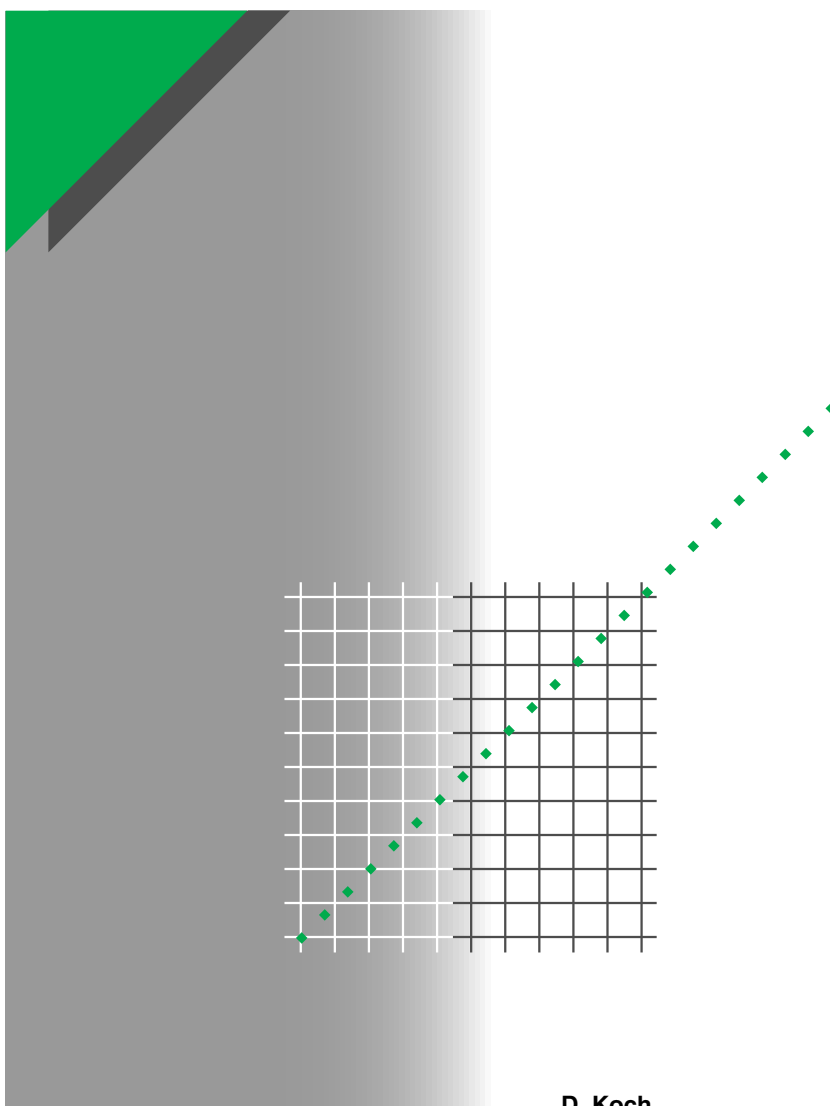


Cahier technique no. 188

SF₆ properties, and use in MV and HV switchgear



Merlin Gerin

Modicon

Square D

Telemecanique

D. Koch

"Cahiers Techniques" is a collection of documents intended for engineers and technicians, people in the industry who are looking for more in-depth information in order to complement that given in product catalogues.

Furthermore, these "Cahiers Techniques" are often considered as helpful "tools" for training courses.

They provide knowledge on new technical and technological developments in the electrotechnical field and electronics. They also provide better understanding of various phenomena observed in electrical installations, systems and equipments.

Each "Cahier Technique" provides an in-depth study of a precise subject in the fields of electrical networks, protection devices, monitoring and control and industrial automation systems.

The latest publications can be downloaded from the Schneider Electric internet web site.

Code: <http://www.schneider-electric.com>

Section: **Experts' place**

Please contact your Schneider Electric representative if you want either a "Cahier Technique" or the list of available titles.

The "Cahiers Techniques" collection is part of the Schneider Electric's "Collection technique".

Foreword

The author disclaims all responsibility subsequent to incorrect use of information or diagrams reproduced in this document, and cannot be held responsible for any errors or oversights, or for the consequences of using information and diagrams contained in this document.

Reproduction of all or part of a "Cahier Technique" is authorised with the prior consent of the Scientific and Technical Division. The statement "Extracted from Schneider Electric "Cahier Technique" no." (please specify) is compulsory.

n° 188

SF₆ properties, and use in MV and HV switchgear



D. KOCH

Graduate Engineer IEG Grenoble in 1979.

He joined the same year Merlin Gerin Group, in HV transmission: first as technical manager of MV circuit breakers and, later, as product manager.

Since 1995, within the T & D organisation, he is in charge, inside the strategic marketing team, of standardisation, technology and environment related with T & D offer.

He is also in charge of geographic development in Eastern Europe.

SF₆ properties, and use in MV and HV switchgear

The general properties of SF₆ gas and its SF₆ by-products are presented. A brief history of the use of SF₆ in switchgear is given. The effects of SF₆ on the environment are discussed. Guidance is given for working with SF₆ gas and SF₆ filled equipment under normal and abnormal conditions of service.

The content of the present document is based on the technical report IEC 1634, entitled « the use and handling of SF₆ HV Switchgear and controlgear ».

Contents

1 Introduction	1.1 A brief history of use of SF ₆	p.4
	1.2 SF ₆ manufacture	p.5
	1.3 Other uses of SF ₆	p.5
2 Physical and chemical properties of SF₆	2.1 Physical properties	p.6
	2.2 Chemical properties	p.8
3 Overview on SF₆ switchgear	3.1 MV and HV switchgear	p.11
	3.2 SF ₆ consumption and switchgear quantities	p.12
	3.3 EDF experience: 20 years of SF ₆ in MV	p.13
	3.4 Future trends	p.13
4 Use and handling of SF₆ in switchgear	4.1 Filling with new SF ₆	p.14
	4.2 Leakage from SF ₆ - filled equipment	p.15
	4.3 Maintenance of SF ₆ - filled equipment	p.15
	4.4 End of life of SF ₆ - filled equipment	p.16
	4.5 Abnormal situations	p.16
	4.6 SF ₆ and the global environment	p.19
5 Conclusions		p.21
Appendix 1: bibliography		p.22

1 Introduction

1.1 A brief history of use of SF₆

Sulphur hexafluoride was first synthesised in the laboratories of the Faculté de Pharmacie de Paris in 1900 by Moissan and Lebeau. Fluorine, obtained by electrolysis, was allowed to react with sulphur and a strongly exothermic reaction, giving rise to a remarkably stable gas.

Gradually thereafter the physical and chemical properties of the gas were established, with publications by Pridaux (1906), Schlumb and Gamble (1930), Klemm and Henkel (1932-35) and Yest and Clausson (1933) concerning particularly the chemical and dielectric properties.

The first research into industrial applications was by the General Electric Company in 1937 who realised that the gas could be used for insulation in electrical plant. In 1939 Thomson-Houston patented the principle of using SF₆ for insulating cables and capacitors.

Immediately after the 2nd world war, publications and applications began to appear in rapid succession:

- towards 1947, work on transformer insulation,
- development of industrial manufacture of SF₆ in the USA in 1948 by Allied Chemical Corporation and Pennsalt,
- large scale commercialisation of SF₆ manufacture for use in electrical plant construction

towards 1960 in the USA and in Europe, coinciding with the appearance of the first SF₆ circuit-breakers and switches at High Voltage – HV – and Extra High Voltage – EHV.

At Merlin Gerin, the research work, concerning the use of SF₆ gas for insulation and circuit-breaking was initiated around 1955. This coincides with the appearance of the first industrial products in the U.S.

The first industrial applications from Merlin Gerin were at EHV, then in Medium Voltage – MV – applications following:

- 1964: the first SF₆ - insulated substation, ordered by EDF and put into service in the Paris region in 1966.
- 1967: the FA circuit-breaker was launched and progressively replaced the compressed air equipment which had established its position in France and elsewhere during the previous 25 years.
- 1971: changes in the needs of the industry led Merlin Gerin to launch the Fluarc SF₆ MV circuit-breaker.
- More recently, SF₆ has been adopted for use in MV switches, ring main units, contactors and circuit-breakers, GIS, covering all the needs of the electrical distribution industry.

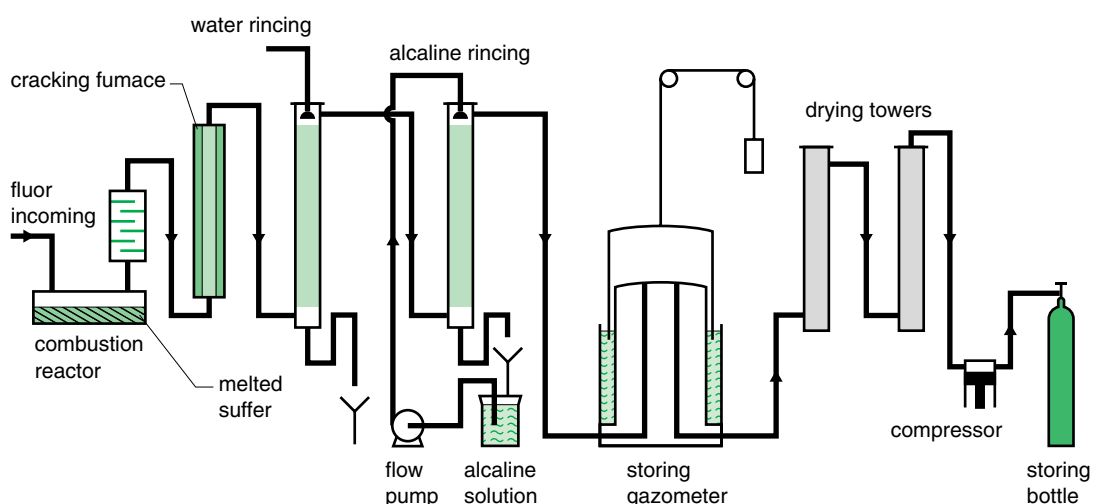


fig. 1 : process of SF₆ production by direct combination. The purification chain is necessary to obtain high purity gas. The quality of SF₆ for delivery is defined by IEC publication 376 which specifies the admissible concentrations of impurities.

1.2 SF₆ manufacture

The only industrial process currently in use is the synthesis of sulphur hexafluoride by allowing fluorine obtained by electrolysis to react with sulphur according to the exothermic reaction:



During this reaction, a certain number of other fluorides of sulphur are formed, such as SF₄, SF₂, S₂F₂, S₂F₁₀, as well as impurities due to the presence of moisture, air and the carbon anodes used for the fluorine electrolysis. These by-products are removed by various purification process (see [fig. 1](#)).

1.3 Other uses of SF₆

The unique properties of SF₆ have led to its adoption for a number of industrial and scientific applications including, for example:

- medical applications: electrical insulation in medical equipment (eg X-ray machines), or surgery,
- electrical insulation in scientific equipment (electron microscopes, particle accelerators such as Van der Graf generators),

- acoustic insulation in double glazed windows,
- as a tracer gas for studying airflow in ventilation systems (for instance in mines) or in the high atmosphere,
- as a tracer for leak detection in pressurised systems,
- to provide a special atmosphere for metallurgical processing (aluminium and magnesium) or for military purpose.

2 Physical and chemical properties of SF₆

2.1 Physical properties

SF₆ is one of the heaviest known gases (see [fig. 2](#)). Its density at 20°C and 0,1 Mpa (that is one atmosphere) is 6.139 kg/m³, almost five times higher than that of air. Its molecular weight

is 146.06. It is colourless and odourless. SF₆ does not exist in a liquid state unless pressurised.

Equation of state

Sulphur hexafluoride gas having an equation of state of the Beattie-Bridgeman type, up to temperature of about 1200 K, behaves as a perfect gas:

$$pv^2 = R T (v + b) - a \quad \text{where:}$$

p = pressure (Pa)

v = volume (m³.mol⁻¹)

R = ideal gas constant (8.3143 J.mol⁻¹.K⁻¹)

T = absolute temperature (K)

$a = 15.78 \times 10^{-6} (1 - 0.1062 \times 10^{-3} v^{-1})$

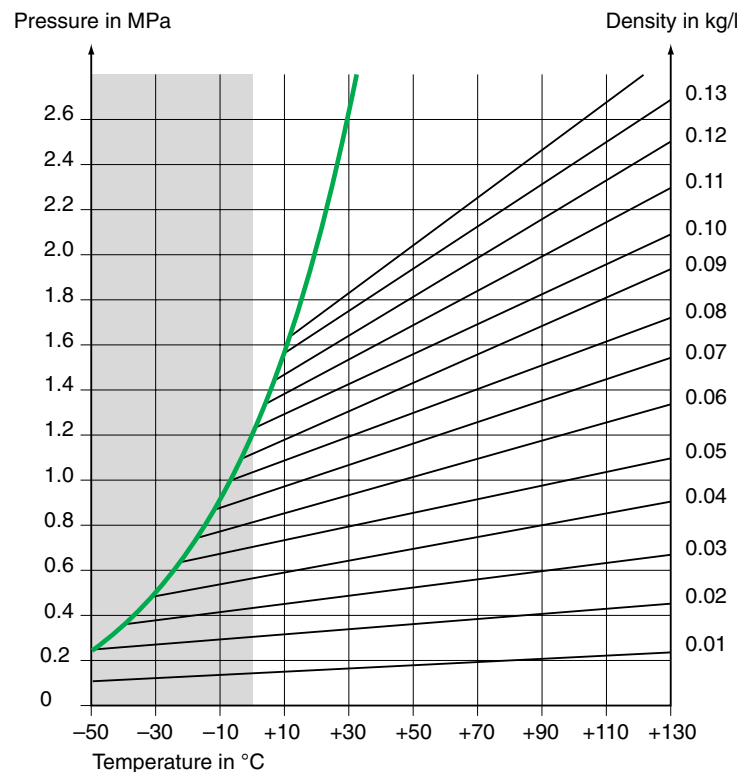
$b = 0.366 \times 10^{-3} (1 - 0.1236 \times 10^{-3} v^{-1})$

Pressure/temperature relation

The variation of pressure with temperature is linear and relatively small in the range of service temperatures (-25 to + 50°C), (see [fig. 3](#)).

Density	6.14 kg m ⁻³
Thermal conductivity	0.0136 W m ⁻¹ K ⁻¹
Critical point:	
■ Temperature	45.55°C
■ Density	730 kg m ⁻³
■ Pressure	3.78 MPa
Sound velocity	136 m s ⁻¹
Refractive index	1.000783
Formation heat	-1221.66 kJ mol ⁻¹
Specific heat	96.6 J mol ⁻¹ K ⁻¹

[fig. 2](#) : main physical characteristics of SF₆ at atmospheric pressure and a temperature of 25°C.



[fig. 3](#) : vapour pressure curve and lines of equivalent gas density of SF₆.

Specific heat

The volumetric specific heat of SF₆ is 3.7 times that of air. This has important consequences for reducing the effects of heating within electrical equipment.

Thermal conductivity

The thermal conductivity of SF₆ is below that of air but its overall heat transfer capability, in particular when convection is taken into account, is excellent, being similar to that of gases such as hydrogen and helium and higher than that of air. At high temperatures, the thermal conductivity curve of SF₆ (see fig. 4) reveals one of the exceptional qualities of the gas, which allows it to be used for extinguishing arcs by thermal transport. The peak of the thermal conductivity corresponds to the dissociation temperature of the SF₆ molecule at 2100 to 2500 K. The dissociation process absorbs a considerable amount of heat which is released when the molecules reform at the periphery of the arc, facilitating a rapid exchange of heat between the hot and cooler regions.

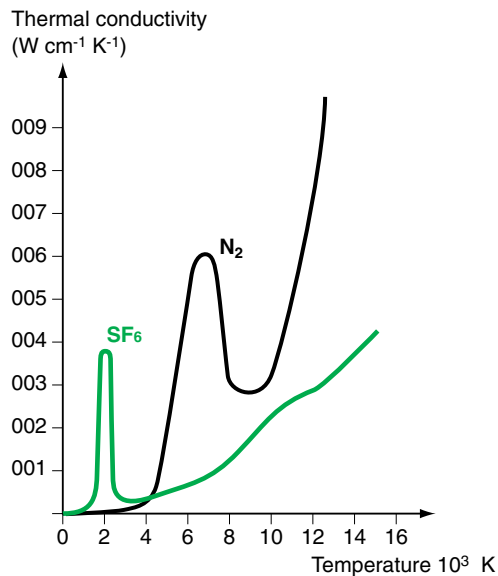
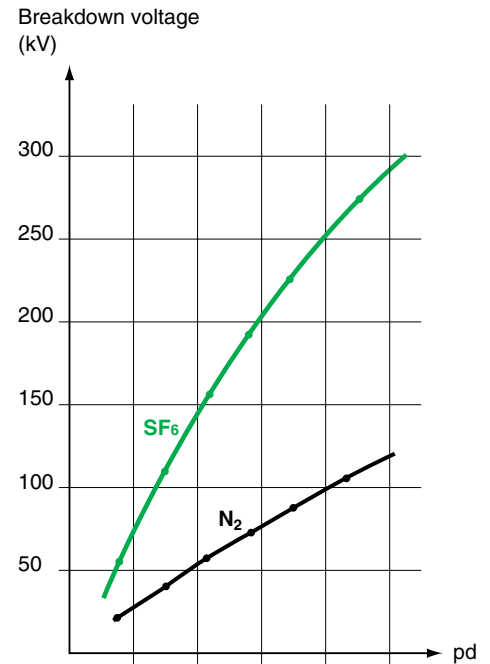


fig. 4 : thermal conductivity of SF₆ and nitrogen.

Electrical Properties

The excellent dielectric properties of SF₆ are due to the electronegative character of its molecule. It has a pronounced tendency to capture free electrons forming heavy ions with low mobility making the development of electron avalanches very difficult.

The dielectric strength of SF₆ is about 2.5 times higher than that of air under the same conditions. The advantage of SF₆ over nitrogen as a dielectric is clearly illustrated by the curve (see fig. 5).



pd product:

p: pressure (MPa)

d: distance between the electrodes (10⁻³ m)

fig. 5 : breakdown voltage as a function of the pd product between two spheres of 5 cm diameter.

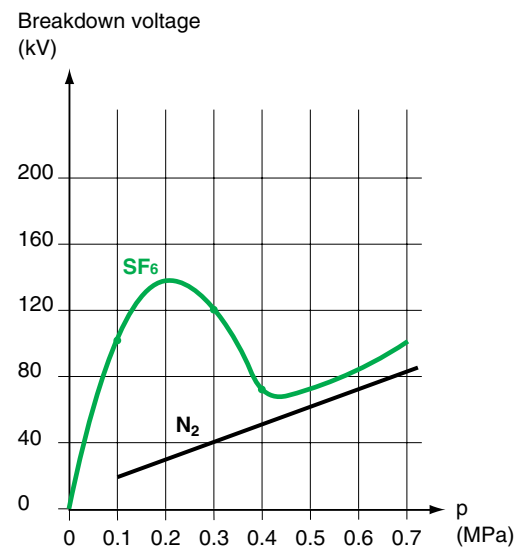


fig. 6 : breakdown voltage as a function of the pressure for a non-uniform electrical field.

For non-uniform fields (see fig. 6) a maximum breakdown voltage is obtained at a pressure of about 0,2 MPa.

Because of its low dissociation temperature and high dissociation energy, SF₆ is an excellent arc quenching gas.

When an electric arc cools in SF₆, it remains conductive to a relatively low temperature, thus minimising current chopping before current zero, and thereby avoiding high overvoltages.

For more information, consult Merlin Gerin Cahier Technique n°145.

Figure 7 lists the main electrical characteristics of SF₆.

Sonic characteristics

The speed of sound in SF₆ is one third of that in air, making SF₆ a good phonic insulator.

Breakdown field relative to pressure	89 V m ⁻¹ Pa ⁻¹
Relative dielectric constant at 25°C and 1 bar absolute	1.00204
Loss factor (tan δ) at 25°C and 1 bar absolute	< 2 x 10 ⁻⁷
Ionisation coefficient	α=A p E/(p - B) α: (m-1) E: (V m-1) p: (Pa) A=2.8 x 10 ⁻² V ² B=89 V m ⁻¹ Pa ⁻¹

fig.7 : main electrical characteristics of SF₆.

2.2 Chemical properties

Sulphur hexafluoride fully satisfies the valency requirements of the sulphur molecule. Its molecular structure is octahedral with a fluorine molecule at each apex.

The effective collision diameter of the SF₆ molecule is 4.77 Å. The six bonds are covalent which accounts for the exceptional stability of this compound.

- SF₆ can be heated without decomposition to 500°C in the absence of catalytic metals.
- SF₆ is non-flammable.
- Hydrogen, chlorine and oxygen have no action on it.
- SF₆ is insoluble in water.
- It is not attacked by acids.

In its pure state SF₆ has no toxicity and this is regularly confirmed on new gas prior to delivery, by placing mice in an atmosphere of 80% SF₆ and 20% oxygen for a period of 24 hours (biological essay recommended by IEC 376).

Arc decomposition products

In an electric arc, the temperature can reach 15,000 K and a small proportion of SF₆ is decomposed. The decomposition products are formed in the presence of:

- an electric arc formed by the opening of contacts normally comprising alloys based on tungsten, copper and nickel, containing residual quantities of oxygen and hydrogen,
- impurities in the SF₆ such as air, CF₄ and water vapour,
- insulating components comprising plastic materials based on carbon, hydrogen and silica.
- other metallic or non-metallic materials from which the equipment is constructed.

The above explains why the solid and gaseous decomposition products contain, in addition to fluorine and sulphur, elements such as carbon, silicon, oxygen, hydrogen, tungsten, copper etc.

The principle gaseous by-products, identified by laboratories which have worked on this subject, combining gas-phase chromatography with mass spectroscopy, are:

- Hydrofluoric acid HF
- Carbon dioxide CO₂
- Sulphur dioxide SO₂
- Carbon tetrafluoride CF₄
- Silicon tetrafluoride SiF₄
- Thionyl fluoride SOF₂
- Sulphuryl fluoride SO₂F₂
- Sulphur tetrafluoride SF₄
- Disulphur decafluoride S₂F₁₀.

Certain of these by-products can be toxic, but it is very easy to adsorb most of them using materials such as activated alumina or molecular sieves. Certain also are formed in extremely minute quantities (S₂F₁₀).

If the adsorbent (molecular sieve or activated alumina) is present in the equipment in sufficient quantity, then the level of corrosion due to SF₆ decomposition products (HF in particular) is very slight if not negligible. This is due to the fact that the adsorbents have a very rapid and effective action such that the corrosive gases do not have sufficient time to react with other materials present.

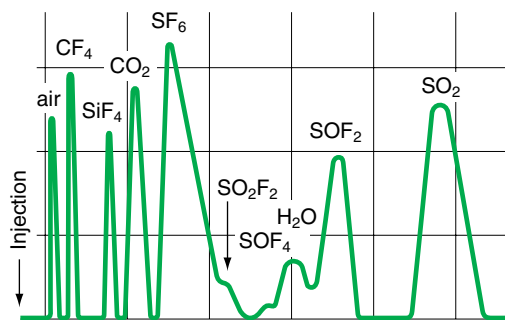
Nevertheless, in order to avoid any risk, Merlin Gerin has prohibited the use of certain materials and constituents which have shown signs of degradation after long tests at high pollution levels, without adsorbents present.

Analysis of gas taken from equipment

Numerous aspects can be studied through analysis of the gas and its decomposition products. Here we will consider only the influence of adsorbents, specifically a molecular sieve. Chromatogram **a** in **figure 8** shows the results of analysis of gas taken from a prototype pole without any adsorbent.

Chromatogram **b** in **figure 8** shows the results of analysis of gas from an identical pole, subjected to the same electrical stresses, but with a molecular sieve fitted.

a - Chromatogram without adsorbent



b - Chromatogram with adsorbent (molecular sieve)

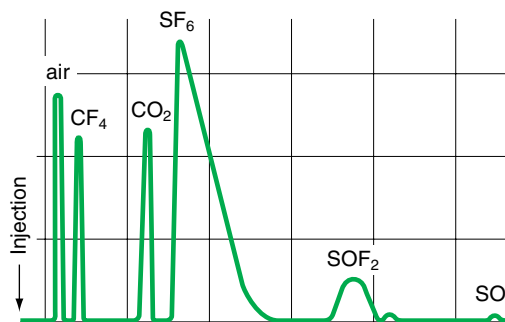


fig. 8 : analysis of gases sampled from equipment.

The table in **figure 9** allows the quantities of gaseous decomposition products in the two cases to be compared. The effectiveness of the adsorbent is clearly apparent.

Health characteristics of pure SF₆

Pure SF₆ is non toxic and biologically inert. Tests performed with animals have shown that when present in a concentration of up to 80% SF₆ to 20% O₂, no adverse effects are experienced.

Gas	No adsorbent (%)	With adsorbent (molecular sieve) (%)
Air	0.17	0.03
CF ₄	2.83	2.80
SiF ₄	2.88	0.25
CO ₂	0.24	—
SF ₆	remainder	remainder
SO ₂ F ₂	0.12	—
SOF ₂	3.95	trace
H ₂ O + HF	0.20	0.05
SO ₂	2.90	trace

fig. 9 : results of analysis of SF₆ from circuit-breakers with and without molecular sieves.

Whilst it is possible therefore for the inhaled atmosphere to contain a high proportion of SF₆ without harmful effects, a maximum concentration of 1,000 ppmv (6,000 mg/m³) has been established for places of work in which personnel spend up to eight hours per day, five days per week.

This TLV (Threshold Limit Value) is that commonly used for harmless gases not normally present in the atmosphere.

Pure SF₆ has no ecotoxic, mutagenic, or carcinogenic (neither genotoxic nor epigenetic) effects on health.

When handling new SF₆, therefore, it is necessary only to adopt procedures which ensure that the specified maximum concentration is not exceeded.

Owing to the manufacturing process, commercially available SF₆ is not perfectly pure. The permitted levels of impurities are laid down in IEC Standard 376. These are shown in **figure 10**.

Impurity	Maximum permitted
CF ₄	500 ppm weight
O ₂ , N ₂	500 ppm weight
Water	15 ppm weight
HF	0.3 ppm weight
Hydrolysable fluorides	1.0 ppm weight expressed as HF

fig. 10 : maximum permitted impurity levels in new SF₆.

Assessment of risk to health posed by arced SF₆

The level of risk to health due to exposure to used SF₆ depends on a number of factors:

- the degree of decomposition of the SF₆ and the types of decomposition products present,
- the of dilution of used SF₆ in the local atmosphere,
- the time during which an individual is exposed to the atmosphere containing used SF₆.

Definition of TLV – Threshold Limit Value –

Potentially toxic gases are assigned a value known as TLV, which is expressed as a concentration in the air, normally in parts per million by volume (ppmv). The TLV is a time-weighted average concentration at which no adverse health effects are expected, for exposure during 8 hours per day, for up to 40 hours per week.

Assessment of toxicity using SOF₂ concentration

Although used SF₆ contains a multi-component mixture of chemical agents, one particular constituent has been shown to dominate in determining the toxicity. This is the gaseous decomposition product thionyl fluoride SOF₂. The dominance of this component results from its high production rate (formed volume in l per arc energy in kJ) relative to those of the other decomposition products, combined with its toxicity rate. The TLV for SOF₂ is 1.6 ppmv.

SOF₂ may further react with water, leading to the generation of sulphur dioxide SO₂ and hydrofluoric acid HF: however due to similar concentration and TLV values, the overall toxicity effect is similar, for SOF₂ or the products of its hydrolysis.

Table of **figure 11** compares the three decomposition products:

- Thionyl fluoride SOF₂
- Sulphuryl fluoride SO₂F₂
- Disulphur decafluoride S₂F₁₀

The first two are the most abundant decomposition products of arcing in SF₆ whereas the latter is estimated to be the most toxic.

To have a toxic effect, a chemical agent must be present in sufficient quantity relative to its TLV. The “risk index” in the table gives an indication of the relative contributions of the three decomposition products to overall toxicity. In a typical sample of arced SF₆, the contribution to toxicity due to SOF₂ outweighs that due SO₂F₂ by about 200 times, and that due to S₂F₁₀ by about 10,000 times. S₂F₁₀ can clearly be neglected, as can SO₂F₂.

In section 4, the quantities of SOF₂ produced under various circumstances will be calculated and used to assess the levels of risk to personnel, taking into account the degree of dilution of the used SF₆ in the local atmosphere and the likely exposure time.

	Thionyl Fluoride SOF ₂	Sulphuryl Fluoride SO ₂ F ₂	Disulphur decafluoride S ₂ F ₁₀
Production rate (l/kJ)	3.7 x 10 ⁻³	0.06 x 10 ⁻³	2.4 x 10 ⁻⁹
TLV (ppmv)	1.6	5	0.01
Production rate relative to SOF ₂ : Pr	1	0.016	0.65 x 10 ⁻⁶
Toxicity relative to SOF ₂ : Tr	1	0.32	160
Risk index: Pr x Tr	1	5.12 x 10 ⁻³	0.104 x 10 ⁻³

fig. 11 : comparison of three SF₆ decomposition products from power arcing.

3 Overview on SF₆ switchgear

3.1 MV and HV switchgear

As mentioned above, switchgear manufacturers use the unique dielectric or/and breaking properties to design their equipment. The main use of SF₆ is in MV and HV switchgear: the place of SF₆ can be globally summarized as detailed in **figure 12**.

Purpose	Switchgear	MV (≤ 52 kV)	HV (> 52 kV)
Insulation	GIS	+++	+++
	RMU	+++	NA
Breaking	CB	++	+++
	LBS	++	+++

Worldwide market share:

Low	+	GIS	Gas Insulated Switchgear
Medium	++	RMU	Ring Main Unit
High	+++	CB	Circuit Breaker
		LBS	Load Break Switch

fig. 12 : the place of SF₆ in switchgear.

In HV field, SF₆ will be soon, on a worldwide basis, the single technology used for GIS (see **fig. 13**) and CB design (see **fig. 14**); the old oil or compressed air technologies are disappearing, due to the numerous advantages related to SF₆.

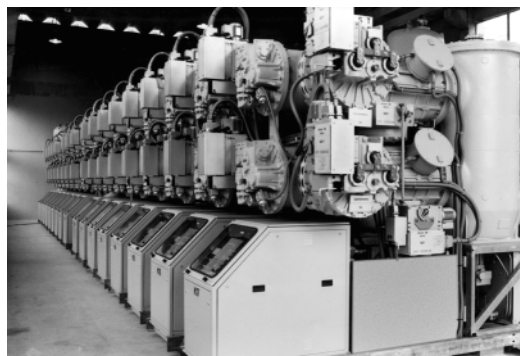


fig. 13 : GIS (Merlin Gerin)

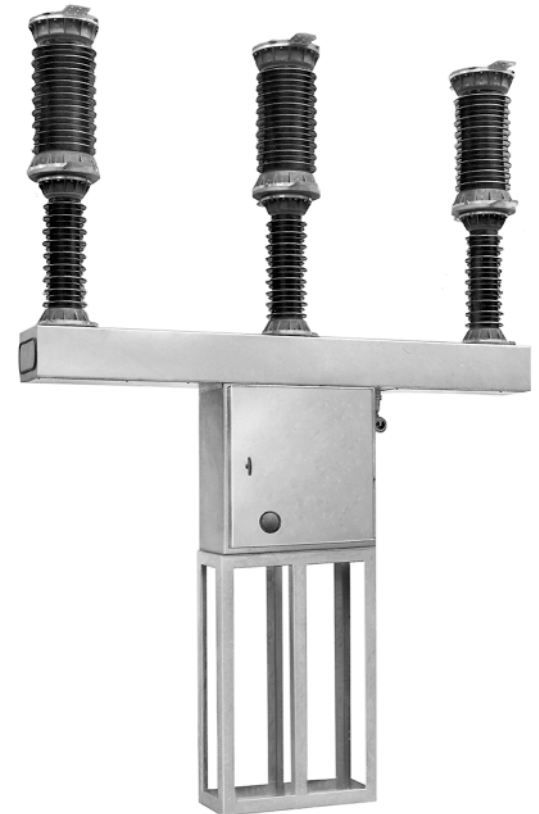


fig. 14 : circuit-breaker for HV substation equipment (SB6 circuit-breaker - Merlin Gerin).

In MV field, when compact switchgear is required, SF₆ is the single proposed solution (GIS, RMU) (see **fig. 15 and 16**). For loose components however, SF₆ technology is sharing the market with air for LBS – Load Break Switches: but air market share is rapidly decreasing to the benefit of SF₆, and with vacuum for CBs. Vacuum and SF₆ CBs are modern solutions, and will continue to expand due to the decreasing influence of minimum oil technology.



fig. 15 : equipment for MV distribution for ring main distribution system ; the output, protected by the circuit breaker is placed in the centre (RM6 - Merlin Gerin).

To be complete in terms of application, we have to mention SF₆ insulated transformers, mainly popular in Japan, and HV gas insulated cables, which are quite similar to HV GIS technology.



fig. 16 : SM6 (Merlin Gerin)

3.2 SF₆ consumption and switchgear quantities

Worldwide SF₆ consumption is shared between switchgear and non electrical applications: IEC estimates a total annual consumption of 5-8000 tons, divided into 2 more or less equivalent parts between these two applications.

In order to understand the relative proportion of SF₆ in MV and HV field, it is useful to estimate the worldwide total installed parc and the quantities annually put into service (see table of **figure 17**).

a - MV switchgear

	SF ₆ mass per unit (kg)	Total installed parc		Annual additional installed switchgear	
		quantity	SF ₆ mass (tons)	quantity	SF ₆ mass (tons)
RMU/ switches	0.6	3,000,000	1,850	240,000 RMU + 70,000 switches	1408
GIS	6	50,000	300	7,000	42
CB	0.3	500,000	150	40,000	17
Total	—	—	2,000 - 2,500	—	≈ 200

b - HV switchgear

	SF ₆ mass per unit (kg)	Total installed parc		Annual additional installed switchgear	
		quantity	SF ₆ mass (tons)	quantity	SF ₆ mass (tons)
GIS	500	20,000	10,000	3,000	1,500
Open type CBs	50	100,000	5,000	8,000	400
Gas insulated cables		30,000 m	1,000	3,000 m	100
Total	—	—	2,0000	—	≈ 2,000

fig. 17 : size of MV and HV SF₆ markets.

It clearly shown in these tables that the use of SF₆ is predominant in HV: 90 % of the total SF₆ volume in switchgear is for HV use,

and only 10 % for MV. In MV, SF₆ consumption concerns mainly RMU/switches and GIS, the part of MV CBs being almost negligible.

3.3 EDF experience: 20 years of SF₆ in MV

EDF is probably the only electricity distribution company having such an experience: 20 years of SF₆ experience in MV CBs and switches, with a Merlin Gerin installed parc of more than 20,000 CBs and 200,000 switches (of modular or compact type) in 1995.

EDF has recently carried out a complete check up of some of the oldest apparatus, having the highest number of operations: tests such as short circuit tests, dielectric tests, temperature rise tests, tightness measurements and mechanical endurance, contact wear measurements, gas analysis... have been made, in order to estimate the probable remaining life.

The results of these tests have been published in IEE 1994 and CIREC 1995 conference. More

precisely concerning CB wear estimation, contact wear measurements showed a maximum value of 25%; gas analysis has been used in order to evaluate the potential toxicity in two different cases: standard leakage and abnormal sudden release due to a fault:

■ In case of a standard leakage, concentration of by-products in the switchgear are extremely low (of the order of 10,000 times lower than the TLV).

■ In the the second case, which occurs exceptionally rarely, the by-products concentrations remain far below any danger limit.

As a consequence, it has been demonstrated, through actual service conditions on site, that the prospective life duration of SF₆ switchgear is at least 30 years.

3.4 Future trends

SF₆ switchgear fully complies with customer requirements, in terms of compactness, reliability, reduced maintenance, personnel safety, life duration... We may expect that in the future, the mechanical energy will continue to decrease due to the mastering of new breaking principles – such as combination of rotating arc and self expansion (see **fig. 18**) – leading to higher reliability (see Cahier Technique n°171). Filling pressures will also decrease, contributing to optimum personnel safety. Concerning maintenance, we can foresee diagnostic features, being able to monitor, in real time, the status of the apparatus and being able to give the information to the user, when maintenance has to be provided.

As far as tightness is concerned, a probable development of HV switchgear can be expected with lower leakage rates such as 0,1 to 0,5% per year. CIGRE WG 23.10 is working on a SF₆ recycling guide, covering purity definition for SF₆ to be re-used in power equipment. By this way, we are considering the use of SF₆ in a closed cycle, which will contribute to minimise its emission in the atmosphere.



fig. 18 : Merlin Gerin LF circuit breaker.

4 Use and handling of SF₆ in switchgear

This section has been included to respond to user's concerns regarding the possible effect with SF₆ gas and its decomposition

products to personnel safety or environment. For more details, please refer to the IEC 1634 technical report.

4.1 Filling with new SF₆

New SF₆ is supplied in cylinders as a liquid. The pressure of SF₆ above the liquid is about 22 bar gauge. New SF₆ should comply with IEC 376 which defines limits for impurity concentrations.

New SF₆ may be handled outdoors without any special provisions. When working indoors with new SF₆, the following should be considered:

- The TLV for new SF₆ is 1,000 ppmv which means that workers may be exposed to concentrations up to this level during eight hours per day for five days a week. The TLV is not based on potential toxicity, rather it is a value which is assigned to gases which are not already present in the atmosphere.
- Temperatures above 500°C, or the presence of certain metals above 200°C, provoke the decomposition of SF₆. At threshold temperatures this decomposition can be extremely slow. It is therefore advised that there be no smoking,

naked flames, welding (except in a neutral atmosphere) or other sources of heat that may approach these temperatures, in areas where SF₆ may be present in the atmosphere.

■ The normal precautions associated with pressurised cylinders of gas should be exercised. For example, a sudden release of compressed gas will give rise to low temperatures which can cause rapid freezing. Workers manipulating equipment where this could occur should wear thermally insulating gloves.

■ When equipment is to be filled with new SF₆, manufacturers' instructions should be followed in order:

- to be sure that the quality of the SF₆ inside the equipment is adequate,
 - to eliminate any risk of over-pressurising the enclosure which is being filled.
- Furthermore spillage of SF₆ to the atmosphere during filling should be avoided.

HV case studied, conditions and calculations

A	Volume of room (m ³)		700
B	Volume of CB enclosure (m ³)		0.5
C	Filling pressure (Mpa)		0.5
D	Volume of SF ₆ /CB (m ³)	B x C	0.25
E	No of CB's		7
F	CB fault rating (kA)		31.5
G	Arc voltage (V)		500
H	Arc duration (s)		0.015
I	Arc energy (1 break/1 pole) (kJ)	F x G x H	236.25
J	Arc energy (3 breaks/3 poles) (kJ)	9 x I	2,126
K	SOF ₂ production rate (l/kJ)		3.7 x 10 ⁻³
L	Quantity of SOF ₂ produced in CB (l)	K x J	7.87
M	Total quantity of SOF ₂ (l)	E x L	55.07
N	Typical leak rage (% year)		1
P	Volume of SOF ₂ released in 1 year (l)	M x N/100	0.55
Q	Concentration after 1 year (ppmv)	P/A x 10 ³	0.79

fig. 19 : leakage of SF₆ in a high voltage (145 kV) indoor substation.

4.2 Leakage from SF₆ - filled equipment

This section examines the implications of leakage of SF₆ gas and gaseous decomposition products into an indoor environment. The potential toxicity of the atmosphere is calculated using the concentration of thionyl fluoride SOF₂.

Two case studies (one high voltage and one medium voltage) are presented. In both cases, the following worst case assumptions are made:

- the switchgear room is sealed from the external atmosphere, ie there is no ventilation,
- the switchgear room contains respectively 7 and 15 circuit breakers,
- the effects of adsorbents in switching enclosures are neglected,

- the circuit-breakers (CBs) have each interrupted their rated fault current three times,

- SOF₂ is produced at a rate of 3.7×10^{-3} litres per kJ of arc energy, (value most frequently cited by the scientific press).

Tables of **figures 19 and 20** summarise the data and the calculations in each case.

The results show that in both cases, the TLV for SOF₂ (1.6 ppmv) is not exceeded after 1 year of leakage at the maximum leak rates into a sealed volume. In reality, normal ventilation would further dilute the SOF₂ leading to a negligible SOF₂ concentration.

There is hence no health risk associated with normal leakage of used SF₆ from switchgear.

4.3 Maintenance of SF₆ - filled equipment

Sealed-for-life MV equipment requires no maintenance to parts inside SF₆ enclosures: they are hence not concerned by this section.

Certain designs of MV GIS may require maintenance and most types of HV circuit breakers are designed to be maintained periodically. Extending a GIS switchboard, both MV and HV, may require the removal of the SF₆.

Many local codes of practice and manufacturer's recommendations exist to advise safe working practises under these circumstances. The following guidelines are common to many of these:

- Care should be taken when removing SF₆ which may contain decomposition products. It should not be released in an indoor environment and should be collected in a storage vessel. Care should be taken not to breathe SF₆ removed from an item of equipment. If this possibility cannot be avoided, a respirator should be worn. This should be fitted with a filter capable of removing the gases described in § "arc decomposition products".

- Enclosures should be evacuated such as to remove as much as possible of the residual SF₆. In some cases, flushing enclosures with dry air

MV case studied, conditions and calculations

A	Volume of room (m ³)		120
B	Volume of CB enclosure (m ³)		45×10^{-3}
C	Filing pressure (Mpa)		0.3
D	Volume of SF ₆ /CB (m ³)	B x C	13.5×10^{-3}
E	No of CB's		15
F	CB fault rating (kA)		31.5
G	Arc voltage (V)		200
H	Arc duration (s)		0.015
I	Arc energy (1 break/1 pole) (kJ)	F x G x H	94.5
J	Arc energy (3 breaks/3 poles) (kJ)	9 x I	850.5
K	SOF ₂ production rate (l/kJ)		3.7×10^{-3}
L	Quantity of SOF ₂ produced in CB (l)	K x J	3.147
M	Total quantity of SOF ₂ (l)	E x L	47.2
N	Typical leak rage (% year)		0.1
P	Volume of SOF ₂ released in 1 year (l)	M x N/100	0.0472
Q	Concentration after 1 year (ppmv)	P/A x 10 ³	0.39

fig. 20 : leakage of SF₆ in a medium voltage (12 kV) indoor substation.

or nitrogen is recommended prior to opening them. In any case, workers should be aware of the presence of residual SF₆ when enclosures are first opened and should wear respirators at that time. Ventilation of the work area should be adequate to remove rapidly any gas released into it.

- Metal fluoride powders are more chemically active in the presence of moisture so efforts should be made to keep these in a dry condition

prior to and during their removal. Fine powders can remain suspended in the air for long periods of time ; where powders are present respirators fitted with sub-micron range powder filters should be used. Particular attention should be paid to protecting the eyes.

- Components, metal fluoride powders and adsorbents removed from equipment in service should be packed in sealed containers for subsequent neutralisation.

4.4 End of life of SF₆ - filled equipment

SF₆ - filled equipment which has been removed from service may require treatment to neutralise any decomposition products remaining after the SF₆ has been removed. For environment reasons. SF₆ has to be removed and not released to the atmosphere, (see § SF₆ and the global environment). The need for neutralisation is dependent on the level of decomposition ; expected decomposition levels are shown in the table of **figure 21** .

Prior to treatment, the SF₆ should be removed and stored for recycling. The equipment should then be treated according to the expected decomposition level. After treatment, the equipment can be disposed of as normal waste (respecting local regulations), for example in a landfill site, or subjected to reclamation processes to recover the metals. Solutions used in the neutralisation process can be disposed of as normal waste.

Low decomposition:

No special action is required.

Medium and high decomposition:

The internal surfaces of gas enclosures should be neutralised using a solution of lime (calcium hydroxide) prepared by diluting 1 kg of lime in 100 litres of water. The enclosure to be treated should, if possible, be filled with the lime solution for a period of 8 hours before emptying. If it is subsequently necessary to work on the enclosure, it should first be rinsed with clean water.

For larger enclosures where filling is impractical, powders should be removed, using a vacuum cleaner equipped with a suitable filter, for neutralisation separately. The internal surfaces should then be washed with the lime solution which should be left in place for at least one hour followed by rinsing with clean water.

Application	Expected degree of SF ₆ decomposition
GIS disconnecter Medium voltage load-break switch and ring-main unit	<ul style="list-style-type: none"> ■ from zero to a few tenths of a percent ■ no visible powder deposit
Medium voltage and high voltage circuit-breaker	medium: <ul style="list-style-type: none"> ■ up to a few percent ■ light powder deposits
Any enclosure in which abnormal arcing has occurred	high: <ul style="list-style-type: none"> ■ could exceed 10% ■ medium to heavy powder deposits

fig. 21 : expected levels of SF₆ decomposition for various equipment types.

4.5 Abnormal situations

This section deals with the assessment of risk to personnel in the case of an abnormal situation leading to an uncontrolled release of SF₆ gas into the atmosphere. Such situations, which occur only very infrequently, are:

- abnormal leakage, due to a failure of the SF₆ enclosure seals to contain the gas,

- internal fault, resulting from uncontrolled arcing inside the SF₆ enclosure,
- external fire, giving rise to abnormal leakage.

Abnormal leakage

The method of risk assessment is similar to that used in section "leakage from SF₆ - filled

equipment” which deals with normal leakage. The same case study data will be used for high and medium voltage situations. In the calculations that follow it is assumed that all of the SF₆ in one circuit-breaker escapes suddenly and it is again assumed that the switchroom is sealed and that ventilation is inoperative. (see **fig. 22**).

Thus if all of the SF₆ were to escape into the switchroom, the concentration of SOF₂ would reach 9.0 ppmv, or about 6 times the TLV.

In practice, attention would be drawn to an abnormal leak by underpressure detectors fitted

to the CBs. These normally operate around 80% of normal filling pressure, and at this point in time, only 20% of the available SF₆ would be in the atmosphere, leading to an SOF₂ concentration of 1,8 ppmv.

In the case of abnormal leakage of SF₆ in a medium voltage indoor substation (see **fig. 23**), the SOF₂ related to complete escape of SF₆ from one CB would reach 17,5 ppmv.

The concentration of SOF₂ in the switchroom at 20% relative pressure loss (commonly the alarm level) would be 3.5 ppmv.

HV Case studied, conditions and calculations

A	Volume of room (m ³)		700
B	Volume of CB enclosure (m ³)		0.5
C	Filling pressure (Mpa)		0.5
D	Volume of SF ₆ /CB (m ³)	B x C	0.25
E	No of CB's		7
F	CB fault rating (kA)		31.5
G	Arc voltage (V)		500
H	Arc duration (s)		0.015
I	Arc energy (1 break/1 pole) (kJ)	F x G x H	236.2
J	Arc energy (3 breaks/3 poles) (kJ)	9 x I	2,126
K	SOF ₂ production rate (l/kJ)		3.7 x 10 ⁻³
L	Quantity of SOF ₂ produced in CB (l)	K x J	7.87
M	Filling pressure relative to atmospheric (Mpa)	C - 0,1	0.4
N	Amount of SOF ₂ which could leak (l)	L x M/C	6.3
P	Switchroom SOF ₂ concentration (ppmv)	N / A	9.0

fig. 22 : abnormal leakage of SF₆ in a high voltage (145 kV) indoor substation.

MV Case studied, conditions and calculations

A	Volume of room (m ³)		120
B	Volume of CB enclosure (m ³)		45 x 10 ⁻³
C	Filling pressure (Mpa)		0.3
D	Volume of SF ₆ /CB (m ³)	B x C	13.5 x 10 ⁻³
E	No of CB's		15
F	CB fault rating (kA)		31.5
G	Arc voltage (V)		200
H	Arc duration (s)		0.015
I	Arc energy (1 break/1 pole) (kJ)	F x G x H	94.5
J	Arc energy (3 breaks/3 poles) (kJ)	9 x I	850.5
K	SOF ₂ production rate (l/kJ)		3.7 x 10 ⁻³
L	Quantity of SOF ₂ produced in CB (l)	K x J	3.147
M	Filling pressure relative to atmospheric (Mpa)	C - 0,1	0.2
N	Amount of SOF ₂ which could leak (l)	L x M/C	2,098
P	Switchroom SOF ₂ concentration (ppmv)	N / A	17.5

fig. 23 : abnormal leakage of SF₆ in a medium voltage (12 kV) indoor substation.

In both cases above, the TLV for SOF₂ (1.6 ppmv) may be exceeded, but by a relatively small factor. Under these circumstances exposure for a short period would present negligible risk. The pungent, unpleasant odour of SOF₂ is noticeable from concentrations of around 1 ppmv and this would mean that, for most people, attention would be drawn immediately to concentrations approaching the TLV. Smell is however not recommended as a detection method.

Internal fault

An internal fault can develop when an arc is formed abnormally between the main conductors of an item of switchgear, or between a main conductor and an earthed conducting part. Such faults occur very rarely. Abnormal arcing gives rise to a rapid increase in pressure which can cause hot gases and other materials to be expelled. Whilst an internal fault could develop in any high-voltage enclosure, this section is concerned with internal faults within enclosures filled with SF₆. There are three possibilities for such faults:

- 1 - Internal fault which does not lead to an abnormal release of SF₆. This can occur when the energy delivered to the fault is insufficient to lead to burn-through or pressure relief of the enclosure.
- 2 - Internal fault where heat from the arc causes the enclosure wall (usually metallic and forming one arc electrode) to melt or vapourise such that a hole is formed. This type of fault is associated mainly with high-voltage GIS equipment.
- 3 - Internal fault where the pressure-rise within the enclosure is sufficient to lead to operation of pressure relief devices. This is controlled by a pressure-relief valve or by a well-defined, stress releasing zone of the enclosure, allowing hot exhaust to be directed.

The risks to personnel associated with faults of types 2 and 3 will be considered here. The risks associated with the use of SF₆ are evaluated based on the quantity of SOF₂ released into the atmosphere. The potentially harmful effects of other toxic vapours not related to the use of SF₆ are also considered ; it will be seen that these other by-products, which are also present during an internal fault in any type of equipment, can be the dominant contributors to toxicity.

The following assumptions are made:

- For medium-voltage equipment containing small volumes of SF₆, it is assumed that the majority of the gas is expelled from the enclosure within 50 ms. This assumption is supported by pressure measurements made during internal fault tests. The quantity of SOF₂ formed is therefore calculated using a 50 ms production period.
- For high-voltage equipment a SOF₂ production period of 100 ms will be used, because fault-times in high-voltage systems are usually limited to around 100 ms.
- It is assumed that the switchroom is closed to the external environment.
- The effects of adsorbents are likely to be negligible within the time period of interest.
- All of the SOF₂ generated during the fault is released into the switchroom. (see **fig. 24 & 25**).

The results indicate that significant concentrations of SOF₂ can be generated within a switchroom. Detailed toxicological data for SOF₂ are unfortunately not available but it is known that larger mammals (rabbits) can withstand exposure for one hour at concentrations of up to 500 ppmv (see section 4.2.2. of IEC 1634 -1995).

Other potentially toxic substances are produced during an internal fault including metal and plastic vapours and it can be shown that these inevitable

HV Case studied, conditions and calculations

A	Volume of room (m ³)		700
B	CB fault rating (kA)		31.5
C	Arc voltage (V)		1,000
D	Arc duration (s)		0.1
E	Arc energy (2 arcs, phase-phase) (kJ)	B x C x D	6,300
F	SOF ₂ Production rate (Al electrodes) (l/kJ)		10 x 15 ⁻³
G	Quantity of SOF ₂ produced in CB (l)	E x F	94.5
H	Switchroom SOF ₂ concentration (ppmv)	G/A	135

fig. 24 : internal fault in a high voltage (145 kV) indoor GIS substation.

products, which are not related to the use of SF₆, can dominate when the overall toxicity of the atmosphere is considered. This applies to any type of switchgear, SF₆ filled or otherwise (see section C 4.7.2. and C 4.7.3 of IEC 1634 -1995).

If, for example during a busbar fault, only 10 grammes of copper were evaporated into the example medium voltage switchroom atmosphere, the concentration (neglecting the effects of oxidation) would be (mass of Cu / room volume) = 83 mg/m³. The TLV for copper vapour is 0.2 mg/m³. This means that the copper vapour concentration could reach 400 times the TLV.

Similarly, the full vaporisation of only 32 grammes of PVC (equivalent to the insulation from 1.2 m of standard 1 mm² wire) could give rise to an atmospheric concentration of 100 times the TLV (2.6 mg/m³) of vinyl chloride.

It can be therefore concluded that in any internal fault situation, corrosive and/or toxic fumes are produced whether or not SF₆ is present. In cases where these fumes enter the switchroom atmosphere, it has been shown that non SF₆ related products are likely to be the dominant contributors to overall toxicity. This further strengthens the

view that the use of SF₆ in switchgear does not significantly add to the risks associated with an internal fault.

External fire

Fires in outdoor installations rarely cause problems because of the relative absence of flammable material in the vicinity of the switchgear. In indoor installations, particularly in the case of medium voltage consumer substations, there is a greater risk of fire in the proximity of the switchgear.

Research has shown that fire temperatures rarely exceed 800°C and the temperatures in the region of SF₆ enclosures which are protected by metal cladding, are likely to be much lower than this. A release of SF₆ is very unlikely to be provoked by a fire; if it should occur, average temperatures are likely to be too low (because SF₆ will be rapidly dissipated by convection to lower temperature regions) to lead to significant decomposition, which requires at least 500°C. SF₆ is non-flammable and will have an extinguishing effect.

Personnel engaged in fighting a fire will be adequately protected by precautions normally used against vapours from burning plastics.

MV Case studied, conditions and calculations

A	Volume of room (m ³)		120
B	CB fault rating (kA)		31.5
C	Arc voltage (V)		1,000
D	Arc duration (s)		0.5
E	Arc energy (2 arcs, phase-phase) (kJ)	B x C x D	1,575
F	SOF ₂ Production rate (Cu electrodes) (l/kJ)		3.7 x 10 ⁻³
G	Quantity of SOF ₂ produced in CB (l)	E x F	5.83
H	Switchroom SOF ₂ concentration (ppmv)	G/A	48.6

fig. 25 : internal fault in a medium voltage (12 kV) indoor substation.

4.6 SF₆ and the global environment

Atmospheric pollutants produced by human activity are divided into two major categories according to their effects:

- stratospheric ozone depletion (hole in the ozone layer),
- global warming (greenhouse effect).

SF₆ does not contribute significantly to stratospheric ozone depletion because it contains no

chlorine which is the main agent in ozone catalysis, or to the greenhouse effect because quantities present in the atmosphere are very small (see annexe D of IEC 1634 (1995) and Electra n° 164 (2), 1996).

Schneider Group Policy

Schneider group has set up an environmental policy in order to provide systems and products to

help people use electricity safely: actions are taken in order to protect the environment and promote its care, not only inside the group, but also outside, by providing appropriate information to our customers, suppliers and partners.

As far as SF₆ handling is concerned, regulations and qualified procedures have been set up for internal and customer purpose:

■ Internal procedures specify the quality of SF₆ necessary to guarantee the switchgear performances, either for dielectric or breaking application.

Criteria here are based on IEC 376 standards for personnel and environment safety, adequate procedures and qualified equipment (coupling, pumping) have been chosen to minimize SF₆ release at each stage (production, site, maintenance, end of life).

■ For the user (customer) relevant information is displayed in the switchgear leaflet, for different situations (normal use, maintenance...). However, for personnel safety and environmental care reasons, maintenance specifically heavy maintenance, can be carried out by Schneider group or under his supervision, in our facilities or specially designed workshops.

In these procedures, special operations are described, in terms of gas treatment ; A gas which is not in accordance with the specified values can be locally on site treated, by using adequate gas cart equipment ; Gas treatment for arc decomposed gas may also be carried out by Schneider, a patented procedure using lime solution for neutralisation purpose has been developed in order to answer to customers requirements, for instance for end of life disposal. This service is supported by Schneider Services.

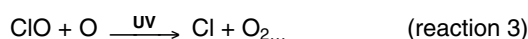
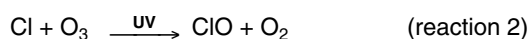
The existing procedures are applied:

- in our facilities (filling, recycling),
- during maintenance (rincing, refilling),
- for end of life disposal.

Ozone depletion

The international community has recognised the risks, due to destruction of the ozone layer, to health and the environment.

The ozone (O₃) destruction mechanism in the case of CFC's (chlorinated fluorocarbons) requires the presence of free chlorine atoms which are released when CFC molecules are exposed to ultraviolet radiation. The reactions are:



CFC molecular bonds are broken by UV irradiation and free chlorine atoms are released (1). These react with ozone to producing ClO, which in turn

reacts with free oxygen, liberating the chlorine atom which can go once more through reaction 2. This is termed the catalytic cycle. A single atom of chlorine can participate in this cycle ten thousand times before it is neutralised by a reaction not involving ozone.

SF₆ however is not photo-decomposed at ozone layer altitudes (32-44 km), so very little atomic fluorine is released. Any free fluorine which is released has a strong tendency to combine with free hydrogen rather than with ozone. Moreover, the concentration of SF₆ is 1,000 times less of that of the CFC's.

Greenhouse effect

The temperature at the surface of the earth rises during the day due to solar radiation and falls during the night as heat is lost due to infra-red radiation. Some of the infra-red radiation, particularly in the range of wavelengths between 7 and 13 μm, is reflected back to the surface of the earth and does not escape. The reflectivity of the atmosphere at these wavelengths is enhanced by the presence of "greenhouse" gases such as CO₂, H₂O and O₃ and is particularly increased by man-made gases such as CO₂ from the burning of fossil fuels, N₂O from intensive agriculture, CFC's from spray propellants and refrigerators and CH₄ from intensive cattle farming. SF₆ has infra-red absorption characteristics and is considered as a minuscule greenhouse gas, having a very long life duration in the atmosphere ; however, its contribution to global warming is very small, due to the extremely low concentration of SF₆ in the atmosphere (see fig. 26).

The contribution of SF₆ is less than one part in ten thousand of the total contribution of the other agents and is thus negligible. However, very long term environmental considerations make it advisable to SF₆ reclaim, during maintenance or end of life treatment, in order to minimize its accumulation in the atmosphere.

Gas	Concentration (ppbv)	Contribution
CO ₂	353 x 10 ³	60
CH ₄	1.7 x 10 ³	15
N ₂ O	310	5
O ₃	10-50	8
CFC-11	0.28	4
CFC-12	0.48	8
SF ₆	0.002	10 ⁻²

fig. 26 : estimated contribution of various gases to the greenhouse effect.

5 Conclusions

The adoption of SF₆ in switchgear for all operating conditions has brought advantages in performance, size, weight, global cost and reliability. The cost of ownership, which includes maintenance costs, can be much lower than for older types of switchgear: for instance, in the case of MV CBs, EDF has reduced the total cumulated maintenance time per CB from 350 hours to 30 hours.

Many years of service experience have substantiated the assertions made in this document that the use of SF₆ does not constitute any threat to personnel or to the environment, as long as elementary working practices are employed.

Appendix 1: bibliography

Standards

- IEC TR 1634: High-Voltage Switchgear and Controlgear-Use and Handling of Sulphur Hexafluoride (SF₆) in High-Voltage Switchgear and Controlgear First Edition.
- IEC 376: Specification and Acceptance of New Sulphur Hexafluoride First Edition ; (Supplement A-1973) (Supplement B-1974).

Cahiers Techniques Merlin Gerin

- Etude thermique des tableaux électriques BT, Cahier Technique N°145, january 1990 - C. KILINDJIAN
- Breaking by auto-expansion, Cahier Technique N°171, december 1993 - G. BERNARD

Other publications

- CIGRE WG 23-01 Task force 01 (08.96): SF₆ recycling guide.
- CIRED (1995): Developpement et suivi du palier technique EDF utilisant de l'appareillage moyenne tension SF₆ - B. JOYEUX, G. PERRISSIN, M. REBOUL
- ELECTRA N°164 (02.96): SF₆ and the global atmosphere (Task force 01 of WG 23.10).
- IEE (1994): MV switchgear breaking in SF₆: the situation after 20 years in service.

Schneider Electric

Direction Scientifique et Technique,
Service Communication Technique
F-38050 Grenoble cedex 9
Fax: 33 (0)4 76 57 98 60
E-mail : fr.tech-com@mail.schneider.fr

Edition: Schneider Electric

- 100 FF -