2</sub> or SO<sub>2</sub>F<sub>2</sub> it is indicative of overheating.

## **References**

- [1] Electric Technology Research Association of Japan, Report Vol. 54 - No.5.