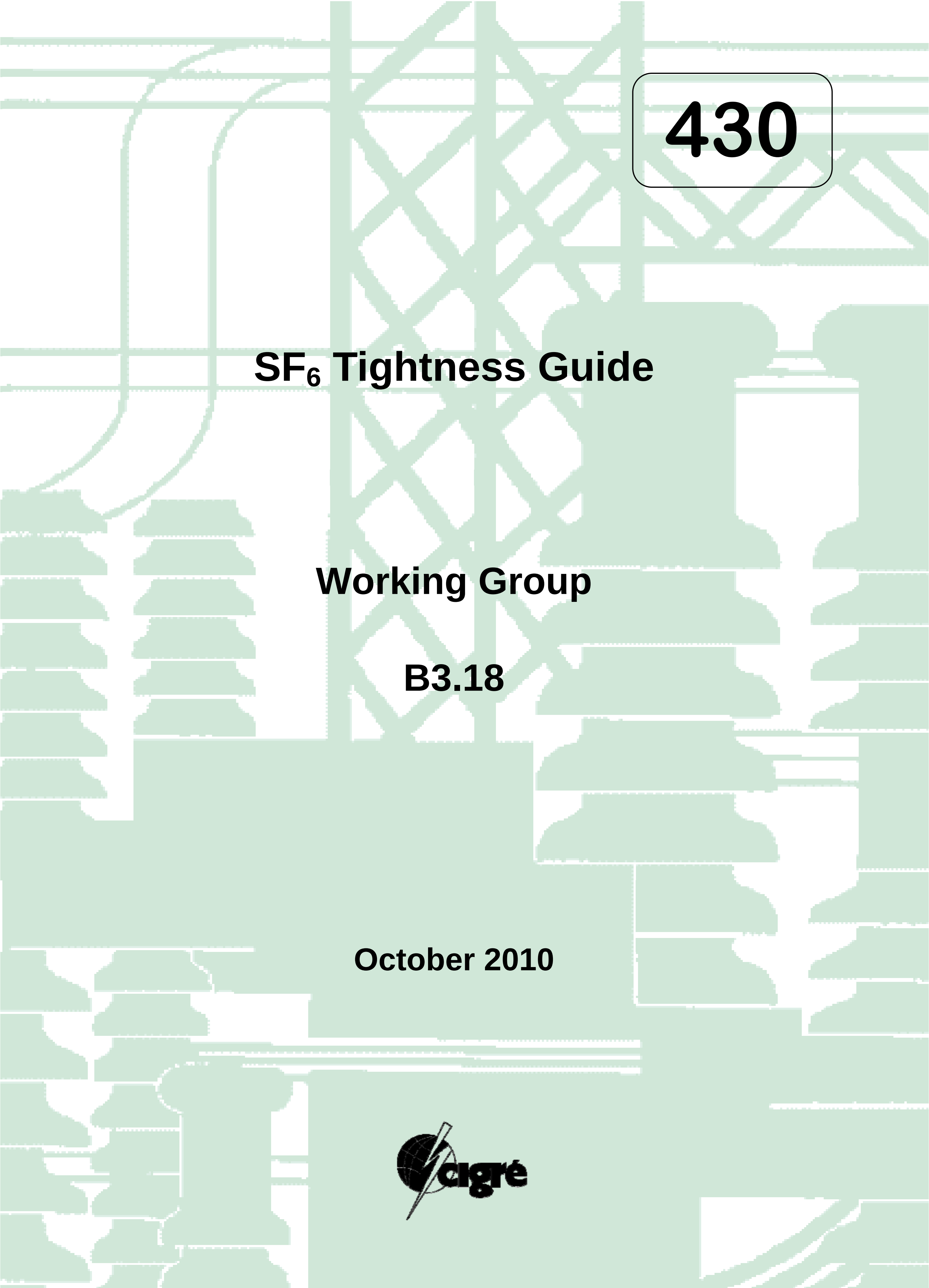

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SF$_6$ Tightness Guide

Working Group

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SUMMARY

This document reviews all significant aspects of measuring and how to ensure the tightness of electric power equipment during its expected lifetime. The equipment may contain SF_6 as a pure gas or combined with other gases (i.e.: N_2) to form a gas mixture.

Requirements from the International Standard are critically reviewed. A functional description concerning state-of-the-art test procedures, test methods and instrument devices is then performed. The difference between what can be measured (and how it can be done) and what can be assessed forms the conclusions.

Type testing, factory routine testing, on-site testing during service are described, continuous on-line monitoring (i.e.: supervision of the SF_6 density using on-line monitoring systems) is included.

Any mechanical withstanding or rupture test (i.e.: water rupture test), performed at pressures above the maximum operating gas pressure, is carried out for safety purpose and therefore are not covered in this document except for the impact of mechanical pressure test procedures on tightness test results.

In general, any procedure concerning the tightness of electric power equipment shall be defined and implemented so as to assure the lowest possible quantity of SF_6 is released to the environment. In particular, any test not depending on the gas nature can be performed without SF_6 (e.g. mechanical operational tests).

SF_6 emissions as a consequence of gas handling are treated in the CIGRE brochure no. 276, “Guide for the preparation of customised practical SF_6 handling instructions”.

Contents

1 Introduction

State-of-the-art electric power equipment is designed and manufactured to maintain integrity and tightness for decades so that it is compatible with the environment for its whole service life. This implies:

- Very low leakage rates: the quality of the encapsulation including its material, the machining process, the design of gaskets, the sealing material itself, the quality of secondary connections (e.g. piping, valves, sensors, bursting disk, current transformer) and the factory testing procedures are of major importance;
- Very low handling losses: smaller gas compartments, reduced frequency of maintenance activity (e.g. opening a gas compartment for inspection, checking the gas quality, checking the gas density/pressure with an external density/pressure gauge), state-of-the-art tools, procedures for SF_6 recovery and/or reuse at the end-of-life of the electric power equipment, and instruments to handle and to check the gas quality, specific training of designated personnel. Refer to CIGRE Brochure no. 276, "Guide for the Preparation of Customised SF_6 Handling Instructions" for further information.

2 Definitions

Accumulation volume

The volume bounded by a cover (e.g. plastic sheet, metal box, tent, gas tight sheath) surrounding the object under test used for accumulating leaked SF_6 over time.

Detectable leakage

Any leak detected above the sensitivity of the method used to perform the measurement.

Emissions

Referring to a pressurised vessel or gas compartment, the total mass of gas released to the environment during its expected lifetime. Emissions are the sum of handling losses plus leakage losses.

Gas-filled compartment (often abbreviated to: Gas compartment)

As per IEC 62271-1, it is a compartment of switchgear and controlgear in which the gas pressure is maintained by one of the following systems:

a) controlled pressure system;

b) closed pressure system;

c) sealed pressure system.

NOTE Several gas-filled compartments may be permanently interconnected to form a common gas-system (gas-tight assembly).

Gas mixture

Any gas mixture containing SF_6 (e.g. SF_6 and N_2).

Recommendations, procedures and/or best practices applicable to SF_6 are generally also applicable to gas mixtures.

Leakage rates

Absolute leakage rate

As per IEC 62271-1, this is the amount of gas leaked per unit time.

The absolute leakage rate indicates the loss of gas per unit time caused by the leak. When the preferred unit of measurement is "grams of gas lost per year" [g/a] the quantity is the mass flow indicated by the symbol $\dot{m}$. Other units in use are [Pa.cm^3/s] or [Pa.m^3/s] and the corresponding symbol is L:

$$1 \cdot \boldsymbol{Pa} \cdot \boldsymbol{cm}^3 / \boldsymbol{s} = 10^{-6}\, \boldsymbol{Pa} \cdot \boldsymbol{m}^3 / \boldsymbol{s} = 1.89 \cdot \boldsymbol{g} / \boldsymbol{a}$$

This conversion is valid for gaseous SF_6 at 20 °C as 0.0607 µg is the mass of 1 cm^3 of SF_6 at 20 °C and 1 Pa and there are 3 600 x 24 x 365 = 31 536 x 10^3 seconds in 1 year. Alternatively the following unit is used:

$$1 \cdot \boldsymbol{mbar} \cdot \boldsymbol{l} / \boldsymbol{s} = 0.1 \cdot \boldsymbol{Pa} \cdot \boldsymbol{m}^3 / \boldsymbol{s}$$

Permissible leakage rate

As per IEC 62271-1, this is the maximum permissible absolute leakage rate of gas specified by the manufacturer for a part, a component or a sub-assembly, or by using the tightness coordination chart (TC), for an arrangement of parts, components or sub-assemblies connected together in one pressure system.

The values defined in the Standards consider the functionality of the electric power equipment.

For a system containing mass m of SF_6 in [kg] and having a permissible relative leakage rate F_p in [% p.a.], the permissible mass flow $\dot{m}_p$ in [g/a] is:

$$\dot{m}_p = 10 \cdot F_p \cdot m$$

For a system of internal volume V in [m^3], having a rated filling pressure p in [Pa] and a permissible relative leakage rate F_p in [% p.a.], the permissible leakage rate L_p in [Pa.m^3/s] is:

$$L_p = F_p \cdot \frac{p \cdot V}{100 \cdot 3600 \cdot 24 \cdot 365}$$

Obviously the specific gas density ρ [kg/m^3] at a given temperature and pressure relates p [Pa] and V [m^3]

$$m = V \cdot \rho$$

By differentiation considering a constant specific gas density, it becomes

$$\dot{m} = L \cdot \rho$$

Under normal environmental conditions, 100 kPa and 20 °C, the SF_6 density ρ is 6.07 kg/m^3

NOTE: For the purpose of tightness and to preserve the environment, the absolute SF_6 mass released to the atmosphere is the important issue. During the last decades, the evolution of the state-of-the-art SF_6 technology has enabled a considerable reduction of the absolute leakage rate.

Relative leakage rate

As per IEC 62271-1, this is the absolute leakage rate related to the total amount of gas in the system at rated filling pressure (or density). It is expressed in percentage per day or per year; the quantity is indicated by the symbol F and the preferred unit is percentage per year [% p.a.].

For a system containing mass m of SF_6 in [kg] and having a mass flow $\dot{m}$ in [g/a], the relative leakage rate F in [% p.a.] is:

$$F = 0.1 \cdot \frac{\dot{m}}{m}$$

For a system of internal volume V in [m^3], having a rated filling pressure p in [Pa] and an absolute leakage rate L in [$Pa.m^3/s$], the relative leakage rate F in [% p.a.] is:

$$F = 100 \cdot L \cdot \frac{3600 \cdot 24 \cdot 365}{p \cdot V}$$

Leaking location

Place where leakage occurs and causes a loss of gas.

Losses

Handling losses

Referring to a pressurised vessel or gas compartment, the total mass of gas released to the environment when the gas is handled during the expected lifetime. Typical cases are gas recovery during service or at the end-of-life of electric power equipment and sampling the gas for checking its quality.

Leakage losses

The total mass of gas released to the environment due to leakage from the pressurised vessel or gas compartment containing the gas.

Pressure systems

Closed pressure system for gas

As per IEC 62271-1, this is a volume which is replenished only periodically by manual connection to an external gas source.

NOTE Example of closed pressure systems are SF_6 single-pressure circuit-breakers.

Controlled pressure system for gas

As per IEC 62271-1, this is a volume which is automatically replenished from an external compressed gas supply or internal gas source.

NOTE 1 Examples of controlled pressure systems are air-blast circuit-breakers or pneumatic operating mechanisms.

NOTE 2 A volume may consist of several permanently connected gas-filled compartments.

Sealed pressure system

As per IEC 62271-1, this is a volume for which no further gas or vacuum processing is required during its expected operating life.

NOTE 1 Examples of sealed pressure systems are tubes of vacuum circuit-breakers or some SF_6 circuit-breakers.

NOTE 2 Sealed pressure systems are completely assembled and tested in the factory.

Sniffer or sniffing device

Instrument for detecting the presence of low local concentrations of SF_6 by taking a quantity of SF_6 into the instrument.

Sniffing or probing

Sniffing or probing is the action of moving the probe head of a sniffer with a constant speed of approx. 10 mm/s and at a constant distance of less than 50 mm along a specimen.

Tightness

The tightness, or tightness rate, of pressurised vessels or gas compartments is their ability to contain gases over a defined temperature range. It can be considered as the complement of the relative leakage rate F_{rel}:

$$\text{tightness} = 100 - F_{rel} \qquad [\% \text{ p.a.}]$$

For the remainder of this document, tightness is used to describe the concept, whilst leakage rate is used as a value.

3 Requirements from Standards

3.1 IEC

The aim of the IEC Standards is to specify electrical components and systems as well as their interactions within the power grid. The focus is on ensuring both safety and continuity of network operations. In case of electric power equipment utilising SF_6, the following Standards are relevant:

- IEC 62271-1 High-voltage switchgear and controlgear – Part 1: Common specifications;

- IEC 62271-200 “High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV”, currently under revision;
- IEC 62271-203 “High-voltage switchgear and controlgear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV”, currently under revision.
- IEC 62271-303 “High-voltage switchgear and controlgear – Part 303: Use and handling of sulphur hexafluoride (SF_6)”

The next paragraphs give a short summary of the Standards with the scope of identifying and listing the technical requirements both / either a type test and / or a factory routine tightness tests should fulfil.

Some comments which can be considered as proposals for amendment to Standards are also included. The focus is on maximising the environmental compatibility of the SF_6 technology and reducing any SF_6 release down to the minimum level achievable with new electric power equipment and state-of-the-art handling equipment and procedures.

3.1.1 IEC 62271-1

The Standard defines requirements for the tightness of electric power equipment at the stages of design, type test, and factory and/or on-site routine test in order to ensure the equipment functionality and the continuity of operation.

The standard distinguishes between controlled, closed and sealed pressure systems for gas. While controlled pressure systems are no longer produced, but still in use, the state-of-the-art equipment for high-voltage applications is defined to be a closed pressure system and for medium-voltage equipment it is defined to be a sealed (for life) pressure system. Controlled pressure systems shall not be used for new equipment and the installed base shall be replaced with either closed or sealed pressure systems (see paragraph 7.1),

Standardized values for the permissible leakage rate F_p for closed pressure systems at ambient temperature are 1 % and 0.5 % p.a. and per gas compartment.

Preferred values for the expected operating life of sealed pressure systems, with regard to leakage performance, are 20 years, 30 years and 40 years. To fulfil the expected operating life requirement, the leakage rate for sealed pressure systems is considered to be of the order of 0.1 % p.a.

The tightness type test shall be performed in connection with the tests required in the relevant standards, typically before and after the mechanical operation test or during the operation tests at extreme temperatures. The purpose of tightness tests is to demonstrate that the absolute leakage rate ***F*** does not exceed the specified value of the permissible leakage rate F_p.

The Standard assumes the ambient temperature to be any temperature between defined limit values. An increased leakage rate during operation at extreme temperatures is acceptable, provided that this rate resets to a value not higher than the maximum permissible value at normal ambient air temperature. The increased temporary leakage rate shall not exceed the values given in table 13 of the standard.

During type testing, the tightness tests shall be performed with the same fluid (i.e. gas) and under the same conditions as used in service. If the fluid itself is not traceable additional traceable fluids might be added, for example helium.

During factory routine testing, no restrictions are given to the kind of testing gas. Allowance is made for manufacturer's best practice with respect to filling pressure. Also, sniffers may be used.

As already stated in the previous CIGRE brochure no. 276, "Guide for the preparation of "Customised SF_6 Handling Instructions", the following recommendations should be taken into account during further revision work of the standard:

- Because of their high leakage rate, controlled pressure systems should no longer be used in new equipment and those already installed should be replaced by closed pressure systems;
- The permissible leakage rate F_p for closed pressure systems should not exceed 0.5 % p.a. and per gas compartment and the time between two consecutive replenishments should be in line with the expected service life, typically 25 years;
- Appropriate measures should be arranged to locate and eliminate a leak as soon as it is detected and intermediate repair should be limited;
- Frequent topping up of leaking compartments should be avoided;
- Checking the SF_6 quality in the gas compartments should be done on a reliability based system instead of a time based system;
- The use of other gases (e.g. helium) to perform the tightness test should be allowed as they enable the higher sensitivity and accuracy required for medium-voltage equipment;
- The information given in Table 1 and Table 2 should be taken into account.

A final recommendation is given to OEMs about performing the safety rupture test of compartments utilising a gas (e.g. helium) instead of a liquid (e.g. water) because the liquid, penetrating the possible porosities, gives a temporary tightness which can affect future tightness tests.

3.1.2 IEC 62271-200

The standard regulates equipment with a rated voltage lower than and including 52 kV and mainly refers to IEC 62271-1 for issues related to tightness. It defines a design temperature, which is equal to the upper limit of the ambient temperature range increased by the temperature rise of the gas due to the rated current.

The majority of state-of-the-art equipment produced at this voltage level is assembled in the factory and utilises a "sealed pressure system". IEC 62271-1 gives 0.1 % p.a. as a considered value for sealed pressure systems and the standard refers to this value.

The factory routine tightness test is normally performed using helium as tracer gas and a mass spectrometer to measure the leakage rate as described in paragraph 4.2.2 below.

3.1.3 IEC 62271-203

The standard regulates equipment with a rated voltage equal to or higher than 52 kV and mainly refers to IEC 62271-1 for issues related to tightness. The leakage rate F_p from any single compartment of GIS to atmosphere and between compartments shall not exceed 0.5 % p.a. for the service lifetime of the equipment. However, this is the only standard giving also a statement concerning SF_6 emissions, as they are the sum of leakage and handling losses.

The overall value given in the Standard as a note of 15 % in 25 years averaged over the whole substation may be significantly reduced by adopting an appropriate strategy for monitoring and maintenance (see paragraph 7).

SF_6 emissions should be considered for each gas compartment instead of being averaged over the whole substation. The minimisation of the emissions should be based on:

- The state-of-the-art electric power equipment;
- The state-of-the-art maintenance strategy;
- The state-of-the-art gas handling equipment and procedures;
- Trained and educated personnel handling SF_6.

The factory routine tightness test can be performed on sub-assemblies using helium as tracer gas and the mass spectrometer to measure the absolute leakage rate as described in paragraph 4.1.3.

The standard requires that for the mechanical operation tests, the measurement of gas tightness shall be performed before and after the test to show that the leakage rate is not influenced by the mechanical type tests.

A qualitative gas tightness test shall be carried out on all field assembled connections performed on-site. A sniffer can be used for this purpose.

So far, the standard is under revision.

3.1.4 IEC/TR 62271-303

The standard addresses the procedures for safe and environmental compatible handling of SF_6 during installation, commissioning, normal and abnormal operations, and disposal at the end of life of high-voltage switchgear and controlgear. Storage and transportation of SF_6 are also covered. These procedures should be regarded as minimum requirements to ensure the safety of personnel working with SF_6 and to minimize the SF_6 emission to the environment.

This first edition of the standard is a major revision of the old IEC 61634 based on the CIGRE brochure no. 276.

IEC 61634 was issued in 1995 when the focus was on safety. In 2008, safety is a very well known and established concept and the focus is nowadays on the environmental compatibility. SF_6 must be kept in a closed cycle and any intentional release must be forbidden. The implementation of the SF_6 reuse concept suggested in the CIGRE brochure was updated with the most recent information. Today SF_6 can be recovered and reclaimed for either being reused on-site or given back to the gas supplier to be reused as raw material for the production of “technical grade SF_6”.

Detailed procedures for appropriate SF_6 handling are given together with the description of the state-of-the-art equipments and measuring devices.

IEC/TR 62271-303 is now under revision to become IEC 62271-4. It will consist of a normative part (sections 7, 8, 9 and 10 of IEC/TR 62271-303) and an informative part (the remaining sections).

3.2 IEEE

In case of electric power equipment utilising SF_6, the following IEEE Standards are relevant:

- IEEE Std C37.100.1-2007 IEEE Standard of Common Requirements for High-Voltage Power Switchgear Rated Above 1000 V. At the present time the standard gives no common requirements for SF_6 tightness and requires reference to be made to the relevant equipment standards.
- IEEE Std C37.04-1999 (R2006) IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers. The standard distinguishes between closed and sealed pressure systems. For closed pressure systems the maximum leakage rate shall be less than 1 % p.a. No indication is given for sealed pressure systems.
- IEEE Std C37.10.1-2000 IEEE Guide for the Selection of Monitoring for Circuit Breakers. The standard describes circuit breaker failure modes. In the mode “Fails to provide insulation”, a cause is listed as “Loss of dielectric medium” due to gradual leaks over time. The monitoring options are described in Table 12.
- IEEE C37.122-1993 IEEE Standard for Gas-Insulated Substations. The standard is currently under revision. The latest draft issued in 2010 is harmonized with IEC 62271-203.
- IEEE Std C37.122.1-1993 (R2002) IEEE Guide for Gas-Insulated Substations. The standard is currently under revision. The revised document is planned to be issued in 2011.
- P1712 "Guide for SF_6 Handling with High Voltage Equipment" (Under Development). This document is presently under development – and is based on the CIGRE brochure no. 276, “Guide for the Preparation of Customized Practical SF_6 Handling Instructions”. The issues the guide raises on gas tightness are presented in Section 3.1.2 of this document. The corresponding IEEE Guide will contain the same issues. The goal of the development of the IEEE Guide is to maintain as much of the original CIGRE brochure guidance as possible, with only the minor changes necessary to convert it to an IEEE Guide. This will help facilitate alignment on the global issue of SF_6.

3.3 JEC-2350 (Japanese Electrotechnical Committee standard for GIS)

The standard was published in 1994, and revised in 2005. The outline is given below.

3.3.1 Design

The standard requires closed pressure systems to be designed for a leakage rate less than 0.5 % p.a. which has to be proved by type testing. The evaluation criterion of less than 0.5 % p.a. is adopted to coincide with the requirement of IEC 62271-203.

3.3.2 Type test

The standard requires a leakage test and the standard leakage test method is the accumulating method. Nevertheless the use of sniffers is also allowed during type testing.

3.3.3 Routine test

The standard requires a leakage test, but no method is prescribed. The use of sniffers is common practice. The evaluation criterion is less than 1.0 % p.a.

3.3.4 On-site test

As for routine test, the standard requires a leakage test, but no method is prescribed. The use of sniffers is common practice. The evaluation criterion is less than 1.0 % p.a.

In JEC-2350, there is an explanation about the leakage test to coincide with the requirement of IEC 62271-203 and the field data about SF_6 leakage from GIS (see Appendix 3 below for field data on SF_6 leakage from GIS and gas insulated circuit breakers in Japan).

3.4 Chinese Standards

The following Chinese Standards are relevant for electric power equipment utilising SF_6:

- GB/T 11022 Common specifications for high-voltage switchgear and controlgear standards. The standard has been modified according to IEC 60694: 1996 and it is planned to update it according to IEC 62271-1;
- GB/T 3906 Alternating current metal-enclosed switchgear and controlgear for rated voltages above 3.6 kV and up to and including 40.5 kV. The standard has been modified according to IEC 62271-200: 2003;
- GB/T 7674 Gas-insulated metal-enclosed switchgear for rated voltages of 72.5kV and above. The standard has been modified according to IEC 62271-203: 2003.

3.5 GOST Standards

The technical requirements of SF_6 are defined in TU 6-02-1249-83 for electric power equipment utilising SF_6.

The only requirement of SF_6 leakage for high-voltage equipment is mentioned in GOST R 52565-2006 (Alternating-current circuit-breakers from 3 to 750 kV). According to the standard the leakage rate must be less than 1 % p.a.

There are no requirements for other equipment. In that case it is common practice for the manufacturer to define the leakage rate by experience.

4 Test procedures

4.1 Introduction

The tightness of electric power equipment is defined in the various standards given in paragraph 3 above. The permissible leakage rates depend on the kind of switchgear: sealed pressure systems mainly for medium-voltage equipment or closed pressure systems mainly for high-voltage equipment. The design and size of these two systems are quite different. Also different tightness testing procedures are applied for the proof of tightness in the factory or on-site.

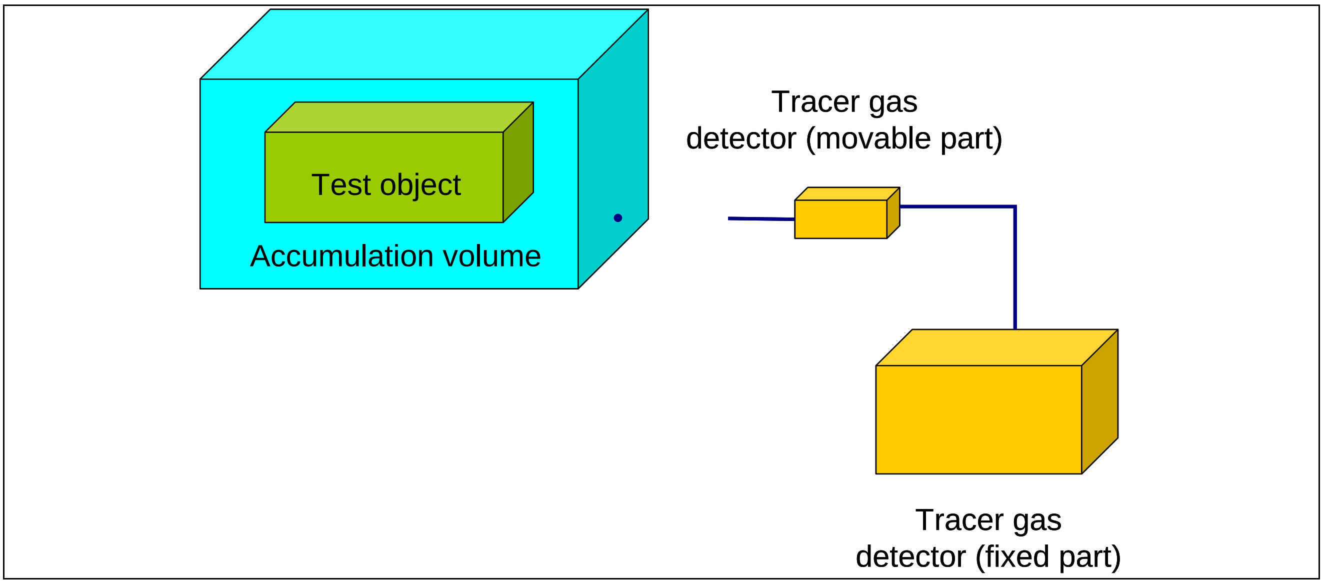
For these reasons, tightness tests are performed differently on high-voltage and medium-voltage equipment.

The testing procedures are well known and described in the standard IEC 60068-2-17 “Basic environmental testing procedures – Part 2: Tests – Test Q: Sealing”. It is worthwhile to have a closer look into this standard and to apply the general procedures to the tightness tests used in the electric industry. In the subsequent paragraphs specific procedures are described in detail separately for type and routine tests. Finally recommendations are given for commissioning activities and monitoring in service.

4.1.1 Test Q_m method 1 as per IEC 60068-2-17

Figure 1 shows the test Q_m method 1 which is defined as a “tracer gas sealing test with internal pressurisation”. It is performed as a cumulative sealing test and normally applied during a type test or factory routine test.

Figure 1: Test Q_m method 1 (tracer gas sealing test with internal pressurisation, cumulative sealing test)

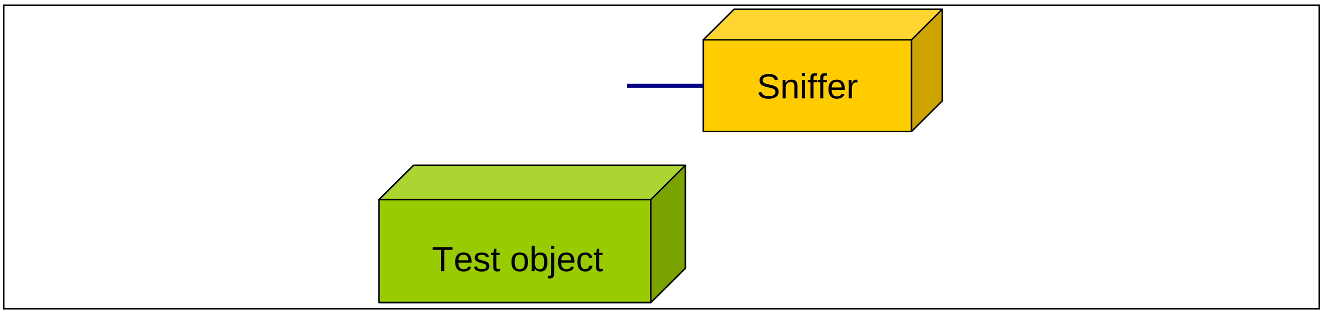


The test object is filled with SF_6 at the rated filling pressure/density and is then placed into the accumulation volume. The concentration of the tracer gas in the accumulation volume is measured at the beginning and end of the test. The leakage rate can be calculated from the net accumulation volume and the accumulation time. The description of some SF_6 detectors is given in paragraph 5.2. The practical application of the test method is given in paragraph 5.3.1.

4.1.2 Test Q_m method 2 as per IEC 60068-2-17

Figure 2 shows the test Q_m method 2 which is also defined as a “tracer gas sealing test with internal pressurisation”. It is performed as a probing test and normally applied for the factory routine test of high-voltage equipment or for tightness checking on-site.

Figure 2: Test Q_m method 2 (tracer gas sealing with internal pressurisation, probing test)

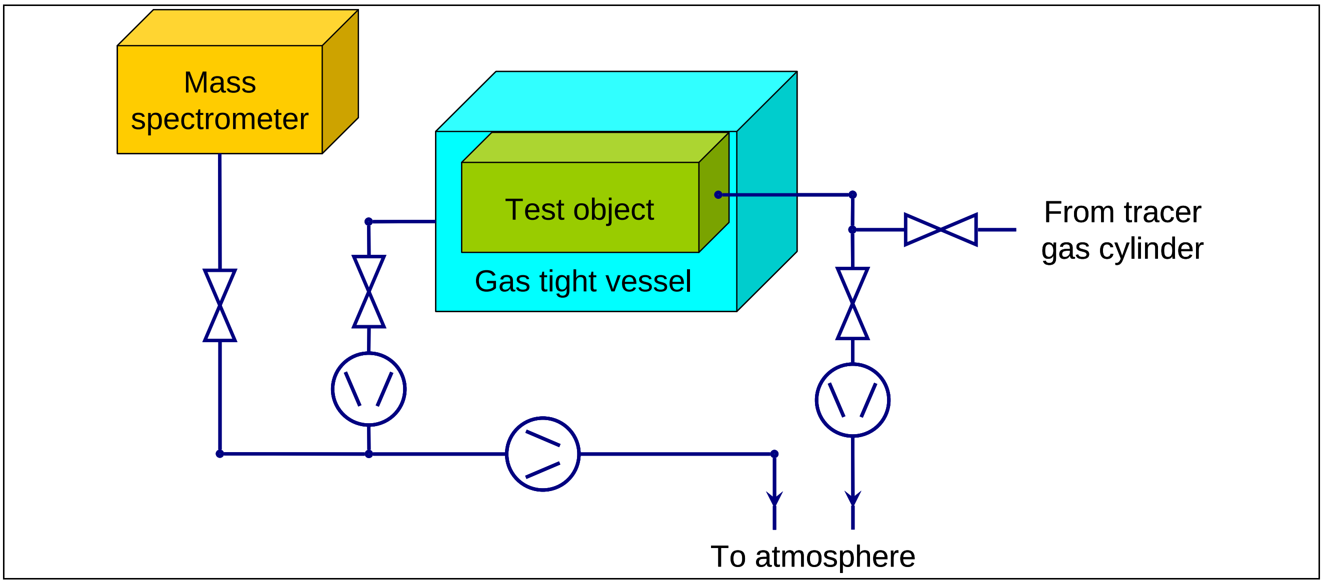


The test object is filled with SF_6 and a sniffer is then placed near to the test object and moved slowly at a constant speed over its surface. The sniffer alarms when its probe is over a leak resulting in a local SF_6 concentration above the detection threshold of the sniffer. Although sometimes it may be possible to roughly estimate the order of magnitude of the leakage rate, this method is usually not able to give quantitative information. The description of some SF_6 detectors is given in paragraph 5.2. The practical application of the test method is given in paragraph 5.3.2.

4.1.3 Test Q_k method 2 as per IEC 60068-2-17

Figure 3 shows the test Q_k method 2 which is defined as a “sealing tracer gas method with mass spectrometer”. It is performed as an integral leakage rate test and commonly used for factory routine tests of components of high-voltage equipment (e.g. aluminium castings) and medium-voltage equipment.

Figure 3: Test Q_k method 2 - sealing tracer gas method with mass spectrometer



The test object is placed into a gas tight vessel and then evacuated. It is then filled with the tracer gas at a certain pressure. For better sensitivity and for environmental reasons, helium or a calibrated gas mixture containing helium are commonly used as the tracer gas instead of SF_6. The amount of tracer gas leaking out of the test object is determined by evacuating the gas tight vessel and running the resulting gas flow into a mass spectrometer sensitive to the tracer gas. The description of the mass spectrometer is given in paragraph 5.2.7. The practical application of the test method is given in paragraph 5.3.3.

4.2 Medium-voltage equipment (sealed pressure systems)

4.2.1 Type testing

Electric power equipment has to provide the required tightness in accordance with IEC standards. Almost all modern medium-voltage Gas Insulated Switchgear (GIS) is designed as a sealed pressure system having an operating life of 20, 30 or 40 years. This expected lifetime can be converted to a relative SF_6 loss in the order of 0.1 % p.a. depending on the SF_6 quantity banked in the device.

As an example for GIS, a volume of 0.2 m^3 is chosen filled at a pressure of 130 kPa. Assuming a relative SF_6 loss of 0.1 % p.a., the corresponding leakage rate according to the equations in paragraph 2 would be $8.24\text{x}10^{-7}$ Pa·m^3/s or 1.56 g/a for the mass loss. For smaller equipment such as a load-break switch having a 0.03 m^3 typical volume, the calculated absolute leakage rates are even lower, $1.24\text{x}10^{-7}$ Pa m^3/s or 0.23 g/a.

The proof of such low leakage rates requires the use of the most sensitive test methods available e.g. the cumulative sealing test described in paragraph 5.3.1 or the integral leakage rate test described in paragraph 5.3.3 using helium as a tracer gas. Medium-voltage equipment is so compact that often all compartments belonging to one feeder unit can be completely assembled and tested for tightness as a whole.

The cumulative sealing test is the preferred test according to the latest release of IEC 62271-1 since it allows the use of the insulating gas at rated pressure inside the test object. The total leakage rate is determined from the temporal increase of the SF_6 concentration in the accumulation volume containing the test object. Small test objects can be placed inside a completely sealed metallic container or inside a gas-tight plastic bag. Large objects have to be wrapped into a plastic foil with the seams carefully welded and any joints sealed with tape. In order to detect a relative loss of SF_6 of 0.1 % p.a. of the 0.2 m^3 test object in the example and assuming the net accumulation volume around the object is not larger than 3 times the volume of the test object, the resulting SF_6 concentration after 24 h would be 1.2 ppmv. The same SF_6 concentration is obtained for smaller equipment if the net accumulation volume is correspondingly reduced. Only very sensitive test methods such as electron capture detection or photo-acoustic infrared spectroscopy are able to measure with proper accuracy these very low leakage rates. As it is quite difficult to achieve smaller accumulation volumes, a higher SF_6 concentration can only be obtained when the test objects are filled at higher SF_6 pressure or when the accumulation times reach several days or even weeks.

These tests always carry the danger of losing SF_6 out of the accumulation volume through tiny gaps and holes, thereby falsely indicating a tight object because the concentration of SF_6 in the accumulation volume is lower than it should be. Such gas loss can be checked after the tests by e.g. the injection of a defined quantity of tracer gas into the bag and subsequent determination of the time of decrease of tracer gas. The determined loss rate must be appreciably lower than the permissible leakage rate to be measured.

In parallel, the cumulative sealing test can be confirmed by the integral leakage rate test described in paragraph 5.3.3 using helium as a tracer gas. This test can serve as a consistency check. In contrast to the former standard IEC 60694, the current IEC 62271-1 limits the application of this test method to routine test procedures, because for type tests it requires using the same fluid under the same conditions as in service. Since for the helium leakage test the objects have to be placed into an evacuated chamber instead of the open atmosphere, the filling pressure of the test object has to be correspondingly adapted to maintain almost the same pressure difference. Experience has shown in the past that this test is as reliable as the cumulative sealing test and much more sensitive.

4.2.2 Routine testing

Most manufacturers use the integral leakage rate test method with helium (also called helium leakage test) for their routine testing, since it is faster than the other methods. When considering high production quantities, the higher investment costs of the evacuation chamber with pumps and control valves and associated detectors is of lower importance than the duration of the test. The insertion of the test object in the evacuation chamber, connection to pumps, leakage rate test and final filling with SF_6 takes about 30 min. This allows testing several tens of units per day; which is adequate for the number of medium-voltage equipment typically produced in one factory every day. On a random basis the 100 % routine tightness test can be supplemented by the accumulation test, if required. Some manufacturers apply the cumulative sealing test as a routine test for small medium-voltage equipment like switches, which is adequate as long as the accumulation volumes are carefully checked for unintentional loss of gas. Because of the long accumulation times, an appropriate number of boxes or bags have to be used in parallel.

In order to accommodate all medium-voltage equipment, test chambers of sufficient volume are needed for the helium leakage test. Figure 4 shows a rectangular chamber having a volume of more than 10 m^3 consisting of two halves, one fixed and one movable.

Figure 4: Helium leakage test chamber used for routine testing of large medium-voltage equipment. A complete functional unit of a switchgear can be placed between the two halves.

In other cases cylindrical vessels are used (see Figure 5) taking up to three panels forming a Ring Main Unit.

Figure 5: Helium leakage test device used for routine testing of Ring Main Units. The RMU is visible inside the chamber.

A typical procedure for a tightness test is as follows:

- The test object is placed into the open test chamber, fixed on a support and connected to the pipework.

- The test chamber is then closed and evacuated by large pumps down to e.g. 1 Pa (using e.g. a roughing pump or a booster pump). With some delay the test object is evacuated down to typically 500 Pa or even less.
- Major leaks are recognized by not reaching the preset low vacuum level in the test chamber. (In this case the chamber is ventilated again and a leak search is started on the test object according to the probing test method described in paragraph 5.3. For this purpose, the test object is filled with helium.)
- When the preset vacuum levels are reached in the test object and in the test chamber, the gas flow from the chamber is diverted into the helium mass spectrometer to measure the background level.
- After having reached a constant background signal, which has to be below the maximum allowed leakage rate assigned to the test object, the test object is filled with pure helium or a calibrated helium mixture up to a pressure of e.g. 50 kPa depending on the application.
- If the leakage rate does not fall below the preset limit value during the helium filling process, the test object is rejected.
- The leakage rate measurement is continuously carried out till a constant signal is obtained. If the leakage rate is below the permissible value, the object is accepted. This measurement typically takes several minutes.
- Afterwards the test object is evacuated again to less than 500 Pa to recover the gas used for testing.
- The test chamber is then ventilated and the test object is filled with SF_6 at the rated filling pressure/density.

The filling pressure/density during the tightness test is chosen according to the following principles:

- The pressure difference between the test object and the evacuated test chamber should be as high as under rated filling pressure in service. This ensures the same mechanical forces and deformations acting on the equipment.
- If the switchgear is intended to be erected at higher altitudes i.e. above 1 000 m, the filling pressure during the tightness test is increased accordingly or the equipment is de-rated.

Clearly, the leakage rates measured with helium have to be converted to SF_6 leakage rates. Details of this conversion can be found in Appendix 7. The detection limits can be as low as 10^{-9} Pa.m^3/s equivalent to a mass flow of 2 mg/a at 20 °C. This high sensitivity can only be achieved with a low background signal. For this reason the test chamber has to be occasionally flushed with dry nitrogen or air and then evacuated without the test object. Every day, a reference leak source is used to check the calibration. The routine tests reveal that most of the tested units have leakage rates far below 0.1 % p.a.

4.3 High-voltage equipment (closed pressure system)

4.3.1 Type testing

For better illustration, the requirement of a permissible maximum leakage rate of 0.5 % p.a. can be converted into a maximum allowed absolute leakage rate. According to the equation given in paragraph 2 and assuming e.g. a circuit breaker having a volume of 0.4 m^3 and a rated filling pressure of 600 kPa, the resulting leakage rate is 3.8×10^{-5} Pa.m^3/s and the corresponding mass loss is 72 g/a.

The measurement of the leakage rate of large high-voltage equipment can be performed by the cumulative sealing test described in paragraph 5.3. A plastic foil is wrapped around the test object and taped to the floor to form the accumulation volume. For the maximum permissible leakage rate of 0.5 % p.a. choosing e.g. a 2 m^3 high-voltage bay containing a 40 kg SF_6 mass and assuming the net volume of the plastic bag around the object is not larger than 3 times this value i.e. 6 m^3, the resulting SF_6 concentration accumulated during 24 h is 15 ppmv. This can be measured with reasonable accuracy by existing detectors. Again, the loss of SF_6 out of the accumulation volume due to inevitable leakage through the seams of the plastic foil has to be checked carefully.

The sensitivity of the test can be improved by wrapping the foil closely around the equipment, thereby decreasing the size of the accumulation volume. However, this complicates the determination of the net volume, which can be made easier by providing a rectangular rack covered by plastic foil, as shown in Figure 14. However, this has the disadvantage of a larger volume, which decreases the sensitivity of the test. In large volumes, SF_6 tends to concentrate on the floor because of its higher density compared to air. Therefore the resulting gas mixture inside the envelope may be mixed by a small fan, as shown in Figure 15.

4.3.2 Routine testing

In compliance with IEC 62271-1 the routine test on high-voltage equipment is most often done as test on components or sub-assemblies. Each aluminium casting intended for a circuit-breaker or disconnector unit is pre-assembled with feed-through, windows and pipework. These are then sealed with proper gaskets and/or O-rings and blind flanges. As the presence of grease may temporarily mask a leak, it is recommended that the use of grease is reduced as much as possible. These components are small enough to be tested according to the integral leakage rate test using helium as a tracer gas. The testing procedure is in principle as given in paragraph 4.1.3 with the test pressure in helium equal to the rated SF_6 filling pressure. It is common practice to validate the components for a maximum leakage rate of 0.1 % p.a. in order to ensure a total leakage rate lower than 0.5 % p.a. for the assembled unit consisting of several components. The leakage rates of the pre-assembled components determined in integral tests with helium are simply summed together.

Cast aluminium housings may contain cavities and/or pores in the material originating from the casting process. These are detected by the helium leakage test with high probability. However, the use of water for the safety pressure test may leave water remaining in the pores and this will invalidate the result of the tightness test. If a casting with high leakage rate is detected and the leak is due to a cavity, the casting must not be used. Casting impregnation or welding of the casting surface is not recommended because it does not provide permanent tightness.

The complete units assembled from several components are too big to be placed into an evacuation chamber. Therefore, the probing test described in paragraph 5.3 is applied to the complete unit. The inter-connection flanges, welding seams, feed-through and windows are carefully scanned with a sensitive SF_6 detector. IEC 62271-203 requires a sensitivity of the sniffing probe of at least 10^{-8} $Pa.m^3/s$ corresponding to around 20 mg/a of SF_6. However, this does not mean that leaks having this low leakage rate are detected, since only part of the gas flow penetrating through leaks can be absorbed by the SF_6 sensor. From experience it is concluded that leaks having a leakage rate larger than 10^{-6} $Pa.m^3/s$, corresponding to around 2 g/a of SF_6, have a high probability of being detected and localized. This is sufficiently low compared with the maximum permissible leakage rate of 72 g/a given in the previous paragraph 4.3.1. This gives confidence to the probing test. As an example this method may detect the leakage caused by one human hair across an O-ring.

4.4 Type tests at low and high temperature

The standards require testing of tightness of electric power equipment at normal ambient temperature with the switching devices either closed or open. According to IEC 62271-100, the tightness shall also be measured for circuit-breakers after mechanical endurance tests and, if requested, during high and low temperature tests. The standard allows for an increased leakage rate during the tests, which reduces to the normal rate afterwards. IEC 62271-1 allows for 3 times the permissible leakage rate at temperatures of 40 and 50 °C or at the minimum specified operating temperature. For equipment suitable for -50 °C, the acceptable leakage rate at -50 °C can be increased by 6 times.

For other than normal ambient temperatures, the test chamber including the test object has to be placed into a temperature controlled chamber. The devices available for measuring integral leakage rates using helium, however, are so large and immovable that placement into such a chamber is only of theoretical possibility. Only the cumulative sealing test has the possibility of being performed inside a temperature controlled chamber. However, it has to be remarked that the accumulation method itself and the detectors might be influenced by temperature. For example, loss of SF_6 out of the accumulation volume could be considerably increased at higher temperatures because of permeation of SF_6 through thin foils. Also, the accumulation volume changes during the test in accordance with the temperature dependence of the ideal gas law. If the accumulation volume is not gas-tight, air will be lost until pressure balance is achieved. Vice versa, external air may enter the accumulation volume when the chamber is cooled down. The detection sensors normally are only calibrated within a prescribed range of temperatures e.g. from 0 to 40 °C. Care has also to be taken over the zeroing of the detectors. Since the humidity of air is different at different temperatures, the electron/negative ion capture detector, which is sensitive to humidity, cannot be simply referenced to the air outside the temperature controlled chamber. Another source of experimental error may be the cross sensitivity of the detectors to traces of refrigerants potentially released from cooling apparatus. Therefore leakage tests at temperatures other than normal ambient temperature have to be treated with special caution, because the execution of the test is difficult and may easily lead to questionable and irreproducible results.

The probing test method i.e. sniffing for SF_6 over the object as described in paragraph 5.3, is the simplest to be applied during the high and low temperature tests provided the detectors are suitable for and calibrated at these temperatures. Although the test provides numerical results, these can only indicate the presence of local leaks, if any, which cannot be considered as representative of the cumulative leakage rate.

For smaller test objects the probing test method described in paragraph 5.3.4 could also be used. The object is placed in a temperature controlled chamber and evacuated by a vacuum pump, which is placed outside the chamber. In this case, the detector i.e. the mass spectrometer is not affected by the temperature in the chamber. However, depending on the design of the test object and on the experimental set-up, this method may not always deliver reliable results.

In conclusion, it seems to be quite difficult to reliably measure leakage rates during type tests at high and low temperatures as required by IEC 62271-100. Therefore details for the test procedure and testing equipment must be given for this purpose.

4.5 On-site commissioning testing

Typically sealed pressure systems are filled with SF_6 in the factory and no further SF_6 handling is required during its expected operating life. An on-site tightness test is therefore not necessary.

For closed pressure systems working with SF_6 is required, since components have to be assembled finally on-site. As the working conditions during on-site installation are less controlled than in the factory (the environment is harsher), special precautions and strict installation procedures are necessary.

In particular, for certain outdoor installation conditions, a temporary shelter is necessary to prevent the ingress of e.g. rain, wind and dust, especially when making gas tight connections or during opening of and/or accessing gas compartments.

All gas tight connections made on-site have to be checked for tightness. Suitable sensitive sniffing devices should be used. The influence of the background pollution should be considered.

Independently on the kind of pressure system, factory-made gas tight connections do not require further checking on-site unless there is evidence of damage e.g. during transportation.

4.6 Diagnostic testing of tightness in service

4.6.1 Sealed pressure systems

The tightness of a sealed pressure system is specified by the expected operating life. Therefore these systems do not require gas processing on-site. In principle no density or pressure monitoring is needed, nevertheless most of these systems are equipped with gauges. Experience shows that no diagnostic testing of tightness in service is required.

4.6.2 Closed pressure systems

The tightness of closed pressure systems is defined by the relative leakage rate, which does not exceed 0.5 % p.a. Experience has shown that in most cases no gas refilling is necessary during the life time of the equipment. This indicates the actual leakage rate to be much lower than 0.5 % p.a. as requested by the standards.

In order to ensure the continuity of operation of the switchgear, a pressure/density monitor is always installed to provide alarms if the pressure drops below pre-set values. Trend analysis of the pressure/density readings over the years as well as their comparison with adjacent gas compartments enables the detection of a possible leak as early as possible, far before the first step of the alarm occurs. Pressure/density readings might be recorded during periodic routine visits to the substation, in connection with other tasks. Details about the application of pressure/density monitoring are given in paragraph 5.2.3.

5 Test equipment

5.1 Overview

Table 1 summarizes possible leak detection methods or tightness test procedures together with commonly used detectors as well as their sensitivity given as SF_6 mass flow and/or minimum detectable SF_6 concentrations.

Table 1: Leak detection methods or tightness test procedures

Leak / Tightness Detection Procedure	Sensitivity abs. leakage rate (best case)	Kind of method	Comments	See para.
Vacuum / pressure increase test	100 Pa/h (equiv. to approx. 10 kg/a SF_6)	Qualitative	Equipment integrity check before SF_6 filling. However the equipment must be designed for the purpose of the test	4.2.2
Infrared Camera using BAGI (Backscatter/ Absorption Gas Imaging)	1 kg/a SF_6 (range of 35 m)	Qualitative	Suitable for remotely determining the approximate location of major leaks	5.2.1
Bubble test with soap or special fluids	1 kg/a SF_6	Qualitative	Simple and useful for determining the exact location of major leaks	5.2.2
Density monitoring (pressure drop)	600 g/a SF_6 (observation time 1 year)	Quantitative	Suitable for long term trend analysis leakage detection or for equipment integrity check	5.2.3
Infrared absorption spectroscopy	60 mg/a SF_6 3 ppmv	Quantitative, qualitative for sniffing test	Type test, routine test, commissioning test, no cross-sensitivities to the most common gases and water	5.2.4
Negative ion capture detector (using corona discharge)	20 mg/a SF_6 or 1 ppmv, extended sensitivity for sniffing	Quantitative, qualitative for sniffing test	Type test, routine test, commissioning and maintenance	5.2.6
Electron capture detector (using radioactive source)	2 mg/a SF_6 100 ppbv	Quantitative, qualitative for sniffing test	Type test, routine test, commissioning and maintenance	5.2.5
Helium mass spectrometer	2 mg/a SF_6 if checked by a calibration source	Quantitative	Type test, routine test	5.2.7
Photo-acoustic infrared spectroscopy	0.2 mg/a SF_6 or 10 ppbv	Quantitative	Type test, routine test	5.2.8

It has to be clearly stated that the detectable minimum leakage rate depends on several conditions. Also, some test methods only provide qualitative results especially when the detectors are used as sniffing devices to locate leaks.

The requirement of a permissible leakage rate in the order of 0.1 % p.a. in medium-voltage equipment and lower than 0.5 % p.a. in high-voltage equipment is used in Table 2 as the criterion for the selection of suitable tightness test methods.

In the same table, the following terms are used:

- “minor leak” qualitatively indicates a leak having a leakage rate L in the order of the permissible leakage rate L_p ($L \approx L_p$);
- “major leak” qualitatively describes leaks having at least one order of magnitude higher than the permissible leakage rate ($L >> L_p$);

- “integral test” means a test resulting in a numerical figure, the cumulative leakage rate, quantifying the overall tightness performance of the test object.

Table 2: Suitability of tightness test methods

Test method	**Tightness test of**		**Detection of major leaks**
	high-voltage equipment	**medium-voltage equipment**	
Vacuum/pressure increase test	Not suitable		Integral test
Infrared camera using BAGI (Backscattered/Absorption Gas Image)	Not suitable		Leak localisation
Bubble test with soap or special fluids	Not suitable		Leak localisation
Density monitoring (pressure drop)	Not suitable		Integral test
Infrared absorption spectroscopy	Integral test	Hardly suitable	Integral test
	Minor leak localisation		Leak localisation
Negative ion capture leak detector (using corona discharge)	Integral test		
	Minor leak localisation	Hardly suitable	Leak localisation
Electron capture leak detector (using radioactive emitter)	Integral test		
	Minor leak localisation	Hardly suitable	Leak localisation
Helium mass spectrometer	Integral test on components	Integral test	
Photo-acoustic infrared spectroscopy	Integral test		

The results of the analysis in Table 2 are based on the following assumptions about volume and rated SF_6 filling pressure/density:

- Typical medium-voltage equipment: a switchgear or a circuit breaker with a volume of 0.2 or 0.01 m^3 and a rated SF_6 filling pressure of 130 or 400 kPa, respectively;
- Typical high-voltage equipment: a gas compartment or a circuit breaker with a volume of 2 or 0.4 m^3 and a rated SF_6 filling pressure of 450 or 600 kPa, respectively.

The vacuum/pressure increase method only gives an indication of major leaks originating e.g. from wrong assembly or defective materials.

Experience shows the localisation of minor leaks in medium-voltage equipment is hardly possible.

Appendix E in IEC 62271-1 contains a similar table, which roughly classifies detection methods in terms of leakage rates.

5.2 Detection methods and detectors

5.2.1 Back-scatter Absorption Gas Imaging (BAGI) camera

This technology allows the visualization of SF_6 leak sites using a unique video detection system. The main benefits over traditional SF_6 leak detection (halogen detectors and soapy water) are twofold: Firstly the ability to perform leak detection without having to take equipment out of service and secondly the dramatic reduction in time necessary to detect a leak site. The technology exploits the strong infrared absorption of SF_6 to make it visible to the camera operator. A laser illuminates the leak area at a wavelength that coincides with strong spectral absorption of SF_6. The returning infrared signal is captured and processed to generate a real-time video image. Areas of the image where SF_6 is present strongly absorb the reflected infrared – and this allows SF_6 leaks to be visualized in real-time as a plume of black gas. Because of the strength of the optical absorption by SF_6, the laser camera is sensitive to SF_6 leaks as low as 1 kg/p.a., viewed at distances as far as 35 m, which might be appropriate to detect major leaks in high-voltage equipment [17]. On the other hand, typical leaks in medium-voltage equipment are too small to be localized by this method.

5.2.2 Bubble detection test

A soap-like solution is spread over a suspected leaking location. The gas flow generates bubbles which can be easily seen. The method can be used to detect the location of major leaks allowing the field staff to pin-point it and qualitatively estimate its size.

5.2.3 Pressure/Density monitoring

State-of-the-art pressure/density sensors are installed for functional and safety reasons. They are based on the elastic deformation of a stainless steel membrane produced by the pressure difference. A first alarm is provided when about 5 % of the banked SF_6 mass has leaked out; while a second alarm is provided at 10 % which usually locks out the breaker. It is almost impossible, due to variations in temperature between different parts of the equipment, to monitor the amount of SF_6 banked with an accuracy of better than several percents.

Gas monitoring that continuously measures the SF_6 pressure/density, rather than just giving an alarm after having lost a certain amount of gas, could provide leakage rate information. A pressure drop of few percents of the gauge scale e.g. 25 kPa should be noticeable while reading a 1 MPa gauge. For a typical high-voltage circuit breaker this is equivalent to a relative leakage rate of 4 % p.a. resulting in a mass loss of 600 g/a.

For environmental reasons some effective techniques have been developed using continuous on-line monitoring systems in conjunction with trend analysis (microprocessor polling the gauge at a fixed interval of time) which enable a higher sensitivity in measuring leakage rates on high-voltage equipment in service. However, in this case extreme care should be taken during data collection and evaluation because of the drift and variable offset of the electronics and their variation with the temperature. In addition the impact of the ambient temperature and load conditions on the electric power equipment should be considered in the definition of the thresholds in order to avoid the possibility of false indications.

5.2.4 Infrared absorption spectroscopy

When white light passes through a certain gas some energy is absorbed at the absorption peaks which can be recognised in the spectral analysis of the transmitted light.

The spectral analysis can be performed in two ways:

- A narrow band or a monochromatic light source (i.e. a filtered lamp or a laser), the wavelength of which is scanned over the whole absorption wavelength range;
- A scan of the chromatic dispersion of the transmitted white light.

The absorption line spectrum is given by the vibrational excitation mode of the molecule and can be used as finger print for the identification. By calibration with a gas of known pressure, the detector signal can be converted to absolute concentrations. Since these two methods need expensive equipment, they are suitable for off-line analysis. Both methods measure the real concentrations of gases, instead of their flow rates.

A portable SF_6 detector for on-site analysis makes use of a light source tuned to a specific absorption peak. The intensity of the absorbed light can be calculated by subtracting the transmitted light from the incident light, being measured at the detector. The amount of absorbed light is proportional to the concentration of gas pumped into the detection volume. An appropriate choice of the absorption peak results in a very selective method for a certain gas with no known cross sensitivities to other gases. In particular, the SF_6 molecule has a very strong absorption peak around the wavelength of 10.7 μm, which is in the range where moisture or the most volatile organic compounds have no absorption at all. However, the precision and long term stability of the light source and the detector determine the sensitivity and the reproducibility of the measurement.

5.2.5 Electron capture detector

An electron capture detector is used to detect SF_6 with high sensitivity below 1 ppmv. This device makes use of the high electron attachment coefficient of SF_6, i.e. the ability of capturing electrons. The free electrons to be attached to the SF_6 molecules are created by a radioactive source. The electron capture detector uses a radioactive emitter, typically, a metallic membrane coated with the radionuclide nickel-63. The emitted electrons are accelerated in an electric field and ionize the background gas, normally ambient air. Ions and electrons are collected at the electrodes resulting in a steady state ionisation current. The presence of SF_6 besides air reduces the number of free electrons, as they are now attached to the SF_6 molecules. The decrease in the ionisation current is proportional to the SF_6 concentration. However, other molecules (e.g. hydrocarbons, refrigerants, moisture) also have a certain electron attachment coefficient. For this reason, the detector is also sensitive to those molecules. This cross sensitivity effect is described in more detail below using moisture as an example.

In principle this device is a flow rate detector, since the sensor is pumping the gas at a constant speed of approx. 5 cm^3/min (equivalent to $8.3x10^{-3}$ $Pa{\cdot}m^3/s$ at atmospheric pressure) through the electric field. By calibration this flow rate is internally converted into SF_6 concentrations and recorded as ppmv. Calibration can be done by commercially available leak sources.

As said before, the electron capture detector is subject to the cross sensitivity effect. In particular, the sensor is quite sensitive to moisture. The device has to be zeroed before a measurement to compensate electronically for the effect of moisture, the concentration of which might change during the test duration. This effect could influence the result of the accumulation tests considerably, if the expected SF_6 concentrations are very low. If during the accumulation test the moisture concentration in the accumulation volume is subject to substantial changes, the signal obtained might not be representative of the actual SF_6 concentration. As a consequence, the test result could be random and might not be reproducible. Even zeroing the detector before each reading does not help as the moisture content in the accumulation volume might differ. When the cumulative sealing test is performed at temperatures other than the normal ambient temperatures, this effect could be more pronounced, impairing the result of the leakage test.

5.2.6 Negative ion capture detector

The negative ion capture detector is similar to the electron capture detector. The radioactive source is replaced by a corona discharge from a wire or needle at negative potential to produce free electrons. The presence of SF_6 reduces the number of free electrons lowering the corona current. The long term stability of the radioactive source compared to the corona discharge provides a higher long term stability of the electron capture detector. On the other hand, the negative ion capture detector is much more user- friendly and easy to operate.

5.2.7 Mass spectrometer

A mass spectrometer is able to detect molecules with different masses by separation of ions in a high frequency quadrupole electric field. Typically the mass spectrometer is tuned to the number of mass equal to 4 which corresponds to helium but if the range of mass detection is extended, the detection of SF_6 is also possible. Absolute concentrations can be obtained by direct comparison with a gas containing a defined concentration of SF_6.

5.2.8 Photo-acoustic infrared spectroscopy

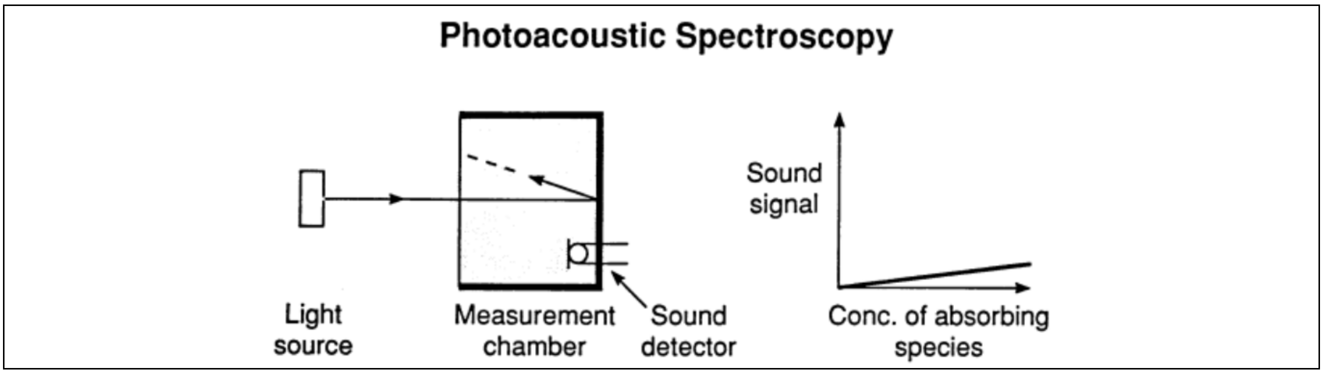
In the early 1970s interest in Photo-Acoustic infrared Spectroscopy (PAS) arose because it offered a very sensitive method for the identification and quantification of traces of atmospheric pollutants.

An SF_6 detector based on that method makes use of the light absorbed by a substance at a specific wavelength. The infrared light causes the gas molecules in the test chamber to bend, twist and vibrate. This generates pressure fluctuations and/or waves, which are detected by special microphones.

The pure acoustic signal is directly proportional to the amount of energy absorbed (see

Figure 6). This direct measuring method can provide a sensitivity down to 10 ppbv which is far superior to other methods. It also gives long term zero-point stability and consequently reliability. On the other hand, the response time of about 15 seconds prevents the device being used for leak localisation. The practical detection limit is around 100 ppbv, which is equivalent to 2 mg/a. Under the best conditions this can be lowered by a factor of 10.

Figure 6: Photo-acoustic infrared spectroscopy



5.3 Tightness test methods

5.3.1 Cumulative sealing test with internal pressurisation

This is one method for measuring the total leakage rate of medium-voltage or high-voltage equipment. It is equivalent to the sealing test Q_m method 1 described in paragraph 4.1.1. The test object is filled with SF_6 or with a tracer gas such as helium at rated filling pressure and placed into an accumulation volume. The concentration of SF_6 or of the tracer gas in the accumulation volume is measured by an appropriate detector at the beginning of the test and after some time. The test may typically require from one day to one week.

The total leakage rate L in [Pa.m^3/s] can be calculated using the following equation:

$$\boldsymbol{L} = \frac{10^{-6}(\boldsymbol{c}_1 - \boldsymbol{c}_0) \cdot \boldsymbol{p}_{\boldsymbol{ATM}} \cdot (\boldsymbol{V}_{\boldsymbol{s}} - \boldsymbol{V}_{\boldsymbol{o}})}{\Delta \boldsymbol{t}}$$

The corresponding mass flow in [g/s] is obtained from:

$$\dot{\boldsymbol{m}} = \boldsymbol{L} \cdot \rho_{\boldsymbol{gas}}$$

Where:

- $\boldsymbol{c_0}$ and $\boldsymbol{c_1}$ [ppmv] are the concentrations of the tracer gas within the accumulation volume at the beginning and at the end of the test, respectively;
- $\boldsymbol{V_s}$ and $\boldsymbol{V_0}$ [m^3] are the gross accumulation volume and the external volume of the test object, respectively;
- $\boldsymbol{p_{ATM}}$ [kPa] is the pressure within the accumulation volume, which is conventionally the atmospheric pressure of 100 kPa;
- $\Delta \boldsymbol{t}$ [s] is the time duration of the test e.g. 24 h = 86 400 s;
- $\rho_{\boldsymbol{gas}}$ [g/(Pa.m^3)] is the density of the tracer gas at a pressure of 1 Pa, i.e. 6.07×10^{-2} g/(Pa.m^3) for SF_6 and 1.64×10^{-3} g/(Pa.m^3) for helium.

If the accumulation volume is difficult to determine, it may be estimated by injecting a defined quantity of tracer gas into it and measuring the concentration of the tracer gas before and immediately afterwards. The following equation may be used:

$$\boldsymbol{V}_{\boldsymbol{s}} - \boldsymbol{V}_{\boldsymbol{o}} = \frac{\boldsymbol{V}_{\boldsymbol{gas}}}{\boldsymbol{c}_1 - \boldsymbol{c}_0}$$

Where:

- $\boldsymbol{V_s}$ and $\boldsymbol{V_0}$ [m^3] are the gross accumulation volume and the external volume of the test object, respectively;
- $\boldsymbol{V_{gas}}$ [cm^3] is the defined quantity of tracer gas injected into the accumulation volume
- $\boldsymbol{c_0}$ and $\boldsymbol{c_1}$ [ppmv] are the concentrations of the tracer gas within the accumulation volume before and after injecting the tracer gas, respectively;

The tightness of the accumulation volume should be carefully checked. It is common practice to use plastic bags made of polyethylene foils with a wall thickness around 100 µm, the seams of which should be welded one- or two-fold. Small holes in the seams, at edges where the bag is taped to the test object, the floor or at the access plug give rise to leakage of tracer gas out of the bag. In addition, SF_6 diffusion through the plastic foil might be present at higher temperatures, since diffusion rapidly increases with temperature. Depending on the volume and tightness of the bag, the contents of SF_6 might be lost within a couple of days.

The loss rate of the accumulation volume can be measured after the injection of a defined quantity of tracer gas into the accumulation volume (e.g. by a syringe) from the temporal decrease of the resulting tracer gas concentration. This concentration can be measured with the same detector used for the sealing test. However, it should be checked that the pumping speed of the detector does not influence the result.

It is possible to use gas-tight welded steel containers instead of plastic bags. In this case the variation of pressure in the accumulation volume with temperature has to be accounted for. It can be calculated by the ideal gas law.

5.3.2 Sniffing test with internal pressurisation

This test method is used for localising leaks. It is named Q_m method 2 and described in paragraph 4.1.2.

The test object is filled with a tracer gas (e.g. helium, SF_6) at the rated filling pressure. The gas streaming out of the leak is detected by scanning the outer surface of the test object with a sniffer, sensitive to the tracer gas. The method requires the operator to move the head of the probe over all potential leak sites. For large units or for a large number of compartments (e.g. GIS), this method is time consuming and needs great care in order to avoid overlooking leaks.

For example, if the leak is located directly below the scanned surface, the response time of the detector is fast and the leak can be located precisely. This is e.g. the case for small holes in a welded seam. However, if the leak is in a recessed position (e.g. in an O-ring groove between two flanges) the response time of the detector is slow. Also, it takes a long time till dead spaces filled with gas are evacuated afterwards i.e. the signal stays for a long time and drops very slowly. This sometimes gives rise to a high background signal, complicating the search. It is recommended that only trained personnel should carry out such measurements.

Suitable detectors are based on electron capture (see paragraph 5.2.5), negative ion capture (see paragraph 5.2.6), or infrared absorption spectroscopy (see paragraph 5.2.4). A small mass spectrometer calibrated for helium (see paragraph 5.2.7) could also be used; this has the advantage of a higher sensitivity in revealing minor leaks (see Appendix 7). Minor leaks having an absolute leakage rate smaller than 10^{-6} Pa m^3/s, corresponding to approx. 2 g/a, are hardly detectable as a consequence of the mixing process of the gas stream with the ambient air (see paragraph 4.3.2). For this reason, sensitive detectors having sensitivity higher than 10^{-8} Pa m^3/s are required.

Another limitation is given by the cross sensitivity of the electron/negative ion capture detectors. In the case of minor leaks, the leak search can be biased by offsets generated by e.g. hot surfaces, evaporating water droplets, hydrocarbons, and refrigerants. Even blowing into the head of the probe or touching it with the hands gives a clear signal as the breath or the skin are moist.

The use of helium as a tracer gas overcomes the limitations given by the cross sensitivity. However, the high diffusion rate of helium through polymers may complicate the localisation of leaks (see Appendix 7). In contrast to SF_6, the helium diffusion processes in polymers can not be neglected. As it may take from minutes to hours for helium to diffuse through rubber seals, the helium concentration may be continuously rising around the test object. This could be misinterpreted as a leak with a continuously rising leakage rate when all rubber seals and polymeric materials start to liberate helium. This effect is more pronounced at 40 °C or even higher ambient temperatures resulting in a strong increase of the diffusion rate, while the absolute leakage rate is almost independent of the temperature.

5.3.3 Integral leakage rate detection with internal pressurisation using helium

This test is sometimes simply called a “helium test”. It is the most commonly used and most sensitive method applied in routine test. It is described in IEC 60068-2-17 as Q_k method 2 (see paragraph 4.1.3).

First, the test object is placed into a gas tight vessel i.e. a completely welded steel container with gaskets, which can be evacuated. The test object is then connected to a gas handling device and both the test object and the vessel are evacuated. At this stage the gas flow from the vessel is diverted into a mass spectrometer sensitive to helium and the background signal is measured. When the test object is filled with the tracer gas (e.g. helium or calibrated gas mixtures containing helium) at the test pressure, a second measurement is performed to determine the amount of helium leaking from the test object. The tracer gas is finally recovered from the test object which is then filled with air or SF_6.

The reading of the mass spectrometer is typically expressed in $Pa \cdot m^3/s$ and refers to the tracer gas. It provides the integral leakage rate of the test object, since each helium molecule leaking out of the test object is counted by the mass spectrometer. The conversion of the absolute leakage rate in helium from the reading of the mass spectrometer to the equivalent absolute leakage rate in SF_6 depends on the regime of the gas flow in the leaks, on the pressure inside and outside the test object during the helium test, and on the SF_6 rated filling pressure/density. Appendix 7 contains the relevant equations.

The test device has to be calibrated utilising a reference leak source. A low background signal and a computing algorithm for background compensation are the key factors in achieving a minimum detectable leakage rate as low as 10^{-9} $Pa \cdot m^3/s$.

In principle, the integral leakage rate detection with internal pressurisation could be done replacing helium with SF_6. The mass spectrometer should be adapted to be sensitive to the molecular mass of SF_6. However, helium is preferred as it has a much higher flow rate than SF_6 for minor leaks, resulting in a higher sensitivity. Last but not least, environmental reasons should not be disregarded as the use of helium helps to minimize emission of SF_6.

5.3.4 Sniffing test with internal evacuation and helium or SF_6 from outside

This test is equivalent to Q_k method 3 described in IEC 60068-2-17. In order to localise a leak, the interior of the test object normally filled with SF_6 is permanently evacuated and connected to a mass spectrometer sensitive to the tracer gas (e.g. helium or SF_6). The external surface of the test object is scanned with a pistol spraying the tracer gas. This does not provide quantitative leakage rates, but it is an alternative to the sniffing test described under 5.3.2 for the localisation of leaks. The sensitivity, however, is higher, since it is ensured that all helium penetrating through leaks is detected by the mass spectrometer. The drawback of this method is that the sample is stressed with the opposite pressure condition to that in service and the materials and the sealing systems may have a substantially different behaviour in tightness. For this reason the method is rarely applied.

6 Conclusions

Tightness is influenced by design, manufacturing and commissioning. Tightness measurements are used to confirm that the parts and the assembly are properly done and to ensure the tightness of the equipment during its entire service life. In order to avoid unnecessary emissions of SF_6, tightness should be carefully considered. Leaking equipment should be repaired or replaced as soon as possible.

Extremely sensitive tightness tests have to be applied to ensure the conformity of switchgear with the low permissible leakage rates required by the relevant standards. These tests can only be done under controlled conditions as type or routine tests in the factory. On-site tests with lower sensitivity are done to check the correct assembly. For leak detection on-site, the sniffing test is the most commonly used method. Other methods with different sensitivities can be used as described above.

For the purpose of measuring the actual leakage rate of the equipment, pressure or density readings can be recorded and evaluated as trend analysis over time starting with a footprint at commissioning. In general, the equipment does not reach the first alarm threshold and does not require refilling to keep its full functionality before the period specified for maintenance. The impact of the ambient and load conditions should be considered in the definition of the thresholds in order to avoid the possibility of false indications, therefore the use of state-of-the-art on-line monitoring systems should be carefully assessed.

Experience shows that the pressure decrease over the expected lifetime is far below that anticipated from the permissible leakage rate. In the rare event of a failure, a sudden drop in pressure will indicate a leak.

7 Recommendations

7.1 General recommendations

Controlled pressure systems shall not be used for new equipment and the installed base shall be replaced with either closed or sealed pressure systems.

Only equipment having a leakage rate below 0.5 % p.a. shall be installed.

On-site testing, operation, maintenance and repair as well as decommissioning of equipment containing SF_6 must be performed by suitable trained personnel or under their supervision in order to minimise SF_6 emissions during the whole life of equipment and to ensure the functionality of the SF_6 electric power equipment. During these activities the environmental conditions have to be carefully controlled in order to avoid possible future leaks.

Corrosion has to be prevented by strictly following the manufacturer’s instructions, since it is one of the main causes for leakage

Special care should be taken for interface connections (e.g. direct transformer connections, high-voltage cable connections, high-voltage testing on-site) requiring SF_6 to be handled and therefore impacting the tightness of the equipment.

7.2 Recommendations to Original Equipment Manufacturers (OEM)

OEMs shall work towards being able to guarantee a specific level of tightness higher than the current Standards. This might be achieved by:

- Reducing the amount of gas pipework or, even better, avoiding it whenever possible;
- Reducing the number of gas connections and flanges;
- Reducing or, even better, avoiding, connecting separated gas compartments with pipework;
- Reducing the overall length of gaskets;
- Optimizing the sealing of movable components e.g. using rotating shafts instead of sliding rods to transfer movement from outside to inside the gas compartment;
- Optimizing the pressure co-ordination (nominal versus alarm pressure);
- Using prefabricated and pre-tested units to minimise assembly on-site;
- Recommending the use of high-voltage plug-in dry cable connections;
- Optimizing the design of power connections between GIS and bushings to minimise the amount of SF_6;
- Optimizing the size and number of gas compartments;

- Adopting appropriate means to avoid corrosion in critical areas e.g. sealing areas, flanges;
- Designing the equipment e.g. utilizing adsorbers for adsorption of by-products and humidity to prolong the maintenance intervals as much as possible.

7.3 Recommendations to Users of electric power equipment containing SF_6

Users of electric power equipment containing SF_6 shall work towards maintaining a high level of tightness and minimising SF_6 handling losses. This might be achieved by:

- Following the recommendations contained in the operating instruction manual of the equipment;
- Keeping a record of the amount of gas used for refilling each gas compartment and monitoring trends;
- Checking the installed base to identify equipment having high leakage rates, repairing it as soon as possible;
- Considering the replacement of old leaking equipment as a strategy for reducing SF_6 emissions;
- Adopting the overall SF_6 emission during the whole life of the equipment as an important selection criterion for the purchase of SF_6 electric power equipment;
- Avoiding the specification of gas pipework for centralized gas supply and monitoring systems as they are part of the gas compartment and will affect tightness;
- Considering the tightness and capability of handling and measurement equipment and replacing older equipment with state-of-the-art devices;
- Adopting the SF_6 recovery capability as an important selection criterion for the purchase of measurement equipment;
- Avoiding frequent checking of the gas quality.

8 Acknowledgements

The authors wish to thank M. Ratzke for a substantial contribution to this guide: Appendix 1 and 2.

9 References

[1] CIGRE brochure no. 276, Guide for the preparation of customised “practical SF_6 handling instructions”;

[2] IEC 60068-2-17 “Basic environmental testing procedures – Part 2: Tests - Test Q: Sealing”

[3] IEC 62271-1 “High-voltage switchgear and controlgear – Part 1: Common specifications”;

[4] IEC 62271-200 “High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV”, currently under revision;

[5] IEC 62271-203 “High-voltage switchgear and controlgear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV”, currently under revision.

[6] IEC 62271-303 “High-voltage switchgear and controlgear – Part 303: Use and handling of sulphur hexafluoride (SF_6)”

[7] JEC 2350, Japanese Electrotechnical Commission Standard for Gas Insulated Switchgear

[8] GB/T 11022, Chinese Electrotechnical Commission Standard “Common specifications for high-voltage switchgear and controlgear standards”

[9] GB/T 3906, Chinese Electrotechnical Commission Standard “Alternating current metal-enclosed switchgear and controlgear for rated voltages above 3.6 kV and up to and including 40.5 kV”

[10] GB/T 7674, Chinese Electrotechnical Commission Standard “Gas insulated metal-enclosed switchgear for rated voltages of 72.5kV and above”

[11] TU 6-02-1249-83, Russian Electrotechnical Commission Standard defining the specifications of SF_6 to be used in electric equipment

[12] GOST R 52565-2006, Russian Electrotechnical Commission Standard “Alternating-current circuit-breakers from 3 to 750 kV”

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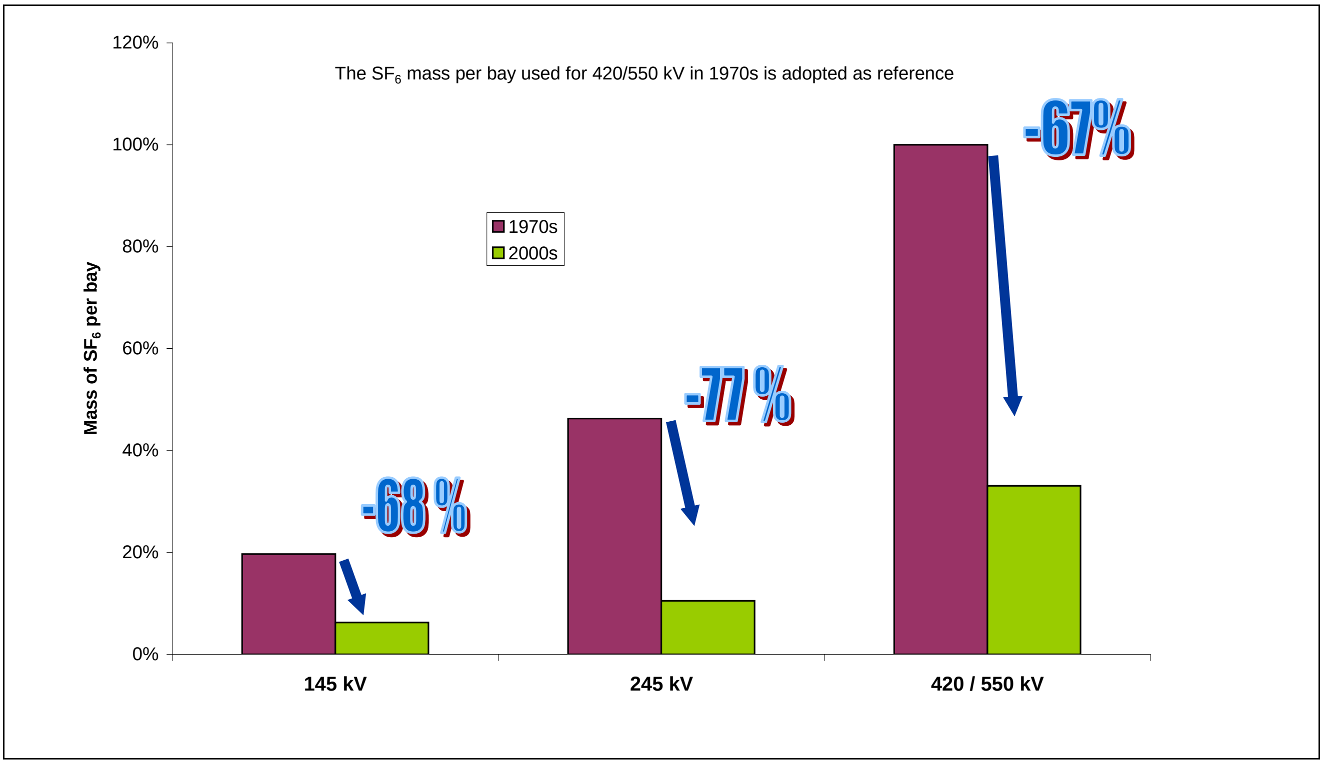
APPENDIX 1

DEVELOPMENT OF THE SF_6 TECHNOLOGY FOR GIS

The developments within the last decades have led to smaller gas compartments of the switchgear. For example, the space requirements since 1968 for a 145 kV GIS have been reduced by approximately 80%. Consequently the mass of SF_6 has been significantly reduced for the same performance (see Figure 7) as well as the leakage losses.

Figure 7: Reduction of the mass of SF_6 used per GIS bay and for different voltage levels



The improvement of the SF_6 switchgear technology not only resulted in a significant reduction of the banked SF_6 per bay, but also in a reduction of the SF_6 emissions due to handling. In spite of great carefulness during gas handling, there is always a risk to loose a small amount of SF_6 when carrying out maintenance operations, gas quality checking, etc.
Table 3 lists several handling operations and areas of improvements of the SF_6 technology which have led to reduced SF_6 emissions.

Table 3: Development of some specific areas of the SF_6 technology over the last 40 years leading to a reduction of SF_6 emissions

State-of-the-art around 1970s	State-of-the-art today
Large gas compartments	Optimized gas compartments
Frequent maintenance involving opening of gas compartments	2 openings during life time: once after 25 years of service, once during end-of-life procedure after 40-50 years.
Insufficient SF_6 handling instruction and unnecessary SF_6 handling	Detailed SF_6 handling instruction and minimized SF_6 handling
SF_6 service units with a SF_6 recovering pressure of 5-10 kPa	SF_6 service units with SF_6 recovering pressure down to 0.1 kPa
SF_6 leakage detectors with limited sensitivity	Sensitive SF_6 leakage detectors capable to find very smal leaks
SF_6 measuring instruments with loss of the used gas	SF_6 measuring instruments collecting the gas
Use of SF_6 for leakage detection during manufacturing	Using helium for leakage detection where possible (e.g. housing leakage test)
Fundamental tests for development of SF_6 technology and new production processes, using SF_6	Mature SF_6 handling procedures and manufacturing processes are well established
No possibility to handle and purify used SF_6	Used SF_6 is purified and reused (closed loop concept)
No special care on SF_6 emissions	Book keeping and reporting of banked SF_6 and SF_6 losses, self commitments, voluntary agreements, and implementation of F-gas regulation in Europe

Although the number of SF_6 high-voltage GIS substations has been increased in the grid, the amount of SF_6 has not risen in the same proportion because of the use of state-of-the-art technology with reduced SF_6 inventory.

APPENDIX 2

REDUCTION OF SF_6 EMISSIONS IN GIS: FIELD EXPERIENCE FROM BERLIN

1 Existing high-voltage Gas Insulated Switchgear (GIS) at Vattenfall Europe in Berlin

SF_6 has been successfully used as a non-flammable, insulating and quenching gas since the early 1960´s by the Electric Industry in power equipment for high-voltage transmission and medium-voltage distribution of electricity.

Figure 8 shows the first high-voltage GIS which was installed in 1968 in Berlin on the 110 kV level named “UW Wittenau” (UW=Substation). After more than 40 years the substation is still in operation.

Figure 8: “UW Wittenau”, one of the first SF_6 GIS ever manufactured

Today in Vattenfall Europe Berlin there are 91 high-voltage gas insulated substations in operation (110-420 kV). In total the inventory of banked SF_6 is approximately 10 % of the total SF_6 banked in Germany in electric power equipment (status Jan 2008).

2 Reduction of SF_6 handling losses

In the last four decades the emphasis on maintenance has been changed from time-based to more condition-based through the service experience collected over the years. This has enabled the cycles for opening of the gas compartments to be extended and has finally led to a reduction of the SF_6 handling losses. For switchgear produced in 1968, the cycle was scheduled every 3 years.

Once per month in conjunction with safety at work meeting, a continuous updating of staff ensures the correct handling of SF_6.

According to the F-gas regulation the recovery of used SF_6 from GIS is performed by certified personnel. State-of-the-art handling equipment reduces the SF_6 handling losses. The SF_6 remaining in a compartment depends on the residual pressure.

When the SF_6 quality is checked during service, measuring equipment with SF_6 recovery feature is used.

Figure 9 gives an example of SF_6 collection device, which can be connected to one or two measuring devices. The gas is collected and stored in an internal vessel by means of a compressor. After having carried out several measurements or if required the stored gas can be transferred from the internal vessel into an external gas bottle.

Figure 9: SF_6 collecting device in service

3 Minimization of SF_6 leakage losses

Information to and awareness of staff involved in operation and maintenance of SF_6 switchgear is very important. To identify SF_6 leakages at an early stage it is a common procedure to continuously check the SF_6 pressure. This can be done during regular checking of the substations. In the case of a gas leakage an immediate repair reduces the SF_6 emission.

4 Development of the emission of SF_6 in Berlin

Since the Kyoto Conference in 1997 the monitoring and recording of data of SF_6 emission is indispensable. The ***Ecofys-Study*** (06.2005) states: “Design-related leakage rates for new equipment are commonly far below 0.5 % p.a. with an overall emission rate – including design related leakage, emissions from small leaks and handling losses – for the existing EU 25+3 banks of 1.8 % in 2003.” The ***German voluntary commitment*** (Jun 2005) is more rigorous and demands 0.8 % p.a. for high-voltage systems in Germany.

Figure 10 shows the splitting of SF_6 emission into handling losses and SF_6 leakage commonly adopted for electric power equipment.

Figure 10: Splitting of SF_6 emission

Today according to the experience of Vattenfall Europe Berlin, under normal service conditions, the handling losses account for 70 % of the annual total emissions and SF_6 leakage for the remaining 30 %.

From 1997 to 2007 the average emission of SF_6 from high-voltage GIS in Berlin is 0.54 % p.a. This corresponds to a leakage rate of 0.16 % p.a. and handling losses of 0.38 % p.a. according to the splitting ratio given above.

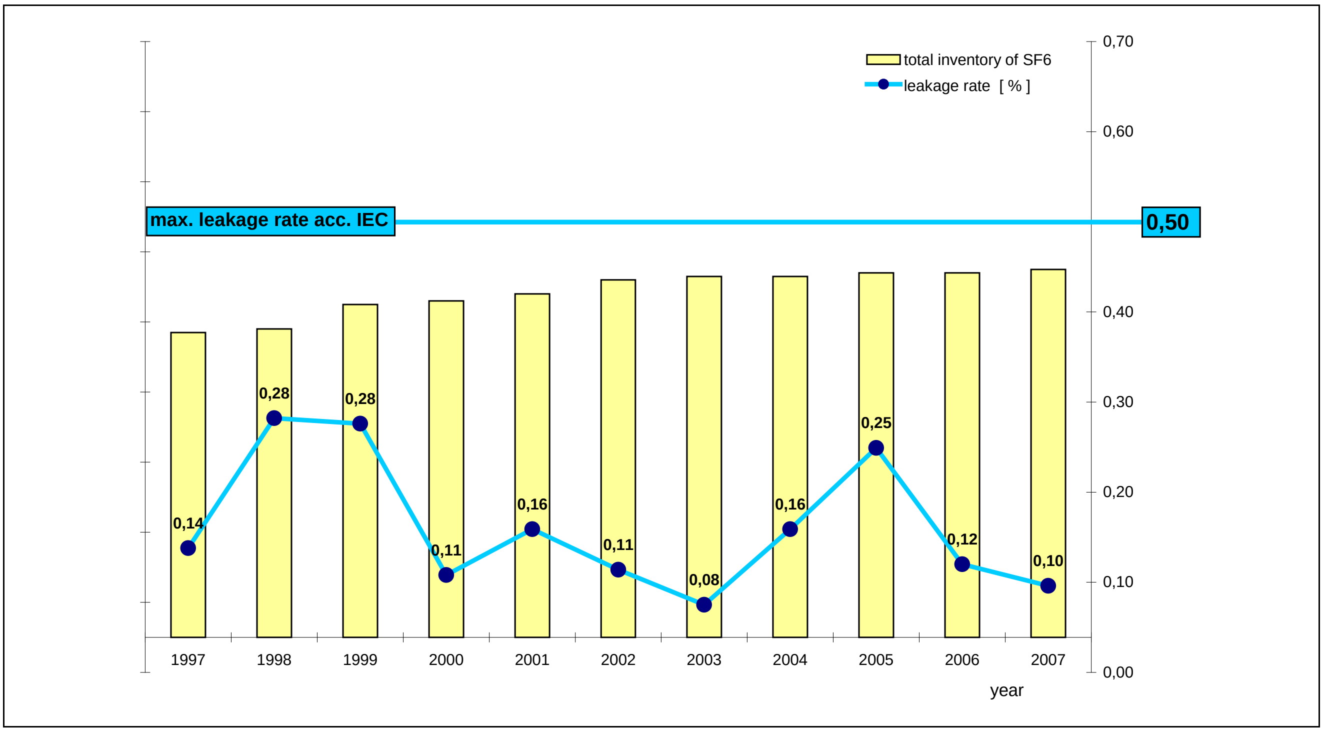
Some figures useful for a comparison could be found in IEC 62271-203. Note 1 in clause 5.15 sets the target of “a total loss (leakage and handling) as low as possible. A value of less than 15 % averaged over all gas compartments and for the service period of minimum 25 years should be achieved.” On the other hand, clause 5.15.101 requires the leakage rate from any single compartment of closed pressure systems to atmosphere and between compartments not to exceed 0.5 % per year for the service life.

Vattenfall Europe in Berlin is clearly below both figures. The result becomes even more positive the age profile of the installed base given the fact that when considering the IEC Standards apply to new equipment.

Figure 11 shows the annual leakage rates based on the splitting ratio given above together with the total SF_6 inventory. Deviations from the average are a consequence of single and not repetitive events.

This overall result has been achieved by the adoption of tight equipment, state-of-the-art maintenance strategies and measurement devices, highly trained and certified staff, and early detection and repair of leaks.

Figure 11: Calculated SF_6 leakage rate and total inventory of SF_6 in Berlin since 1997



APPENDIX 3

SF_6 LEAKAGE MEASUREMENT ON GCB/GIS AFTER 12 OR 24 YEARS FIELD OPERATION IN JAPAN

As a part of a joint study for technical standards dealing with recycling and handling of SF_6 in Japan, field measurements related to the leakage of SF_6 from GIS/GCB were carried out in order to assess the condition of the gaskets of gas insulated equipment in operation. Participants of this study were some members of the Academic Society, Utilities, OEMs and SF_6 producers.

1 Selection of equipment to be subjected to measurement

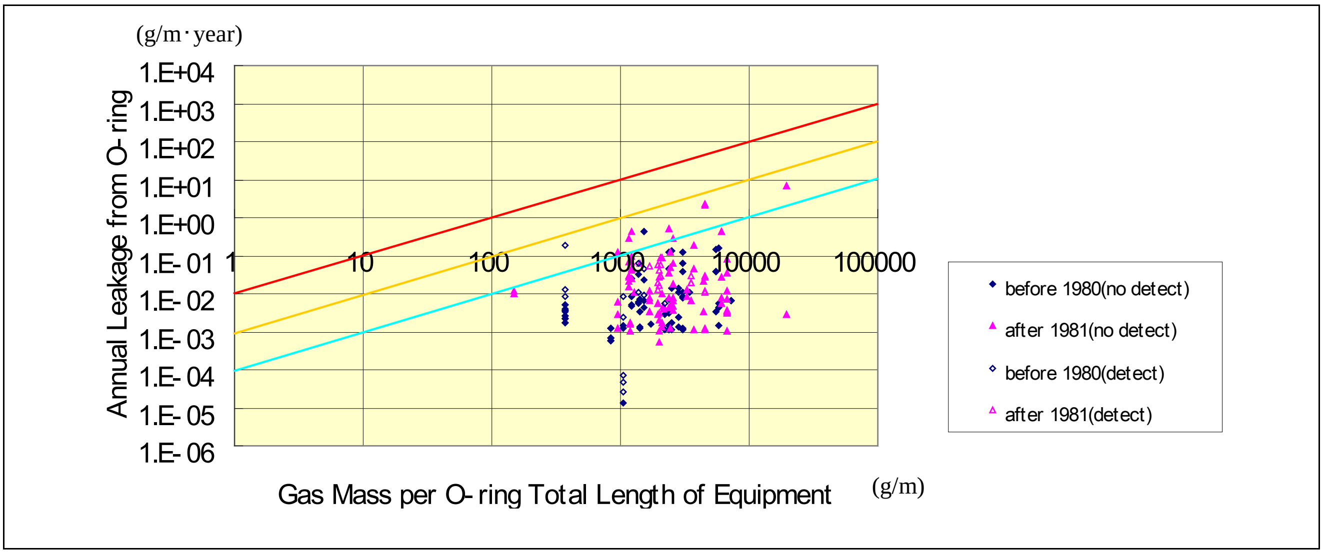
Measurements were conducted on GIS and GCB. Equipment for investigation was categorized into two groups as follows: One group consists of equipment manufactured in or after 1981 with an assumed low leakage rate of SF_6. Another group includes the equipment manufactured in or before 1980 with an assumed high leakage rate of SF_6 due to the use of early generation of SF_6 technology. Measurements from both populations were carried out on the occasion of periodical maintenance of each installation, which is carried out every 12 years.

2 Measurement Results

The accumulation method was used to measure the absolute leakage rates at 300 points in 40 GIS/GCB installations. The absolute leakage rate and the gas quantity in the compartment were then normalised to the sealing length. It was found that for each measurement point the great majority of them was below the limits of detection. When SF_6 could not be detected, the value of the minimum detection sensitivity of the measurement method was adopted.

As a result, no difference between categories of before 1980 and after 1981 in the distribution of the leakage rate was recognized. Actually, all measurement points were below 0.1 % p.a. (central line on Figure 12) and the majority of them were even smaller than 0.01 % p.a. (bottom line on Figure 12). Accordingly, it is understood that original gasket performance as measured at the time of installation remains at a high level after the years of field operation.

Figure 12: Investigation on-site (300 points on 40 GCB/GIS in operation)



3 Conclusion

According to JEC 2350 (see paragraph 3.2), the permissible leakage rate shall not exceed 0.5 % p.a. in the case of typetest and 1.0 % p.a. and per gas compartment in the case of routine and on-site tests.

The feasibility of lowering the permissible leakage rate for routine and on-site tests down to 0.1% p.a. was evaluated. It turned out that this is not of practical use because the test duration is too long. In addition, the test equipment has to be calibrated frequently and the background level of the tracer gas easily introduces systematic errors in the measuring process.

The final conclusion reconfirmed that from the manufacturing efficiency, test facility and cost point of view, the permissible leakage rate for SF_6 insulated equipment should be not less than 0.5 % p.a. and per gas compartment for type testing and not less than 1% p.a. and per gas compartment for routine and on-site tests. Perhaps, the permissible leakage rate for routine and on-site tests could be lowered down to 0.5% p.a. in order to align with IEC 62271-203 in the future. However the experience in Japan shows the current values for the permissible leakage rate are good enough to ensure reliable tightness during long term field service.

4 References

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- Y.Fushimi, M.Meguro; et.al, Activities for Huge SF_6 Emission Reduction in Japan, CIGRE Paris Session 2004, (B3-213)

APPENDIX 4

THE VERIFICATION OF GAS TIGHTNESS OF GAS INSULATED TRANSFORMERS & GAS INSULATED REACTORS

Gas Insulated Transformers (GIT) and Gas Insulated Reactors (GIRe) as well as GIS, offer excellent performance in terms of compactness and non-flammability.

When delivering GITs, GIRes, and GIS, SF_6 tightness test is carried out at every appropriate step, as described below, to ensure the performance. There are different sizes of GITs and GIRes depending their ratings. Some may be tested in the factory and some other on-site, based on the agreement with the customer.

No value for the permissible leakage rate of gas is given in the standard covering transformers, JEC-2200. The IEC standard for gas filled type power transformers, which was issued as part 15 of IEC 60076, prescribes that the relative leakage rate of SF_6 shall not exceed 0.5 % p.a. and per gas compartment, which is in line with current IEC requirements for GIS.

1 Method of leakage measurement in factory

When leakage measurement of GITs & GIRes is performed in the factory, using the accumulation method is normally used (see Figure 13 and Figure 13) and sometimes the sniffing method is applied.

Figure 13: Leakage test on 39 MVA – 132 kV / 11 kV GIT

Figure 14: Leakage test with defined accumulation volume (example with Gas Insulated Switchgear)

2 Typical procedure for routine test or type test in the factory for GIT

a) After full assembly and filling with SF_6 at the rated filling pressure, the whole GIT is covered with plastic sheet to create an accumulation volume.

b) The initial SF_6 content inside the accumulation volume is measured and recorded. Temperature, pressure inside the GIT, and time are recorded. Conditions are kept constant for approximately 12 hours or more, as appropriate.

c) The final SF_6 content inside the accumulation volume is measured and recorded. Temperature, pressure inside the GIT and time are also recorded.

d) Initial SF_6 content is compared with final SF_6 content inside the accumulation volume after 12 hours or more as appropriate.

Some technical details should be considered

- Air and/or SF_6 should not easily enter or leave the accumulation volume. Special care should be taken to tighten the cover and avoid leaks (e.g. gaps at the floor, holes).
- As SF_6 is about 6 times heavier than air, it may accumulate on the floor. It is recommended to place a mixing fan in the accumulation volume to obtain a SF_6 concentration as uniform as possible (see Figure 15).

Figure 15: Mixing fan

- The long term accuracy of the leakage detector depends on the structure and the sensitivity of the SF_6 detection part of the measuring unit. The calibration of the leakage detector is recommended to be executed every 6 months or every year to meet the requirements of the accuracy and the quality assurance.
- Before carrying out the leakage test, it is very important to measure the SF_6 background level outside of the accumulation volume as initial condition. A high SF_6 background level (e.g. after SF_6 handling near the accumulation volume) might affect the accuracy of the leakage test. The best conditions are achieved when the SF_6 background level is lower than the sensitivity of the sensor.

3 Method of leakage measurement on-site

Leakage measurement on GITs & GIRes is carried out on-site, in accordance with the agreement with the customer. The sniffing method as well as the accumulation method can be applied. When the accumulation method is used, a plastic sheet partially covers the GIT as shown in Figure 16. The test duration is approximately 8 to 12 hours.

4 Procedure on-site

Basically, on-site the same procedure as in the factory is applied. Due to the various limitations on-site, the accumulation method is only applicable to the connections made on-site and therefore, no leakage measurement is carried out on the flanges where the assembly work has been carried out at factory.

a) After full assembly and filling with SF_6 at the rated filling pressure, all the gas sealing parts, flanges, and valves of the transformer are covered with plastic sheet.

b) The initial SF_6 content inside the accumulation volume is measured and recorded. Temperature, pressure inside the GIT, and time are recorded. Conditions are kept constant for approximately 12 hours or more, as appropriate

c) The final SF_6 content inside the accumulation volume is measured and recorded. Temperature, pressure inside the GIT and time are also recorded.

d) Initial SF_6 content is compared with final SF_6 content inside the accumulation volume after 12 hours or more as appropriate.

If no appreciable modification in the SF_6 concentration is detected, a precise evaluation of the accumulation volume can be disregarded.

Figure 16: Typical on-site leakage measurement on 330 kV-400 MVA GIT (main compartment)

Figure 17: Typical on-site leakage measurement on GIT connection part

Figure 18: Typical on-site leakage measurement on 330 kV-400 MVA GIT (Water-SF_6 heat exchanger parts)

APPENDIX 5

BOOK KEEPING

The basic principles of book keeping on greenhouse gases emissions are defined by IPCC. An adapted version could be derived for SF_6. Book keeping is a simple and useful tool to increase awareness of personnel, control SF_6 emissions, identify areas for improvement, assign priorities to those areas, and in the long run achieve a reduction in the emissions from electric equipment.

The following equation can be used to summarise the concept of emission estimation by book keeping in a simple manner:

$$\boldsymbol{EMISSIONS} = \sum \boldsymbol{M_{IN}} - \sum \boldsymbol{M_{OUT}} - \Delta \boldsymbol{M}$$

Where:

- $\boldsymbol{EMISSIONS}$ are the total SF_6 emissions calculated in [kg] during the period of observation. As $\boldsymbol{EMISSIONS}$ are always greater than zero by definition, a negative value indicates a mistake in the process of book keeping;
- $\sum \boldsymbol{M_{IN}}$ is the total amount of incoming SF_6 accounted in [kg] during the period of observation;
- $\sum \boldsymbol{M_{OUT}}$ is the total amount of outgoing SF_6 accounted in [kg] during the period of observation;
- $\Delta \boldsymbol{M}$ is the variation of SF_6 on stock and banked in equipment in [kg] during the period of observation,

$$\Delta \boldsymbol{M} = \boldsymbol{M_{STOCK}^{END}} - \boldsymbol{M_{STOCK}^{BEGINNING}} + \boldsymbol{M_{BANKED}^{END}} - \boldsymbol{M_{BANKED}^{BEGINNING}}$$

Where:

- $\boldsymbol{M_{STOCK}^{END}}$ and $\boldsymbol{M_{STOCK}^{BEGINNING}}$ are the amounts of SF_6 in [kg] on stock at the end and at the beginning of the period of observation, respectively;
- $\boldsymbol{M_{BANKED}^{END}}$ and $\boldsymbol{M_{BANKED}^{BEGINNING}}$ are the amounts of SF_6 in [kg] banked in equipment at the end and at the beginning of the period of observation, respectively.

In certain countries self commitments and/or local regulations have introduced book keeping and reporting of SF_6 emissions

The following paragraphs give some examples.

1 Norway

A simple database system that assists the utilities in keeping track of their use and emission of SF_6 has been developed. The quantities of SF_6 banked in individual equipment and compartments as well as gas on stock (in gas bottles and/or containers) are registered. Gas used for topping up leaking equipment or for compensating gas losses during maintenance and repair is defined as emissions and recorded. The system also accounts the return of contaminated gas in containers as well as gas in equipment being discarded. A “Report” function calculates the SF_6 emissions on an annual basis, both in absolute quantities (kg of gas) and as a percentage of the amount of gas banked. The system is distributed free of charge to the utility members of the GIS user group. Most utilities record all their use of SF_6 in this database, not only the part related to their GIS's.

Once a year the GIS user group collects information about emissions and use of SF_6 from their members and compiles this information into a single report that is forwarded to the authorities according to the local agreement. This is the key document that allows the authorities to monitor use and emission of SF_6 in the electric utility sector, and to verify that the emissions are in line with the targets.

2 Czech Republic

The SF_6 emission inventory reporting system in the Czech Republic follows stipulations included in the Kyoto protocol. Since 2007 Czech importers, exporters and users of SF_6 and equipment containing SF_6 have to report annually, by the end of March, about their emissions to Czech Hydro-meteorological Institute. This Institute was authorized by the Czech Ministry of Environment to manage and control a National Inventory System.

The Czech Utility, CEPS a.s., has developed a simple database system that assists the utility in keeping track of SF_6 use and its emission.

$$E = M + MN - MK$$

Where:

- M is the SF_6 inventory at the beginning of the year (M = M11 + M12 + M2);
- MN is the SF_6 inventory of delivery and controlled disposal during the year (MN = M3 + M4 – M5 – M6);
- MK is the SF_6 inventory at the end of the year (MK = MK11 + MK12 + MK2)

Table 4 gives the symbols utilised in the inventory, their description, as well as their source and management.

Table 4: Meaning, data source and management of the inventory items

Symbol	**Description**	**Note**	**Source and management**
M11	Total mass of SF_6 banked in equipment in service at the beginning of the year	4	SAP module PM, automatic calculation
M12	Total mass of SF_6 banked in equipment not in service at the beginning of the year	1	Worksheet with data provided by individual Regional Centres
M2	Total mass of SF_6 stored in bottles and/or containers at the beginning of the year	2	
M3	Total mass of SF_6 received in bottles and/or containers during the year	2	
M4	Total mass of SF_6 received in new equipments during the year	3	
M5	Total mass of SF_6 sent in bottles and/or containers to disposal or sold out during the year	2	
M6	Total mass of SF_6 sent in equipment to disposal or sold during the year	3	
MK11	Total mass of SF_6 banked in equipment in service at the end of the year	4	SAP PM calculation

MK12	Total mass of SF_6 banked in equipment not in service at the end of the year	1	Worksheet with data provided by individual Regional Centres
MK2	Total mass of SF_6 stored in bottles and/or containers at the end of the year	2	

NOTE 1 Some equipment (or their parts) are stored with a slight SF_6 overpressure, or are filled by N_2 or dry air - automatic calculation from SAP is impossible.

NOTE 2 Weighing of bottles and/or containers (and subtracting their tare).

NOTE 3 Documentation or recalculation (transport mass at about 0.03 MPa calculated from known mass at rated pressure).

NOTE 4 The SAP file of each class of equipment contains the rated SF_6 mass at rated SF_6 pressure.

Once a year the data are collected and the emissions are calculated as shown above. A report is compiled and forwarded to the Czech Hydro-meteorological Institute as described above. This is the key document that enables monitoring of the use and emission of SF_6 and to verify that the emissions are in line with the targets.

3 Japan

In Japan a joint study by some members of the Academic Society, Utilities, OEMs and gas producers, established a concept for SF_6 book keeping:

- Standardized procedure for SF_6 handling. Table 5 shows a standardized slip which is applied to all the gas handling works for recording the SF_6 masses including the handling losses. Responsible persons are appointed for each SF_6 handling works. As far as the mass of SF_6 banked in equipment is concerned, the SF_6 mass on the nameplate of the respective equipment is used. And as far as SF_6 emissions from equipment are concerned, the calculated values are based on the SF_6 volume and its pressure. Instruments measuring the SF_6 mass (e.g. flow meters, mass balance) can also be used, if they are available on-site.
- Standardized measuring methods and instruments. Minimum requirements for instruments (e.g. hydrometer, SF_6 purity measuring instrument) are specified based on the results of the joint study. The instruments are subject to periodical calibration. A SF_6 handling report contains standardized items such as the instrument manufacturer and type, registration number and last calibration date, date and time of the measurement, ambient temperature, relative humidity and result of measurement.

Once a year FEPC (Federation of Electric Power Companies) and JEMA (Japan Electrical Manufacturers’ Association) respectively report to the Ministry of Economy, Trade and Industry that discloses the overall SF_6 emissions of the electrical industry. This report is the key document about the use and emissions of SF_6 in the electrical industry and is used to verify that the emissions are in line with the targets.

Table 5: Example of standard slip used for handling SF_6 in Japan

Site	**** S/S	Content of work	Inspect / retrofit / repair etc
Date of work		Unit No	
Volume of gas compartment(litres)		Rated gas pressure(MPa･G)	
Gas pressure before work(MPa･G)			
Gas pressure after gas-collecting(MPa･abs)			
Gas pressure after work(MPa･G)			
Gas mass of handling loss(kg)			
Gas mass of additional use(kg)			
Source of additional gas		Prepared by equipment manufacture / Spare gas cylinder	
Classification of collected gas (Refer to the following SF_6 quality criteria)		Criteria are fulfilled / not fulfilled	
Purity of gas (% vol)			
Gas moisture (ppmv)			
Decomposition HF		Not detected / Detected (ppmv)	
Decomposition SO_2		Not detected / Detected (ppmv)	
Mass of gas recovered not suitable for reuse on-site (not fulfilling criteria)(kg)			
Notes			

< SF_6 quality criteria >

Item		Criteria
Purity		Above 97 % vol
Moisture	Switching equipment	Below 500 ppmv
	Non-switching equipment	Below 150 ppmv
Decomposition		No detected by detection tube

4 Germany

According to the ***Voluntary Agreement*** from May 2005 between SF_6 producers, OEMs and Utilities book keeping in Germany is mandatory.

The ***Voluntary Agreement*** requires that since the beginning of 2004 emissions and masses of SF_6 have to be accounted. Every year by 31st March the consolidated data for the year before the previous year and the estimated data for the previous year shall be reported to the Ministry of Environment. For high-voltage equipment reporting is performed by the SF_6 producers and the associations of OEMs and Utilities. For medium-voltage equipment this is done by ***ZVEI*** (Zentralverband Elektrotechnik- und Elektronikindustrie). Actually, the book keeping procedure is fast enough to provide consolidated data for the previous year by the 31st March of the current year.

Companies participating in the book keeping procedure are responsible for the quality of the data provided.

APPENDIX 6

EFFICIENT MEASURES FOR REDUCING EMISSIONS OF SF_6 FROM HIGH-VOLTAGE EQUIPMENT – EXPERIENCE FROM NORWAY

1 Abstract

The means, measures and results of collaboration between Norwegian authorities and electric utilities aiming at reducing SF_6 emissions from high-voltage equipment are described. The utilities have committed themselves to keep detailed and verifiable accounts of their SF_6 inventory and emissions, to provide annual reports on this to the authorities, and to reduce the already low SF_6 emissions significantly. A GIS user group contributes actively in the efforts by providing database tools for keeping track of SF_6 inventory and emissions, by offering training in SF_6 handling and recycling, and in other ways promotes SF_6 emission control. The efforts are considered highly successful, since the annual emissions are reduced to approximately 0.4 % p.a. of the banked SF_6 amount.

2 Introduction

To fulfil Norway's obligations according to the Kyoto-protocol the Norwegian Pollution Control Authority proposed measures to reduce the emissions of all the gases mentioned in the protocol. For SF_6 it was at first proposed to introduce an import tax. The tax rate should reflect the high Global Warming Potential (GWP) of SF_6, and be based on existing tax rates for CO_2 emissions. This approach led to an import tax proposal of approximately 850 €/kg; a rather extreme measure. For example, it would have approximately doubled the investment cost of a gas insulated substation (GIS) overnight, and caused the value of the SF_6 contained in old GIS's to become greater than the value of the GIS itself.

The electric power sector initiated negotiations with the authorities and eventually reached an agreement in 2002 where heavy taxation was not an element. In return, utilities and industry committed themselves to, among other things, significant and verifiable reductions in their SF_6 emissions. A GIS user group that had been active for more than ten years played a crucial role in negotiating the agreement and is also essential in the various sides of its implementation.

This appendix describes the key points in the agreement, the tasks taken up by the GIS user group and the utilities, and the experience and results obtained after the agreement has been in effect for five years. In particular, SF_6 emissions for the years 2003 to 2008 are reported and discussed. Initially, a brief overview of the SF_6 filled high-voltage equipment in use in Norway is given.

3 SF_6 in high-voltage equipment in Norway – use and emissions

In year 2000 a quick survey was carried out in order to estimate the banked amount of SF_6 in high-voltage equipment in Norway, the magnitude of the annual emissions and their origins. These were assessments compiled by interviewing utility representatives and others. Table 6 summarizes the findings on banked amount and the emissions sorted after what type of components they come from.

Table 6: Estimated SF_6 inventory and emissions from Norwegian utilities in 2000

	Banked amount [tons]	Annual emissions [tons]	Annual emissions [%]
GIS (U ≥ 132 kV)	200	2.00	1.0
Medium-voltage (12, 24 and 36 kV) switchgear	60	0.12	0.2
Other standalone switchgear components	16	0.17	1.1
Total	276	2.29	0.8

As can be seen, nearly three quarters of the total quantity banked of almost 300 tons was assumed to be contained in the already installed 83 GIS substations. The majority of these 83 substations were put into service between 1973 and 1990. Around 20 000 medium-voltage switchgear contributed around 60 tons, whereas other standalone switchgear components used in AIS substations, SF_6 circuit breakers and SF_6 insulated instrument transformers were assumed to hold around 16 tons.

Concerning the emission estimates, the picture is quite similar. Close to 90 % of the emissions were believed to come from GIS.

With regard to identifying the causes for the emissions, i.e. the operations or the mechanisms that led to the emissions, the outcome of the study was as listed in Table 7.

Table 7: Causes of the SF_6 emissions in 2000 (rough estimates)

Cause	Annual emissions [tons]	Proportion of annual emissions [%]
Handling losses on GIS	1.30	57
Leakage losses from GIS	0.25	11
Handling losses on other components	0.11	5
Other (see text)	0.63	27
Total	2.29	100

More than half of the total emissions of around 1300 kg presumably occurred during planned and unplanned repair and maintenance on GIS. In essence, the available gas handling equipment at that time did not allow for very good recovery before the GIS compartments were opened.

Leaks from GIS were assumed to result in emissions of a few hundred kilos annually, leaks from other components even less. The most likely reasons for the good tightness are that the equipment has a good built-in quality, that it has been well maintained over the years, and that all GIS are installed indoor and thus are less susceptible to corrosion and leaks. Furthermore, the old dual pressure SF_6 breaker technology that in many cases represents the major source for leaks is completely absent in this population.

The “Other” causes include a wide variety of events and actions, such as sudden and unpredictable gas emissions due to disruptive failures and/or activated overpressure relief systems (“burst discs”) in GIS and other components, deliberate SF_6 venting, leaking gas bottles, leaks from other components than GIS, etc.

The overall emission rate, in this investigation estimated to well below 1 % annually, is rather low compared with many countries. However, even with these low emissions there was a general consensus between authorities and electric power sector that there was still possibility for further improvement.

4 Agreement between the utilities and the government

The agreement on SF_6 emissions reduction signed in 2002 establishes upper limits for the SF_6 emissions in a ten year perspective, i.e. until 2010, see Table 8. The compiled information about banked amount and emissions of SF_6 in 2000 (base line column in Table 8) serves as a baseline. The two columns to the right show the maximum permissible emissions in 2005 and 2010. The numbers in brackets are the estimated emission forecasts assuming no extra measures being taken. The users have committed themselves to reduce their (already low) emission rate from GIS by 30 % of the estimated emissions forecast for 2010.

Table 8: Permissible annual emissions according to the agreement. Numbers in brackets are predicted emissions without the agreement in effect

	Annual emissions [tons]		
	2000 (base line)	2005 targets	2010 targets
GIS	2.00	1.98 (2.20)	1.54 (2.20)
Other equipment	0.29	0.37 (0.37)	0.45 (0.51)
Total	2.29	2.35 (2.57)	2.05 (2.71)

The agreement states that the utilities have to keep detailed and verifiable accounts of their SF_6 inventory and emissions and to provide annual reports to the authorities.

The utilities are also obliged to use a recycling system for discarded SF_6 filled electrical equipment and contaminated SF_6 gas. This system has been established by the government and funded by a 0.2 % fee on all purchases of electrical equipment, including high-voltage apparatus.

5 GIS user group efforts

5.1 User group role and membership

The GIS installed in Norway are spread among a large number of utilities, with several utilities owning just a few installations. Hence, many of the utilities feel that they lack the resources and competence needed to operate and maintain these substations in a good manner. For example, the gas handling, cleaning and repair associated with internal arc faults require special equipment, skills and experience.

To meet this need for a meeting-place where GIS users can bring up and discuss matters of mutual interest a Norwegian GIS user group was established in 1991. At present the group has 21 utility members representing nearly all the GIS substations in operation. All major GIS manufacturers and service providers present in the Norwegian market are also members.

It is obvious from the numbers in Table 6 to Table 8 that focussing on the GIS is crucial to meet the emission requirements set up in the agreement. Hence, the GIS user group took a leading role by representing the utilities in the negotiations with the authorities and has also accepted several responsibilities according to the agreement. These will be described in the following sections.

5.2 Personnel training and gas handling equipment

As pointed out above, the largest contribution to the SF_6 emissions is assumed to be insufficient recovery of gas during invasive work on GIS. Hence, making major improvements here are necessary to be able to comply with the agreement. Two matters are identified as essential in this context:

- better gas handling equipment, especially with regard to its recovery capacity and efficiency
- personnel training and education.

In order to contribute to the latter, the user group offers courses in SF_6 handling to personnel from its member utilities. The courses are typically carried out as a two day event that includes both theoretical and practical aspects of gas handling. An SF_6 service cart is available, and normally the practical training is carried out as realistic and full scale exercise on a part of a GIS bay that has been taken out for maintenance. Several utilities have purchased new service carts or upgraded existing carts with recovery compressors complying with IEC 62271-303. The training offered by the user group will be in line with the European Commission regulation no. 305/2008 after minor adjustments.

5.3 SF_6 emission awareness

Every second year the GIS user group hosts a two-day conference which is very well attended by the domestic GIS community. In recent years issues related to SF_6 emission control have been on the agenda several times. This helps raising the awareness of the SF_6 users and has contributed in bringing about a change in the general attitude towards SF_6 emissions.

Furthermore, this user conference creates publicity and focus on SF_6 emissions which also attracts the attention from the management of the utilities. Reducing SF_6 emission quite often requires investments in rather expensive gas handling equipment, and therefore an increasing awareness on this issue, makes it easier to allocate the necessary funds for such investments.

5.4 SF_6 emissions in Norway in 2003 to 2008

Table 9 shows the reported SF_6 inventory and emissions for 2003 to 2008. The numbers include nearly all GIS and a large part of the population of medium-voltage switchgear and of the AIS circuit-breakers.

Table 9: Quantity and emissions of SF_6 collected from members of the GIS user group

	2003	2004	2005	2006	2007	2008
Banked quantity [tons]	199.5	201.5	205.3	210.1	213.1	236.0
Quantity in stock [tons]	5.5	7.2	7.5	7.9	8.8	9.9
Total quantity in use [tons]	205.1	208.8	212.8	218.0	222.0	245.9
Annual emission [tons]	0.569	0.677	0.830	1.521	0.950	1.116
Annual emission [%]	0.28	0.32	0.39	0.69	0.43	0.45

The listed quantities of SF_6 are based on careful estimates of gas volumes in each and every GIS and other piece of equipment, and by weighing all gas bottles in stock, and are thus assumed to be fairly accurate. The corresponding estimates in the simple and quick survey carried out in year 2000; see the second column of Table 4, turned out to be in good agreement with this more precise enquiry.

The reported annual emissions for 2003 to 2008 are low, in average 0.41 % p.a., and thus well within the limits set up in the agreement. The yearly reported emissions are strictly related to the maintenance activity and to the occurrence of single events as in 2006.

Although the accuracy of the estimated emission of nearly 1 % for GIS in year 2000 (see Table 6) which serves as a baseline for the agreement certainly can be questioned, it is believed that a real and significant reduction in the emission has taken place over the period. This comes from the facts that most utilities have improved their SF_6 handling procedures, several have purchased new and state-of-the-art equipment for this purpose, and there has been an obvious and general shift in the attitude in favour of SF_6 recycling and emission control.

However, much effort is needed to maintain the emissions at these very low levels in the years to come and it has to be considered that one single incident can have a great impact on the yearly emission rate (see year 2006). Therefore it is expected the emission rate will fluctuate year by year.

6 Conclusions

In a detailed survey the quantity of SF_6 in use (i.e. banked in equipment and kept in stock) and the associated annual emissions of a population of high-voltage equipment in Norway, mostly GIS, have been determined. The actual annual emissions have been significantly reduced over the years 2003 to 2008 compared to the estimated annual emissions of 0.8 % from year 2000, and are also in average lower than the targets given in the agreement between the utilities and the government.

From 2003 to 2008, the precision of the recorded data has increased year by year due to better awareness and procedures within the utilities.

This very positive result was reached by contributions from several organizations, and by the implementation of several measures. The most important ones are:

- A binding and verifiable agreement between the utilities and the government that obliges the utilities to gradually reduce their SF_6 emissions.
- An active GIS user group serving as an interface between utilities and government, that developed a database system for SF_6 inventory and emission registration, collects and compiles information about SF_6 use and emissions, offers training to utility personnel in gas handling, organizes conferences and in other ways contributes to an increased understanding of the necessity of reducing the SF_6 emissions.

- A concerted effort from the utility side to reduce the emissions during invasive work on GIS: by purchasing new state of the art SF_6 service carts, upgrading existing carts with better recovery compressors, and improving the gas handling procedures.

The general impression among all parties involved is that these measures have a more positive effect on the SF_6 emissions than a very high import tax would have had. On the other hand, the experience shows setting realistic targets for the reduction of SF_6 emissions produces positive results and encourages doing it even better.

APPENDIX 7

BASICS ON LEAKAGE SEARCH

1 Gas flow in leaks

The gas flow in leaks depends on the pressure range and the geometrical dimensions of the leak. Viscous flow is present, when the flow is determined by collisions of gas molecules with each other i.e. for higher pressures or large leaks. This is normally the case for major leaks originating from casting cavities, pores, or welding capillaries. Practically these leaks have mass flows above 20 g/a or leakage rates above 10^{-5} Pa·m^3/s. For the theoretical case of a circular capillary, the leakage rate is calculated by:

$$\boldsymbol{L} = \frac{\pi \cdot \boldsymbol{r}^4}{16\eta \boldsymbol{l}}\left(\boldsymbol{p}_1^2 - \boldsymbol{p}_2^2\right)$$

Where:

- ***L*** is the leakage rate in [Pa·m^3/s];
- ***r*** is the radius of the capillary in [m];
- η is the viscosity of the gas measured in [Pa·s];
- ***l*** is the length of the capillary in [m];
- $\boldsymbol{p_1}$ and $\boldsymbol{p_2}$ are the absolute pressures on both sides of the capillary in [Pa].

Molecular flow on the other hand is present, when the flow is determined by collision of the molecules with the walls of the leak. This is the case e.g. in vacuum interrupters and also in gas insulated switchgear in narrow gaps like rubber seals. Practically all minor leaks up to 0.2 g/a or 10^{-7} Pa·m^3/s in GIS show molecular flow:

$$\boldsymbol{L} = \frac{4\sqrt{2\pi}}{3}\sqrt{\frac{\boldsymbol{RT}}{\boldsymbol{M}}}\frac{\boldsymbol{r}^3}{\boldsymbol{l}}\left(\boldsymbol{p}_1 - \boldsymbol{p}_2\right)$$

Where:

- ***L*** is the leakage rate in [Pa·m^3/s];
- ***r*** is the radius of the capillary in [m];
- ***l*** is the length of the capillary in [m];
- ***R*** is the universal gas constant with 8314 J/(kmole K);
- ***T*** is the absolute temperature in [K];
- ***M*** is the gas molar mass in [kg/kmole] that is 4 kg/kmole for helium and 146 kg/kmole for SF_6;
- $\boldsymbol{p_1}$ and $\boldsymbol{p_2}$ are the partial pressures of the tracer gas on both sides of the capillary in [Pa].

In the intermediate range of leakage mass flow i.e. between 0.2 and 20 g/a, the molecular flow gradually changes into viscous flow. The molecular flow regime can be easily validated on a test sample by measuring the leakage rate as a function of the internal filling pressure during the tightness test. A linear relationship confirms molecular flow conditions, whereas a square dependence is in favour of viscous flow.

2 Conversion from absolute leakage rate in helium to mass flow in SF_6

2.1 Major leaks

For leaks having an absolute leakage rate $L > 10^{-5}$ Pa m^3/s where viscous flow is prevailing, the mass flow $\dot{m}_{visc}$ in [g/a] of SF_6 is provided by the following formula:

$$\dot{m}_{visc} = L_{He} \cdot \delta_{SF6} \cdot k_{visc} \cdot \frac{\left(p^2 - p_{ATM}^2\right)}{p_{test}^2} \cdot 3600 \cdot 24 \cdot 365$$

Where:

- L_{He} is the helium leakage rate given by the mass spectrometer in [Pa m^3/s];
- $\delta_{SF6} = 6.07\text{x}10^{-2}$ g/(Pa m^3) is the density of SF_6 at 1 Pa and 20 °C;
- $k_{visc} = 18.63/15.02 = 1.240$ is the dynamic viscosity ratio which is the conversion factor from helium to SF_6 for viscous flow;
- p is the SF_6 rated filling pressure in [kPa];
- $p_{ATM} = 100$ kPa is the atmospheric pressure;
- p_{test} is the helium filling pressure during the tightness test in [kPa].

2.2 Minor leaks

For minor leaks having an absolute leakage rate $L < 10^{-7}$ Pa m^3/s where molecular flow is the predominant leaking mechanism, the mass flow $\dot{m}_{mol}$ in [g/a] of SF_6 is provided by:

$$\dot{m}_{mol} = L_{He} \cdot \delta_{SF6} \cdot k_{mol} \cdot \frac{p}{p_{test}} \cdot 3600 \cdot 24 \cdot 365$$

Where:

- L_{He} is the helium leakage rate given by the mass spectrometer in [Pa m^3/s];
- $\delta_{SF6} = 6.07\text{x}10^{-2}$ g/(Pa m^3) is the density of SF_6 at 1 Pa and 20 °C;
- $k_{mol} = (4/146)^{½} = 0.166$ is the square root of the molecular mass ratio which is the conversion factor from helium to SF_6 for molecular flow;
- p is the SF_6 rated filling pressure in [kPa];
- p_{test} is the helium filling pressure during the tightness test in [kPa].

2.3 Intermediate leaks

For leaks having an absolute leakage rate L so that $10^{-7} < L < 10^{-5}$ Pa m^3/s the mass flow $\dot{m}$ in [g/a] of SF_6 can be bounded by the following:

$$\dot{m}_{mol} < \dot{m} < \dot{m}_{visc}$$

3 Dependence of leakage rates on gas, pressure and temperature

For major leaks or viscous flow, SF_6 and helium have similar leakage rates. Because of the slightly higher viscosity of helium compared with SF_6, the leakage rate measured with helium even is only 78 % of the equivalent SF_6 leak. Also, because it is assumed that the flow in the capillary is unidirectional i.e. directed from higher to lower pressures, no backflow of molecules is possible as long as a pressure gradient exists. Therefore the total pressure on both sides of the capillary is clearly independent of the nature of the gas.

However, the square root dependence of the two pressure values has to be considered; therefore the leakage rate is not simply depending on the pressure difference! For major leaks, there is no advantage working with helium instead of SF_6 as tracer gas besides avoiding the handling of SF_6.

For minor leaks, which determine the tightness of equipment designed for a leakage rate of less than 0.1 % p.a., helium as tracer gas clearly has an advantage over SF_6. Because of the applicability of the molecular flow and because of the different masses of SF_6 and helium, the leakage rate of the same leak measured with helium is 6 times higher than with SF_6! This can be simply deduced from the square root dependence of the molar masses. The second consequence of molecular flow is that the molecules inside the capillary or leak are independently moving. Gas mass flow can coexist in both directions! Therefore the difference of partial pressures of each gas on both sides of the capillary has to be considered. Let's take a gas compartment filled with SF_6 at the rated filling pressure. Two mass flows having opposite directions coexist: SF_6 leaking out of the compartment and air entering into it. For SF_6 the mass flow is controlled by the SF_6 rated filling pressure (the partial pressure of SF_6 is assumed as zero outside); while for air the mass flow is controlled by the atmospheric pressure (the partial pressure of air is assumed as zero inside).

The leakage rates slightly increase with the temperature. For both flow regimes there is only a small variation between 0 and 100 °C. In the viscous regime the viscosity determines the temperature dependence giving a variation of approx. 15 %. In the molecular flow regime the square root of the absolute temperature causes a variation of approx. 10 %. Both variations therefore are negligible.

4 Diffusion of gases through polymers

The gases have the capability of diffusing through polymers like e.g. gaskets. This physical process is called permeation. The rate of permeation depends on the gas, the shape of the polymeric part, the physical properties of the material, and the ambient temperature.

$$\boldsymbol{P} = \boldsymbol{K}\frac{\boldsymbol{A}}{\boldsymbol{d}}\left(\boldsymbol{p}_1 - \boldsymbol{p}_2\right)$$

Where:

- $\boldsymbol{P}$ is the permeation rate in [Pa m^3/s]
- $\boldsymbol{K}$ is the coefficient of diffusion in [m^2/s]. Often the coefficient of diffusion $\boldsymbol{K}$ is given in [mbar l/s mm/m^2/bar], 1 mbar l/s mm/m^2/bar = 10^{-9} m^2/s;
- $\boldsymbol{A}$ is the total area available for diffusion e.g. the area of gasket grooves normal to the direction of the pressure in [m^2];
- $\boldsymbol{d}$ is the penetration length of the gas molecules e.g. the thickness of gaskets in [m];
- $\boldsymbol{p_1}$ and $\boldsymbol{p_2}$ are the partial pressures of gases on both sides of the gaskets in [Pa].

Polymers have different diffusion coefficients $\boldsymbol{K}$ depending on the material and on the gas. For a given material, SF_6 shows a much smaller diffusion coefficient $\boldsymbol{K}$ than helium because of its larger molecule dimension. Normally permeation of SF_6 through gaskets can be neglected.

Permeation of helium or SF_6 can have significant temperature dependence; which is hidden in the coefficient of diffusion $\boldsymbol{K}$. As for most thermodynamic processes, $\boldsymbol{K}$ can be assumed to double for a temperature increase of 10 K within the temperature range from 0 to 100 °C.