TECHNICAL REPORT

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First edition
1995-04

High-voltage switchgear and controlgear – Use and handling of sulphur hexafluoride (SF_6) in high-voltage switchgear and controlgear

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH-VOLTAGE SWITCHGEAR AND CONTROLGEAR – USE AND HANDLING OF SULPHUR HEXAFLUORIDE (SF_6) IN HIGH-VOLTAGE SWITCHGEAR AND CONTROLGEAR

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international cooperation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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Technical reports of types 1 and 2 are subject to review within three years of publication to decide whether they can be transformed into International Standards. Technical reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

IEC 1634, which is a technical report of type 2, has been prepared by sub-committee 17A: High-voltage switchgear and controlgear, of IEC technical committee 17: Switchgear and controlgear.

The text of this technical report is based on the following documents:

Committe draft	Report on voting
17A(Sec)433 10(Sec)334 17C(Sec)155	17A/449/RVC

Full information on the voting for the approval of this technical report can be found in the reports on voting indicated in the above table.

This document is issued in the type 2 technical report series of publications (according to G.4.2.2 of part 1 of the IEC/ISO Directives) as a "prospective standard for provisional application" in the field of high-voltage switchgear and controlgear because there is an urgent requirement for guidance on how standards in this field should be used to meet an identified need.

This document is not to be regarded as an "International Standard". It is proposed for provisional application so that information and experience of its use in practice may be gathered. Comments on the content of this document should be sent to the IEC Central Office.

A review of this type 2 technical report will be carried out not later than three years after its publication, with the options of either extension for a further three years or conversion to an International Standard or withdrawal.

INTRODUCTION

SF_6 gas has been used in electrical switchgear and controlgear for more than 30 years. Its application is mainly in equipment for rated voltages exceeding 1 kV up to the highest rated voltages for which switchgear and controlgear are manufactured. It is estimated that several millions of the different types of SF_6-filled units are currently in service.

The long experience with SF_6 in electrical switchgear and controlgear has demonstrated that there are no major problems concerning its use, provided that certain elementary precautions and procedures are established and observed.

A number of international and national standards and codes of practice exist, covering various aspects of SF_6 gas. Additionally, many articles and technical papers on SF_6 and its use have been written. An extensive literature survey is given in a report prepared by WG 23.03 of CIGRE [1]*; the report includes the results of a survey concerning the safety of personnel working with GIS equipment. Very few injuries were reported including only one with any permanent consequences. The report states: "It should be noted that in all cases where injury occurred, the individuals concerned did not wear proper protective clothing and did not adopt proper safety procedures".

SF_6 is used in closed or sealed pressure systems. The small quantity of SF_6 which may leak into the atmosphere does not deplete the ozone layer and has a negligible influence on the greenhouse effect.

The by-products of SF_6 created in switchgear and controlgear by thermal effects (heating, arcing, spark, discharge, etc.) may have toxic properties. However, the real toxicity depends on the concentration in the switchgear and controlgear room and the exposure time. Taking these factors into consideration it is shown that the presence of SF_6 does not impose a greater risk to the operator under normal (operating) or abnormal (internal fault, fire) conditions than the other materials used in any other type of switchgear and controlgear (metals, plastics, etc.).

The overall toxicity and health risks to persons due to arced SF_6 should be estimated using the quantity of thionyl fluoride (SOF_2) generated. SOF_2 decomposes in time in the presence of moisture to form suphur dioxide (SO_2) and hydrogen fluoride (HF). The toxic effects of this mixture are not greatly different from those due to SOF_2.

Five situations are dealt with concerning working with SF_6:

a) Working with new SF_6: filling.

b) SF_6 switchgear and controlgear under normal service conditions: leakage.

c) Working with used SF_6 which may contain decomposition products: maintenance or extension of switchgear and controlgear.

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* The figures in square brackets refer to annex G, "Bibliography".

d) Abnormal situations: e.g. internal fault or external fire provoking opening of the enclosure.

  1) During and immediately after the fault: operator safety.

  2) After the fault or external fire: restorative work.

e) End of life of equipment: recycling, disposal.

Approximate concentration limit values are given below for the different situations. These values are indications for those cases where measurements can be made and are related to the threshold limit value (the TLV) of the corresponding gas. If these values are exceeded, ventilation should be used until the concentrations fall to acceptable values. If this cannot be achieved, respirators should be used.

For situation a) (filling):
1 000 ppmv of SF_6.

This is the TLV for new SF_6.

For situations b) (leakage), c) (maintenance and extension) and e) (end of life):
1,6 ppmv of SOF_2 or 200 ppmv SF_6.

The value given for SOF_2 is the TLV of SOF_2. This does not take account of the possible hydrolysis of SOF_2 whereby SO_2 and HF are formed. In order to take account of this and to simplify the requirements for measurement and interpretation, a concentration limit of 200 ppmv SF_6 is also given. This value corresponds to a mixture of the ambient air with SF_6 which has been subjected to *medium decomposition*. It takes account of the TLVs of the potentially toxic components SOF_2, SO_2 and HF.

For situation d)2) (after an internal fault or external fire):
1,6 ppmv of SOF_2 or 20 ppmv SF_6.

The value given for SOF_2 is the TLV of SOF_2. An alternative concentration limit of 20 ppmv SF_6 is given which corresponds to a mixture of the ambient air with a small volume of SF_6 which has been subjected to *high decomposition*. It takes account of the TLV of SOF_2 and allows for possible (although unlikely) hydrolysis.

For situation d)1) (for example during and immediately after an internal fault), evacuation will be the initial response. For such short-term exposure there is no established limit for the SOF_2 concentration.

In order to assess the potential risks to health in such exceptional cases, the likely SOF_2 concentrations in the switchroom atmosphere are calculated for various fault situations. These concentrations are then compared with a reference value for non-repetitive momentary exposure.

A reference value of 500 ppmv SOF_2 in air has been adopted. This is taken from toxicological research performed on rabbits which were exposed for a period of 1 h. It is assumed that in a fault situation, the exposure time would be significantly shorter than this and that momentary exposure of persons to this level will not present unacceptable risk.

HIGH-VOLTAGE SWITCHGEAR AND CONTROLGEAR – USE AND HANDLING OF SULPHUR HEXAFLUORIDE (SF_6) IN HIGH-VOLTAGE SWITCHGEAR AND CONTROLGEAR

Section 1: General

1.1 Scope

Up to now there has been no international document giving guidance with regard to the safety of personnel working with SF_6. To give such guidance is the aim of this report.

It is impossible to incorporate all the existing instructions relating to SF_6 in this report, which considers mainly safety aspects and gives basic information and guidelines for working with SF_6 used in switchgear and controlgear during normal and abnormal service conditions.

These recommendations should be considered as the minimum necessary to ensure the safety of personnel who work with SF_6.

This report is concerned with switchgear and controlgear filled with industrially pure SF_6 gas.

1.2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this technical report. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this technical report are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 56: 1987, *High-voltage alternating-current circuit-breakers*

IEC 298: 1990, *A.C. metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV*

IEC 376: 1971, *Specification and acceptance of new sulphur hexafluoride*

IEC 480: 1974, *Guide to the checking of sulphur hexafluoride (SF_6) taken from electrical equipment*

IEC 517: 1990, *Gas-insulated metal-enclosed switchgear and controlgear for rated voltages of 72,5 kV and above*

IEC 695-7-1: 1993, *Fire hazard testing – Part 7: Guidance on the minimization of toxic hazard due to fires involving electrotechnical products – Section 1: General*

1.3 General characteristics of SF_6 gas

Clean, unused SF_6 gas has no colour, smell or taste. It is non-combustible and is chemically inert at room temperatures. Although in principle a mixture of 20 % oxygen and 80 % pure SF_6 can be inhaled without adverse effect, it is generally accepted that the maximum concentration permitted in a working environment during an 8 h period of exposure is 1 000 ppm by volume (see A.5). This value is not related to toxicity, but is an established limit for all non-toxic, harmless gases which have not been present in the atmosphere for a long period of time.

The general properties of new SF_6 are described in section 2 of IEC 376 and in annex A of this report. Acceptable methods of working with new SF_6 are given in section 2 of this report.

Guidance for working safely with SF_6 is required for the following reasons:

a) SF_6 gas is about five times heavier than air and will, if released into the atmosphere in a sufficient quantity, tend to accumulate initially in low-lying areas. This could present a danger of asphyxiation due to oxygen deficiency if personnel are working, for example, below ground in ducts or trenches. After a period of time depending on the amount of air movement, the SF_6 becomes diffused into the surrounding atmosphere.

b) SF_6 decomposes at high temperatures (above about 500 °C in the absence of catalytic material). Decomposition may occur if the gas is heated for example by a flame and will occur if there is an electric arc, spark or other electrical discharge within it. Some of the decomposition products may have toxic effects, but under normal service conditions in switchgear and controlgear these are contained within a well-controlled and enclosed environment.

When maintenance is required, or if gas is exhausted into the atmosphere, precautions are needed to ensure the safety of personnel (see sections 4 and 5).

c) SF_6 gas, when released into the atmosphere, has a relatively long life. It is therefore desirable to minimise the quantity released. Annex D provides information concerning the effects of SF_6 gas on the environment.

1.4 Application of SF_6 in switchgear and controlgear

The main features of SF_6 which determine its suitability for use in electrical equipment are:

- its high dielectric strength;
- its excellent arc-quenching capabilities;
- its high chemical stability and non-toxicity.

1.5 Definitions

There are many different types of switchgear and controlgear which use SF_6 gas as a dielectric and/or arc-quenching medium. For the purpose of this Technical Report, the following definitions apply:

1.5.1 *Rated voltage*

medium-voltage: Rated voltages from 1 kV up to and including 52 kV.

high-voltage: Rated voltages above 52 kV.

This distinction is made because there are often significant differences in design, construction and size between the two categories.

1.5.2 *Construction*

enclosed equipment: Equipment using mainly air as the primary insulating medium. The SF_6 is contained in switching enclosures made from metal or cast resin. SF_6-filled medium-voltage circuit-breaker and load-break switch equipment is frequently of this type of construction.

SF_6-insulated cubicles: Medium-voltage Ring Main Units (RMU) are frequently of this type of construction.

gas-insulated or GIS: Equipment using mainly SF_6 as the primary insulating medium. Compartments within a gas-insulated assembly, containing various functional modules (circuit-breakers, switches, busbars), may be physically isolated from each other, such that each can be regarded as a separate gas enclosure.

open terminal apparatus: Item of equipment for direct connection to lines or cables.

1.5.3 **new SF_6:** New or supplier Quality SF_6 is SF_6 which complies with the requirements for purity stated in IEC 376. These requirements and the properties of the gas are detailed in annex A.

New SF_6 is chemically non-reactive at normal temperatures, has no colour, smell or taste and it is non-toxic [2]. It is an asphyxiant, acting by displacement of the air. As such it can constitute a hazard if released in quantity and especially into a confined space.

Any SF_6 not complying with the above definition will be regarded as used SF_6 (see section 4).

1.5.4 **leakage:** Leakage from equipment in service is the unplanned, usually continuous, emission of gas from a sealed or closed system. Leakage occurs at seals and joints and by molecular diffusion through certain enclosure materials. Leakage does not include releases of gas due to intervention with the systems intended to contain it.

1.5.5 **used SF_6:** SF_6 which may have been contaminated by impurities or which has been subjected to operating conditions after energisation of the switchgear and controlgear.

Annex B provides information regarding the decomposition products of SF_6, which occur as gaseous and solid by-products. The quantities of decomposition products are small but some of them may have toxic effects, so certain precautions are required when handling used SF_6.

1.5.6 **handling:** Any process which might involve contact of workers with used SF_6 or SF_6 decomposition products.

This includes removing the gas from an item of switchgear or controlgear either completely or as a sample to be tested, opening a gas-filled enclosure, cleaning out an open enclosure and working inside large enclosures.

1.6 Types of gas enclosure

A gas enclosure as normally used in SF_6 switchgear and controlgear is classified as either:

- closed pressure system, or
- sealed pressure system.

(See annex EE of IEC 56, annex GG of IEC 298 and annex DD of IEC 517.)

For a closed pressure system, replenishment of losses due to leakage may be necessary and periodic maintenance involving removal and replacement of the gas is possible.

For a sealed pressure system, the SF_6 gas is in "sealed-for-life" enclosures, which are never opened during the service life of the equipment.

1.7 Quantities of SF_6 used in switchgear and controlgear

SF_6 gas in switchgear and controlgear is generally at relatively low pressure (0,1 MPa to 0,9 MPa absolute); the quantity used in a gas-filled compartment depends on the rating and design of the equipment. The quantity varies approximately between 0,1 kilogram in one pole of a medium-voltage switching device and several hundreds of kilograms in the largest compartment of a large high-voltage GIS substation.

The world production of SF_6 gas per year is estimated to be between 5 000 and 8 000 tonnes (1990). Of this, between 2 000 and 4 000 tonnes is used in high-voltage switchgear and controlgear.

1.8 Other uses of SF_6 gas

The remainder of the SF_6 produced annually is used in other high-voltage applications, for example in cables, tubular transmission lines, transformers and electrostatic generators and in non-electrical applications such as for leak detection, studies requiring a tracer gas, foundry practices and double glazing.

1.9 Guidance for working with SF_6 gas and its decomposition products

This report deals with working with SF_6 gas and those of its chemical derivatives which are produced in switchgear and controlgear during normal service and under certain abnormal conditions. Two main aspects are covered:

- the effects on humans of exposure to SF_6 and its decomposition products;
- the effects on the environment of SF_6 and its decomposition products.

The risks associated with contact with SF_6 gas and suitable precautions are discussed for each stage in the normal life cycle of an item of equipment and under abnormal conditions.

1.9.1 *Equipment life cycle – sections 2 to 6*

1.9.1.1 *Filling*

Manufacture and commissioning of the equipment. It is filled with new SF_6. Section 2 deals with this stage.

1.9.1.2 *Normal service*

The equipment is installed and in service. It releases a small amount of SF_6 due to leakage, which may contain decomposition products. This is covered in section 3.

1.9.1.3 *Maintenance*

SF_6, possibly containing gaseous decomposition products may have to be removed. Access may be required to enclosures containing solid decomposition products. Section 4 provides guidance for safe working.

1.9.1.4 *Abnormal release*

Abnormal incidents, during which SF_6 gas is released, due to abnormal leakage, internal fault, or external fire are dealt with. Such incidents occur very infrequently. Guidance is given in section 5.

1.9.1.5 *End of life*

The SF_6 has to be removed and the equipment is recycled or disposed of. This is dealt with in section 6.

1.9.2 *Technical information*

General technical information concerning SF_6 gas, its decomposition products, their sources and toxicities and their effects on the environment and humans is given in the annexes.

Section 2: Working with new SF_6 gas

This section provides guidance for working with new SF_6, i.e. when a gas enclosure is filled, either in the factory or after the equipment has been installed on site.

2.1 Purchasing

SF_6 is supplied by manufacturers as a liquid in containers of various sizes at a pressure of approximately 2,2 MPa gauge. All SF_6 purchased should meet the requirements of IEC 376 and consignments should be accompanied by a certificate of compliance.

2.2 Handling and storage of cylinders

Cylinders shall be handled carefully and stored in a cool, dry, well-ventilated area away from flammable or explosive material. They should be protected from direct sunlight, mounted clear of wet ground and secured to prevent falling over, with their outlet valves upwards.

Cylinders should be clearly labelled to identify their contents; cylinders containing new gas should be physically separated from those containing used gas.

As with any pressurised gas, there is a risk of explosion of cylinders if they are excessively heated as might occur in a fire. Storage outdoors with suitable protection from weather and intense solar radiation is recommended.

2.3 Equipment for handling new SF_6

New SF_6 has to be transferred from a cylinder at high pressure into the gas enclosure of the switchgear and controlgear or controlgear to be filled. The filling pressure is invariably much lower than the cylinder pressure. Equipment used for filling should comply with the following requirements:

- pipework should be adequately protected against mechanical damage;
- valves and regulators should be maintained or replaced as necessary;
- pressure gauges should be calibrated regularly;
- delivery pipes and associated valves should be arranged so that they can be evacuated along with the enclosure to be filled in order to avoid a need for purging.

2.4 Working with new SF_6

Workers handling new SF_6 gas should be familiar with the properties of the gas (see annex A) and with the contents of this section.

As is the case with any pressurised gas, a sudden escape of SF_6 gives rise to a local drop in temperature and may result in freezing. When working on high-pressure piping, valves or connectors where there is a risk of a sudden release, suitable gloves should be worn.

2.4.1 *Indoor working*

When handling new SF_6 indoors, some gas may accumulate in the air, so adequate ventilation should be provided. If there is a possibility that SF_6 may be released into the work area then open fire, smoking, heating exceeding 200 °C and welding without special precautions should not be permitted.

2.4.1.1 *Maximum concentration of SF_6 in work areas*

Where new SF_6 gas is handled in an indoor environment such as a factory or substation where equipment is being filled, SF_6 may accumulate over a period of time. Written procedures for periodically measuring the SF_6 concentration should be provided along with equipment for performing such measurements.

The maximum permissible concentration of SF_6 in a workroom is 1 000 ppm by volume (ppmv). If the concentration exceeds this level, the area should be ventilated so as to restore the concentration to below 1 000 ppmv.

Particular attention should be given to low-lying areas such as cable-ducts, cellars, etc., where SF_6 gas could accumulate. If work is to be carried out in such an area, it should be ventilated adequately using forced air movement if necessary.

2.4.1.2 *Safety information for work areas*

In workrooms where SF_6 gas is handled, an appropriate safety notice should be displayed. This should state at least that smoking and open fire are not permitted.

2.4.2 *Outdoor working*

Where new SF_6 has to be handled outdoors, natural ventilation generally prevents accumulation of the gas. Special precautions as detailed in 2.4.1 are therefore only required if work is to be carried out in close proximity to the equipment.

2.5 Filling switchgear and controlgear with new SF_6

The large majority of medium-voltage switchgear and controlgear uses sealed pressure systems, as defined in 1.6. This type of equipment is filled with SF_6 in the factory and no further handling of the gas is required during its life.

High-voltage switchgear and controlgear and medium-voltage equipment of certain types use closed pressure systems as defined in 1.6. Such equipment may require filling or topping up on site.

The procedures used during manufacture and commissioning should be defined to ensure that four fundamental requirements are met:

a) that personnel working on the equipment are not subjected to unacceptable risk;

b) that losses of gas into the atmosphere are kept to a minimum;

c) that enclosures, when filled, do not leak at a rate greater than that specified for the equipment;

d) that enclosures when filled, contain gas of the required quality, as specified by the manufacturer.

2.5.1 *Filling procedures*

The most common method of filling an enclosure is by evacuating the air from the enclosure and the filling pipework to a specified residual pressure using a vacuum pump, before introducing the SF_6. This method will be referred to as the evacuation method.

If a method other than the evacuation method is to be used, it shall be specified by the manufacturer.

The method chosen is likely to affect the purity of gas in the equipment and for this reason the evacuation method is preferred.

Filling other than at the time of manufacture should be carried out in accordance with the manufacturer's instructions.

Manufacturers' instructions for filling should specify at least the following:

a) the filling method;

b) if the evacuation method is used, the maximum allowable residual pressure, expressed in millibars, to be achieved during evacuation, prior to introducing any SF_6. The time during which the enclosure is maintained under vacuum may also be considered important; if so it should be stated;

c) the required filling pressure at a specified temperature (preferably 20 °C) or the required SF_6 density. It should be noted that the temperature of the gas may differ from the temperature of the ambient atmosphere. Account may also need to be taken of cooling of the gas as it passes through a pressure-reducing valve. If filling at other than the specified temperature requires a correction to the filling pressure to maintain the SF_6 density within a given range, this should be stated, and guidance should be given for performing the correction.

When filling an enclosure with SF_6, the filling equipment should include means for monitoring the pressure or density in the enclosure.

A pressure-reducing regulator, preferably including in the lower pressure output line an adjustable over-pressure relief device, should be used when transferring SF_6 gas from a pressurised vessel or cylinder.

When the required filling pressure or density is reached, means should always be available for quickly turning off the flow of gas.

Filling other than with automated delivery equipment should be closely monitored to avoid accidental over-filling.

2.5.2 *Gas tightness of equipment filled with SF_6*

Requirements for establishing that acceptable levels of gas tightness are achieved in switchgear and controlgear installations containing SF_6 are stated in appendix EE of IEC 56, annex GG of IEC 298 and annex DD of IEC 517.

In cases where equipment is to be assembled and filled on site, manufacturers' instructions should state that checking for leaks should be performed following installation. Suitable methods and any special equipment required should be specified.

2.5.3 *Checks on SF_6 gas quality after filling*

The quality of the gas in an enclosure after it has been filled may be influenced by the condition of the enclosure before filling, or by impurities introduced from filling equipment.

Manufacturers' instructions should state whether it is necessary to check the quality of the gas in an enclosure after it has been filled. If this is to be done, the impurities to be checked should be identified and maximum acceptable quantities for each impurity should be given.

Procedures for checking SF_6 gas removed from enclosures are given in IEC 480.

2.6 Release of SF_6 gas to the atmosphere during filling

SF_6 gas does not contribute to stratospheric ozone depletion nor significantly to the greenhouse effect [3] (see annex D). However, because SF_6 is manufactured rather than naturally occurring and because of its long lifetime, precautions should be taken to minimise the quantity of SF_6 gas which is released to the atmosphere.

2.6.1 *Release of SF_6 gas to the atmosphere during filling of medium-voltage equipment*

Factory installations for filling enclosures with SF_6 gas should be designed and operated so that the quantity of SF_6 released to the atmosphere is negligible.

For medium-voltage equipment which is to be filled after erection on site, care should be taken to minimise the amount of SF_6 released. If such equipment has to be emptied during installation or commissioning, means for storing the gas should be provided. Due to the low operating pressures, small volumes and relatively small numbers of these types of equipment, the quantity of SF_6 released during filling and commissioning is negligible.

2.6.2 *Release of SF_6 gas to the atmosphere during filling of high-voltage equipment*

The manufacture and commissioning of high-voltage equipment involves the handling of relatively large quantities of SF_6 gas, particularly in the case of GIS equipment. Gas handling installations should be designed to minimise the quantity of SF_6 gas which is released to the atmosphere.

When new SF_6 has to be removed from an enclosure for any reason, equipment should be available to allow it to be stored.

Section 3: Leakage of SF_6 from equipment in service

This section examines the effects of leakage of SF_6 from equipment in service and together with the conclusions of annex C, shows that operators are subjected to negligible risk, even at leak rates much higher than the maximum rates normally specified by manufacturers. This conclusion is supported by the findings of CIGRE working group 23.03 [1].

3.1 Types of gas-filled enclosure

Three types of gas-filled enclosure are defined in annex EE of IEC 56, annex GG of IEC 298 and annex DD of IEC 517. These are:

a) controlled pressure system: an assembly which is automatically refilled from an internal or external gas source;

b) closed pressure system: an assembly which is refilled only periodically by manual connection to an external gas source;

c) sealed pressure system: an assembly for which no further gas processing is required during its expected operating life. Sealed pressure systems are completely assembled, filled and tested in the factory.

Medium-voltage switchgear and controlgear of the metal-enclosed or insulation-enclosed type most commonly contain switching enclosures of category c), sealed pressure systems.

Medium-voltage switchgear and controlgear of the gas-insulated type normally uses a closed pressure system category b) but may use a sealed pressure system category c) if it is factory-assembled.

The majority of high-voltage switchgear and controlgear uses closed pressure systems, category b). Sealed pressure systems, category c), are used in some equipment types.

Category a) is not relevant to equipment manufactured currently but certain items of category a) equipment are in service. The number of category a) units is very small however and for this reason this type of equipment is not covered by this report. The principles for calculating exposure levels outlined in annex C could be adopted if necessary to assess the risks of exposure where controlled pressure systems are in use.

3.2 The implications of leakage

Switchgear and controlgear containing SF_6 gas is designed, manufactured and tested to ensure that losses of the gas are kept to a minimum.

Preferred maximum permissible relative leakage rates of 1 % and 3 % of the total initial mass of SF_6 gas per annum are specified in IEC 56, IEC 298 and IEC 517, for closed pressure systems. The lower leakage rate limit of 1 % per annum is readily accepted by manufacturers and is easily achieved using standard materials and sealing techniques.

The gastightness of sealed pressure systems is specified in terms of the expected operating life; preferred values are 10, 20 and 30 years. For equipment using sealed pressure systems, manufacturers report that they are able to achieve relative leak rates of less than 0,1 % per annum. The filling pressure of medium-voltage sealed for life equipment is often just above atmospheric pressure and this reduces the tendency to leak. The combined use, during cumulative leakage measurement, of electron capture detectors and gas collectors, the latter made possible by the small size of the gas enclosures of medium-voltage equipment, allows absolute leakage rates, at room temperature, as low as 10^{-7} atmospheric cm^3/second (equivalent to $3,15 \cdot 10^{-3}$ litres per year) of SF_6 to be measured.

Quantities of SF_6 gas lost due to leakage vary according to the type of equipment and are greater for higher voltage equipment because these usually contain greater amounts of gas at higher pressures and because sealing surfaces are much larger. The leakage of SF_6 gas from switchgear and controlgear shall be minimised for the following three reasons:

a) functional impairment

The switching capacity and/or insulation level of the equipment may be reduced if the SF_6 density falls as a consequence of abnormal leakage (see clause 3.3).

b) safety of personnel

Depending on the nature of the installation, the atmosphere local to the equipment may contain SF_6 and its by-products as a consequence of leakage. The risk to health in such a case shall be considered. This is covered in clause 3.4.

c) environmental effects

The effect on the atmosphere of SF_6 used in electrical equipment, shall be considered. This includes SF_6 gas which is released to the atmosphere during filling and maintenance as well as the effects of leakage during service. The quantity of SF_6 gas lost to the atmosphere due to leakage is discussed in clause 3.5.

3.3 Abnormal leakage

Abnormal leakage is covered in clause 5.2.

3.4 Safety of personnel

Leakage from equipment in service is of gas which may contain impurities. The degree of contamination of the gas varies according to the type of equipment and its service history and will be the greatest for circuit-breakers which have interrupted short-circuit current [4].

Annex C deals in detail with the risks of exposure to SF_6 by-products emitted by leakage. It is shown that the quantity of SF_6 leaked per day at normal leak rates is very small and the concentration of impurities it contains is low. The effects of natural dilution into the surrounding atmosphere are considered as this further reduces the concentration of impurities by a large factor. The effects of adsorbents are neglected in the analyses, but when these are installed, as is normal in circuit-breakers, the purity of the gas leaked is greatly improved. It is shown that contamination of the local atmosphere as a result of leakage is insignificant.

Operation of high-voltage switchgear and controlgear containing SF_6 is similar to that of any other type of SF_6 equipment in this voltage range. Therefore personnel in charge of SF_6 equipment do not need special training to carry out their duty, because handling of SF_6 is not implied.

NOTE – For cold climate applications, the quantity of adsorbent should be reduced in order to limit excessive SF_6 adsorption. The action on decomposition products is correspondingly reduced.

3.4.1 *Outdoor installations*

In outdoor installations, leaked gas will disperse rapidly and provides no risk. It is unlikely, due to the effects of diffusion (Dalton mixing law) into the surrounding atmosphere, that leaked SF_6 would accumulate in low-lying areas.

3.4.2 *Indoor installations*

The effects of leakage from typical indoor medium- and high-voltage equipment are examined in annex C. The results (see C.4.5 and C.4.6) clearly show that, for leak rates as high as several thousand times the normal permitted rates, the risks are negligible.

Buildings containing indoor SF_6-filled equipment should be provided with ventilation designed to deal with SF_6 released during installation and maintenance (see section 4). The results presented in annex C show that natural ventilation would normally be adequate to prevent the accumulation of SF_6 released due to leakage.

SF_6 may accumulate in cable ducts, cellars or other low-lying areas; these should be ventilated if they are to be entered.

3.5 Environmental implications of leakage

SF_6 gas does not contribute to stratospheric ozone depletion or significantly to the greenhouse effect [3] (see annex D). It is however desirable to minimise the release of any gas, which is not present normally in the atmosphere, so it is relevant to consider the quantity of SF_6 released to the atmosphere as a result of leakage.

3.5.1 *Estimation of leakage from medium-voltage equipment*

Medium-voltage equipment contains only small quantities of gas, at relatively low pressures. The quantity of SF_6 leaked from individual units is therefore small, although since the numbers in service are large, the total amount released has to be considered.

There are currently in service throughout the world about 500 000 medium-voltage SF_6 circuit-breakers and around 1,5 million load-break switch units. The total installed mass of SF_6 for medium-voltage equipment is believed to be between 1 000 and 1 500 tonnes. Even at a leak rate of 1 % per annum all medium-voltage units currently in service throughout the world could only contribute between 10 and 15 tonnes of SF_6 to the atmosphere annually. The actual quantity of SF_6 released will be very much less than this as actual average leak-rates are much lower than 1 % per annum.

3.5.2 *Estimation of leakage from high-voltage equipment*

The quantity of gas released to the atmosphere due to leakage from high-voltage equipment may be estimated as for medium-voltage equipment. There are in service some 40 000 open-terminal high-voltage SF_6 circuit-breakers and about 20 000 GIS units. The total installed mass of SF_6 is believed to be between 10 000 and 20 000 tonnes. The total quantity of SF_6 released world-wide due to leakage from high-voltage equipment would be in the range of 100 to 200 tonnes if all units were leaking at 1 % per annum. The true average leak rate is believed to be considerably lower than this.

Section 4: Handling of used SF_6

This section deals with operations involving SF_6 which has been inside a switchgear or controlgear enclosure and which may have become partially decomposed or contaminated. Such operations include removing and replacing the SF_6 during maintenance or extension.

4.1 Circumstances where handling of used SF_6 is necessary

The need to handle used SF_6 arises where:

a) topping up of the SF_6 in closed pressure systems is carried out;

b) the gas has to be removed from an enclosure to allow maintenance, repair or extension to be carried out;

c) the gas has been wholly or partially expelled due to an abnormal release;

d) the gas has to be removed at the end of the life of an item of equipment;

e) Samples of the gas must be obtained or the gas pressure measured through temporary connection of measuring apparatus.

The safety provisions in this section are applicable to all four situations; situations c) and d) are further considered in sections 5 and 6 respectively.

Situations a) and b) arise mainly with respect to high-voltage equipment and may arise with medium-voltage GIS equipment in particular if it is required to add further equipment to an existing switchboard. They do not arise with equipment using sealed pressure systems.

4.2 Equipment required when handling used SF_6

4.2.1 *Gas handling equipment*

Where used SF_6 has to be removed from an enclosure, precautions should be taken to prevent avoidable release of the gas into the atmosphere and in particular into the work area.

Gas recovery equipment should be used where possible to allow the gas to be stored, usually under pressure. Such equipment should be capable of evacuating the enclosure to remove as much of the gas as possible.

Gas recovery equipment is available which is specially designed for use with SF_6 and is provided with re-processing facilities for removing gaseous and solid decomposition products. This type of equipment is preferred, particularly for the removal of more heavily contaminated SF_6, for example from circuit-breaker enclosures.

4.2.2 *Personal safety equipment*

Workers engaged in handling used SF_6 should be provided with personal safety equipment. Suitable equipment is listed in annex E (see clause E.2 and E.3.1). Manufacturers' instructions and users' codes of practice should specify which items of equipment are required for each type of activity listed in clause 4.1.

No specific safety equipment is normally required for operations involving only the topping up of an enclosure with SF_6 gas apart from gloves, safety glasses and detection equipment, which may be considered desirable for checking the condition of the working atmosphere (see 4.3.4.1).

4.3 Working with used SF_6

Workers handling used SF_6 should be familiar with the properties of SF_6 decomposition products and should be aware of the risks to health and the precautions necessary to minimise them. General safety recommendations are given in annex E (see clause E.1).

4.3.1 *Training of workers*

Specific safety training should be given to workers required to handle used SF_6. It is not considered necessary that such workers have any pre-qualifying training or qualifications.

Workers should be trained in the use of SF_6-handling equipment used to transfer gas from an enclosure into a storage vessel; the manufacturer's operating instructions for such equipment should be complied with whenever it is used.

The first-aid instructions according to E.3.2 should be included in the safety training.

4.3.2 *Facilities and services*

Where enclosures containing used SF_6 have to be emptied and opened, it is desirable that adequate washing facilities for workers be available, and a supply of water for preparing cleaning solutions may be required.

4.3.3 *Outdoor working*

When working outdoors, while removing used SF_6 from an enclosure, no special precautions are necessary other than those to prevent personnel from being directly exposed to the used SF_6 or its decomposition products. When opening or entering enclosures outdoors, certain precautions should be taken.

- Wind could cause solid SF_6 decomposition products to be blown around before they can be removed with a vacuum cleaner. If it is windy, steps should be taken to prevent this.
- Rain or high ambient humidity will accelerate hydrolysis of certain decomposition products, resulting in the production of hydrofluoric acid HF. For this reason, any residual gas and solid decomposition products should be removed quickly after an enclosure is opened. Temporary shelter may be required to prevent the ingress of rain while this is being carried out.

4.3.4 *Indoor working*

Indoor installations should be provided with adequate ventilation, sufficient to ensure that the requirements of 4.3.4.1 can be met.

4.3.4.1 *Maximum concentration of used SF_6 in work areas*

When used SF_6 has to be removed from an enclosure in an indoor installation, it is necessary to ensure that the concentrations of potentially toxic decomposition products remain at safe levels in the working area.

This is ideally achieved by direct measurement of the concentrations of the main contributor to toxicity, thyonyl fluoride SOF_2 and of the by-products of SOF_2 hydrolysis, sulphur dioxide SO_2 and hydrogen fluoride HF (see C.3.2.1).

NOTE – Methods for making and interpreting such measurements are under consideration.

A practical alternative method is to measure the concentration of (used) SF_6 in the air. This measurement should be made whenever there is a possibility that used SF_6 has been released into the atmosphere.

The SF_6 concentration shall not exceed 200 ppmv.

Ventilation should be provided, preferably using forced air movement to prevent the accumulation of used SF_6.

The maximum SF_6 concentration of 200 ppmv is explained in F.4.1 and is applicable to SF_6 which has undergone low to medium decomposition as defined in 4.3.5.1, items a) and b). If there is reason to believe that the level of decomposition may be higher than should normally be expected, for example if abnormal arcing is known or believed to have occurred within an enclosure (see 4.3.5.1, item c)), then the precautions presented in 5.3.3 should be taken.

When enclosures are first opened, depending on the degree of evacuation applied during gas removal, residual used SF_6 may enter the atmosphere. At this time, any workers present should use respirators as described in annex E (see clause E.2, item h)), at least until it is confirmed that the above criterion for SF_6 concentration is satisfied.

4.3.4.2 *Safety information for work areas*

A notice stating that open fire, smoking, heating to more than 200 °C and welding without special precautions are prohibited and giving first-aid instructions (see clause E.3) should be displayed while used SF_6 is being handled in an indoor location.

4.3.5 *Condition of the SF_6 in an enclosure*

4.3.5.1 *Expected condition of the SF_6*

The condition of the used SF_6 in an enclosure will depend on the types and energies of any electrical discharges or arcs which have occurred within it. Four commonly encountered situations are:

a) SF_6 is in an enclosure which does not contain active parts of a circuit-breaker and which is not linked to a circuit-breaker enclosure so that an exchange of gas could occur.

Gas: zero to low decomposition.

Solids: little or no powder deposits.

b) SF_6 is in an enclosure containing active parts of a circuit-breaker, or linked to such a compartment.

Gas: medium decomposition.

Solids: quantity of deposits will depend upon the current interruption history.

c) SF_6 is in any enclosure in which abnormal arcing has occurred but where the enclosure has not opened to the atmosphere due to pressure relief or burn-through. In this case an internal fault has occurred but a circuit-breaker has cleared the fault before the pressure in the enclosure has risen sufficiently to cause a release of SF_6.

Gas: unknown but high decomposition should be expected.

Solids: large quantity of deposits expected. Their compositions depend on which materials have been heated by the arc.

d) As c) but where some or all of the SF_6 gas has already been exhausted to the atmosphere due to pressure relief or burn-through.

Gas: a mixture of partially decomposed SF_6 and the ambient air. Hydrolysis of fluoride decomposition products may have occurred, leading to a higher degree of acidity than would occur in the other cases.

Solids: Large quantity of solids, much of which may have been expelled.

Precautions required in case d) are given in clause 5.3.

4.3.5.2 *Sampling and testing SF_6 from an enclosure*

If it is intended that the SF_6 is to be re-used without processing, tests for the following should be performed:

- moisture content;
- oxygen content;
- acidity;
- hydrolysable fluoride content.

Methods for the above tests are detailed in IEC 480.

Manufacturers' instructions should give permitted concentration limits for each of the above impurities which, if not exceeded, would allow the gas to be used again after storage. The gas should not however be regarded as new SF_6; rather as SF_6 which may be re-used without further treatment. The following handling precautions for used SF_6 should be applied.

If the recommended limits for the above values are exceeded, the SF_6 may be re-conditioned using appropriate equipment, or returned to a supplier for re-conditioning.

4.3.6 *Removing used SF_6 from an enclosure*

Before SF_6 is removed from a switchgear and controlgear enclosure, sampling and testing (see 4.3.5.2) may be carried out so that the level of decomposition is known prior to further handling of the gas.

Gas recovery equipment, as described in 4.2.1, should be provided wherever possible to allow SF_6 to be removed whilst minimising leakage to the atmosphere. Such equipment would normally comprise at least a compressor, suitable means for controlling the flow of the gas and a storage vessel or vessels. It will preferably contain means for re-processing contaminated SF_6.

Gas which has not been re-processed within the recovery equipment may be returned to the supplier for re-processing to its new condition.

Recovered gas should be tested for impurities using the methods given in IEC 480, before it is re-used.

Manufacturers' instructions should recommend suitable handling equipment and provide procedures for its use, covering at least the following:

- the flow rate of SF_6 being removed may need to be controlled to prevent an excessive amount of powder from entering recovery equipment;
- the highest final pressure to which an enclosure should be evacuated should be stated. A few hundred millibars should be achievable, where only a compressor is used to create a partial vacuum upstream. It may be desirable to avoid the use of a vacuum pump in certain circumstances because of the sensitivity of vacuum pumps to powders; a powder filter could reduce the flow rate to an unacceptably low level;
- any further action required should be described. For example purging with dry air or nitrogen and then allowing time for any powders to settle may be necessary prior to opening the enclosure.

4.3.7 *Opening and entering an enclosure*

The following applies to cases a), b) and c) of 4.3.5. Manufacturers' instructions for maintenance, extension or repair should recommend suitable precautions to ensure:

- that as little as possible SF_6 gas remains in an enclosure following emptying;
- that personnel are adequately protected from the effects of any remaining SF_6 and associated impurities;
- that the importance of excluding moisture is understood, to minimise acid formation through hydrolysis;
- that solid SF_6 by-products are adequately removed. Means for this should be recommended, for example a vacuum-cleaner, reserved for "SF_6 use only" and clearly marked accordingly, fitted with a suitable dust filter (see clause E.2, item j));
- that personnel are aware of the irritant nature of solid by-products and are equipped with suitable protective clothing, respirators and eye protection (see clause E.2);
- that items such as tools, clothes and components removed are in a suitable condition for further handling. Cleaning with a neutralising solution is generally required; details of makeup and preferably means for assessing whether a used solution can be used again, should be given (see 6.5.6 and 6.5.7);
- that instructions are given for the handling and disposal of filter bags or canisters containing contaminated adsorbent material (see 6.5.5).

4.4 Release of used SF_6 to the atmosphere

Personnel, working on or around an installation where used SF_6 is handled, should not be exposed to the gas and for this reason, care should be taken to prevent the release of used SF_6 to the atmosphere.

Section 5: Abnormal release of SF_6

This section describes abnormal conditions under which SF_6 might be released from equipment in service and provides guidance on precautions to take if an abnormal release occurs.

5.1 Circumstances leading to abnormal release of SF_6

Although very unlikely, abnormal releases of SF_6 can occur for several reasons. Among these are:

a) Abnormal leakage. This could be due either to mechanical failure of components or seals or to mechanical failure induced by abnormal shock.

b) Internal fault leading to pressure relief or burn-through of the enclosure. The internal pressure rise produced by uncontrolled arcing may cause the operation of an over-pressure relief device or the opening of a well-defined part of an enclosure, or an arc to the enclosure wall may cause it to melt; if a hole forms, the SF_6 gas escapes.

c) External fire. Heat applied to an enclosure may cause it to fail to contain pressurised SF_6. Seals may be damaged or relief devices may operate. This is very unlikely, requiring a local fire of high intensity.

5.2 Abnormal leakage

The following applies to case a) of clause 5.1 and covers any release of SF_6 not due to internal fault or fire. The rate of an abnormal leak has to exceed normal leak rates by a large factor before decomposition product concentrations in the air become significant (see 3.4.2).

Attention to the presence of an abnormal leakage may be alerted in one of several ways:

- in an installation where an SF_6 alarm is fitted a release of SF_6 gas may cause this to operate;
- a low SF_6 pressure indication may be given by an under-pressure detector or gauge fitted to an item of equipment;
- The characteristic odour of SF_6 decomposition products may be noticed (see clauses B.5 and F.1).

Before work is permitted it is necessary to ensure that the concentrations of SF_6 decomposition products in the air are at safe levels. This is ideally achieved by direct measurement of the concentrations of the main contributor to toxicity, thyonyl fluoride SOF_2 and of the by-products of SOF_2 hydrolysis, sulphur dioxide SO_2 and hydrogen fluoride HF (see C.3.2.1).

NOTE – Methods for making and interpreting such measurements are under consideration.

A practical alternative method is to measure the concentration of (used) SF_6 in the air.

The SF_6 concentration shall not exceed 200 ppmv (see F.4.1).

If the SF_6 concentration exceeds 200 ppmv, ventilation should be provided, preferably using forced air movement to disperse accumulated gas. If the SF_6 concentration remains above 200 ppmv, or if means to measure the SF_6 concentration are not available, then a respirator according to clause E.2, item h) should be used.

5.3 Abnormal release due to internal fault

The following applies to case b) of clause 5.1. Manufacturers' instructions cannot be expected to deal with unforeseen failure situations so it is necessary to present guidelines, of which personnel responsible for SF_6 equipment should be aware.

Definitions and other information relevant to internal faults are given in annex AA of IEC 298 and in annex BB of IEC 517.

An internal fault occurs when abnormal arcing is initiated inside a switchgear and controlgear enclosure. In certain types of equipment, particularly metal-enclosed medium-voltage switchboards, air insulation is used for the busbars between cubicles and around cable connections and SF_6 is present only within switching chambers. In this case an internal fault could occur within the switchboard but outside the switching chamber, so that no SF_6 is released.

An internal fault is a very rare occurrence but cannot be completely disregarded. It can occur as a result of:

- a defect in the insulation system;
- a mechanical defect leading to a disturbance of the electric field distribution inside the equipment;
- the mal-operation of part of a switching device due to faulty assembly, components or malfunction or misuse of interlocks.

An internal fault will cause an increase of pressure inside the enclosure, the effects of which will depend upon circumstances.

The pressure rise is caused by the transfer of the electrical energy from the arc into the gas. The increase in pressure will depend upon the value of the arc current, the arc voltage, the arc duration and the volume of the enclosure in which the arc has developed. Following an internal fault leading to pressure relief or enclosure burn-through, the SF_6 and much of any solid decomposition products (powders) will have been expelled from the SF_6 enclosure.

Any person present at the time of an internal fault should evacuate the area immediately, irrespective of whether SF_6 is known or believed to have been released (see clauses C.5 and C.6).

5.3.1 *Composition of SF_6 and by-products released*

Several case studies are presented in annex C which show that the concentrations of decomposition products, present in SF_6 expelled during an internal fault, can vary widely according to circumstances. Even in the most severe cases, however, it is unlikely that immediate exposure to the SF_6 decomposition products would present a significant health risk, as long as the exposure time is limited. There are, however, other sources of toxic fumes (organic materials, metal vapours) which could pose a greater threat than that from SF_6 by-products.

5.3.2 *Outdoor installations*

In the case of outdoor installations, the contaminated gas will disperse quickly and the concentration of SF_6 in the air will rapidly become negligible.

The solid decomposition products may remain on and around the equipment and it is important that personnel should wear adequate protective clothing while the affected areas are cleaned. Cleaning should be carried out using a vacuum cleaner where appropriate or by spraying with abundant fresh water or, preferably, with a weak alkaline solution (see 6.5.3). Protective footwear should continue to be worn unless the ground has been proven to be non-acidic.

5.3.3 *Indoor installations*

Following an internal fault leading to pressure relief or enclosure burn-through in an indoor installation it is necessary to ventilate the area thoroughly before entering or to use respirators as defined in clause E.2, item h) until adequate ventilation can be provided. Before any work is carried out, time should be allowed for dust to settle and this should be removed using a vacuum cleaner. It is important that personnel should wear adequate protective clothing while the affected areas are cleaned.

It is necessary to ensure that the concentration of the decomposition product thionyl fluoride SOF_2 (the principal contributor to toxicity, see clause C.3), remains at a safe level for prolonged exposure. This is preferably achieved by direct measurement of the concentration of SOF_2 in the air; this should remain below the TLV of SOF_2, i.e. 1,6 ppmv (see C.8.1).

If means to measure the SOF_2 concentration are not available, a measurement of the SF_6 concentration can be made, following the guidelines given in F.4.2.

The SF_6 concentration shall not exceed 20 ppmv.

The above criteria should be satisfied before personnel enter without respirators. Attention should be paid to areas below the point at which the release occurred; if such areas are occupied they should be evacuated and ventilated thoroughly.

5.4 Abnormal release due to external fire

The following applies to case c) of clause 5.1. To analyse in detail what happens during a fire, it is necessary to consider the temperature/duration characteristics and the exact configuration of the installation.

However, the results obtained with actual fires show that maximum flame temperatures rarely exceed 800 °C and that the temperature of metallic parts is generally lower than 600 °C.

SF_6 gas in electrical switchgear and controlgear is only used in closed or sealed enclosures; if a fire reaches the SF_6 enclosure the gas inside is heated relatively slowly, at a rate which depends on the external temperature.

The heated gas creates a pressure inside the vessel. Before reaching a pressure which would lead to enclosure rupture, the pressure relief devices which are normally fitted to SF_6 enclosures will operate. Where cast resin enclosures or bushings are used (medium-voltage equipment), the enclosure material may soften before the internal pressure becomes high enough to operate a relief device. In both cases, SF_6 could be released into the area surrounding the enclosure.

5.4.1 *Decomposition of released SF_6*

As SF_6 is non-flammable it cannot feed the fire and could indeed have an extinguishing effect. Moreover, the temperature of the SF_6 required to raise the internal pressure to a level at which a pressure relief device would operate would invariably be less than 500 °C. SF_6 gas, being stable below this temperature [5], would not undergo significant decomposition prior to its release.

After release, SF_6 would be rapidly dissipated by convection and should therefore not be exposed to direct heat for long enough for further significant decomposition to occur.

5.4.2 *Outdoor installations*

In the case of outdoor substations, the distance between the installation and the nearest area used by the public should be sufficient to ensure that any used SF_6 reaching such areas is at a very low concentration.

5.4.3 *Indoor installations*

5.4.3.1 *Medium-voltage equipment*

Medium-voltage SF_6 switchgear and controlgear uses low SF_6 pressures in small volumes (< a few hundred litres). During a fire where the local temperature exceeds 150 °C, cast resin gas enclosures would begin to soften and SF_6 may escape before pressure relief devices can operate. In this case, SF_6 could be released at fire temperatures below the decomposition temperature.

Access to electrical substations is normally restricted to specialist staff and in the event of a fire, a building with access to the public or employees will invariably be evacuated. Substations are normally built so as to minimise the risk of fire propagation and the means employed will also serve to contain any SF_6 gas released. Fire-fighting in larger electrical substations is often by automatic systems.

The risk of public exposure to SF_6 by-products is expected to be extremely low as a result of the low decomposition rate of SF_6 at fire temperatures and normal substation design factors.

Electrotechnical products are usually a very minor source of fire effluent compared for example with furnishings (see IEC 695-7-1).

5.4.3.2 *High-voltage equipment*

Access to the site or building is restricted to specialist staff. No problems associated with SF_6 decomposition have been reported in cases of fire [1].

In indoor installations, specific design features to minimise fire risk are incorporated; automatic fire detection and extinguishing systems are normally present. The risk of release of SF_6 is thus very small.

5.4.4 *Precautions during and following a fire*

For persons fighting a fire, precautions normally adopted for protection against vapours from burning plastics will be adequate if equipment has to be approached.

Following a fire in an indoor installation, precautions as outlined in 5.3.3 should be exercised.

NOTE – All the materials subjected to heat and the fumes and vapours emitted by them have to be considered when assessing the risks to personnel in a fire. The toxicity of decomposed SF_6 is likely to be very much lower than that of fumes from materials used for wiring, insulation and paint. Carbon monoxide is by far the most significant agent contributing to hazard. Other agents of major significance are hydrogen cyanide, carbon dioxide, heat, hypoxia, and irritants (see IEC 695-7-1 and C.4.7.2 and C.4.7.3).

Section 6: End of life of SF_6-filled equipment

This section provides guidelines for the disposal and/or re-cycling of SF_6-filled switchgear and controlgear which has been removed from service and of parts and materials removed from such equipment.

6.1 General

Environmental protection and materials conservation considerations are applicable to products of all kinds (for example: motor vehicles, packaging, domestic electrical equipment). The re-cycling of recoverable materials where possible is desirable from both the economic and environmental viewpoints. Larger items of equipment, such as medium- and high-voltage switchgear and controlgear units, containing a significant material value (for example, copper and other metals), are attractive candidates for re-cycling. The use of SF_6 does not detract from this position; the SF_6 itself can also be re-cycled.

The SF_6 should be removed from an item of equipment prior to the disposal or recovery of materials. Gas enclosures may contain solid decomposition products which should be neutralised. Procedures for neutralisation and cleaning are simple to apply and require only readily available materials; they are described in clause 6.5. The residues from these processes are safe to handle and can be disposed of according to local regulations (see 6.5.4).

SF_6-filled switchgear and controlgear was first introduced in the 1960s at high-voltage and during the following decade at medium-voltage. The prospective service life for switchgear and controlgear is around 30 years, so at the present time, only a few of the total number of switchgear and controlgear units installed have fulfilled their life expectancy. Hence no industrial scale recovery process has yet begun.

6.2 Material content of switchgear and controlgear

A typical item of equipment is made up of the following approximate relative quantities of material by weight:

Metals, ferrous and non-ferrous:	75 % to 90 %
Dielectric materials:	10 % to 25 %

Where SF_6 is present, it constitutes only a very small part of the total weight and its presence adds little to the effort required to prepare the equipment for recovery or disposal.

Most of the weight of the dielectric material is provided by solid insulation (cast resin, plastics, ceramics).

The major part of the reclaimable value is in the metals.

6.3 Quantity of SF_6 decomposition products

The quantity of SF_6 decomposition products within an item of equipment depends on the cumulative arc energy which has been supplied to it. This depends on the function and service history of the equipment in question. A load-break switch is likely to contain much smaller quantities of decomposition products than a high breaking-capacity circuit-breaker with a history of frequent fault clearances.

In the large majority of cases, the degree of decomposition, even in circuit-breakers, is low. SF_6 circuit-breakers checked after 10 years of operation in a typical medium-voltage distribution system were found to contain [6]:

Air:	a few ppmv;
CF_4:	40 ppmv to 600 ppmv;
SOF_2:	negligible;
SO_2F_2:	negligible.

The reasons given for these findings are:

- on average, very few high-current interruptions are performed in normal service;
- adsorbents are fitted in circuit-breaker gas enclosures.

Expected degrees of decomposition for various types of equipment are given in table 1.

Table 1 – Expected degrees of SF_6 decomposition

Application	Expected degree of SF_6 decomposition
GIS busbars Cable box GIS earth switch GIS disconnector Medium-voltage load-break switch and ring-main unit	Low: from zero to a few tenths of a percent No visible powder deposit
Medium-voltage and high-voltage circuit-breaker	Medium: up to a few percent Light powder deposits
Any enclosure in which abnormal arcing has occurred	High: could exceed 5 % Medium to heavy powder deposits

6.4 Options for treatment of equipment at end of life

There are three possibilities for users of SF_6-filled equipment:

6.4.1 *Option 1: Complete treatment by a sub-contractor*

The re-cycling/disposal can be sub-contracted to the equipment manufacturer or to a specialist company. This approach may be particularly attractive for equipment which is small enough to be transported in its complete form. If equipment containing used SF_6 has to be transported, local regulations should be adhered to (this may require that information be given concerning the composition of the contents).

If this option is adopted, the user has no special action to take for SF_6-filled equipment, other than specifying the expected degree of decomposition, so that appropriate treatment can be applied (see clause 6.3).

6.4.2 *Option 2: Removal of the SF_6 by the user; treatment by a sub-contractor*

The user may wish to remove the SF_6, for example in the case of larger equipment or where the internal SF_6 pressure is considered to be too high to allow the equipment to be transported (see 6.5.1).

The remainder of the equipment can then be submitted to a specialist company for re-cycling or disposal.

The only further action necessary is to specify the expected degree of decomposition, so that appropriate treatment can be applied (see clause 6.3).

6.4.3 *Option 3: Complete treatment by the user*

The guidance given in clause 6.5 should be followed by the user or by any party undertaking the treatment of used SF_6-filled equipment.

6.5 Treatment at end of life of SF_6-filled equipment

Treatment applied at the end of life of SF_6-filled equipment should be such as to ensure that gas enclosures and internal parts can be handled, re-cycled, or disposed of as normal waste.

6.5.1 *Removal and treatment of the SF_6*

The SF_6 gas should be removed following the procedure given in 4.3.6; it may then be re-processed within recovery equipment for re-use or submitted to a manufacturer of SF_6 for re-processing to the new condition.

If used SF_6 has to be transported, local regulations should be adhered to (this may require that information be given concerning the composition of the gas).

6.5.2 *Treatment of the gas enclosure*

According to the expected degree of decomposition, as indicated by the type of equipment (see clause 6.3), treatment of gas enclosures should be applied as follows. During such treatment, care should be taken to avoid contact of powders and cleaning fluids with skin or eyes. For this reason, compressed gas should not be used for removing powders. Appropriate clothing and equipment should be used (see annex E).

a) *Low decomposition*

No special action is required; non-recoverable parts can be disposed of normally, according to local regulations.

b) *Medium decomposition*

The enclosure should, where practicable, be filled with a neutralising solution which should be allowed to remain inside for a time period T_1 (see 6.5.3). The enclosure should then be rinsed with clean water.

Alternatively, all interior surfaces should be washed thoroughly with a neutralising solution and then rinsed with clean water.

Guidance for the disposal of used neutralising solutions is given in 6.5.4.

c) *High decomposition*

Enclosures should be filled, if it is possible, with a neutralising solution, allowing the solution to remain in the enclosure for a time period T_2 (see 6.5.3). The neutralising solution should then be removed and the enclosure rinsed with water.

Alternatively, for example for larger enclosures, loose powder deposits should be removed using a vacuum cleaner reserved for this purpose.

Adsorbent materials and vacuum cleaner bags should be removed and stored in sealed containers prior to neutralisation or disposal according to local regulations.

The internal surfaces should be washed thoroughly with a neutralising solution and then rinsed with water (see 6.5.3).

Guidance for the disposal of used neutralising solutions is given in 6.5.4.

Guidance for the neutralisation and disposal of powder deposits and adsorbents is given in 6.5.5.

6.5.3 *Solution for neutralisation of solid SF_6 decomposition products*

Three formulations for neutralisation are described in the literature [1, 7, 8, 9, 10], each one having slightly different properties. They are all solutions of an active agent in water, made up according to the concentrations given in table 2, in kilograms of active agent per 100 l of water.

In choosing a neutralising solution the following criteria should be considered:

- the solution chosen should not be unduly corrosive or irritating. If it is necessary to apply it by hand, gloves should be worn;
- it should be sufficiently alkaline during the neutralisation process to ensure that acidic residues are effectively neutralised;
- it should not be too alkaline at the end of the process so that it can be disposed of in accordance with local regulations.

Table 2 – Solutions for neutralization of the SF_6 decomposition products

Active agent	Formula	Concentration kg/100 l	T_1 h	T_2 h	Reference
Lime	$Ca(OH)_2$	Saturated	–	24	[8]
Sodium carbonate (washing soda)	Na_2CO_3	1,1 3 10 1) 10-14 1) 3	– Wash – 1 –	24 – 0,25 48 –	[7] [8] [9] [1] [10]
Sodium bicarbonate	$NaHCO_3$	1 2)	–	–	[9]

NOTES

1 When using alkaline solutions at such high concentrations, care should be taken to avoid contact with the skin, eyes, etc.

2 Recommended for washing the skin.

The above table reflects the current state of the art. The various treatment methods suggested in the literature differ widely with respect to neutralising fluid formulation and treatment time. Optimisation of the neutralising process may lead to greater uniformity of approach.

6.5.4 *Disposal of cleaning and neutralising fluids*

Used neutralising solution or rinsing water should be disposed of according to local regulations, for example, by pouring into a storm or sanitary sewage drain.

6.5.5 *Treatment and disposal of powder deposits and adsorbents*

Prior to treatment these should be stored in a secure fashion in clearly marked containers.

Powder deposits and adsorbent materials should not be subjected to high temperatures or disposed of by incineration as toxic and/or corrosive vapours are likely to be released.

They should be neutralised by immersion, for a time period of at least T_2, in a solution prepared according to 6.5.3. This should be carried out in a well-ventilated area reserved for this purpose, and suitable precautions should be taken to avoid the release of powders into the atmosphere. Workers engaged in this activity should be provided with protective clothing as specified in clause E.2.

Neutralised solid decomposition products, vacuum-cleaner bags and adsorbents should be disposed of according to local regulations.

Guidance for the disposal of used neutralising solutions is given in 6.5.4.

6.5.6 *Treatment of parts removed from SF_6-filled enclosures*

Parts removed from SF_6-filled enclosures with medium decomposition should be immersed in a solution prepared according to 6.5.3 for a time period T_1 prior to further handling.

In cases of high decomposition, immersion for a time period T_2 is recommended. Alternatively the parts should be washed thoroughly with a neutralizing solution and then rinsed with clean water.

Guidance for the disposal of used neutralising solutions is given in 6.5.4.

6.5.7 *Treatment of tools and clothing*

Tools and clothing, including footwear, should preferably be reserved for use during the processes outlined in this section and should not be used for other purposes.

After each use, clothing should be immersed in a solution prepared according to 6.5.3 for a time period T_1 and then rinsed in clean water, before laundering or disposal.

After each use, tools should be washed in a neutralising solution and then in clean water.

Guidance for the disposal of used neutralising solutions is given in 6.5.4.

Annex A
(informative)

New sulphur hexafluoride

A.1 Introduction

Sulphur hexafluoride (SF_6) is a non-toxic, chemically inert, non-flammable compound which is gaseous at normal temperature and pressure (20 °C and 0,1 MPa absolute).

Its excellent dielectric and thermal properties make it suitable for use in [11]:

- equipment for the transmission and distribution of electrical energy (for example gas insulated substations, ring main units, circuit-breakers, transformers, cables);
- medical apparatus (X-ray generators, pneumothorax apparatus, etc.);
- scientific equipment (for example electron microscopes, electrostatic particle accelerators);
- double glazing systems (house windows);
- other minor applications such as meteorology (tracer agent) and metallurgy (protective atmosphere).

A.2 Chemical properties [11]

SF_6 is a very stable and inert gas, colourless, odourless, non-toxic, non-flammable and insoluble in water. It is one of the least reactive known gases and in normal conditions it attacks no substance with which it comes into contact.

Table A.1 lists the main chemical characteristics.

Table A.1 – Main chemical characteristics of SF_6 [11]

Formula	SF_6
Molecular weight	146,05 g/mole
Sulphur content	21,95 %
Fluorine content	78,05 %
Molecular structure	Octahedral with fluorine atoms at the six corners
Bonds	Covalent
Collision cross-section	4,77 Å
Decomposition temperature	500 °C

A.3 Physical properties [11]

SF_6 is one of the heaviest known gases: in normal conditions it is about five times heavier than air, so that, under conditions of insufficient mixing with air the gas has a tendency to accumulate at low levels.

The mixing with air by convection and diffusion is slow, but once it has mixed it does not separate again.

Even though the thermal conductivity of SF_6 is lower than that of air, the overall heat transfer properties are two to five times better due to its lower viscosity and higher density.

In electrical energy transmission and distribution equipment the normal pressure range of SF_6 is between 0,1 MPa and 0,9 MPa absolute. The pressure/temperature/density characteristics of the gas are shown in figure A.1.

Table A.2 lists the main physical characteristics.

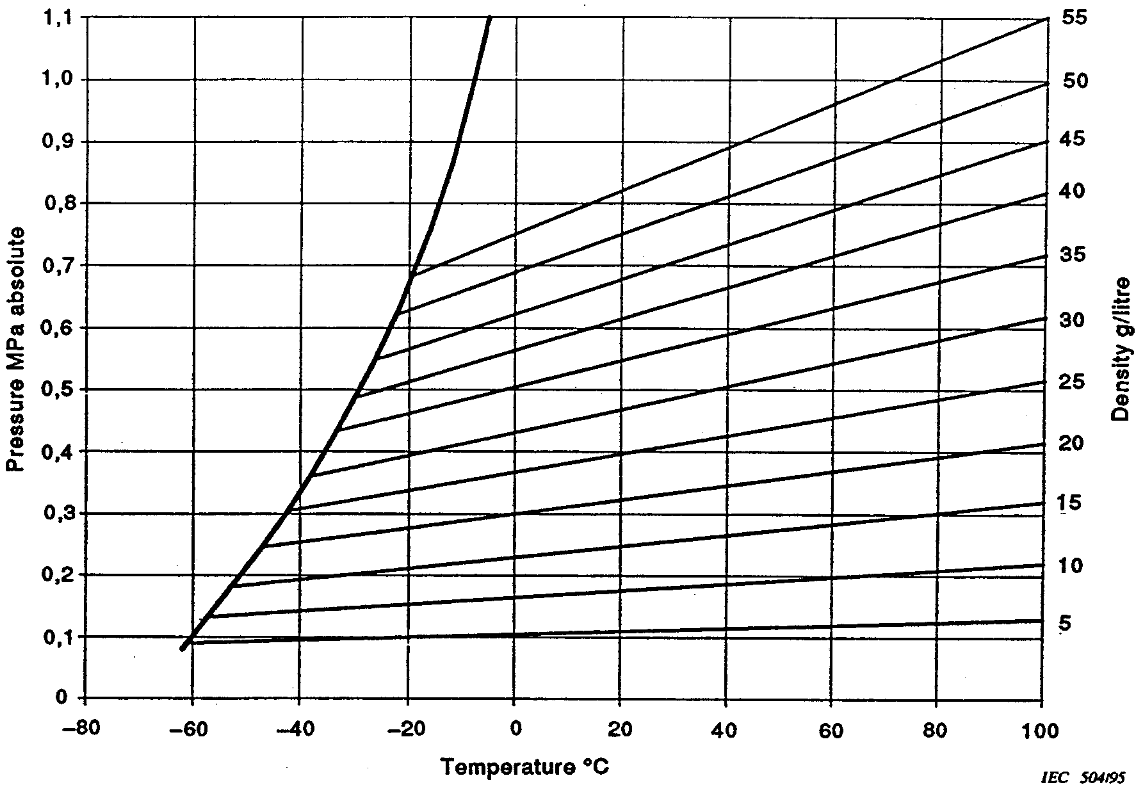

Figure A.1 – Pressure/temperature/density characteristics for SF_6 [11]

Table A.2 – Main physical characteristics of SF_6 at a pressure of 0,1 MPa absolute and a temperature of 25 °C [11]

Density	6,14 kg m^{-3}
Thermal conductivity	0,0136 W m^{-1} K^{-1}
Critical point: – temperature – density – pressure	 45,55 °C 730 kg m^{-3} 3,78 MPa absolute
Sound velocity	136 m s^{-1}
Refractive index	1,000783
Formation heat	–1221,66 J mol^{-1}
Specific heat at constant pressure	96,60 J mol^{-1} K^{-1}
Equation of state	See figure 1

A.4 Electrical properties [11]

The excellent dielectric properties of SF_6 are due to the electronegative character of its molecule. It has a pronounced tendency to bind free electrons forming heavy ions with low mobility making the development of electron avalanches very difficult.

The electric strength of SF_6 is about 2,5 times higher than that of air under the same conditions.

Because of its low dissociation temperature and high dissociation energy, SF_6 is an excellent arc quenching gas.

When an electric arc cools in SF_6, it remains conductive to a relatively low temperature, thus minimising current chopping before current zero, and thereby avoiding high over-voltages.

Compared to liquid dielectrics, SF_6 is not flammable.

Table A.3 lists the main electrical characteristics of SF_6.

Table A.3 – Main electrical characteristics of SF_6 [11]

Critical breakdown field relative to pressure	89 $V\ m^{-1}\ Pa^{-1}$
Relative dielectrical constant at 25 °C and 0,1 MPa absolute	1,00204
Loss factor (tan δ) at 25 °C and 0,1 MPa absolute	$<2 \cdot 10^{-7}$
Effective ionisation coefficient	$\alpha = Ap\left(\frac{E}{p} - B\right)$ α: m^{-1} E: $V\ m^{-1}$ p: Pa A: $2{,}8 \cdot 10^{-2}\ V^{-1}$ B: $89\ V\ m^{-1}\ Pa^{-1}$

A.5 Handling, hazards and health characteristics

Pure SF_6 is non-toxic and biologically inert. Tests performed with animals and human beings have shown that when present in a concentration of up to 80 % SF_6 to 20 % O_2, no adverse effects are experienced [13, 14, 15].

Whilst it is permissible therefore for the inhaled atmosphere to contain a high proportion of SF_6, a maximum concentration of 1 000 ppmv (6 000 mg/m^3) has been established for places of work in which personnel spend up to 8 h per day, five days per week.

This TLV (Threshold Limit Value) is that commonly used for all harmless gases not normally present in the atmosphere and in the case of SF_6, is more than two orders of magnitude lower that the danger level [12, 16, 17].

New SF_6 has no ecotoxic, mutagenic, or carcinogenic (neither genotoxic nor epigenetic) effects on health [18, 19, 20].

When handling new SF_6 it is necessary therefore only to adopt procedures which ensure that the specified maximum concentration is not exceeded.

Owing to the manufacturing process, commercially available SF_6 is not perfectly pure.

The permitted levels of impurities are laid down in IEC 376. These are shown in table A.4.

Table A.4 – Maximum permitted impurity levels in new SF_6

Impurity	Maximum permitted
CF_4	500 ppm weight
$O_2 + N_2$	500 ppm weight
Water	15 ppm weight
Acidity expressed as HF	0,3 ppm weight
Hydrolysable fluorides expressed as HF	1,0 ppm weight

Annex B
(informative)

SF_6 decomposition products

B.1 Decomposition of SF_6

When arcing occurs in SF_6 due either to normal switching operations or fault clearances, or in the unlikely event of an internal arcing fault, different SF_6 decomposition products are generated simultaneously in varying quantities [1, 2, 5, 21, 22]. When the SF_6 molecule is stressed by temperature, radiation or electrical discharge and separation of fluorine atoms occurs, a number of radicals, ions, or neutral molecules are produced, depending on the type of excitation and the energy input, according to:

$$SF_6 \xrightarrow{\Delta E} SF_x + (6\text{-}x)F,\ 0<x<6 \qquad (1)$$

When the input of energy ΔE ceases, most of the atoms recombine to form SF_6, whilst others combine with different substances in the system to form a variety of stable end products. Such substances include in particular oxygen and water and also materials used in the construction of the equipment.

These decomposition products are considered here in relation to the energy delivered to the SF_6.

B.1.1 *The behaviour of SF_6 in an electric arc*

Heavy current arcing occurs normally during circuit-breaker switching and fault clearance operations, and abnormally during an internal arc fault.

From temperatures of 500 °C, SF_6 gas begins to decompose into its constituent parts, with the degree of decomposition being directly proportional to the quantity of energy converted. In the dissociation process defined in equation (1), the SF_6 molecules are broken down into sulphur and fluorine atoms at about 3 000 °C.

The large quantity of heat absorbed during this process is dissipated away from the arc zone by convection and diffusion. Below a temperature of about 1 000 °C, the atoms recombine or react with other substances, such as vaporised electrode metal, the vessel wall, plastics or impurities. Gaseous and solid decomposition products can arise, including metal fluorides and sulphur fluorides, of which the most important are CuF_2, AlF_3, WF_6, CF_4 and SF_4.

These products, generally known as primary decomposition products, are formed during or shortly after a discharge in the less-than-one-second range. Dust-like deposits which may appear on the surfaces of insulators during normal operation have no detrimental effect on their dielectric performance.

Some of the decomposition products are chemically stable; others are very unstable, particularly in the presence of water.

In the presence of oxygen, decomposition products can arise as follows:

$$S + O + 2F \longrightarrow SOF_2 \qquad (2)$$

$$SF_4 + O \longrightarrow SOF_2 + 2F \qquad (3)$$

$$SF_3 + O \longrightarrow SOF_2 + F \qquad (4)$$

$$SF_5 + O \longrightarrow SOF_4 + F \qquad (5)$$

It is believed that reactions (2), (3) and (4), involving oxygen released from the electrode materials during arcing, are the principal mechanisms whereby SOF_2 is produced [4, 23, 24]. This is significant as SOF_2 is the main contributor to the toxicity of arced SF_6 (see C.3.2.1).

In the presence of water vapour, the following reactions occur:

$$F + H_2O \longrightarrow HF + OH \qquad (6)$$

$$SF_5 + OH \longrightarrow SOF_4 + HF \qquad (7)$$

$$\begin{tikzcd} SF_4 \arrow[r, "+\ H_2O"] \arrow[d, dashed, "+\ 1/2\ O_2"'] & SOF_2 + 2HF \arrow[d, dashed, "+\ 1/2\ O_2"] \arrow[dl, dashed, "+\ F_2"'] \\ SOF_4 \arrow[r, "+\ H_2O"] & SO_2F_2 + 2HF \end{tikzcd}$$

(8)

The broken lines in equation (8) indicate reactions that occur only to a limited degree during SF_6 decomposition in an arc [22]. Whilst the reactions of equation (8) imply the formation of significant quantities of HF, this product has not been reported in large quantities following power arcing in switchgear and controlgear. This is probably because decomposition product formation is mainly according to equations (2), (3) and (4). It is also possible that HF formed by the reactions of equation (8) further reacts with metal vapours to produce metal fluorides.

SF_4 is produced in significant quantities but hydrolyses rapidly (equation (8)) in the presence of moisture.

In the continued presence of water, further hydrolysis occurs, leading to:

$$SOF_2 + H_2O \longrightarrow SO_2 + 2HF \qquad (9)$$

Other reactions have been reported in the literature; additional by-products of arcing such as S_2F_{10} may be formed. However, the quantity of S_2F_{10} formed under arcing conditions is extremely low, because SF_5 radicals, produced at high temperatures, form S_2F_{10} only when cooled very rapidly, a condition not likely to apply in the arc [25].

B.1.2 *SF_6 decomposition with low current discharges*

Whilst operating voltage is applied to equipment containing SF_6, the possibility of low current discharges such as corona, sparking and partial discharges cannot be ruled out. However, the concentrations of decomposition products resulting from such discharges are likely to be very low, and personnel involved in maintenance and repair work on such equipment should not be affected adversely (see C.4.6). When SF_6 is decomposed in spark discharges, the reactions shown in broken lines in equation (8) will predominate [22].

B.1.3 *Catalytic decomposition of SF_6 (high-temperature behaviour)*

SF_6 can be heated to 500 °C in quartz vessels without decomposing. Up to temperatures of about 150 °C, all commonly used materials, such as metals, glass, ceramics, rubber and polyester resin are fully resistant to SF_6. It is only at temperatures higher than 200 °C that some metals begin to have a decomposing effect on the gas, but in the case of the metals and alloys normally used, this effect is not observed to any marked degree until the temperature range of 400 °C to 600 °C is reached [5].

Since the maximum operating temperatures inside SF_6 switchgear and controlgear in the absence of arcing are far below these values, no SF_6 decomposition of this kind is to be expected during operation. What cannot be avoided, however, is the escape of residual gas or leakage, for instance during repair work. Decomposition can then be brought about by heaters and internal combustion engines, or by smoking, soldering or welding in the immediate vicinity of the SF_6 switchgear and controlgear [1].

B.2 Corrosion behaviour of SF_6 and its decomposition products

Chemically pure SF_6 is a completely non-reactive gas. There is no possibility therefore that corrosion will be caused directly by the SF_6 itself. However, the primary and secondary decomposition products of SF_6, on contact with moisture, can form corrosive electrolytes which may cause damage to some of the material used inside the equipment.

The metals commonly used, such as aluminium, steel, copper and brass, are hardly attacked at all, but materials such as glass, porcelain, insulation paper and the like are more vulnerable to damage, depending upon the concentration of the corrosive substances concerned. Other insulating materials, such as epoxy resin, polyester, polyethylene, polymethylene oxide, PTFE, PVC, etc., are not significantly affected.

It is important that measures be taken in the design to take account of the corrosive properties of the decomposition products. Corrosion can be prevented by the thorough exclusion of moisture and by using suitable materials.

B.3 Measures for the removal of SF_6 decomposition products

Moisture and SF_6 decomposition products inside equipment in service can be reduced to acceptable levels by adsorption. Material such as alumina, soda lime, molecular sieves or mixtures thereof are suitable for this purpose. They adsorb the gaseous acid products very effectively and practically irreversibly, and at the same time ensure that the gas maintains a low dewpoint temperature [5]. In most electrical equipment, static filters are used, but in some circumstances, such as circuit breakers where arc quenching can generate decomposition products in particularly high concentrations, the gas may be circulated through a filter by a pump [5, 26].

Disposal of decomposition products removed from equipment is straightforward. The acid components (sulphuric acid and hydrogen fluoride) are degraded by means of alkaline compounds, such as calcium hydroxide (lime) to form calcium sulphate or calcium fluoride. Both these compounds occur as minerals in nature, and are know as gypsum and fluorspar respectively.

Most of the solid reaction products are not soluble in water, or can be dissolved only with difficulty, but certain metal fluorides can react with water to form hydrofluoric acid. It is necessary therefore to treat the solid reaction products with calcium hydroxide (lime), for example, to neutralise the acid components. The resultant sludge can then be disposed of according to local regulations.

B.4 Recycling of SF_6

SF_6 gas can be reclaimed from electrical equipment. Gas handling plant is available commercially which is capable of restoring contaminated gas to its as-new condition, or used gas can be returned to the manufacturer for reprocessing.

B.5 Physiological characteristics of SF_6 decomposition products

SF_6 decomposition products can cause irritation of the skin, eyes and mucous membranes, such as in the respiratory tract, and in high concentrations can cause pulmonary oedema, given sufficient time of exposure.

SF_6 containing decomposition products has an unpleasant pungent smell that in itself is associated with an irritant effect. The olfactory thresholds, especially for SOF_2, SO_2 and HF, are of the same order as the TLVs. Because of these characteristics, even small quantities of gaseous decomposition products may give rise to unmistakable warning indications within a matter of seconds, before any risk of poisoning can arise [1].

Care should be taken when handling SF_6 containing decomposition products and the powders produced by switching operations. The pertinent operating instructions and accident prevention instructions should be followed at all times (see annex E and IEC 480) [27].

Annex C
(informative)

Release of SF_6 from switchgear and controlgear – Potential effects on health

C.1 Introduction

This annex examines the risks to health due to SF_6 released into the local atmosphere by leakage during normal service and in the event of an internal fault. Release of SF_6 during maintenance is not specifically treated but the principles established here can be applied to studying these situations if necessary.

During normal service the SF_6 gas remains inside the switchgear and controlgear and the decomposition products formed are neutralised by molecular sieves as well as by natural recombination processes. SF_6 can become present in the atmosphere because of leakage or if a gas enclosure fails to contain the gas, for example in the unlikely case of an internal fault. It is necessary to differentiate clearly between normal leakage conditions and internal fault situations leading to a sudden release of SF_6, when evaluating health risk.

In the case of leakage it is necessary to consider the effects of long-term exposure to the gaseous decomposition products of SF_6. The concentrations of these products in the air shall remain low enough to present no threat to unprotected personnel during a normal working period of, for example, 8 h.

In the case of a sudden release of SF_6 due to an internal fault, mandatory evacuation and ventilation procedures imply a momentary exposure. Decomposition product concentrations of higher levels than would be tolerable during, for example, 8 h can be tolerated if the exposure time is considerably reduced. Clearly in this case account should be taken of all possible sources of toxic emanations and this requires detailed knowledge of all of the products formed. In this respect a full treatment shall consider contributions from metal vapour, burnt plastics, cable insulation, paint, etc., on an equal footing to those attributable to the SF_6.

NOTE – For example, by comparison of long-term exposure limits, copper fumes from vaporised electrodes are about four times as toxic as arc-decomposed SF_6 (SOF_2) whilst aluminium fumes are about four times less. Both can be produced in large quantities in any incident where electrical arcing occurs, regardless of the insulation medium employed, and may constitute the major risk to health (see C.4.7.2). The contribution of fumes from the combustion of plastics (see C.4.7.3) is also highly significant.

The first aim of this annex is to lay out the basic guidelines for estimating the concentrations of toxic SF_6 by-products in the air in an environment into which SF_6 has been released. The effects of other potentially toxic substances released under fault conditions are also considered.

The general conclusions for the various situations of interest are:

Leakage:	There is no risk to health because concentrations of the significant toxic components remain at negligible levels, well below established long-term exposure limits.
Abnormal situations:	Case studies of internal fault situations involving uncontrolled arcing inside an SF_6 enclosure, engendering burn-through or pressure relief, show that the concentrations of SF_6 arc decomposition products remain below substantiated limits for momentary exposure.

C.2 Overview

Methods are presented for calculating the risks associated with the presence of SF_6 decomposition products in the atmosphere due to leakage and to internal fault. The principles adopted for performing the calculations are presented in clause C.3. Case studies for leakage and internal fault situations are presented in clause C.4. The implications of the results are discussed in clause C.5 and conclusions are presented in clause C.6.

Each case study in clause C.4 includes a presentation of the calculation method used and the results of performing the calculation using data representing an appropriate installation. The data used are selected from representations of typical switchgear and controlgear installations presented in clause C.7. Exposure limits for toxic substances are introduced in clause C.8.

C.2.1 *Leakage situations*

Subclauses C.4.5 and C.4.6 present case studies for the following leakage situations:

- circuit-breakers which have interrupted normal fault current. High-voltage and medium-voltage installations are used as examples. Consideration is given to the effects of further transformation, by hydrolysis, of the decomposition products formed during arcing.
- equipment in which low-energy discharges (partial discharge, corona discharge and spark discharge) have occurred. The effects of the highly toxic decomposition product S_2F_{10} are considered.

C.2.2 *Internal fault situations*

Subclause C.4.7 presents case studies for internal fault situations:

- Five different installations are studied. The effects of the gases and vapours emitted are considered including SF_6 decomposition products, metal vapours, and vapours emitted by plastic materials.

C.3 Formation and health effects of SF_6 decomposition products

C.3.1 *Formation of SF_6 decomposition products*

During high power arcing in SF_6 the arc core reaches temperatures of the order of 10 000 K [28]. At these temperatures the molecules of the gas are completely broken down into their parent atoms, sulphur and fluorine (see B.1.1), [16, 29]. Any impurities present, such as air or water vapour, are dissociated in a similar manner. The result of this is a localised region containing only single atoms of: S, F, H, N, O and diverse ions. The heating of the electrodes by the arc roots adds vapours of copper, tungsten, graphite and/or aluminium to this atmosphere.

After arc extinction or in regions where cooling commences, these atoms start to bind together again and reform mainly SF_6. However, chemical reactions take place with the impurities present and in particular with water vapour, giving rise to the so-called arc decomposition products, (see annex B) [4, 30, 31]. The quantities formed are directly related to the electrical discharge energy.

The most frequently encountered by-products are: SOF_2, SO_2, HF and also CF_4, SF_4 and SO_2F_2 [31]. The existence of these by-products is of importance only if they enter the local atmosphere. Their concentrations inside the switchgear and controlgear are of no direct significance, especially since the presence of adsorbents (such as molecular sieves) will tend to purify the gas.

For some time there were concerns that the highly toxic gaseous by-product S_2F_{10} might constitute a major contributor to the toxicity of SF_6 in which arcing has occurred. However over the past five years experiments show that this idea is not substantiated [32, 33]. In fact S_2F_{10} appears now to be formed in such minute quantities during arcing as to contribute negligibly to the overall toxicity of the SF_6.

It is also known that S_2F_{10} is formed by low-energy electrical discharges in SF_6 and that under these conditions, higher S_2F_{10} production rates are encountered [34, 35, 36, 37] than during arcing. However, S_2F_{10} decays in the presence of moisture [36, 38] and at temperatures exceeding 200 °C. The high toxicity of this compound, at concentrations that until recently were difficult to detect, has prompted considerable investment in research into the potential risks associated with its presence [25]. However, S_2F_{10} decays in the presence of moisture [36, 38], at temperatures exceeding 200 °C, and at ambient temperature by catalytic wall decomposition. The last mechanism is so efficient that the S_2F_{10} generated in equipment is reduced to a negligible quantity [59].

C.3.2 *Effects of SF_6 decomposition products on health*

If SF_6, which has been subjected to arcing or to low-energy discharges, is exhausted into the work place then the potential health risk will depend on the concentration of each decomposition product in the air, and hence on the switchgear and controlgear room volume. Toxicity estimations should take account of the concentration of each component present in terms of the permissible concentrations for appropriate exposure times.

C.3.2.1 *Health effects of arc decomposed SF_6*

For multi-component mixtures, toxicologists define three general cases [39]:

- each component acts in a different manner, or on different target organs; the effects are hence not cumulative and each component is treated separately;
- the components act in a similar manner on the same target organs; their effect is thus cumulative and calculations will take this into account;

- one component largely outweighs the contribution of the others; the overall toxic effect can be estimated by studying the concentration of this component alone.

A survey of the majority of work carried out over the last 18 years on high power arc decomposition of SF_6 (from, for example [4, 30, 31, 60]) allows the following conclusion to be drawn:

- the toxicity of arc decomposed SF_6 is dominated initially by one specific component, the gas thionyl fluoride SOF_2.

This conclusion justifies the adoption of the following:

- the overall health risk to personnel, due to arc decomposed SF_6, should be estimated using the SOF_2 concentrations generated.

In this report the by-product SOF_2 is used as the indicator of the overall toxic effect of arc decomposed SF_6. This allows the health risk in various situations to be assessed together with the implications to safety procedures.

Hydrolysis of the SOF_2 may occur in the presence of significant concentrations of water vapour, producing SO_2 and HF (see B.1.1). The risks of exposure to such a mixture, neglecting that HF is unlikely to remain in the atmosphere for long periods because of its high reactivity, are slightly higher than for SOF_2, as detailed in C.4.5.1. This is taken into consideration when assessing the risks due to leakage, where sufficient time may elapse for the hydrolysis reaction to occur, either inside the equipment or in the atmosphere. Hydrolysis of SOF_2 may be neglected for internal fault situations where the time between the fault and subsequent ventilation and repair work is short.

C.3.2.2 *Health effects of SF_6 decomposed by low-energy discharges*

During low-energy discharges, the decomposition product S_2F_{10} may be formed albeit in very small quantities. It is the most toxic decomposition product of SF_6 known; for this reason it is also considered in the assessment of the risks due to leakage from high-voltage equipment. The contributions to toxicity of other decomposition products such as SOF_2, SO_2 and HF are negligible in SF_6 which has been decomposed by low-energy discharges, so these products are not considered.

C.3.2.3 *Exposure duration and dilution in air*

The two key notions essential to any evaluation of risk to health due to toxic substances are:

a) dilution into the surrounding volume;

b) time duration of exposure.

The first notion is required to enable the conversion from the concentration of decomposition products formed inside the switchgear and controlgear, into a concentration level in the workplace atmosphere (see note).

The second notion will determine the method of evaluating the potential health risk, applicable under either normal conditions (basic leakage) or abnormal ones (internal fault).

Under normal conditions the TLV (Threshold Limit Value) concentration, defined as an 8 h average exposure limit, should be employed (see C.8.1). This ensures the security of those working full time in the vicinity of the SF_6-filled switchgear and controlgear.

Under abnormal conditions, workers leave the switchgear and controlgear room within a few minutes and the exposure is hence momentary. For this type of exposure, very much higher concentrations than the TLV can be tolerated (see C.4.2).

NOTE – For example, a somewhat alarming by-product concentration of 1 000 ppm by volume (ppmv), generated in a 1 l experimental chamber, will lead to the very low value of 0,04 ppmv when released into a 3 m x 3 m x 2,5 m room.

C.4 Calculation of decomposition product concentrations

The following presents the methods and results of calculations giving the concentrations of gaseous SF_6 decomposition products in the switchgear and controlgear room atmosphere for various types of installation. The contributions of other sources of risk, which arise during an internal fault, such as smokes, fumes and vapours, have also been assessed.

For the case of leakage, the quantities of SOF_2 and S_2F_{10} leaked during 24 h are considered. It is assumed that no gas escapes from the switchgear and controlgear room. The effects of hydrolysis of SOF_2 are considered.

For the internal fault situations all of the SOF_2 formed is considered to be emitted rapidly into the surrounding atmosphere and is considered to be stable during the time period of interest.

For the case of switchgear and controlgear maintenance, particular to high-voltage equipment, guidance is given in section 4 and in F.4.1. In such situations working procedures require the recovery of all the SF_6 before opening the switchgear and controlgear.

C.4.1 *Calculation criteria*

The following criteria have been used throughout this treatment, for both leakage and internal fault situations:

a) The switchgear and controlgear room is assumed to be completely closed and ventilation is assumed to be inoperative during the period of interest.

b) Arc by-product adsorbents, fitted in the switchgear and controlgear, are assumed to be inoperative during the period of interest.

c) The gas emitted is assumed to mix uniformly with the air in the switchgear and controlgear room in a short time with respect to the working day or exposure duration.

C.4.2 *Risk evaluation*

C.4.2.1 *Leakage situations*

The results of the example calculations give the concentrations C of SOF_2 (see C.4.5) and of S_2F_{10} (see C.4.6) in the switchgear and controlgear room air. Each value of C should be compared with the concentration permitted for full-time work, (TLV), (see C.8.1). The final result of each calculation is expressed as a ratio C/TLV; this must have a value of less than unity for there to be no significant risk and for full-time working to be permitted.

For the case of SOF_2 hydrolysis (see C.4.5.1), the concentrations of SO_2 and HF are calculated. HF and SO_2 are considered to have a similar effect on the human organism (see note) and for such a multi-component mixture, the sum R_{tot} of the individual ratios of concentration to TLV should not exceed unity [39].

$$R_{tot} = \frac{SO_2 \text{ concentration}}{\text{TLV } (SO_2)} + \frac{\text{HF concentration}}{\text{TLV (HF)}} \leq 1$$

The TLVs for the four compounds of interest are given in table C.1 [39, 41, 42]:

Table C.1 – TLVs for the four compounds

	SOF_2	SO_2	HF	S_2F_{10}
TLV (ppmv)	1,6	2	3	0,01

NOTE – This is a cautious assumption which results in the maximum permitted concentration of each component being lower than its TLV. It is adopted here in order to maintain a worst-case approach.

C.4.2.2 *Internal fault situations*

For these abnormal cases the SOF_2 concentrations are much higher than for leakage because all of the SF_6 is released in a short period of time. Standard procedures impose evacuation and ventilation of the switchgear and controlgear room. The exposure to arc decomposed SF_6 should therefore be momentary. For this reason, comparing a calculated SOF_2 concentration with the TLV is no longer appropriate (see C.8.1).

In general, an IDLH (Immediately Dangerous to Life or Health) value provides guidance for short-term exposure (see C.8.2). There is however no published IDLH value for SOF_2. It is therefore necessary to turn to the results of toxicological data (see note) in order to obtain a reference value for non-repetitive momentary exposure (C_m).

C_m = 500 ppm by volume (ppmv) (see note)

The calculated SOF_2 concentrations are compared with C_m to assess the risks to health due to SF_6 decomposition products during or following an internal fault. Other factors which may be more significant shall be considered in risk assessment and in the appraisal of safety procedures (see C.4.7.2 and C.4.7.3).

NOTE – Toxicological data exist for exposure of test animals to atmospheres containing SOF_2 [40, 41], covering the effects of 1 h exposure of three distinct mammal species to concentrations of up to several thousand ppmv of SOF_2. The results show that for exposure to concentrations of up to 100 ppmv (mice and rats) and 500 ppmv (rabbits), all animals exhibit an apparently normal general state [40], 24 h after the exposure period.

For human exposure, higher concentrations than 500 ppmv for 1 h could be tolerable, as larger organisms are generally less sensitive to toxic agents. It can therefore be inferred that the use of a momentary exposure limit, C_m of 500 ppmv, as a reference value for comparison with the calculated concentrations, is acceptable.

C.4.3 *Calculation limits for cases of internal fault*

C.4.3.1 *Very small room volumes*

In these situations, such as for an internal fault in a MV/LV substation, the main health risk is not that due to SF_6 arc by-products. The arc itself, the hot gas blast, the smoke, the fumes from burnt paint, plastics or metal vapours and finally the shock wave, probably constitute the major risks (see C.4.7.2 and C.4.7.3).

Extrapolation to room volumes much smaller than about 50 m³ is hence probably not a valid procedure for estimating health risks. An example calculation using a smaller room volume than 50 m³ has nevertheless been included to allow the SOF_2 contribution to the overall toxicity to be estimated.

C.4.3.2 *Very long arcing times*

For all internal fault calculations a constant environment for the arc is assumed, leading to a constant SOF_2 production rate, during an arcing time of 100 ms (see C.7.3.2). The constant production rate will almost certainly not be valid for arcing times above about 100 ms, as explained below:

Internal fault in medium- and high-voltage circuit-breakers and in Ring Main Units (RMU)

In these cases, burn-through or venting will rapidly open the enclosure to the atmosphere. The high, arc-induced, pressure rise will tend to empty most of the SF_6 in a fraction of a second but the arc will remain burning mainly in the metal vapour formed by evaporation of the electrodes. Clearly, only a fraction of the total arc energy goes to SF_6 by-product formation. Experimental work is thus needed to enable extrapolation above about 100 ms.

GIS burn-through (high-voltage)

In these situations, a significant quantity of metallic vapour is formed and an exothermic reaction takes place between the SF_6 and the aluminium electrodes. The arcing environment will be profoundly modified and the use of a constant by-product production rate may not be justifiable.

C.4.4 *Situations studied*

Ten representative situations have been studied as follows:

a) Leakage from a medium-voltage circuit-breaker after three consecutive interruptions of a 31,5 kA three-phase fault current (see IEC 56, test duty 4).

b) Leakage from a high-voltage circuit-breaker after three consecutive interruptions of a 31,5 kA three-phase fault current (see IEC 56, test duty 4).

c) Leakage from a high-voltage enclosure in which partial discharges have occurred during a period of 30 years.

d) Leakage from a high-voltage enclosure in which corona discharges have occurred during a period of 30 years.

e) Leakage from a high-voltage switch-disconnector in which sparking has occurred 200 times per year during a period of 30 years.

f) Internal fault leading to pressure-relief or burn-through in a 245 kV GIS bus at 40 kA (single-phase fault).

g) Internal fault leading to pressure-relief or burn-through in a 145 kV GIS bus at 31,5 kA (fault involving two phase-to-phase arcs).

h) Internal fault leading to pressure-relief or burn-through in a medium-voltage GIS switchboard at 25 kA (single-phase fault).

i) Internal fault leading to pressure-relief in a medium-voltage circuit-breaker at 25 kA (single-phase fault).

j) Internal fault leading to pressure-relief in a medium-voltage Ring Main Unit at 16 kA (fault involving two phase-to-phase arcs).

C.4.5 *Determination of concentrations due to leakage of SOF_2 from circuit-breakers*

Leakage from circuit-breakers only is considered here because the degree of SF_6 decomposition in circuit-breakers is higher than in other types of equipment.

The concentration of the reference gaseous decomposition product SOF_2 in the switchgear and controlgear room is calculated for a circuit-breaker which has just interrupted a three-phase fault current three consecutive times (as required for IEC 56, test duty 4) and is consequently leaking SF_6 containing arc decomposition products. The quantity of SOF_2 leaked during a 24-h period is calculated and compared with the room volume to establish the concentration.

The procedure for calculating the concentrations of decomposition products is as follows. Data and intermediate calculation results are given in clause C.7 as indicated for each stage.

a) Calculate total arc energy in kilojoules ($E = I.U.t.n.m$) where n is the number of phases and m is the number of interruptions (for data, see C.7.3.1).

b) Calculate the quantity of SOF_2 formed in litres (from production rate, r, in litres/kilojoule, see C.7.4 and C.7.5) (see note 1).

c) Calculate the SOF_2/SF_6 volume ratio inside the breaker (taking account of filling pressure, see C.7.7).

d) Determine the leakage rate L in litres per day (from manufacturer's data, see C.7.6).

e) Calculate the quantity of SOF_2 leaking into the switchgear and controlgear room (see C.7.7).

f) Calculate the quantity of SOF_2 accumulated during a 24 h period (in litres, see C.7.7).

g) Calculate the ratio of accumulated SOF_2 to the switchgear and controlgear room air volume (in ppmv, for data see C.7.1).

h) Compare this concentration with the TLV (see C.8.1) and express the result as a ratio $R = C/\mathrm{TLV}$. If the value of R is less than unity, then no health risk is to be expected.

The equation for calculation of the switchgear and controlgear room concentration C of SOF_2, in ppmv, for a 24 h period is thus:

$$C = \frac{r.E.L.10^6}{V.v.p_f}$$

where

r is the production rate in litres/kilojoules;

E is the arc energy, in kilojoules;

L is the leakage rate, in litres per day;

V is the room volume, in litres;

v is the switchgear and controlgear volume, in litres;

p_f is the ratio of the SF_6 filling pressure (MPa absolute) to the atmospheric pressure.

Results of example calculations for leakage situations (see clause C.7 for data):

Table C.2 – Results of example calculations for leakage situations

Circuit-breaker	V_l SOF_2 leaked litres	V Room volume litres	C SOF_2 Concentration ppmv	TLV (see note 2) of SOF_2 ppmv	R
MV	$1{,}3 \times 10^{-6}$	120×10^3	11×10^{-6}	1,6	$6{,}8 \times 10^{-6}$
HV	108×10^{-6}	700×10^3	154×10^{-6}	1,6	96×10^{-6}

V_l is the quantity leaked into the atmosphere in 24 h (see note 3, C.7.5, C.7.6 and C.7.7). The concentrations C are very much smaller than the TLV, as shown by the values of ratio R.

NOTES

1 The arcing takes place between copper-tungsten contacts.

2 TLV: Threshold Limit Value: exposure levels based on repetitive 8 h exposure [42]; (see C.8.1).

3 Extrapolation to longer accumulation times requires detailed data concerning the rate of air replacement due to ventilation.

C.4.5.1 *Additional calculation to take account of the effects of SOF_2 hydrolysis*

In B.1.1, equation (9) describes the hydrolysis of SOF_2 whereby SO_2 and HF are formed. This can occur when SOF_2 remains in the presence of humidity for long periods of time, either inside the switchgear and controlgear enclosure or in the switchroom atmosphere. Adsorbents should however maintain a low humidity within switchgear enclosures, limiting the degree to which hydrolysis can occur prior to leakage. Normal ventilation should prevent the accumulation of SOF_2 in the atmosphere.

Assuming that inadequate ventilation does allow SOF_2 to accumulate, it is necessary to consider the final products in evaluating any risk to health.

Each molecule of SOF_2 involved in the hydrolysis reaction gives rise to one molecule of SO_2 and two molecules of HF. Thus, every mole of SOF_2 gives rise to one mole of SO_2 and two moles of HF, each mole occupying the molar volume. Therefore, a given volume of SOF_2 produces an equal volume of SO_2 and twice that volume of HF and the concentrations in a given room volume are similarly related. HF, however, is highly reactive and is unlikely to remain in the atmosphere for long enough for high concentrations to be reached.

HF and SO_2 are considered to have a similar effect on the human organism (see note 1) and for such a multi-component mixture, the sum R_{tot} of the individual ratios of concentration to TLV should not exceed unity [39].

$$R_{tot} = \frac{SO_2 \text{ concentration}}{\text{TLV } (SO_2)} + \frac{\text{HF concentration}}{\text{TLV (HF)}} \leq 1$$

Assuming that all the SOF_2 undergoes hydrolysis and that all of the resultant SO_2 and HF remain in the atmosphere, the results of C.4.5 give the following values of R_{tot}. The very low values of R_{tot} (and of the individual ratios of concentration to TLV) indicate negligible risk.

Table C.3 – Results for leakage situations taking account of SOF_2 hydrolysis

Circuit-breaker	SOF_2	SO_2		HF		R_{tot}
	Concentration ppmv	TLV ppmv (see note 2)	Concentration ppmv	TLV ppmv (see note 2)	Concentration ppmv	
MV	11×10^{-6}	2,0	11×10^{-6}	3,0	22×10^{-6}	$12,6 \times 10^{-6}$
HV	154×10^{-6}	2,0	154×10^{-6}	3,0	308×10^{-6}	180×10^{-6}

NOTES

1 This is a cautious assumption which results in the maximum permitted concentration of each component being lower than its TLV. It is adopted here in order to maintain a worst-case approach.

2 The TLVs for SO_2 and HF are given in reference [39, 41, 42].

C.4.6 *Determination of concentrations due to leakage of S_2F_{10}*

The rates of decomposition of SF_6 in the presence of low-energy discharges are generally considered to be extremely low for normal service conditions, implying a negligible risk to health. For *partial discharge* (PD) and *corona* activity this is mainly due to the fact that the energies involved are extremely low; significant decomposition would only occur if the discharges were active during a prolonged period of time (weeks or months). Moreover:

- partial discharge activity located inside solid insulators cannot affect the gas;

- SF_6-filled switchgear and controlgear is generally corona free and any significant corona discharges detected usually originate outside the equipment, for example on bushings, etc;
- standard PD testing procedures screen equipment for this type of discharge, as do radio interference measurements.

High-voltage *disconnect switch sparking* has limited impact firstly because the overall energy per operation is low, secondly because the time between operations is very long in typical service conditions and thirdly because the peak spark current is high [35, 43].

However, regardless of the above, concern has been voiced as to the possible existence of S_2F_{10} in switchgear and controlgear because of its high relative toxicity [33, 35, 44], even though it is known to decay rapidly in practical situations [34, 36, 37, 38, 44, 45].

In order to illustrate the extremely low health risk associated with S_2F_{10} in practical switchgear and controlgear situations, estimations are presented below for the three cases cited above. Severe scenarios have been adopted for each situation.

The precise values of discharge energy employed can be multiplied by many orders of magnitude without significantly modifying the conclusions. This provides a considerable margin of safety to allow for abnormally high discharge levels.

The approach to the calculations is similar for each case:

- it is assumed that the discharge activity forms unconditionally stable S_2F_{10} which accumulates for 30 years inside the HV switchgear and controlgear (see note);
- this gas then leaks into the switchgear and controlgear room (700 m^3) at the standard rate of 1 % per year ($27 \cdot 10^{-6}$ per day);
- the quantity built up in 24 h is then estimated and the concentration *C* found is compared to the TLV, (0,01 ppmv) [42], to give the ratio *R*;
- ratios *R* much less than unity clearly imply that the risk to health would be negligible.

In the three cases studied, the calculated maximum concentrations built up are in the region of one hundred thousand times less than the TLV. This result implies that in practice there is no risk to health due to S_2F_{10} produced in switchgear and controlgear under low-energy discharge conditions of this nature. The decay of S_2F_{10} in practical situations should greatly reduce the quantity accumulated, considerably reinforcing this conclusion. Furthermore, the calculations neglect any reduction in S_2F_{10} production rates due to the presence of humidity.

NOTE – The decay rates reported in the references cited lead to S_2F_{10} concentrations about 100 times smaller than those estimated here.

C.4.6.1 *Partial discharge situation.*

The following assumptions are made:

- the PD level (in the gas) (see note 1) is 5 pC. The number of discharges per cycle is high (see note 2) [43];
- the nominal voltage is 245 kV at 50 Hz;
- the S_2F_{10} production rate (see note 3) is $0,2 \cdot 10^{-9}$ mole/J [34, 35]; the discharges run continuously for 30 years and the S_2F_{10} formed does not decay.

NOTES

1 This is a typical maximum level used during acceptance testing of GIS.

2 All discharges have identical amplitudes and are assumed to be distributed uniformly over the voltage wave.

3 S_2F_{10} production rates for partial discharges under a.c. excitation are not available in the literature. This calculation is therefore based on an extrapolation of the results of spark discharge measurements.

The results are shown by the following table. The quantity of S_2F_{10} leaked during the 24 h period would be extremely small ($88,3 \cdot 10^{-9}$ litres), the concentration built up would be $C = 126 \cdot 10^{-9}$ ppmv and the ratio $R = C/\text{TLV}$ would be $12,6 \cdot 10^{-6}$.

Table C.4 – Sample calculation of S_2F_{10} concentration for partial discharges

Charge transferred per discharge	q	$5 \cdot 10^{-12}$ C
Number of discharges per cycle	n	20
Charge transferred per cycle	$Q = q\,n$	$0,1 \cdot 10^{-9}$ C
Nominal voltage	U_n	245 kV
Energy dissipated per cycle	$E = Q\,U_n/\sqrt{3}$	$14,1 \cdot 10^{-6}$ J
Energy dissipated per second	$E_s = 50\,E$	$0,707 \cdot 10^{-3}$ J
Energy dissipated per year	$E_y = 31,5 \cdot 10^6\,E_s$	$22,3 \cdot 10^3$ J
S_2F_{10} production rate	r	$0,2 \cdot 10^{-9}$ mole/J
S_2F_{10} produced per year	$P = r\,E_y$	$4,46 \cdot 10^{-6}$ mole
Volume S_2F_{10} in litres (per year)	$V = 24,45\,P$	$109 \cdot 10^{-6}$ l
S_2F_{10} accumulated in 30 years	$U = 30\,V$	$3,27 \cdot 10^{-3}$ l
S_2F_{10} leaked in 24 h	$v = 27 \cdot 10^{-6}\,U$	$88,3 \cdot 10^{-9}$ l
Concentration (700 m³ room)	$C = v/(700 \cdot 10^3)$	$126 \cdot 10^{-9}$ ppmv
TLV for S_2F_{10}	TLV	0,01 ppmv
Ratio *R*	$R = C/\text{TLV}$	$12,6 \cdot 10^{-6}$

C.4.6.2 *Corona situations*

The following assumptions are made:

- the overall corona (see note) voltage (RIV) is 3 µV measured across 300 Ω;
- the nominal system voltage is 245 kV;
- the S_2F_{10} production rate is $0{,}05 \cdot 10^{-9}$ mole/J [34]. The S_2F_{10} does not decay.

NOTE – For discharge activity inside the equipment.

As shown by the following table, the S_2F_{10} leaked during the 24 h period would be about $45 \cdot 10^{-9}$ l, the concentration C would be $64 \cdot 10^{-9}$ ppmv and the ratio $R = C/\text{TLV}$ would be $6{,}4 \cdot 10^{-6}$.

Table C.5 – Sample calculation of S_2F_{10} concentration for corona discharges

Corona voltage	V_c	$3 \cdot 10^{-6}$ V
Measurement impedance	Z	300 Ω
Corona current	$I = V_c/Z$	$10 \cdot 10^{-9}$ A
GIS nominal voltage	U_n	$245 \cdot 10^3$ V
Energy dissipated during one second	$E_s = I\,U_n/\sqrt{3}$	$1{,}41 \cdot 10^{-3}$ J
Energy dissipated per year	$E_y = 31{,}5 \cdot 10^6\,E_s$	$44{,}5 \cdot 10^3$ J
S_2F_{10} production rate	r	$0{,}05 \cdot 10^{-9}$ mole/J
S_2F_{10} produced per year	$P_v = E_y\,r$	$2{,}2 \cdot 10^{-6}$ mole
S_2F_{10} volume per year	$V = 24{,}45\,P_y$	$54{,}4 \cdot 10^{-6}$ l
S_2F_{10} accumulated in 30 years	$U = 30\ V$	$1{,}63 \cdot 10^{-3}$ l
S_2F_{10} leaked in 24 h	$v = 27 \cdot 10^{-6}\,U$	$44{,}7 \cdot 10^{-9}$ l
Concentration (700 m³ room)	$C = V/\,(700 \cdot 10^3)$	$63{,}8 \cdot 10^{-9}$ ppmv
TLV for S_2F_{10}	TLV	0,01 ppmv
Ratio R	$R = C/\text{TLV}$	$6{,}4 \cdot 10^{-6}$

C.4.6.3 *Disconnector sparking*

The following assumptions are made:

- the disconnector operates 200 times per year. The energy (see note 1) per operation is 0,25 kJ;
- the production rate (see note 2) is $0{,}05 \cdot 10^{-9}$ mole/J [34] and the S_2F_{10} formed does not decay.

NOTES

1 The average values used are: arc voltage, 1 kV and capacitive current, 0,25 A. The arc duration used is 1 s.

2 The individual arcs during disconnector sparking can have peak currents of up to 3 kA but last only a few tens of microseconds. In the absence of published data, the production rate chosen reflects this situation being at the lower end of the spark discharge range but more than 2 000 times greater than for high power arcs [34].

As shown by the following table, the S_2F_{10} leaked during the 24 h period would be $50 \cdot 10^{-9}$ l, the concentration built up would be $C = 72 \cdot 10^{-9}$ ppmv and the ratio $R = C/\text{TLV}$ would be $7{,}2 \cdot 10^{-6}$. These theoretical estimates have been confirmed as being realistic by measurements on a real switch-disconnector under highly accelerated operation conditions [36].

Table C.6 – Sample calculation of S_2F_{10} concentration for disconnector sparking

Energy per operation	$E_o = i.u.t$	0,25 kJ
Energy dissipated per year	$E_y = 200\ E_o$	50 kJ
Production rate S_2F_{10}	r	$0{,}05 \cdot 10^{-9}$ mole/J
S_2F_{10} produced per year	$P_y = r\ E_y$	$2{,}5 \cdot 10^{-6}$ mole
S_2F_{10} volume per year	$V = 24{,}45\ P_y$	$61 \cdot 10^{-6}$ l
S_2F_{10} accumulated in 30 years	$U = 30\ V$	$1{,}8 \cdot 10^{-3}$ l
S_2F_{10} leaked in 24 h (litres)	$V = 27{,}4 \cdot 10^{-6}\ U$	$50 \cdot 10^{-9}$ l
Concentration (700 m³ room)	$C = V / (700 \cdot 10^3)$	$72 \cdot 10^{-9}$ ppmv
TLV for S_2F_{10}	TLV	0,01 ppmv
Ratio R	$R = C/\text{TLV}$	$7{,}2 \cdot 10^{-6}$

C.4.7 *Determination of concentration due to internal fault*

An internal fault does not necessarily cause SF_6 to be released (see section 5). The only situations in which a release will occur are:

- failures provoking over-pressure relief operation or enclosure opening;
- internal fault situations provoking arc burn-through of the enclosure.

The assumptions made for these situations, in addition to those given in C.4.1, are as follows:

a) The totality of gaseous by-products formed is rapidly exhausted into the surrounding air.

b) The very strong convective and gas blast forces induce rapid mixing of the emitted gas with the switchgear and controlgear room air.

c) The SOF_2 generated is assumed to be stable during the time period of interest.

The SOF_2 concentration in the switchgear and controlgear room air is calculated as follows for each situation. Data and intermediate results are given in C.7 as indicated for each step:

1) Calculate the arc energy E, in kilojoules (see C.7.3.2)

2) Calculate the quantity V_f of SOF_2 formed in litres (from production rates, r, in litres/kilojoules, see C.7.4 and C.7.5).

3) Calculate the switchgear and controlgear room volume V in litres (see C.7.1).

4) Calculate the ratio C of SOF_2 volume/switchgear and controlgear room volume, in ppmv.

5) Compare this SOF_2 concentration to the momentary exposure limit C_m (see note 1) for SOF_2. The basic equation for room concentration C of SOF_2 in volume ppm is thus:

$$C = \frac{r.E \cdot 10^6}{V}$$

Results of example calculations for internal fault situations (see clause C.7 for data) are given in table C.7.

Table C.7 – Sample calculation of SOF_2 concentrations for internal fault situations

Internal fault	V_f	V	C	C_m 1)
	SOF_2 formed	Room volume	SOF_2 Concentration	for SOF_2
	litres	litres	ppmv	ppmv
245 kV GIS	60	$2\ 000 \cdot 10^3$	30	500
145 kV GIS	95	$700 \cdot 10^3$	135	500
MV GIS	11,3	$120 \cdot 10^3$	94	500
MV CB	1,9	$120 \cdot 10^3$	15	500
MV RMU²	3,0	$30 \cdot 10^3$	100	500

NOTES

1 C_m: see C.4.2.2.

2 In this case the room volume is small: see C.4.3.1.

C.4.7.1 *Estimate of the relative contributions of SF_6 by-product*

Arc decomposed SF_6 is a multi-component product. The relative contribution of each component to the risk of exposure should be evaluated by dividing the concentration C of that component by the corresponding permissible level (TLV, IDLH, etc.) [39]. The smaller the ratio found, the lower the contribution to overall toxicity. Comparing the ratios obtained for the different components indicates their relative importance. This is illustrated by considering the results obtained for the well-known SF_6 by-products SOF_2, SO_2F_2 and S_2F_{10} for which reliable data are available (see notes 1 and 2) [4, 32, 33, 40, 42, 46].

Applying the method of C.4.7 to the medium-voltage circuit-breaker example yields the following C/TLV ratios:

$SOF_2 = 9,3$ $SO_2F_2 = 0,05$ $S_2F_{10} = 0,001$

For short-term exposures (see notes 1 and 2), the ratios shown below are calculated as C/C_m for SOF_2 and as C/IDLH for the other by-products:

$SOF_2 = 3,0 \cdot 10^{-2}$ $SO_2F2 = 2,5 \cdot 10^{-4}$ $S_2F_{10} = 4,0 \cdot 10^{-5}$

Both cases clearly show the negligible contribution of S_2F_{10} and above all, the dominance of SOF_2.

Even a variation of two orders of magnitude in the S_2F_{10} production rate has no influence on this conclusion. Although S_2F_{10} may exist in arc decomposed SF_6, its high toxicity is greatly offset by the extremely small quantities formed. Its presence may thus be neglected in so far as overall toxicity is concerned.

NOTES

1 The production rates used are SOF_2: 3,7 ml/kJ; SO_2F_2: 0,06 ml/kJ; S_2F_{10}: $2.4 \cdot 10^{-6}$ ml/kJ. The TLV's are SOF_2: 1,6 ppmv; SO_2F_2: 5 ppmv and S_2F_{10}: 0,01 ppmv. For short-term exposure, C_m for SOF_2 is 500 ppmv; the IDLH values are SO_2F_2: 1 000 ppmv and S_2F_{10}: 1,0 ppmv [40, 46, 47].

2 The experimental conditions used in obtaining the production rate data differ between researchers. The orders of magnitudes are nevertheless thought to be comparable for the purpose of these estimations.

C.4.7.2 *Contribution of metallic vapours*

During high power fault arcing in any medium, the energy dissipated at the electrodes by the arc roots melts and evaporates large quantities of metal. In the event of an internal fault leading to the opening of an SF_6 enclosure, most of the fumes formed will be expelled into the switchgear and controlgear room and will constitute a contribution to the overall toxicity.

As a first approximation, the upper limit of this contribution can be estimated by assuming all the energy injected from the arc roots to go to heating, melting, then evaporating the metal which is then exhausted into the room. The results can then be compared with experimental arc erosion data to check the orders of magnitude.

This treatment is however not valid for high-voltage burn-through situations due to the strong exothermic reactions which occur between aluminium vapour and SF_6 and which further increase vapour production. Overlooking this would give rise to a gross under-estimation of the amount of metal vapour produced for a given arc energy.

The following comments apply to the results of these calculations:

- For internal faults the contribution of arc decomposed SF_6 shall not automatically be assumed to dominate the overall toxicity of the atmosphere. Regardless of the approximate nature of this calculation, it indicates that, for both medium-voltage situations of C.4.4, copper fumes may dominate the overall toxicity.

- This conclusion can be seen to remain valid even if only 10 % of the energy dissipated at the arc roots goes to vapour formation, or if 90 % of the vapour formed is condensed or transformed inside the switchgear and controlgear.
- Similar safety precautions should therefore be applied to all switchgear and controlgear, regardless of the insulation medium. It may well be advisable to build these safety precautions around a solid understanding of metal vapour generation rather than on SF_6 decomposition values.

This treatment ignores the presence of chemical reactions between the metal vapour and the insulating gas.

In the absence of more reliable methods, the following approximate treatment has the merit of highlighting a potential major contributor to overall toxicity in an internal arc situation involving any type of switchgear or controlgear.

The procedure followed for estimating the absolute maximum contribution of copper fumes to toxicity is as follows; it assumes all the energy dissipated by the arc roots to go to metal vapour formation:

- The total anode plus cathode voltage drop is taken as about 30 V. This gives an energy injected into the electrodes of 75 kJ and 96 kJ respectively for the medium-voltage circuit-breaker and RMU of C.4.4, cases i) and j).

- The energy required to transform one mole of copper, initially at room temperature, into vapour has been calculated to be 390 kJ [48].
- Comparing the above values gives upper limits for the quantities of vapour formed in each case as 0,19 moles for the medium-voltage circuit-breaker and 0,25 moles for the RMU.
- Based on a molecular weight of 64 g/mole for copper, these values correspond to 12 g and 15,8 g of evaporated metal respectively.
- This represents erosions of about 1,4 cm^3 and 1,8 cm^3 of metal which is reasonable given the arc energies involved.
- These values are about 40 % higher than those extrapolated from experimental data obtained for multiple-shot, 4 kA tests, which give erosion rates between 2,5 and 4,5 mg/A/s copper electrodes.
- Employing the switchgear and controlgear room volumes given in C.7.1 of 120 m^3 and 30 m^3 respectively, final concentrations of about 100 mg/m^3 and 520 mg/m^3 are obtained.
- This is compared to the TLV of copper of 0,2 mg/m^3 [42].

NOTE – These results, using approximate data and methods, have been derived theoretically and have not been substantiated practically.

C.4.7.3 *Contribution due to the combustion of plastics*

This subject has not been treated as such, being outside the general scope of this report. However, the highly significant potential toxic contribution of these elements justifies their consideration. The combustion of plastic materials, such as wire insulation, following an internal fault, will produce a variety of toxic fumes, independent of switchgear and controlgear technology.

As an example, the case of polyvinyl chloride (PVC) will be considered. The TLV for vinyl chloride is 1 ppmv = 2,6 mg/m^3 [42]. This means that the full vaporisation of only 8 g will raise the atmospheric concentration of a 30 m^3 room to 100 times the TLV. For a 120 m^3 room, 32 g of PVC will give the same result. This represents the insulation of 1,2 m of standard 1 mm diameter wire.

A normal medium-voltage switchgear and controlgear room can contain several kilometres of wire of these dimensions, comprising about 7 kg of PVC per kilometre.

These estimations can be carried out for each of the plastic materials susceptible to combustion during an internal fault. The preceding observations indicate that the contribution of fumes due to the combustion of plastics should not be ignored and that exposure to such fumes should be kept as low as is reasonably practicable.

The conclusion is that the presence of SF_6 in switchgear and controlgear adds little to the toxicity of the atmosphere generated by an internal fault. This was indeed the conclusion drawn by a study carried out in 1987 [10].

Procedures and regulations should not thus single out switchgear and controlgear using SF_6 as requiring separate treatment.

NOTE – PVC vapours react with other products in the atmosphere to produce less toxic by-products. The above is hence a worst-case situation.

C.5 Assessment of results

C.5.1 *Leakage situations*

The SF_6 decomposition products, formed by arcing and by low-energy discharges, released due to leakage from SF_6-filled equipment, reach negligible concentrations in the workplace atmosphere. Under worst-case conditions the concentrations found for both medium-voltage and high-voltage cases are of the order of ten thousand times lower than the TLVs.

There is no cause for concern and no need for precautions other than the normal ventilation practices for low-lying areas. This conclusion is reinforced in consideration of the initial simplifying assumptions made in C.4.1.

Even in the case of abnormal leakage situations (a leakage rate for example of a thousand times the normal rate), these conclusions are unchanged.

C.5.2 *Internal fault*

To illustrate these cases, five rare but plausible situations covering the medium- and high-voltage spectrum have been chosen. In the most severe of these situations, the switchgear and controlgear room concentrations of SOF_2 remain below the momentary exposure limit C_m (see C.4.2).

In any situation of this sort, basic safety procedures include evacuation rules designed to ensure that personnel are not exposed to exhausted materials for more than a few minutes. Furthermore, forced ventilation and/or venting ensure the reduction of the concentration levels to much lower values within minutes. The added safety margins inherent in the application of either or both of the above are considerable.

Finally, SOF_2 is easily detectable by smell at concentrations between about 1 ppmv and 5 ppmv allowing very rapid preventative measures to be taken.

Therefore simple safety procedures will ensure that the practical exposure will be momentary and that the health of personnel will not be jeopardised.

C.5.3 *Outdoor installations*

Both for leakage and failure cases the calculations are carried out in an identical manner as above, but in this case the volume of air into which the arc decomposed SF_6 escapes is large if not infinite. Prevailing winds and the high exhaust velocity also speed up dispersion. Clearly, for the cases of leakage, the concentrations obtained will be infinitesimal. For the internal fault cases, within seconds the concentrations will fall well below the TLV values.

In conclusion no health risk is to be expected due to the toxicity of SF_6 decomposition product emission from outdoor switchgear and controlgear.

C.6 Conclusions

The results of the sample calculations show that, for leakage situations, there is no risk to health due to exposure to SF_6 decomposition products.

The results also show that, in the unlikely event of an internal fault leading to a release of SF_6, significant concentrations of SF_6 decomposition products can occur in a switchgear and controlgear room. However, the calculated concentrations do not exceed a substantiated limit for short-term exposure.

It is thus concluded that, as long as normal safety procedures are followed, there is minimal risk specifically associated with the use of SF_6 in switchgear and controlgear.

It has also been stressed that in any internal fault situation, corrosive and/or toxic fumes are produced whether or not SF_6 is present. In cases where these fumes enter the switchroom atmosphere, it has been shown that non-SF_6 related arc products are likely to be the dominant contributors to overall toxicity. This further strengthens the view that the use of SF_6 in switchgear and controlgear does not significantly add to the risks associated with an internal fault.

C.7 Data for calculations

C.7.1 *Switchgear and controlgear room volume (typical values)*

245 kV GIS hall (7 bays): 25 m x 12 m x 6,5 m = 2 000 m^3

145 kV GIS hall (7 bays): 12,5 m x 8 m x 7 m = 700 m^3

MV distribution hal (used for CB and MV GIS cases) (15 circuit-breaker panels):
10 m x 4 m x 3 m = 120 m^3

MV RMU room (1 ring main unit) (see also C.4.3.1): 4 m x 3 m x 2,5m = 30m^3

C.7.2 *Switchgear and controlgear volume and filling pressure*

Table C.8 – Switchgear volume and filling pressure

	Volume litres	Pressure MPa absolute
MV breaker	45	0,3
MV RMU	200	0,1
MV GIS	1 000	0,1
HV breaker	500	0,5
GIS bus	2 000	0,3

C.7.3 *Arcing characteristics*

C.7.3.1 *Fault current interruption/leakage situation*

Arc energy figures are totals for three interruptions of three-phase fault current, i.e. nine times the value for one single-phase interruption.

Table C.9 – Arc energies for interruptions

	I kA	U_{arc} V	t_{arc} ms	$9 \times E_{arc}$ kJ
MV CB	31,5	200	15	851
HV CB	31,5	500	15	2 126

C.7.3.2 *Internal fault/exhaust situation*

Arc energy figures are for N simultaneous arcs. The number of arcs has been chosen to represent the most likely internal fault situation.

Table C.10 – Arc energies for internal faults

	I kA	U_{arc} V	t_{arc} ms	N	E_{arc} kJ
245 kV GIS	40	1 000	100	1	4 000
145 kV GIS	31,5	1 000	100	2	6 300
MV GIS	25	300	100	1	750
MV CB	25	200	100	1	500
MV RMU	16	250	100	2	800

The values for arc time represent a compromise between real arcing times, rupture-disk operation, burn-through, constancy of the arcing environment and validity domain of available production rate data. Linear extrapolation above about twice these values is thus expected to grossly overestimate the results (see C.4.3.2).

C.7.4 *SOF_2 production rates*

The quantity of gas formed during an electrical discharge is quoted generally as a quantity generated per joule of energy dissipated (the production rate, *r*).

Experimentally determined SOF_2 production rates depend on the electrode material used and the type of discharge considered. Exothermic reactions, which occur with aluminium electrodes, seem to enhance the production rate.

Experimental results are generally quoted in moles/joule but in most practical cases it is more convenient to convert this to litres/kilojoule. This conversion is effected using the fact that one mole of any gas occupies 24,45 l, at 25 °C and at atmospheric pressure.

The values used here have been averaged over the range of presently available data found in the literature [4, 30, 31, 60].

Table C.11 – SOF_2 production rates

	SOF_2 production rate(*r*)	
Electrode material	Moles/joule	Litres/kJ
Cu, Fe, WCu	$150 \cdot 10^{-9}$	$3,7 \cdot 10^{-3}$
Al	$600 \cdot 10^{-9}$	$15 \cdot 10^{-3}$

NOTE – Aluminium electrodes are assumed only for GIS busbar situations.

C.7.5 *Quantity of SOF_2 formed*

This is found from arc energy and production rates.

Table C.12 – Quantities of SOF_2 formed

	Medium-voltage		High-voltage	
	Moles	Litres at 0,1 MPa	Moles	Litres at 0,1 MPa
Leakage	0,13	3,15	0,319	7,87
Internal fault				
245 kV GIS			2,4	60
145 kV GIS			3,8	95
MV GIS	0,45	11,25		
MV CB	0,075	1,9		
MV RMU	0,12	3,0		

C.7.6 *Leakage rates*

Leakage rates for sealed-for-life switchgear and controlgear are given as SF_6 volume lost per second per bar gauge of filling pressure.

For refillable switchgear and controlgear the leakage rate is given as a percentage of total gas loss per year.

Typical values for three-phase circuit-breakers are given below with conversion into total leaked SF_6 per day (24 h) and, for the medium-voltage case, per bar gauge of filling pressure.

Table C.13 – SF_6 leakage rates

	MV breaker	HV breaker
Basic rate	$3 \cdot 10^{-6}$ cm³/s/MPa gauge	0,5 % total SF_6 volume l/year
Daily rate	$27 \cdot 10^{-5}$ l/day/MPa gauge	$13,7 \cdot 10^{-6}$ x (SF_6 vol) l/day

C.7.7 *SOF_2 leakage rates (using data from C.7.5 and C.7.6)*

Table C.14 – SOF_2 leakage rates

	MV	HV
Volume SOF_2 formed (litres at 0,1 MPa absolute)	3,15	7,87
Total volume of SF_6 (litres at 0,1 MPa absolute)	135	2 500
SOF_2/SF_6 ratio inside circuit-breaker	2,33 %	0,31 %
Filling pressure (MPa absolute)	0,3	0,5
Leakage SOF_2 (litres per day)¹⁾	$1,26 \cdot 10^{-6}$	$107,8 \cdot 10^{-6}$

¹⁾ This is the amount of SOF_2 accumulated after 24 h leakage in a non-ventilated room.

C.8 Exposure limits

Terms used to define tolerable exposure limits can be separated into two groups:

- those intended to specify conditions under which a person can work continuously with no protective equipment, for example, Threshold Limit Value (TLV);
- those used to specify exceptional or abnormal situations of momentary exposure under which a person must leave the room, for example, Immediately Dangerous to Life or Health (IDLH).

C.8.1 *TLV-Threshold Limit Value*

The threshold limit value (TLV) is a term instigated by the American Conference of Industrial Hygenists (ACGIH). It refers to the maximum concentration of an element or substance, considered physiologically and physically acceptable during a specified exposure period.

The threshold limit value, time weighted average (TLV-TWA) is the time weighted average concentration at which a person can work for 8 h a day, 40 h a week with no adverse health effects. The averaging allows for instantaneous concentration levels of several times the TLV-TWA. Throughout this report the TLV-TWA is referred to simply as TLV and all references to TLV should be taken to mean TLV-TWA.

C.8.1.1 *TLV for SOF_2*

The official allowable workplace concentration of SOF_2 for full-time occupation (TLV) is expressed in terms of its fluoride content [41, 42, 49]:

TLV = 2,5 mg of fluoride F/m^3 of air at 25 °C and atmospheric pressure.

This corresponds to 5,66 mg/m^3 of SOF_2 in air (see note 2) at 25 °C and atmospheric pressure.

Expressed as a volume-per-volume atmospheric concentration of SOF_2:

TLV = 1,6 ppmv (see note 3).

NOTES

1 The TLV for SOF_2 has been quoted as 0,65 ppmv in certain publications. It appears that this value has been derived using the molecular weight of SOF_2 (86,1) rather than that of its fluoride content (2 x 19).

2 The conversion is obtained by calculating the mass of SOF_2 (per cubic metre of air) which corresponds to the TLV, expressed as 2,5 mg of fluoride F/m^3 of air. The molecular weight ratio of SOF_2 to its fluoride content is 86,1/(2 x 19) = 2,266; the mass of SOF_2 present per m^3 of air at the TLV is thus 2,5 x 2,266 = 5,66 mg SOF_2/m^3.

2 The conversion from mg/m^3 to volume ppm is carried out by multiplying by the molar volume (24,45 l at 25 °C) and dividing by the molecular weight (86,1 g/mole) [39, 42].

C.8.2 *IDLH - Immediately Dangerous to Life or Health*

This value of concentration is one from which a person can escape with no irreversible health effects, as long as the exposure does not exceed 30 minutes [42].

Annex D
(informative)

Environmental effects of SF_6

D.1 Introduction

Every human activity has an effect on the environment; the impact of a particular activity depends on its scale and on the materials involved. Activities where gases are produced or used may cause atmospheric pollution. Man-made atmospheric pollution has two major effects:

- stratospheric ozone depletion (hole in the ozone layer);

- average global temperature increase (greenhouse effect).

The gases causing these effects can be divided into two groups:

- Non-halogenated gases, mainly CO_2, CH_4, N_2O, produced by the burning of fossil fuels and by agriculture.
- Halogenated compounds, mainly aerosol spray propellants, foaming agents, solvents and refrigerants. The most common of these are chlorinated fluorocarbons (CFCs) [50, 51].

In 1990, a total of one million tonnes of CFC were produced, compared with about 8 000 tonnes of SF_6 [2, 3]. In the same year, the concentration of CFCs in the atmosphere was measured at 1,6 parts per billion volume (ppbv). This is compared with 0,0015 ppbv of SF_6, giving a concentration of SF_6 in the atmosphere 1 000 times lower than that of the CFCs [50, 52, 53].

D.2 Ozone depletion

The depletion of the ozone layer in the stratosphere has been recognised by the international community as a cause of adverse effects on the environment and on human health.

The ozone destruction mechanism in the case of CFCs [51] is catalysed by free chlorine atoms released when ultraviolet radiation breaks the bonds in a CFC molecule. The reactions are as below [54]:

$$\mathrm{CFC} \longrightarrow \mathrm{Cl} + \mathrm{CFC}_{\mathrm{remainder}} \tag{1}$$

$$\mathrm{Cl} + \mathrm{O_3} \longrightarrow \mathrm{ClO} + \mathrm{O_2} \tag{2}$$

$$\mathrm{ClO} + \mathrm{O} \longrightarrow \mathrm{Cl} + \mathrm{O_2} \tag{3}$$

$$\mathrm{O} + \mathrm{O_3} \longrightarrow 2\mathrm{O_2F} \tag{4}$$

The reaction paths shown above indicate that ultraviolet radiation breaks up the CFC molecules to produce free Cl (line 1). This Cl then destroys ozone (O_3) by forming ClO and O_2 (line 2). The end products of this reaction chain are Cl and O_2 (line 3).

Once a free Cl atom appears, it can immediately react again with O_3, thus forming a repetitive cycle for each individual Cl atom, passing many times through the reactions of lines 2 and 3 and destroying one O_3 molecule each time.

This is the so-called catalytic cycle, and one atom of Cl can go around the cycle ten thousand times before it is neutralised by other reactions. In the case of SF_6, the only halogen constituent is the fluorine F, for which the above catalytic reaction scheme is practically impossible for two reasons [50, 55]:

- due to the structure of its ultraviolet absorption spectrum, SF_6 is not photolysed in the critical ozone destruction altitude range between 32 km and 44 km, so that very little atomic fluorine is expected to come from SF_6;

- due to the high chemical affinity of fluorine to hydrogen, which is abundantly present in the stratosphere, any atomic fluorine that may have been produced from SF_6 would rapidly be neutralised by the formation of HF using the hydrogen atoms available from water molecules which are present at a concentration of 10 000 ppmv.

Taking account of the facts that one Cl atom can catalytically destroy 10 000 ozone molecules, that the concentration of SF_6 is 1 000 times lower than that of CFC and that virtually no free fluorine is formed from SF_6 under the circumstances as described, it is clear that SF_6 does not contribute to the destruction of stratospheric ozone.

D.3 Greenhouse effect

The average global temperature of the earth results from a balance between the heating effects of solar radiation and the cooling associated with the infra-red radiation from the earth. Some of the infra-red radiation is reflected back to the surface of the earth and therefore does not escape from the atmosphere.

The range of wavelengths in which this reflection occurs is from 7 µ to 13 µ [50, 56]. The natural reflectivity of the atmosphere within this spectral range is caused by the presence of CO_2, H_2O and O_3 and is increased in particular by man-made gases such as CO_2 from the burning of fossil fuels, N_2O from intensive agriculture, CFCs from spray propellants and refrigerators and CH_4 from intensive cattle farming.

SF_6 has absorption characteristics in the range from 7 µ to 13 µ.

Estimated contribution of various gases to the greenhouse effect [54]:

Table D.1 – Contribution of various gases to the greenhouse effect

Gas	Concentration ppbv	Percentage contribution
CO_2	$353 \cdot 10^3$	60
CH_4	$1{,}7 \cdot 10^3$	15
N_2O	310	5
O_3	10-50	8
CFC-11	0,28	4
CFC-12	0,48	8
SF_6	0,002	10^{-2}

It can be seen from the table that the contribution due to SF_6 is one part in more than 10 000 compared with the contribution of the other agents and is therefore negligible.

D.4 Decomposition products

The quantities of SF_6 decomposition products in switchgear and controlgear gas enclosures are small (see section 6) and they are not released into the atmosphere in significant quantities, even in the very unlikely event of an abnormal release (see section 5). At the end of life of an item of equipment, they are easily converted into stable compounds with no adverse environmental impact (see section 6 and annex B).

D.5 Conclusion

The substantial amount of evidence which is available indicates that SF_6 has a negligible impact on the global environment.

Section 6 and annex B show that SF_6 decomposition products can be transformed without difficulty into neutral products present in nature. Procedures for their treatment, handling and disposal ensure that they have a negligible impact on the local environment.

Annex E
(informative)

General safety recommendations, equipment for personal protection and first aid

Section 2 and annex A cover the handling and properties of new SF_6 gas and identify the precautions needed to avoid exposure to unacceptable risk when handling new gas.

Sections 4, 5 and 6 and annexes B and C cover the handling and properties of SF_6 containing decomposition products. Means of avoiding the potential dangers to health are recommended.

For medium-voltage switchgear and controlgear using sealed pressure systems, the contents of this annex are applicable only during end-of-life treatment (see section 6) or in the very unlikely event of an abnormal release (see section 5).

For other types of equipment, information in this annex is provided for use in situations where workers have to make contact with SF_6 decomposition products. Such situations include:

- maintenance or any other activity involving opening the SF_6-filled enclosures of equipment which has been in service;
- restorative activity after an internal fault or external fire provoking opening of the enclosure.

Experience over more than 25 years in working environments where contaminated gas is handled regularly has shown that personnel are unlikely to suffer adverse effects to their health, as long as they are suitably trained and equipped as indicated in this report and as recommended in the manufacturers' instructions.

E.1 General safety recommendations

If personnel are exposed to a significant concentration of decomposed SF_6 in the air, certain warning indications will be present. These are a pungent or unpleasant odour and/or irritation of the upper respiratory tract and eyes. These symptoms will occur within seconds, well before any significant toxic effects reaction can take place. Under these conditions, personnel should immediately move into the fresh air and wait until the gases have been safely diluted with air before returning to the equipment.

When handling solid decomposition products, adsorbent materials or vacuum-cleaner bags, workers should be aware that adsorbed gaseous decomposition products may be released and should protect themselves accordingly.

When an SF_6 enclosure is opened after the equipment has been in service, in order to avoid contact with the fine metallic fluoride powders which may be present (see B.1.1 and C.3.1), personnel should wear suitable protective clothing (see clause E.2). Particular attention should be given to protecting the eyes and the respiratory tract. Personnel working in or near to opened enclosures which have contained SF_6 decomposition products should:

- observe high standards of personal hygiene;
- not eat, drink or smoke;
- clean themselves and their equipment using disposable materials, before leaving the work area;
- remove protective clothing and wash themselves thoroughly as soon as possible after leaving the work area;
- ensure that clothing, tools and components which have been in contact with SF_6 decomposition products are packed securely in sealed bags or other sealed containers and are subsequently treated to neutralise any residues, as described in 6.5.6 and 6.5.7.

E.2 Equipment for personal protection

Personal protective equipment (PPE) should be used when contact with decomposed SF_6 or with SF_6 decomposition products is unavoidable.

Items selected from the following should be available. The selection will depend on the nature of the installation and of the work to be carried out and on the quantity of SF_6 involved, as well as on the expected degree of decomposition of the SF_6 (see 4.3.5). Manufacturers' recommendations and users' codes of practice should specify which items are necessary.

NOTE – International standards specifying certain items of equipment have not been identified. Where appropriate, European and national standards are referred to.

a) Pocketless, hooded, non-permeable (for example, bonded polypropylene) disposable industrial grade overalls having elastic ankle and wrist grips, overlapping the footwear and gloves.

b) Protective footwear.

c) Industrial type rubber gloves (preferably nitrile or neoprene). It is to be noted that heavy duty gloves may reduce the ability of personnel to work effectively. An adequate supply of lighter duty disposal gloves may be more appropriate.

d) Chemical type industrial goggles. Compliance with BS2092 Grade 1, impact C and D resistance or equivalent is advised.

e) An SF_6 detector capable of detecting 20 ppmv, 200 ppmv and 1 000 ppmv SF_6 in air. Recommended maximum SF_6 concentrations for various situations are given in clauses F.3 and F.4.

f) Equipment for first aid treatment in accordance with E.3.1, taking account of local industrial regulations.

g) Equipment as described in 4.2.1 to allow SF_6 gas to be handled safely without release into the working environment. The capacity of such equipment shall be adequate for the amount of gas to be handled. SF_6 handling equipment may be portable or permanently installed.

h) Suitable equipment for protection of the respiratory tract. The choice of equipment will depend upon the situation.

1) For work in an enclosed area where decomposed SF_6 has been discharged, or inside an SF_6 enclosure, a full face mask respirator with air supply according to European Standard EN 136 or equivalent is recommended.

2) For short-term inspection and work where ventilation can be provided but where the concentration of used SF_6 may exceed the appropriate maximum level, a face-mask with cartridge filter is recommended. European Standards EN 140, EN 141 and EN 143 specify masks, gas filters and particle filters respectively. Combined filters of type A2/B2/E2/K2/P3 manufactured to these standards are available and are able to provide protection against gaseous and solid SF_6 decomposition products including particles of greater than 1 µm diameter.

i) Equipment for forced ventilation of enclosed spaces and other inaccessible areas, for example cable ducts, SF_6 containers, etc. Such equipment might be portable or permanently installed, depending on the size of the installation and shall be of sufficient capacity to ensure that satisfactory working conditions, as recommended in the relevant sections of this report, can be maintained.

j) A high efficiency dedicated vacuum cleaner, equipped with a filter capable of trapping particles in the micron range, and a non-metallic open-ended nozzle. A type H machine in accordance with British Standard BS 5415, Supplement No. 1, 1986, or equivalent is suitable.

NOTE – BS 5415, Supplement No. 1, 1986, specifies the additional requirements for type H industrial vacuum cleaners suitable for the collection of non-explodable dusts hazardous to health. Work is proceeding at the IEC, which is expected to result in the publication of an international standard on this subject.

E.3 First aid equipment and treatment

E.3.1 *First aid equipment*

a) Normal industrial first-aid equipment including eye-wash equipment containing a saline solution.

b) Means for contacting emergency services.

c) Guidance for medical doctors.

E.3.2 *First aid treatment*

The application of the safety precautions described in clause E.1 should minimise the likelihood of accidents. If an accident occurs, first aid treatment should be applied as follows.

E.3.2.1 *Irritation of the skin*

If signs of skin irritation occur, the person should be removed from the area. Contaminated clothing should be removed and the affected part washed in cool running water. Medical advice should be sought if the irritation continues.

E.3.2.2 *Irritation of the eyes*

If signs of high irritation occur, the persons should be removed from the area. Irrigation of the eye or eyes should be carried out immediately and continued until medical or supervisory personnel advise the patient to stop. Should the patient be alone, irrigation should continue for 15 min after which medical assistance should be sought immediately.

E.3.2.3 *Breathing difficulty*

The person affected should be removed to fresh air as quickly as possible. Contaminated clothing should be removed and the patient should be covered with a blanket and kept still and under observation. Emergency medical assistance should be called without delay. If breathing fails, artificial respiration shall be given.

Annex F
(informative)

Detection and recommended maximum concentrations of new and used SF_6 in air

SF_6 gas is easily detected because of its electron capturing capability and for this reason it is used as a tracer gas. The stability and non-toxicity of SF_6 make it particularly attractive for this purpose. Applications include:

- checking the effectiveness of forced ventilation systems in large buildings and mines;
- locating leaks in sealed pressurised systems used for example in chemical processing.

Detectors specifically calibrated for SF_6 concentration measurement have been developed.

F.1 Detection by smell

It is not possible to detect new or clean SF_6 gas by smell as it is completely odourless.

SF_6 which has been subjected to electrical arcing or discharge is likely to contain by-products (see annex B), certain of which have very strong, distinctive odours. The most abundant by-product resulting from arcing, SOF_2, has a smell similar to hydrogen sulphide (H_2S), rather like that of rotten eggs. The smell is normally apparent at concentrations in air of 1 ppmv to 5 ppmv (see annex B). At these concentrations, short-term exposure presents no danger to health (see annexes B and C).

Hydrolysable fluorides including SOF_2 react with atmospheric moisture to produce HF. This has an irritating acidic odour and irritates the eyes. The odour is apparent also at a few ppmv's, at which level, temporary exposure has no harmful effect (see B.1.1 and C.4.5.1).

The odours can serve as an early warning that SF_6 decomposition products are present but the intensity of an odour is subjective and cannot be used as a criterion for safety. For this reason, if an unusual smell is noticed, a respirator should be used until additional ventilation has been provided. An SF_6 detector can then be used to trace the source, if necessary.

F.2 Detection equipment

F.2.1 *Portable SF_6 detectors*

Portable detectors for SF_6 are broadly of two types:

a) Electron capture detector using a ß-particle source to ionise a pumped sample. The ion current between electrodes is measured. An inert gas carrier is usually used. This type is much more expensive and considerably less portable than type b). Sensitivities below 0,1 ppmv of SF_6 in air can be achieved.

b) Corona discharge cell using a high-voltage (1 kV to 2 kV) applied to a point-plane electrode configuration. The discharge current is measured. This type of detector is used in a variety of highly portable, battery-powered units of relatively low cost. Sensitivities of below 10 ppmv can be achieved, but not with all available units [57].

Detectors of type a) are generally used for leak tracing and quantification.

Detectors of type b), if sufficiently sensitive, could be suitable for assessing whether an area contains SF_6 and can be useful for leak detection [57].

F.2.2 *Alarm system SF_6 detectors*

Alarm systems require detectors with very high long-term stability. The infra-red absorption characteristic of SF_6 is used as the basis for most detectors of this type [58]. An infra-red source is used to heat a gas sample in a differential pressure-measuring device using a sensitive capacitance transducer. The pressure rise is measured.

Sensitivities down to 10 ppmv can be achieved. Automatic calibration facilities may be incorporated. In some installations, samples of air are piped from various points to a central detector. The active detection point can be selected automatically or manually. This type of detector tends to be expensive and is not available in a portable form.

Alarm systems incorporating SF_6 detectors are generally used only where very large volumes of SF_6 are contained in equipment housed indoors, such as in high-voltage GIS installations.

F.2.3 *Detection of SOF_2 and other SF_6 decomposition products in air*

The measurement of the concentration of SOF_2 in air may provide a suitable basis for assessing whether or not it is safe to work in a given environment as long as significant SOF_2 hydrolysis has not occurred (see C.3.2.1). If hydrolysis has occurred, the concentrations of SO_2 and HF are of interest.

Equipment for measuring decomposition product concentrations should have a measurement threshold below the TLV of the decomposition product to be measured.

Gas-phase chromatography or infra-red spectroscopy are suitable techniques. Portable detectors using the infra-red absorption characteristics of various gases are available; this technique may be applicable to SOF_2, SO_2 and HF.

F.3 Maximum permissible concentration of new SF_6

As stated in 2.4.1.1, the maximum permissible concentration of new SF_6 in the atmosphere is 1 000 ppmv. This value is appropriate for use when equipment is being filled with new SF_6.

F.4 Recommended permissible maximum concentrations of used SF_6

Recommended permissible maximum concentrations of used SF_6 in the air are given for use during two groups of situations:

a) maintenance or extension of HV equipment, or abnormal leakage;

b) following an internal fault or external fire.

Under the above circumstances it is necessary to ensure that the concentrations in the air of the principal decomposition products remain below the limit values for a multi-component mixture. This can be achieved by direct measurement or, in the absence of suitable equipment, by an indirect method.

The indirect method uses estimated quantities of SOF_2, SO_2 and HF present in the SF_6. A measurement of the SF_6 concentration in the air can then be used for risk assessment. This approach is used to derive the values for decomposed SF_6 given in F.4.1 and F.4.2.

NOTE – Evaluation of the risk of exposure to a multi-component mixture by direct measurement of the concentrations of the individual components is possible but is likely to be complex for practical application. Methods and apparatus for this are under consideration.

F.4.1 *Maximum permissible concentration of used SF_6 during maintenance and extension of high-voltage equipment (see section 4) or abnormal leakage (see clause 5.2): 200 ppmv*

Under these conditions, where no abnormal arcing (internal fault) has occurred, the degree of SF_6 decomposition will be limited. Low to medium decomposition, as defined in a) and b) of 4.3.5.1, is to be expected, depending on the type of equipment and its service history. The calculation results of C.7.7 show that the SF_6 in a high-voltage circuit-breaker, after three interruptions of three-phase current at 31,5 kA, will contain about 0,3 % SOF_2.

The maximum permissible concentration of SOF_2 in air (the TLV) is 1,6 ppmv (see C.8.1.1). The concentration of SF_6, containing 0,3 % SOF_2, necessary for the TLV of SOF_2 to be reached, is given by:

$$C = \frac{\text{TLV } (SOF_2)}{\text{Concentration of } SOF_2 \text{ in } SF_6} = \frac{1{,}6 \text{ ppmv}}{0{,}3\ \%} = 537 \text{ ppmv}$$

If conditions are such that hydrolysis of the SOF_2 can occur (see B.1.1), SO_2 and HF are formed. Each mole of SOF_2 gives rise to one mole of SO_2 and two moles of HF. The maximum acceptable concentration for this mixture is reached when:

$$R = \frac{\text{Concentration of } SO_2}{\text{TLV } (SO_2)} + \frac{\text{Concentration of HF}}{\text{TLV (HF)}} \leq 1$$

The HF concentration is twice the SO_2 concentration, which is the same as the initial SOF_2 concentration (x), giving:

$$R = \frac{x}{2 \text{ ppmv}} + \frac{2\,x}{3 \text{ ppmv}} \leq 1, \text{ so that } x\,(\max) = 0{,}86 \text{ ppmv}$$

The concentration of SF_6 in the air should be such that the concentration of SO_2 does not exceed this figure. This is given by:

$$C = \frac{x}{\text{Concentration of } SO_2 \text{ in } SF_6} = \frac{0{,}86 \text{ ppmv}}{0{,}3\ \%} = 286 \text{ ppmv}$$

A maximum concentration of 200 ppmv of used SF_6 in air should therefore be adopted for situations where SF_6 has to be handled during maintenance or extension of HV equipment or following an abnormal leakage. This value is applicable irrespective of the degree of SOF_2 hydrolysis.

NOTE – This value of 200 ppmv is intended as a guide for use with high-voltage switchgear and controlgear in normal service. In other situations and in particular when tests are being carried out in a research or test laboratory, higher degrees of decomposition could occur. Under such circumstances it may be necessary to adopt a lower maximum concentration than 200 ppmv volume of SF_6 in the air.

F.4.2 *Maximum permissible concentration of used SF_6 following an internal fault or external fire provoking opening of the enclosure (see clause 5.3): 20 ppmv*

When uncontrolled arcing has occurred, high decomposition of the SF_6, as defined in c) and d) of 4.3.5.1, can occur. Annex C (see C.7.5) shows that a high-voltage compartment (145 kV GIS) with a 2 000 l capacity, filled with SF_6 at 0,3 MPa absolute, can contain 95 l of SOF_2 so that the concentration of SOF_2 in the SF_6 would be 1,6 %. The concentration of such SF_6 in the air, for the TLV of SOF_2 to be reached, would be:

$$C = \frac{\text{TLV } (SOF_2)}{\text{Concentration of } SOF_2 \text{ in } SF_6} = 100{,}6 \text{ ppmv}$$

Hydrolysis of the SOF_2 in this case is unlikely to occur because repair work would normally be carried out shortly after the fault. It is considered unlikely, but nevertheless possible, that higher levels of SF_6 decomposition could be encountered, so a maximum concentration of SF_6 in air of 20 ppmv should be adopted during any work following an internal fault. The use of this value should provide a large safety factor and will account for the marginal increase in toxicity due to SOF_2 hydrolysis, in the unlikely event that sufficient time has elapsed for this to occur.

Annex G

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