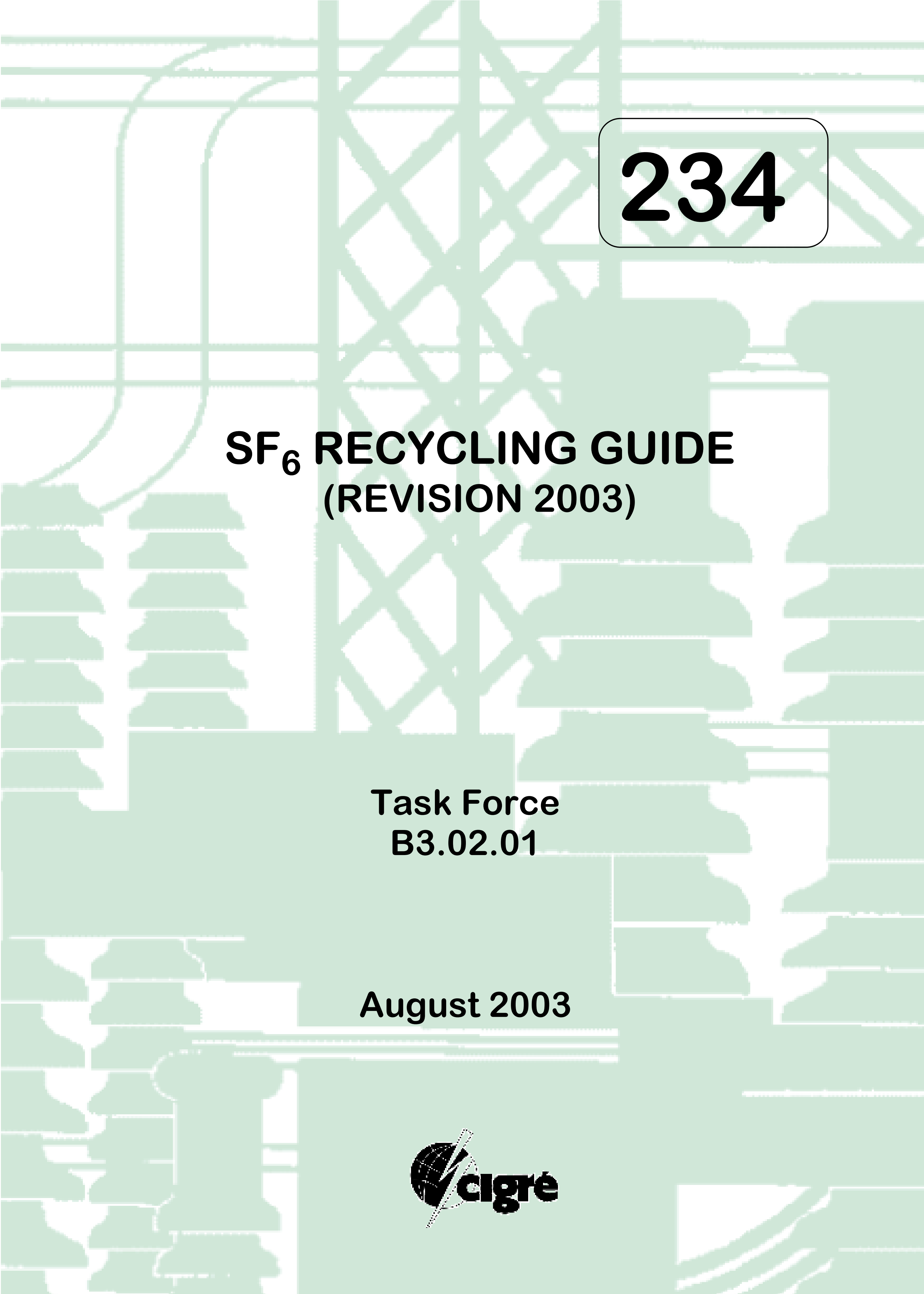

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SF$_6$ RECYCLING GUIDE
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SF_6 RECYCLING GUIDE

Re-use of SF_6 gas in electrical power equipment and final disposal

by

CIGRÉ B3. 02 TASK FORCE 01

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SUMMARY

This document reviews all significant aspects of the recycling of SF_6 gas used in electrical power equipment. It gives recommendations for the design of electrical power equipment utilising SF_6 to allow ease of gas recycling, proposes appropriate gas handling and recycling procedures to be applied and describes essential features of gas handling and recycling equipment. It identifies the origins, quantities and deteriorating effects of contaminants to be expected in SF_6 used in electrical power equipment and proposes purity standards to which SF_6 gas should be reclaimed to allow its safe reuse. Methods of verifying the quality of the reclaimed gas are also given, as are proposals for transportation of the gas with varying degrees of contaminants. Additionally, a final disposal concept is proposed by which SF_6 can be removed from the eco-cycle and transformed into environmentally compatible substances. Finally the document gives general recommendations to be applied when handling SF_6 with further specific recommendations for electrical power equipment manufacturers, users and for SF_6 producers. A number of issues still require resolution and these are listed as recommendations for further work. Extensive background information on important issues is given in appendixes.
A first version of this guide was published in 1997 (CIGRE document N. 117); knowledge improvements of the last 6 years have been taken into account in this revision 2003.

Contents

1 INTRODUCTION

Sulphur hexafluoride, SF_6, an essential material for high-voltage electrical equipment, has been identified as a greenhouse gas with a long atmospheric lifetime [1.1]. Recent findings show a lower, but still significant, figure [1.2]. To address this issue, CIGRÉ WG 23.02 prepared two papers, [1.3] and [1.4]. The first one discusses all the possible effects of SF_6 in the environment; while the second one clearly states that the contribution of SF_6 to the total man-made greenhouse effect in 1999 was less than 0.1%.

As most of the SF_6 purchased by the electrical industry is for use in newly installed sealed electrical power equipment, its contribution to the observed global emission rate can only be negligible. Nevertheless, in view of the longevity of SF_6 in the atmosphere noted in [1.1], [1.2], [1.3] and [1.4] the emission of SF_6 from electrical power equipment has to be minimised by the avoidance of deliberate release and by systematic recycling. The term recycling is understood to comprise reclaiming and reuse, further purification of gas, which cannot readily be reclaimed, and environmentally compatible final removal of gas from the eco-cycle. Recycling of SF_6 has been practised to varying degree by users of SF_6 insulated electrical equipment. What has been lacking, however, is a comprehensive guide for users that addresses all aspects of SF_6 recycling. This document seeks to fill that gap by presenting guidelines on the recycling friendly design of electrical power equipment, by describing the origin and effects of contamination of SF_6, and the tolerable impurities for gas to be reused. In addition, suitable reclaiming equipment and procedures, storage, transportation and reuse procedures, as well as further treatment of gas that cannot be reused are addressed.

As SF_6 applied in electrical power equipment is inherently contained and not consumed or released, recycling can be easily introduced as a natural part of handling. Users of SF_6 gas should therefore establish a policy to minimise SF_6 losses into the atmosphere by minimising leakage losses from equipment and by systematic recycling. Appropriate standards, procedures and equipment should support this policy. The benefits to be obtained from this are:

- Consistency with a general public policy of avoiding release of man-made gases into the environment;
- Conservation of a valuable material;
- The demonstration of a voluntary effort to reduce an emission without formal regulation by authorities.

The minimisation of leakage losses from equipment has been a major issue in the past. Development of gas insulated equipment has resulted in practical leakage rates in the order of 0.1% per year. There are also sealed pressure systems (sealed for life equipment) that do not require any gas handling during service life [1.5].

It is desirable, both from an ecological and economic point of view, to keep SF_6 at a low contamination level by careful handling so that it can be reused many times.

SF_6 should, continually be reused during equipment development, product testing, commissioning, maintenance and repair, and decommissioning. It should also be transferred from equipment being phased out into newly installed equipment. It thus goes through a continuous cycle of reuse.
Such a systematic reuse of SF_6 requires that the gas be kept at the stated quality level at which it can perform its functions. This can be achieved by proper handling and reclaiming. With properly designed and maintained reclaiming equipment, moisture and

reactive by-products can almost always be reduced on-site to tolerable impurity levels for reuse.

Only in rare cases the gas cannot be purified sufficiently on-site, e.g. due to excessive contamination with non-reactive gases such as air and / or CF_4. In those cases, the on-site purification process allows for transporting the non-reusable gas as non-toxic gas, like new SF_6 for off-site purification by a recycling enterprise to be rendered reusable. Such off-site purification process results in only a very small fraction of the residue being processed for final disposal in an environmentally compatible way.

Successful SF_6 handling and recycling requires:

- Knowledge of the origins and quantities of contaminants to be expected in SF6 used in electrical power equipment;
- Electrical power equipment designed for ease of recycling;
- Purity standards for reclaimed SF6 to be reused in electrical power equipment;
- Appropriate gas handling and recycling equipment;
- Appropriate gas handling and recycling procedures;
- Methods to verify quality of reclaimed gas;
- Under a long-term perspective, additionally, a final disposal concept is required by which SF6 can be removed from the eco-cycle by retransforming it into environmentally compatible substances.

These seven issues are the subjects of this document.

In order to explore the present awareness of SF_6 users for SF_6 handling and recycling problems, a questionnaire was circulated by the CIGRÉ Working Group WG 23 - 02 to SF_6 users (equipment manufacturers and utilities) which triggered some 50 responses.

The following conclusions could be drawn from the survey:

(1) There is presently little common consistency in the approach to handling and recycling SF_6 in practice.

(2) Only high voltage Gas Insulated Switchgear (GIS) users systematically recycle SF_6. For other electrical power equipment using smaller quantities of SF_6 recycling is frequently not applied.

(3) The reasons for not recycling SF_6 are equipment and manpower costs, and the extremely stringent purity requirements imposed by the standard IEC 60376, for new gas, which was specified by some manufacturers to guarantee equipment performance.

(4) SF_6 handling and recycling equipment is commercially available ranging from the very basic to very sophisticated.

(5) Presently applied handling and recycling procedures vary widely and are partly inconsistent.

(6) The purity criteria applied for the recycled gas vary over a wide range.

(7) The quantitative knowledge on actual leakage and handling losses is frequently insufficient.

(8) The estimated cost/benefits of recycling varied extremely widely.

The major conclusion is:

The need for recycling SF_6 has been recognised but comprehensive guidelines for handling and recycling are urgently needed, along with realistic purity standards for reclaimed SF_6 to be reused in electrical power equipment. The presently ongoing revision of IEC 60480 aims to satisfy this need.

This document provides an outline of such handling guidelines and a proposal for a future purity standard.

A first version of this guide was published in 1997 (CIGRE document N. 117); knowledge improvements of the last 6 years have been taken into account in this revision 2003.

2 DEFINITIONS

A number of terms are used in this document that require clarification, these are defined below:

Recycling: In the context of this document this term will be understood to comprise the following described processes of recovery, reclaiming, storage, reuse, further treatment and final disposal.

Reclaimer: Device for purification of used gas for the purpose of reuse.

Reclaimed gas: Gas that has been processed by a reclaimer.

Recovery: Transfer of gas from electrical power equipment into a reclaimer or storage container.

Storage: Intermediate storage of reclaimed gas.

Reuse: Use of reclaimed gas for filling new or existing electrical equipment.

Gas Quality Check: Check of reclaimed gas for compliance with the purity requirements for reuse.

Further treatment: Additional purification process required for gas that does not fulfil the purity requirements for reuse.

Final disposal: Transformation of gas into substances, which can be either used for other purposes or disposed of in an environmentally compatible way.

3 DESIGN OF SF_6 INSULATED ELECTRICAL POWER EQUIPMENT

3.1 Low Losses

International discussions have been held concerning reductions in emissions of all greenhouse gas, and, as a consequence, many users of SF_6 have been focusing attention on reducing their losses. SF_6 leakages and handling losses are an important part of these emissions.

For the whole service life the secure performance depends on the optimised quality of all components of the switchgear. In regard of SF_6 leakage, the quality of the encapsulation including its material, the machining process, the design of gaskets and the sealing material itself is of major importance. The tightness of the gas-insulated switchgear over the whole service time is not only a condition for reliable function of the switchgear but also for a prevention of SF_6 leakages.

Sealing designs vary between single O-ring for static sealing, such as enclosure flange connections, to multiple gaskets with closed grease chambers for rotating and axial dynamic seals.

SF_6 technology has been continuously developing since 1964, when SF_6 was first used in switchgear. A lot of fundamental research was done on SF_6 sealing systems in general, in materials, dimensions, surfaces etc. Furthermore the treatment of all kinds of flange connections and interfaces is designed to prevent corrosion.

Most of the presently installed SF_6 insulated electrical power equipment is designed for low leakage rates in accordance with international standards IEC 60694 (future 62271 part 1), IEC 62271 part 100 (former 60056), IEC 60298 (future 62271 part 200), IEC 60517 (future 62271 part 203), IEC 61634 (future 62271 part 303) as well as national standards.

With these details of the design a leakage rate below 1.0%/a per compartment can be guaranteed. At present, a leakage rate of less than 1.0%/a is still specified in the standards for SF_6 insulated electrical power equipment. Preliminary data from utilities indicate that actual leakage rates in operating equipment are often substantially lower, the leakage rate is according to the experience over more than 30 years in average less than 0.5%/a and in special cases, due to the design of the compartments, even down to < 0.1%/a.

For distribution applications, sealed pressure systems (sealed for life equipment) are being produced for which leakage rates below 0.1%/a are obtained.

For new equipment IEC standard 62271 part 1 resp. part 203 is on revision and suggest to limit the permissible leakage rate down to 0.5%/a. The reduction of this value even down to 0.1%/a was discussed. However this suggested limit value can only be measured under laboratory conditions and is therefore not for use in the field. All future equipment should be designed such that the overall leakage rate of an installation is below 0.1%/a. Until more sensitive routine test methods are available the best available techniques should be applied to verify, on routine test, a leakage rate per test unit of better than 0.5%/a.

In the last years the development of SF_6 insulated switchgear was mainly driven by the aim to reduce the use of material and costs at still extremely high reliability. As a result very compact substations designs are on the market with the following changes against older equipment:

- Up to 98% of space reduction in comparison to air insulated switchgear;
- Up to 75% reduced SF_6 volume;
- Delivery of completely closed and tested bay units up to 245 kV;
- Leakage rates down to less than 0.5% per compartment and year.

However it has to be mentioned that losses of SF_6 is not only a matter of design. The handling with SF_6 during installation, on site testing and maintenance activities has a major contribution to the overall SF_6 loss rate. While in the past mainly time-based maintenance has been done, sometimes with unnecessary work, nowadays minimum condition based maintenance is done. Only specialists and skilled people, who know how to handle the matter, will do necessary maintenance work. To reduce all handling losses as much as possible, the switchgear is designed to minimise life time handling losses and the procedure of installation, service, maintenance and repair is described by the manufacturers as detailed as possible.

3.2 Gas Pressure / Density Monitoring

The switchgear can only function correctly if the required gas density in the individual gas compartments is available. In the event of a failure or an impermissible deviation, visual and/or acoustic alarms are initiated. Only if these deviations reach such magnitudes that normal operation can no longer be maintained, automatic lockout features come into effect.

However, the accuracy of commonly used gas monitors provides an alarm after 5 to 10% of the gas has leaked out. The equipment is designed to operate correctly with this loss of gas, and still has a safety margin.

The gas pressure/density of a compartment should be checked continuously by reading the gauge value and analysing the trend of the gas pressure/density versus the time. If the gas pressure/density is dropping by measurable amounts, taking into consideration that the pressure varies with temperature while the density is independent, corrective measures should be organized as quick as possible. The initial step of adding gas to restore normal operating gas content should be followed by action to locate and eliminate the leak or leaks. The rather large leakages apparently allowed by gas monitor systems should not be interpreted as implying that high leak rates are either normal or acceptable.

Modern gas checking systems that continuously measure the SF_6 gas content (density) provide leakage rate information, which allows early detection of small leaks.

3.3 Contamination of Gas

The equipment compartments, in particular those containing a switching function like disconnectors, load switches, circuit breakers, are always equipped with adsorbers that are dimensioned such that they can accommodate, in addition to moisture, all chemically reactive, corrosive, and toxic decomposition products that could be produced during the maximum specified operating cycle (see Chapter 4 for more details).

3.4 Gas Recycling

The following design features of gas insulated electrical power equipment contribute to the ready application of successful gas recycling:

(1) The removal of decomposition products and moisture by internal adsorbers keeps the contamination levels in the gas very low and thus eases the cleaning of the gas during recycling.

(2) Minimizing the gas volume and pressure reduces the quantity of the gas to be recycled.

(3) Subdivision of the equipment in closed compartments limits the quantity of the gas to be recycled, particularly in the case of failure arcing when severely contaminated SF_6 has to be treated.

(4) Sealing systems that are designed to withstand both pressure and vacuum, which will occur during gas removal / filling avoid the possible contamination of SF_6 with air and moisture.

(5) SF_6 specific gas connections and check valves prevent accidental gas loss or contamination with air by handling errors.

(6) Minimizing external gas pipe work reduces leakage from corrosion or mechanical damage.

(7) Minimizing the use of oil and grease as lubricants in the equipment excludes the possibilities of contamination in the gas with lubricant oil, which is difficult to remove.

The above features can be implemented in a straightforward manner, taking also the thermal and mechanical design aspect into consideration, and are state-of-the-art in most present day equipment. Older equipment can be retrofitted at the time of maintenance at relatively low cost.

4 CONTAMINATION OF SF_6 IN ELECTRICAL POWER EQUIPMENT

4.1 Origin of Contamination

The contaminants of SF_6 that may be generated in electrical power equipment originate from six major sources, namely:

- Gas Handling;
- Leakage;
- Desorption from surfaces, bulk materials, and adsorbers;
- Decomposition by electrical discharges;
- Secondary reactions of discharge decomposition products;
- Mechanical generation of dust and particles.

The levels at which these contaminants are present depend mainly on equipment design, manufacturing, assembly, on gas handling procedures, adsorber design, and on the cumulated discharge activity.

4.1.1 Contamination by Gas Handling

During gas handling, i.e. filling and emptying of the equipment, air may be inadvertently added to the SF_6 as residue in pipe-work and valves, by leakage through sealings, by the residual air pressure left in the enclosure after evacuation before filling with SF_6 and by handling errors. The amount of air and gas-entrained dust which is introduced in this way can be minimized by:

- Appropriate design of pipe-work and valves;
- Appropriate handling procedures;
- Careful evacuation of the air from the enclosure before filling with SF_6 (a residual air pressure of < 100 Pa is recommended).

4.1.2 Contamination by Leakage

Air and moisture may diffuse into the pressurized enclosure from the outside because the partial pressure of air and water outside the enclosure is higher than inside. The main leakage paths are enclosure porosity, sealings of mechanically moving transmission elements, and sealing systems. Diffusion through metals is negligible. Diffusion through polymeric materials may play a role but is normally negligible because of the very small diffusion coefficients of air and water vapour in these materials.

4.1.3 Contamination by Desorption

Various gases and vapours such as water and cleaning agents may be adsorbed at the inner surfaces of the equipment or absorbed in bulk materials before the equipment is assembled. Metal surfaces are loaded with moisture and may have cleaning agents adsorbed. Polymeric materials contain substantial quantities of moisture within the bulk, being the most important source of moisture in the system. Field sampling on equipment with adsorbers shows that the partial water vapour pressure in the gas is of the order of 100 Pa [1.15], which corresponds to a dew point around – 20 ^{o}C at operating pressure (see Appendix 4 Section 4).

Adsorbers, which have not been properly handled or are overloaded, may contain both moisture and adsorbed SF_6 by-products, which may be released during evacuation or at elevated temperature.

The quantities of the desorbed substances are difficult to estimate because they depend on the specific materials employed, the production methods, quality control and the assembling and maintenance procedures. For the case of moisture, field sampling on operating equipment shows that its concentration is typically a few hundreds ppmv and is mainly determined by absorption equilibrium with polymeric materials [1.15].

4.1.4 Decomposition by Electrical Discharges

SF_6 is partially decomposed by electric discharges, which can be grouped into four major types, namely:

- Partial discharges of the corona type;
- Spark discharges;

- Switching arcs;
- Failure arcs.

Partial Discharges

Partial discharge activity of the corona type is caused by insulation defects. It decomposes SF_6 mainly into the fragments SF_4 and F, which further react with traces of oxygen, O_2, and water, H_2O, to form the compounds HF, SO_2, SOF_2, SOF_4 and SO_2F_2 [1.11]. Higher molecular compounds such as S_2F_{10}, S_2OF_{10} and $S_2O_2F_{10}$ are also formed, however, in much smaller and practically insignificant quantities [1.6], [1.7]. Due to the low intensity of the discharges, the quantities of decomposition products formed are very low, mostly in the range of several tens of ppmv referred to SF_6 filling pressures of about 500 kPa [1.9].

Spark Discharges

Spark discharges may occur at large scale insulation defects such as floating conductors and during disconnector switching operation. The decomposition products generated are of the same kind as in corona discharges but their quantitative generation rates and composition are different [1.8], [1.12]. The quantities formed in disconnectors are very small because these devices operate rarely and only interrupt small capacitive currents. Higher quantities can only be accumulated if severe insulation defects causing permanent spark-type discharge activity prevail for an extended period of time and if no adsorbers are provided in the equipment. Systematic use of adsorbers is recommended because it mitigates the accumulation of decomposition products also under these worst-case conditions.

Switching Arcs

Switching arcs occur in load break switches and power circuit breakers. The high current flow in these arcs leads to substantial erosion of the contact and insulation materials by the hot arc. The main cause for SF_6 decomposition is the reaction of these erosion products with the fragments of thermally dissociated SF_6 and other trace gasses such as oxygen and water vapour [1.11]. The most important of these reactions can be expressed by the three summarising formulae:

$$Cu + SF_6 \quad \text{--->} \quad CuF_2 + SF_4 \qquad (1)$$
$$W + 3\ SF_6 \quad \text{--->} \quad WF_6 + 3\ SF_4 \qquad (2)$$
$$CF_2 + SF_6 \quad \text{--->} \quad CF_4 + SF_4 \qquad (3)$$

The first two reactions are associated with eroded material from the arcing contacts for which copper tungsten (Cu-W) is normally used. The last reaction is due to eroded PTFE (a CF_2 polymer), which is employed in most switchgear to contain the arc.

The primary products generated by the reactions (1) - (3) are the solid copper fluoride CuF_2 and the two gases SF_4 and WF_6. The latter two gases are very reactive. They are removed from the gas volume by:

- sorption in adsorbers with subsequent transformation by chemical reactions (chemisorption);
- secondary reactions in the gas volume, mainly hydrolysis with residual moisture;

- secondary reactions at the surfaces of the enclosure, mainly hydrolysis with surface adsorbed moisture and reactions with metal oxides/hydroxides and silicon containing substances such as quartz fillers in polymeric insulators.

In switchgear the sorption in the adsorber is the dominant removal mechanism. The two other processes are relatively unimportant from a quantitative point of view. The presence of the adsorber has the consequence that high concentrations of decomposition products cannot build up permanently. Only in the rare event of a short-term high level switching activity, such as a heavy short circuit interruption, an increased concentration may exist for a time interval determined by the speed of the adsorption process, typically several hours to a few days.

Failure Arcs

Failure arcs are the result of insulation breakdown or switchgear interruption failure and occur extremely rarely. In these events the arc burns mainly between metallic materials, which are not designed for arcing such as aluminium, copper and steel. These materials have relatively high arc erosion rates. Additionally, the current is frequently in the short circuit range. The amount of arc eroded material and the corresponding quantity of gas decomposition products can reach concentrations in the range of several percent by volume [1.10]. In addition to that, solid decomposition products (metal fluorides and oxy-fluorides) may be formed in higher quantity.

4.1.5 Mechanical Generation of Dust Particles

Metal dust particles may be generated by mechanical friction of metal surfaces. In properly designed equipment these particles usually fall into areas where they have no effect on the insulation integrity of the installation. If however they fall into an area of high electrical field stress such as an insulating barrier they may cause tracking on the insulator surface and flashover (breakdown). Therefore, wherever gas is handled, care has to be taken to remove particles by appropriate dust filters.

4.2 Effects of Contamination

A functional deterioration of equipment by SF_6 contaminants can, in a general sense, be viewed in the following six respects:

- Health risk;
- Corrosion;
- Insulation performance of gas gaps;
- Insulation performance of insulator surfaces;
- Switching capability (for switchgear only);
- Heat transfer.

Most of the reactive SF_6 decomposition products and their follow-up reaction products have toxicities comparable to SO_2 and therefore may constitute a health risk if present in too high concentrations.

Some of the reactive decomposition products are corrosive (i.e.: SF_4 and HF) and may react with inappropriate materials used in the equipment design. In particular, they may affect surface insulation by the formation of conductive layers along insulators [1.14]. The corrosive effects are controlled by the absolute partial pressure of the corrosive agent. Modern designs, however, avoid the use of corrosion sensitive materials.

Some of the contaminants are chemically inert such as air, CF_4 and moisture may affect the gas insulation capability and the circuit-breaker switching performance, if present in too high concentrations. They may also have an influence on the convective heat transfer by the insulating gas. These influences all enter approximately proportionally, i.e. they are controlled by the relative concentrations of the contaminants.

With respect to **condensed (liquid and solid) contaminants** three categories have to be distinguished:

Form a theoretical point of view; the main **conducting liquid** contaminant is **water** condensing from water vapour (moisture) in the form of water droplets or films. As water has an extremely high dielectric constant and a high electric conductivity it causes local field enhancements at droplets and conducting surface films along insulators, both of which deteriorate the insulation performance. It has to be noted that moisture condensing in the form of ice does *not* affect insulation [1.13] [1.15].
Moisture is mainly introduced by de-sorption from surfaces and from the bulk of polymers, see Appendix 4, Section 4. Its condensation is controlled by the absolute moisture, which is best expressed in terms of the partial water vapour pressure p_{H2O}. Liquid condensation occurs for $p_{H2O} > 611$ Pa and temperatures above 0 ^{o}C.
Besides water, **oil** may be deposited on insulators where it may be carbonised by thermal or chemical reactions and thus give rise to the formation of conductive surface layers. As this contaminant is very difficult to control it should, where possible, be avoided completely, e.g. by using oil-free lubrication and by handling the gas exclusively with oil-free equipment.

Non-conducting solid decomposition products are generated from arc eroded metals by reaction with dissociated SF_6 [1.11]. They mainly consist of copper fluoride CuF_2, tungsten oxide WO_3, the tungsten oxyfluorides WO_2F_2 and WOF_4 originating from switchgear contact erosion ("switching dust") and aluminium fluoride $Al\ F_3$ in case of internal arcing. They are non-critical for insulation as long as they are not exposed to excessive moisture. They have to be taken into consideration only when released from the enclosure on the occasion of repair or failure because they may carry toxic and corrosive gases in adsorbed form.

Conducting solid contaminants such as carbon and metal dust may become critical when deposited on field-exposed insulator surfaces as conducting layer. Carbon may be generated by carbonisation of polymeric materials. Metallic dust particles generated by mechanical friction may be transported by gas flow.

An overview over the major contaminants, their origin, and their deteriorating effects is given in the first 3 columns of Table 1 in Section 4.3.2.
Appendix 1 contains a detailed discussion of the above mentioned degradation mechanisms and an approximate derivation of impurity levels below which functional deterioration effects can be excluded.

4.3 Maximum tolerable impurity levels for the reuse of SF_6 in electrical equipment

4.3.1 Summary of measurement units for impurities

Impurity levels in gases can be measured in various units the most important of which are summarized below for reference:

Mass-based concentrations:

ppmw = mg/kg = μg/g: parts per million by mass (= “weight” = w)

Volume based concentrations:

% vol : percent by volume
ppmv = μl/l = ml/m^3: parts per million by volume

Mass-volume based concentration:

mg/m^3

This latter unit is frequently used for finely dispersed condensed contaminants such as oil mist and dust of solid particles, because it is directly measurable by the weight increase of a filter through which a gas volume has been passed.

For gaseous contaminants the following relations can convert volume concentrations into mass concentrations:

$$c_{H2O}\,[\text{ppmv}] = c_{H2O}\,[\text{ppmw}] \,/\, (M_{cont}/M_0)$$
$$c_{H2O}\,[\text{ppmw}] = c_{H2O}\,[\text{ppmv}]\,(M_{cont}/M_0)$$

where M_{cont} and M_0 are the molecular mass of the contaminant and the background gas, respectively.

For moisture additional units are in use such as the partial water vapour pressure p_{H2O}, the dew point T_d determined at the pressure p at which the gas is used and the dew point T_{d0} determined after expanding a gas sample from the pressure p to atmospheric pressure p_0 = 100 kPa. A detailed discussion of these units is given in Appendix 4, Section 2.

As the use of the different units can lead to confusion **it is recommended that impurity levels be preferentially specified in terms of volume concentrations such as %vol and/or ppmv.** This has the advantages that the impurity levels:

- Are independent of the chemical composition of the background gas and thus do not only apply to pure SF_6 but also to arbitrary SF_6 mixtures
- Are independent of the gas temperature
- Remain unchanged when the gas is compressed or expanded during a gas transfer process
- Are, in the case of gases and vapours, equal to the ratio of the partial pressures of the impurities to the pressure of the background gas.

If other units should be needed they can be calculated by the conversion rules given above. For dew points see Appendix 4, Section 2.

4.3.2 Derivation of maximum tolerable impurity levels for reuse

Four types of contaminants are to be distinguished, namely,

- Non-reactive gases;
- Reactive (toxic and/or corrosive) gases;
- Moisture (water vapour);
- Condensed contaminants (oil, dust).

The choice of maximum tolerable impurity levels for reuse is based on:

- The **maximum tolerable levels** in equipment, i.e. the impurity levels above which the function of the equipment starts deteriorating or health risk occurs. These levels have been transferred from Table 9 in Appendix 1 and are represented in the **4th column of Table 1**.
- The **impurity detection sensitivity**, i.e. the levels which can be detected with practical equipment. These levels are represented in the **6th column of Table 1**.
- The **avoidance of functional over-specifications**, which would lead to an increase of the cost of gas handling and thus discourage reuse.

Non-toxic and non-corrosive gases are tolerable in equipment up to 3% vol (see **Appendix 1**). The level for reuse is chosen equal to this value because a safety margin is not required.

For **reactive** (toxic and corrosive) **gases** toxic risk turns out to be the most critical issue. A sum concentration of all toxic gases is specified with a safety margin of a factor of two under the worst case assumption that only the most toxic gases are present.

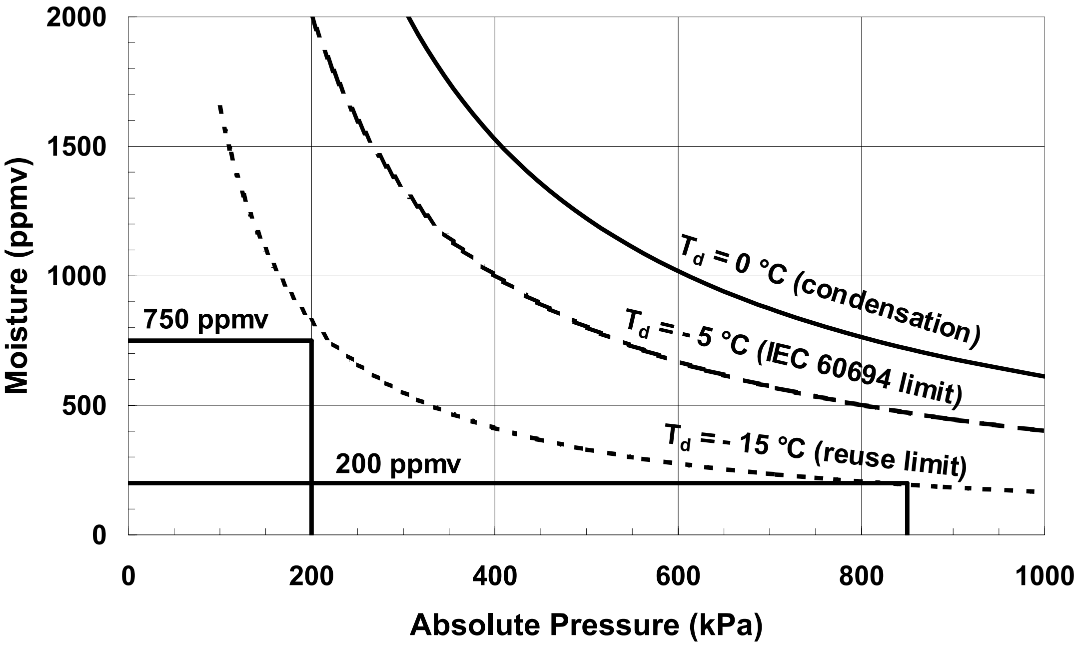
For **moisture**, three basic levels are essential, namely,

- The moisture level above which **liquid condensation** occurs and which, in terms of the partial water vapour pressure, is **611 Pa** [1.16].
- The **maximum tolerable level in equipment** according to **IEC 60694**, which was chosen to safely exclude liquid condensation. It is specified by a dew point of –5 ^{o}C which corresponds to a water vapour pressure of **400 Pa** [1.16], which is about two thirds of the liquid condensation level of p_{H2O} = 611 Pa.
- The **basic moisture level in equipment** which is typically in the range of some **100 … 300 Pa** [1.15]. This level is established as result of sorption-de-sorption processes at the inner surfaces of the equipment and the adsorbers and thus is a characteristic of the enclosure design and state. It can not be reduced by filling in dry gas because the surfaces and adsorber contain about two orders of magnitude more moisture than could be carried in by moist gas (see Appendix 4, Section 4).

It is therefore considered as adequate to require, as **criterion for reuse**, that the water vapour pressure in the gas should not exceed **150 Pa**, which corresponds to a dew point of –15 ^{o}C [1.16]. This level provides a safety margin of a factor of 2.7 with respect to the maximally admissible level in equipment (400 Pa) and a margin of a factor of 4 with respect to the level above which liquid condensation would occur (611 Pa).

Figure 1 reports the above discussed moisture levels in terms of the recommended preferential measurement unit ppmv and the operating pressure p.

Figure 1: Moisture levels [ppmv] in dependence of gas pressure p. Uppermost curve: Liquid condensation limit (611 Pa, Td = 0 °C). Middle curve: Maximum concentration in equipment according to IEC 60694 (400 Pa, Td = -5 °C). Lower curve: Proposed maximum tolerable level for reuse (150 Pa, Td = - 15 °C). Step curve: proposal for simplification distinguishing between low (< 200 kPa) and complete (< 850 kPa) range of reuse pressures.



As the ppmv values are obtained as the ratio of the water vapour pressure p_{H2O} to the gas pressure p they are inversely depending on the gas pressure p. The ppmv scale allows to directly reading the safety margins between the three curves for liquid condensation, IEC 60694 and the proposed maximum impurity level for reuse.

For practical reasons it is considered cumbersome to determine the ppmv levels for reuse for each pressure separately. It is therefore proposed to **simplify the moisture criterion for reuse** by defining the low range of reuse pressures within the complete range of reuse pressures as indicated by the step curve:

- The **complete SF_6 reuse pressure range** below 850 kPa covers both HV and MV insulation systems as well as all circuit breakers. The required general purpose reclaiming equipment has to compress SF_6 to liquefaction.
- The **low SF_6 reuse pressure range** below 200 kPa is only for the MV insulation systems. Low cost reclaiming devices are available and can be utilised, as there is no need to compress SF_6 to liquefaction and therefore provides better economy for this application.

The reuse criteria for both pressure ranges are chosen such that the limit curve corresponding to a water vapour pressure of 150 Pa is practically fulfilled at the highest reuse pressure in the range, namely, at 200 kPa for the low pressure range and at 850 kPa for the complete pressure range.

For **solid contaminants** limit concentrations have not been established, hitherto. However, practical experience has shown that fine-pore dust filters can efficiently remove these contaminants. Table 1 therefore contains, instead of maximum tolerable impurity levels, the condition that a dust filter of a pore size of 1 μm should remove solid contaminants.

Similarly, for **oil** contamination, limit concentrations have not been established. It is therefore recommended that this impurity be avoided by minimising or eliminating the use of oil for lubrication in the SF_6 insulated equipment and by using completely oil-free gas handling and reclaiming equipment. If the presence of oil can not be excluded, a special oil filter should be inserted into the reclaimer. Practical experience shows that such a filter reduces the oil content down to less than 1 mg/m^3. For further details see **Appendix 1**.

Table 1: SF_6 contaminants; main origins, deteriorating effects, maximum tolerable levels in equipment, proposed maximum tolerable impurity levels for reuse of reclaimed SF_6, and practical impurity detection sensitivities.

Contaminant	**Main origin**	**Deteriorating effects**	**Maximum tolerable impurity levels in equipment**	**Proposed maximum tolerable impurity levels for reuse**	**Practical impurity detection sensitivity**
Non-reactive gases: Air CF_4	Handling Switching	Reduction of switching performance Reduction of insulation performance	3% vol	**3% vol total**	< 1% vol
Reactive gases or vapours: SF_4, WF_6 SOF_4, SO_2F_2 SOF_2, SO_2, HF	Arcing Partial discharge Follow-up reactions	Toxicity Surface insulation by corrosion	100 ppmv 2000 ppmv	**50 ppmv** total 1)	~ 10 ppmv total
Moisture	Desorption from surfaces and polymers	Surface insulation by liquid condensation	p_{H2O}<400Pa 2)	p_{H2O}< **150 Pa** (T_d < -15 °C) **750 ppmv for p < 200 kPa 3)** **200 ppmv for p < 850 kPa 3)**	< 10 Pa 4)
Oil	Pumps, lubrication, bushings to oil insulated equipment	Surface insulation by carbonisation	not quantified	**10 mg/m^3 5)**	< 1 mg/m^3
Dust Carbon Dust/particles Switching dust: CuF_2, WO_xF_y,	Arcing, partial discharges Assembling, mechanical wear Contact erosion by arcing	Surface insulation by conducting deposits, gas and surface insulation	Not quantified	Should be removed by dust filter of pore size < 1 μm	

1) or, equivalently, 12 ppmv SO_2 + SOF_2, see Appendix 2, Section 2.
2) Based on IEC 60694 and corresponding to a dew point of T_d = -5°C.
3) Within the complete range of reuse pressures p < 850 kPa, covering all possible applications (both HV and MV insulation systems as well as all circuit breakers), the low reuse pressure range p < 200 kPa has been defined to highlight low pressure insulation systems (typically applied in MV distribution).
4) corresponding to a dew point T_d = –45 °C
5) Corresponding to 0.3 ppmw in pure SF_6 at 500 kPa

4.3.3 Relation to other standards

The impurity levels referring to SF_6 used in electric power equipment are summarised in **Table 2** and presently include 3 IEC standards:

IEC 60376 [1.16] (presently under revision) determines the purity requirements for **new SF_6** as provided by SF_6 producers.

IEC 60694 [1.17] (presently under revision) specifies the maximum tolerable moisture level for **gas in equipment**, i.e. after it has been filled into equipment.

IEC 60480 [1.18] (presently under revision) will specify the purity requirements **for reuse of reclaimed gas**.

Equipment users should check for local standards, which may deviate from the IEC standards.

Table 2: Comparison of impurity levels according to the IEC standards 60376 and 60694 and levels proposed by CIGRE for the revision of IEC 60480. All levels are expressed in concentrations (% vol and ppmv) and are independent of temperature and are also valid for arbitrary SF_6 mixtures.

Contaminant	**Maximum tolerable levels**		
	IEC 60376 **New SF_6** 1st Ed. 1971 (under revision)	**IEC 60480** **Reclaimed SF_6 for reuse** (under revision) ***CIGRE proposal***	**IEC 60694** **SF_6 in equipment** **Ed. 2.1 2001** (under revision)
Non-reactive gases Air CF_4, C_2F_6,	0.05 % 0.05 %	3%vol total	
Reactive gases WF_6, SOF_4 SOF_2,SO_2, SO_2F_2 SF_4, HF	1 ppmw total	50 ppmv total 1)	
Moisture	15 ppmw	750 ppmv for $p < 200$ kPa 2) 200 ppmv for $p < 850$ kPa 2)	Dew point < - 5 °C corresponding to 2000 ppmv at 200 kPa 470 ppmv at 850 kPa
Condensed contaminants (oil and dust)		10 mg/m^3	

1) or, equivalently, 12 ppmv SO_2 + SOF_2, see Appendix 2, Section 2.

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

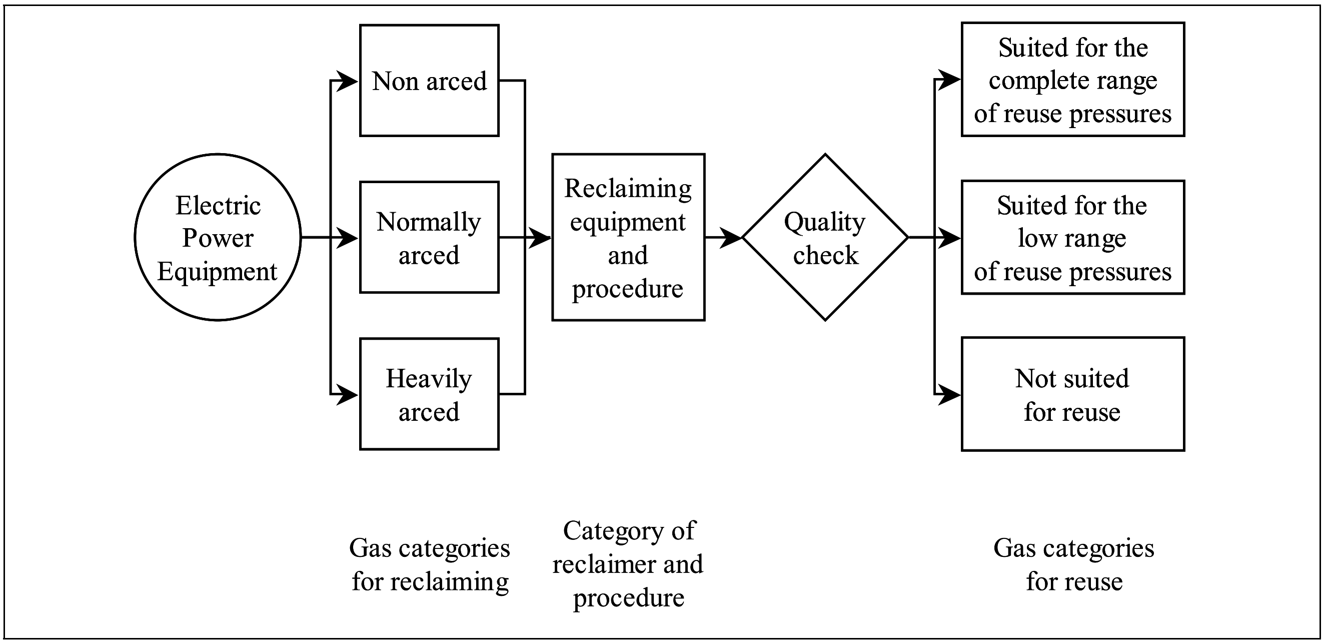
A comparison of the values in Table 2 shows that the reuse criteria proposed by CIGRE lies substantially above the new gas criteria (IEC 60376) and leaves adequate safety margins with respect to the levels in equipment (IEC 60694), as far as moisture is concerned. In order to encourage SF_6 reuse, the CIGRE proposal restricts the purity requirements to the functionally necessary levels.

5 RECLAIMING SF_6 FROM ELECTRICAL POWER EQUIPMENT

5.1 General Considerations

Reclaiming of SF_6 gas for reuse is a process the basic structure of which is represented in the following Figure 2.

Figure 2: Basic structure of the SF_6 reclaiming process.



Before the gas is recovered from the electric power equipment it has to be assigned a **gas category for reclaiming**. This category is based on the severity of contamination with the levels non-arced, normally arced and heavily arced. Based on this category an adequate **reclaimer and reclaiming procedure** are chosen. After the gas has passed the reclaiming process it has to undergo a **quality check** by which it is assigned one of the following three **categories**:

- The higher gas category for reuse is “suited for the **complete range** of reuse pressures”. This gas can be reused in electric power equipment without any limitations.
- The lower gas category for reuse is “suited for the **low range** of reuse pressures”. This gas can only be reused in equipment with filling pressures up to 200 kPa.
- The lowest gas category is “**not suited for reuse**”. This gas requires further treatment, usually off-site.

The following sections describe the reclaiming process in detail.

5.2 Gas Categorisation

With respect to the use in electric power equipment four SF_6 gas categories are distinguished:

New gas: Gas supplied in cylinders as provided by the original SF_6 gas producers and complying with a standard for new SF_6 such as the IEC Standard 60376 or a national standard e.g. ASTMD 2742-92. Once the gas has left the cylinders in which it was supplied by the producer, it has to be considered as used gas and has to be assigned one of the three following categories.

Non-arced gas: Gas that has been handled in any way and has not experienced arcing. Non-arced gas is to be expected at:

- Insulation testing in the factory;
- Insulation testing on-site during erection / commissioning;
- Routine maintenance of insulation compartments;
- Repair of insulation compartments after malfunction without arcing;
- Retrofitting of insulation compartments;
- Decommissioning of insulation compartments in which arcing has not occurred.

The major contaminants in non-arced gas may be air (mainly introduced by handling) and moisture (mainly desorbed from surfaces). Small quantities of SF_6 decomposition products (typically in the 100 ppmv range) may also be present when strong partial discharges have occurred in the gas and no adsorbers were provided.

Normally arced gas: Gas recovered from switchgear compartments after normal switching operation. Normally arced gas is to be expected at:

- Maintenance and repair of switching devices after normal (load or fault) operation;
- Interruption testing during switchgear development;
- Decommissioning of switchgear.

Normally arced gas may contain, in addition to air and moisture:

- The inert gas CF_4 generated by arc erosion of polymers;
- Corrosive gaseous SF_6 decomposition products up to about a few 100 ppmv as residues which have not been removed by adsorbers;
- Solid decomposition products, mainly metal fluorides and tungsten oxifluorides, usually referred to as "switching dust".

Heavily arced gas: Gas recovered from equipment in which failure arcing has occurred. Heavily arced gas is to be expected from:

- Circuit breakers after interruption failure;
- Insulation compartments after internal arcing failure;
- Any kind of arcing failure.

In this case, high levels of solid and gaseous contaminants have to be expected. The gaseous contaminants may reach levels of several % vol, of which a substantial fraction can be highly reactive and toxic and/or corrosive. The solid contaminants will generally be charged with adsorbed reactive gaseous contaminants.

For the **determination of the gas category** two methods can be used (individually or in combination):

- The simplest and most frequently used method is to infer the gas category from the knowledge of the equipment and previous operation history.
- In relatively rare cases, in which it is not possible to infer the gas category or in which there is doubt about the "history" of the gas, a gas sample has to be analysed for the concentration $c_{(SO_2+SOF_2)}$ of the indicator gases SO_2 and/or SOF_2. Based on experience from development testing and field sampling, this measurement can be used for the following order-of-magnitude criterion:
  - If $c_{(SO_2+SOF_2)} < 100$ ppmv then non-arced gas can be assumed;
  - If $c_{(SO_2+SOF_2)} > 1$ % vol then heavily arced gas has to be assumed.

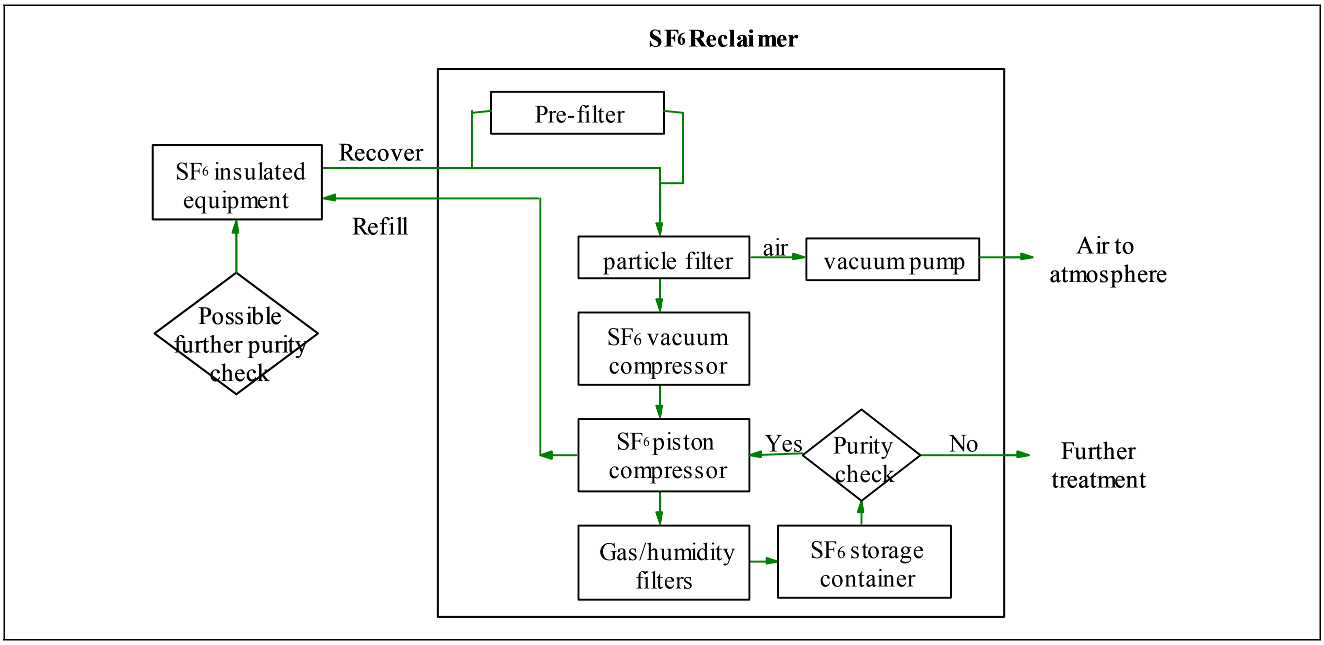
If the analysis cannot be carried out, the gas has to be considered as heavily arced, for safety reasons.

5.3 Reclaiming Equipment

Gas reclaimers have been used successfully since the introduction of SF_6 technology. Standard reclaimers are commercially available in a variety of sizes, processing speeds and storage capacities and range from small portable to large trailer mounted systems. The appropriate type and size of the reclaimer should be chosen according to the gas quantity to be handled. The choice should also consider whether the reclaimer has to operate as a stationary or transportable device. Among the transportable devices, low cost portable versions operating at low pressure levels without SF_6 liquefaction are of particular interest to enable reuse also under conditions where general purpose reclaimers are not available.

Figure 3 shows the basic functional scheme of a **general purpose SF_6 reclaimer.**

Figure 3: Functional scheme of a general purpose SF_6 reclaimer.



The major components of a general purpose SF_6 reclaimer are:

- Filters;
- Compressor(s);
- Vacuum pump;
- Intermediate storage container.

The general purpose reclaimer operates in the following way:

Gas recovery and reclaiming: The SF_6 is extracted from the gas-insulated equipment using compressor(s). It is then processed through a series of filters and compressed into an intermediate storage container.

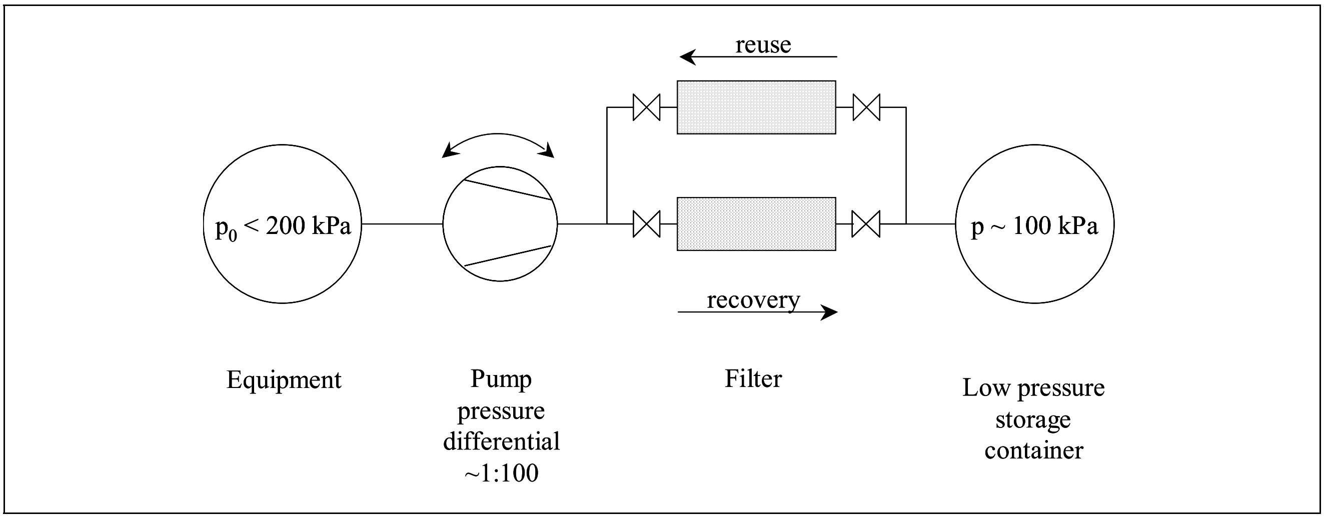
Quality check: The suitability of the processed gas for reuse has to be verified by a purity check of the intermediate storage container (for details see Section 5.5) to assess compliance with the reuse criteria (see section 4.3).

Reuse: Reclaimed SF_6 complying with the reuse criteria can be filled into equipment like new SF_6. The details of evacuation of SF_6 and subsequent gas filling are described in IEC 61634. For carrying out the evacuation the reclaimer is equipped with a vacuum pump. After a sufficient vacuum level has been reached with this pump, the SF_6 can be refilled into the equipment from the intermediate storage container. The reclaimer must be designed such as to avoid re-introducing contaminants during gas transfer. It is advantageous to use separate piping for recovery and refill and/or properly placed particle filters to avoid particulate contamination to be carried into the equipment with the filled-in gas.

Different kinds of general-purpose SF_6 reclaimers are also available on the market. They operate within a lower pressure range and use cryo-technology for gas liquefaction and purification. They have, as additional elements, cooling aggregates and condensers.

Figure 4 shows the basic functional scheme of a **low-pressure reuse SF_6 reclaimer**.

Figure 4: Low-pressure reuse SF_6 reclaimer using a lightweight pump and an intermediate storage at ambient pressure.



As it can be observed from the picture, the device is lightweight and portable. It consists of a small pump with a recovery pressure differential of typically 1:100 and a low-weight intermediate storage container (i.e.: a MV insulation enclosure or a metal coated balloon). The intermediate storage of the gas is performed at about ambient pressure. This concept is of particular interest for applications in which SF_6 has to be handled at pressures of around 100 kPa, such in MV distribution equipment.

An overview over the major filter types as the essential components for the gas purification process is given in **Table 3**. Details on the design of these filters, the reclaimer components and reclaimer operations are given in **Appendix 3**.

Table 3: Filter types used in SF_6 reclaimers

Filter Type	Tasks	Major characteristics
Particle filter	Removes solid decomposition products and other particles at input of reclaimer	Pore size 1 μm
Gas/moisture filter	Removes gaseous decomposition products and moisture	Residual moisture < 100 ppmv. Residual SO_2+SOF_2 < 12 ppmv. Particle retention ability
Prefilter	Reduces concentrations of solid and gaseous decomposition products at input of reclaimer in case of heavily contaminated gas	Pore size 10 μm (low through-flow resistance). Residual moisture < 200 ppmv. Residual reactive products < 200 ppmv. Oil holdback ability.
Detoxification filter	Reduces reactive decomposition products to below 200 ppmv so that the gas can be transported as non-toxic	Same as Prefilter
Oil filter	Removes oil	Special filter equipped with visual oil indicators at input and output

The main **characteristics of a reclaimer** are:

- SF_6 capacity of the intermediate storage container Mst [kg];
- Intermediate storage pressure pst [kPa] or [bar];
- Storage method;
- Processing speed during recovery (kg/h).

Possible storage methods, implemented in the intermediate storage container in the reclaimer, are reported in Section 6.2.

5.4 Reclaiming Procedures

The main elements of the gas reclaiming procedures are:

- Determination of the gas category;

- Selection of filters;
- Gas purification by filtering;
- Quality checks;
- Handling of gas that results non-reusable.

These procedural elements will be discussed separately in the following subsections for the three gas categories.

5.4.1 Non-arced gas

Filters: Input particle filter and standard gas/moisture filter.

Quality checks after filtering:

Non-reactive gases: These may have been introduced by handling and are not removed by the filters. They should be checked in the storage container.

SO_2/SOF_2: No check is required as these gases are only present in very small quantities in the recovered gas and have been removed by the gas/moisture filter.

Moisture: Moisture will also have been removed. Moisture check immediately after refilling into the equipment is recommended to ensure that moisture has not been introduced during the filling process.

If there should be any doubt about the functionality of the reclaimer (possible saturation of the gas/moisture filter, improper maintenance etc.) it is recommended that the moisture in the storage container be checked before reusing the gas as a means of verifying the reclaimer performance.

Handling of non-reusable gas. Non-arced gas can only result in being non-reusable because of contamination with non-reactive gases (essentially air) originating from handling errors. Gas thus contaminated can be rendered reusable by a special purification process generally only available at a gas recycling company. As the contaminants are non-toxic, the gas can be transported to the recycling company under the same conditions as for new SF_6 [See Chapter 6].

5.4.2 Normally arced gas

Filters: Input particle filter and standard gas/moisture filter.

Quality checks after filtering:

Non-reactive gases: These may be present in the reclaimed gas due to the CF_4 generated by arc erosion of polymeric materials and air introduced by handling. Checks for these contaminants should be performed on the gas in the storage container.

SO_2/SOF_2: Although these gases should have been removed by the gas/moisture filter it is recommended that checks for these contaminants should be performed on the gas in the storage container to ensure that the reclaimer filters have been working effectively.

Moisture: If the SO_2/SOF_2 check yields an acceptable result it can be assumed that the gas/moisture filter has also removed the moisture. It is therefore generally considered sufficient to check for moisture immediately after having refilled the reclaimed gas into the equipment.

Handling of non-reusable gas. Arced gas may result in being non-reusable after reclaiming for two reasons:

(1) The gas may be contaminated with non-reactive gases, which cannot be removed by the filters. In this case further treatment is required. As the non-reactive contaminants are non-toxic, the gas can be transported to the recycling company as for new SF_6 [See Chapter 6].

(2) The gas may be contaminated with reactive gaseous decomposition products because the gas/moisture filter has not been working effectively. In this case the gas can be passed through the reclaimer for a second time after the filters have been renewed.

5.4.3 Heavily arced gas

Filters: In addition to the input particle filter and the standard gas/moisture filter, a high capacity pre-filter is recommended to remove the bulk of particles and reactive gaseous decomposition products.

Quality control: All three contaminants have to be checked in the storage container according to the complete procedure of **Figure 5**.

Handling on non-reusable gas: The reclaimed gas may result in being non-reusable for three reasons:

(1) If the gas is only contaminated with non-reactive gases (particularly CF_4 due to strong arc erosion of polymeric materials or air due to handling errors) it requires further treatment. As the contaminants are non-toxic, the gas can be transported to a recycling company as for new SF_6 [See Chapter 6].

(2) If the gas is only contaminated with reactive gaseous decomposition products (because the filter system has not been able to reduce these contaminants to a sufficiently low level) the gas can be passed through the reclaimer for a second time after renewal of the gas/moisture filter.

(3) If the gas is contaminated with both non-reactive and reactive gases, further treatment is required. It is suggested that the gas be passed through a detoxification filter to reduce the concentration of the reactive decomposition products to below 200 ppmv. The gas can then be transported to the recycling company under the same conditions as for new SF_6 [See Chapter 6].

(4) In the unlikely event that even with further treatment and multiple filtration the gas cannot be detoxified, it has to be transported as toxic gas. For details see Section 6.4.

5.5 Gas Quality Checks

The quality checks of the reclaimed gas are performed to check if the residual impurity levels do not exceed the values specified for reuse, as proposed in Table 1 and to be finally defined in the revised standard IEC 60480 [1.18].

There are five basic concepts for carrying out the quality checks of the reclaimed gas:

(1) **Continuous monitoring** of all contaminant levels in the storage container, or in the transfer gas flow form the storage container to the power equipment and triggering an alarm if one of them exceeds the limit specified in the purity requirements. While this would be the most desirable concept, detectors with continuous monitoring ability are currently not available at acceptable cost. However, with the intense development activity in the field of gas sensors they may well be available in the near future.

(2) **Periodical check** of the contaminant levels in the storage container using portable or fixed detectors. This is currently common practice.

(3) **Checking the gas before refilling it into equipment** to avoid equipment contamination.

(4) **"Post-refill" checking,** i.e. checking the gas only after it has been re-filled into electric power equipment. Although this procedure may accelerate gas handling, the risk associated with it is that excessive contamination, if present, may only become apparent when it has resulted in equipment damage. As an example, gas containing excessive moisture could load adsorbers and the internal surfaces of the equipment. Post re-fill checking may be justified where high contaminant levels in the reclaimed gas are not to be expected or where the reclaiming equipment is so well maintained that its cleaning efficiency can be assured.

(5) **Laboratory analysis of a gas sample** of the reclaimed SF_6. Although this would be the most accurate way to determine contaminant levels, this concept would cause a substantial time delay as well as an uncertainty about additional contaminants that might be introduced by sampling or by chemical reactions during sample transportation. This concept is therefore limited to exceptional cases or to confirm a previously measured result.

Gas sampling procedure: When the gas is not compressed to liquefaction gas sampling is not problematic. However, when a gas sample has to be taken from a container with liquefied SF_6, it has to be taken from the liquid phase. With fixed installed containers the sampling valve should therefore be installed at the lowest point of the container. If standard gas cylinders are used as containers, only the standard valve at the head of the cylinder is available for gas sampling. In order to obtain a sample from the liquid phase, the cylinder has to be tilted upside down so that the liquid SF_6 covers the valve. It has to stay in this position for at least 2 minutes to allow for fluid gas collection at the valve and gas bubble removal. Care should be taken to minimise the sampling flow through the connection tubing to the measurement devices so that the liquid SF_6 can vaporise before entering the measurement devices, as liquid SF_6 may cause incorrect readings.

The levels of three **contaminant types** have **to be checked**, namely,

- The total of **non-reactive gaseous contaminants** (mainly air, nitrogen and CF_4);

- **The total of the reactive gaseous** decomposition products;
- **Moisture**

Contaminants such as oil, dust, and particles normally do not have to be verified because reclaimers are designed in such a way that the filters specified in **Table 3** remove them.

The **sequence in which** the three categories of **contaminants are best checked** and the actions required from resultant measurements are shown schematically in **Figure 5**. The square boxes represent the checking measurements and the diamond symbols represent comparisons of the measured levels with the limits specified by purity requirements. The round elements represent the further action to be taken in response to the result. The figure specifies a complete sequence of checks, which may not be necessary in **all** cases. Under specific circumstances some of the measurements may be omitted, refer to **Section 5.4**.

The **measurement devices** required for performing gas quality checks are generally portable but may also be an integral part of the reclaimer.

The content of **inert gases** such as air and CF_4 are best determined with SF_6 detectors, which are based on velocity of sound or thermal conductivity measurements. They directly measure the SF_6 concentration (usually in % vol) so that the impurity level results as the difference between 100% and the SF_6 concentration. Note that the direct measurement of the inert gases is not practical. The measurement precision of the SF_6 concentration is typically of the order of ±1 %.

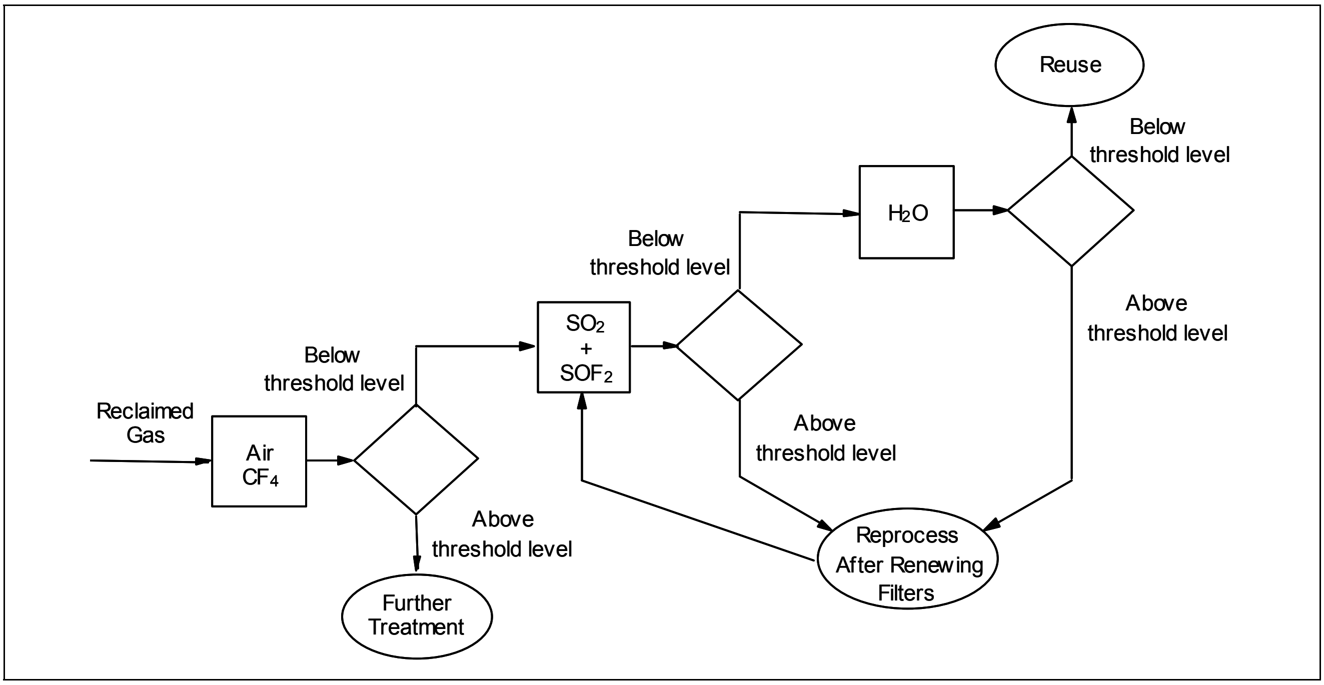
When checking for **reactive gaseous decomposition products**, it is usually impractical to measure the sum of all products. As discussed in **Appendix 2**, a measurement of reactive decomposition products can be replaced by a measurement of indicator gases such as SO_2 and SOF_2, which roughly constitute one fourth of the total quantity of the reactive gases. The impurity level for reuse for the total of reactive gases according to **Table 1**, namely, 50 ppmv, thus translates into an equivalent limit for the practical detection level of the indicator reactive gases, SO_2 and SOF_2, of about one fourth of 50 ppmv, i.e.: roughly 12 ppmv. Reaction tubes sensitive to SO_2 and SOF_2 can measure these levels. They are sensitive down to a few ppmv, which corresponds to a sensitivity of some tens ppmv for the total of these products. There are indications that continuously operating chemical sensors might become available in the future.

Moisture can be measured by dew point meters, reaction tubes, and electronic sensors and can be expressed in different units (see Appendix 4 Section 2). Water vapour pressures can be measured down to better than ±10 Pa. For details see **Appendix 4**.

It has to be noted that the devices for gas quality checking do not need to be full-range measurement devices. As they only have to detect the compliance or non-compliance with the impurity levels of **Table 1**, they only have to serve as level indicators. This means that their measurement range only needs to cover the vicinity of these limit levels.

The **impurity detection sensitivities** given in the 6th column of **Table 1** represent the present state of the art of *practically* usable devices. It has to be noted that more sensitive detection techniques exist, such as gas chromatography, infrared absorption spectrometry and optical particle detection techniques. These techniques are, however, not practical on-site as they are relatively expensive and require advanced personnel skills. For further details on contaminant measurements the reader may refer to **Appendix 2** and **Appendix 4**.

Figure 5: Standard procedure for gas quality check.



5.6 SF_6 services

SF_6 users who only use very low gas quantities and/or have to handle the gas on rare occasions may find it too expensive to invest in their own recovery equipment. It may then be more cost efficient to use the services provided by specialized recycling companies such as equipment manufacturers service organisations, reclaimer manufacturers etc. Such services are emerging with increasing demand.

6 STORAGE AND TRANSPORTATION OF USED SF_6

6.1 Gas categories

With respect to storage and transportation three gas categories have to be distinguished:

(1) **SF_6, which complies with IEC 60480, i.e. which is suited for reuse in electric power equipment**

(2) **SF_6 which does not comply with IEC 60480 and contains toxic by-products**

(3) **SF_6 which does not comply with IEC 60480 and contains toxic and corrosive by-products**

6.2 Storage

Table 4 gives an overview of all possible storage methods, which a storage container may be based on.

Table 4: Storage Methods

Method	Requirements	Features
Gaseous	Typical pressure < 20 bar. Gas remains in the gaseous state.	Requires relatively small recovery pressure differential (typically 100:1) but needs larger storage volumes. Gas cannot be liquefied in cylinders for transportation. Therefore it is limited to small quantities (200 kg) and stationary use.
Liquid-Cooling Assisted	Typical pressure 30 bar. Employs additional cooling system to cool SF_6 after compression, which allows SF_6 to be stored in liquid form.	Requires relatively small recovery pressure differential (700:1) but needs cooling aggregate. Performance of cooling aggregate can influence processing speed. Additional maintenance requirements. Limited storage volume required and generally not suitable for transportation
Liquid-Pressure Only	Typical pressure=50 bar. Gas compressed to 50 bar will liquefy by pressure only.	Requires recovery differential of 1000:1 but eliminates the need of additional aggregates. Can be used with any storage vessel rated 50 bar or higher.

- Residual recovery pressure p_{res} [kPa] or [mbar] (residual pressure in equipment down to which the gas can be recovered and compressed to the rated storage pressure p_{st});
- Recovery pressure differential (performance indicator of compressor(s)): p_{st}/p_{res};
- Recovery speed [m^3/min]: Time required recovering a gas volume of 1 m^3 from 500 kPa down to the specified residual recovery pressure p_{res};
- Evacuation speed [m^3/min]: Time required to evacuate a volume of 1 m^3 from atmospheric pressure down to a residual air pressure of 100 Pa;
- Refill speed [kg/min]: Time required filling gas from the storage container at rated storage pressure into the equipment at its rated operating pressure;
- Failsafe operation control (to avoid gas contamination by false handling);
- Filter exchange/handling/disposal facilities.

All above process speed characteristics refer to the assumption that there are no losses in the piping between equipment and reclaimer.

When used SF_6 has to be stored on-site, the storage containers for this purpose should comply with the local pressure vessel regulations and should be labelled in compliance with the regulations given below in section 6.4. For practical reasons it is recommended to preferentially use transportable storage containers, wherever possible.

6.3 Transportation containers

Each of the three gas categories requires a specific type of container and container labelling, a specified in **Table 5**.

Table 5: Container types and labelling required for transportation of used SF_6

Gas category	Container type	Container labelling
SF_6, which complies with IEC 60480, i.e. which is suited for reuse in electric power equipment	**Same type of container as new SF_6.** Note: Due to the inert gas content (N_2, O_2 etc.), the filling factor [1]) has to be less than 0.8 kg/litre. **Recommendation:** Containers should be specially coloured to avoid confusion between used and new gas (an orange band on the upper third of the cylinder is suggested).	**Stencilled on container:** 3163, sulphur hexafluoride, carbon tetrafluoride or air or nitrogen [2]) **Danger label 2**
SF_6 which does not comply with IEC 60480 and contains toxic by-products	Same as above	**Stencilled on container:** 3163, sulphur hexafluoride, hydrogen fluoride, thionyfluoride [2]) **Danger label 6.1**
SF_6 that does not comply with IEC 60480 and contains toxic and corrosive by-products.	**Special containers approved for storing and transportation of corrosive gases** (such as hydrofluoric acid HCl) with a corrosion-proof valve and adapter	**Stencilled on container:** 3308, sulphur hexafluoride, hydrogen fluoride, thionylfluoride **Danger labels 6.1 + 8**

1) The filling factor is the weight of SF_6 contained in the container divided by the container volume and is usually specified in kg/litre
2) Only the two most abundant contaminants have to be specified

6.4 Transportation modes

The following transportation modes are of interest:

(1) Transportation by road (ADR 2001);
(2) Rail transportation refer to local regulations;
(3) Transportation by ship (IMO);
(4) Air transportation refer to local regulations.

Internationally valid transportation regulations for SF_6 are only available for transportation by road (ADR) and by ship (IMO). For rail and air local regulations have to be observed.

6.5 Regulations for road and ship transportation

The regulations for road and ship transportation are summarised in the following two tables. They contain the items

- UN number with a short characterisation of the transport-relevant features of the gas;
- Class;
- Label(s);
- Final classification.

Table 6: SF_6 transportation regulations by road (ADR 1999)

Regulations	**SF_6 complying with IEC 60480**	**SF_6 not complying with IEC 60480 and containing toxic by-products**	**SF_6 not complying with IEC 60480 and containing toxic and corrosive products**
UN Number	3162 liquefied gas	3163 liquefied toxic gas	3308 liquefied toxic and corrosive gas
Class	2A	2T	2TC
Danger label	2	6.1	6.1 + 8
Final classification	UN 3162 liquefied gas, n.o.s, 2, 2° A	UN 3163 liquefied gas, n.o.s, 2, 2° T	UN 3308 liquefied gas, n.o.s, 2, 2° TC
Transport document	3162 liquefied gas, n.o.s. (sulphur hexafluoride and air or nitrogen or carbon tetrafluoride) 2,2 A ADR	3163 liquefied gas, toxic, n.o.s. (sulphur hexafluoride and hydrogen fluoride and thionylfluoride 2,2 T ADR	3308 liquefied gas, toxic, corrosive, n.o.s. (sulphur hexafluoride and hydrogen fluoride and thionylfluoride 2,2 TC ADR

Table 7: SF_6 transportation regulations by ship (IMO)

Category	**SF_6 complying with IEC 60480**	**SF_6 not complying with IEC 60480 and containing toxic by-products**	**SF_6 not complying with IEC 60480 and containing toxic and corrosive products**
UN number	3162 liquefied gas	3163 liquefied toxic gas	3308 liquefied toxic and corrosive gas
Class	2.2	2.3	2.3
Additional label			8
Final classification	UN 3162 liquefied gas, n.o.s,	UN 3163 liquefied gas, n.o.s,	UN 3308 liquefied gas, n.o.s,
Transport document	3162 liquefied gas, n.o.s. (sulphur hexafluoride and air or nitrogen or carbon tetrafluoride) 2,2 A ADR	3163 liquefied gas, toxic, n.o.s. (sulphur hexafluoride and hydrogen fluoride and thionylfluoride 2,2 T ADR	3308 liquefied gas, toxic, corrosive, n.o.s. (sulphur hexafluoride and hydrogen fluoride and thionylfluoride 2,2 TC ADR

7 REUSE OF RECYCLED GAS

Recycled gas complying with the purity requirements for reuse (as specified in Table 1) **can be reused in electric power equipment like new *SF_6*.**

The only distinction to be made is that:

- **Gas suited for high pressure reuse can be reused in any equipment**;
- Whereas **gas suited for low pressure reuse can only be reused in equipment with filling pressure below 200 kPa**.

The procedures for filling gas into electrical power equipment are described, in general terms, in the standard IEC 61634, section 2.5, [1.19]. As the details of the gas filling procedures depend on the specific design features of the equipment, they have to be defined by the equipment manufacturers.

With respect to moisture, it is essential to consider the following issues:

- Evacuation removes moisture from the interior of the compartment to a certain degree: after having reached and kept for a certain time a sufficient vacuum level, the vacuum stabilisation must be checked by closing the evacuation valve on the equipment and waiting for a reasonable time. No excessive pressure raise should be detected. The manufacturer of the equipment should specify the details, according to the above mentioned IEC 61634, section 2.5, [1.19].
- Adsorbers should be designed to control any residual moisture, which can not be removed by evacuation.

SF_6 not suited for reuse has to be treated off-site by a recycling enterprise. This allows it to be rendered usable in the majority of cases. In particular SF_6 that has an excessive contamination with non-reactive gases can be purified by specially equipped enterprises.

8 FINAL DISPOSAL OF USED SF_6

In cases in which SF_6 cannot be recycled nor is no longer needed it can be disposed of in an environmentally compatible way by a thermal process. Heated to above 1000 ^{o}C, SF_6 starts to dissociate in reactive fragments, which react with added substances, mainly hydrogen and oxygen, to form SO_x and HF. The SF_6 gas can be destroyed with a removal efficiency of greater than 99% when the thermal process operates at 1200 °C. The reaction products are removed by passing the effluents of the reaction through a wet scrubber filled with a calcium hydroxide solution (lime) with which they react to form solid sulphates and fluorides, e.g. calcium sulphate (gypsum) and calcium fluoride (fluor spar).

Typical conversion reactions in the scrubber are

$$SO_3 + Ca(OH)_2 \rightarrow CaS0_4 + H_2O$$
$$2HF + Ca(OH)_2 \rightarrow CaF_2 + H_20$$

Gypsum $CaSO_4$ is a natural mineral used in construction. Fluorspar CaF_2 is a natural mineral used as additive in toothpaste and other healthcare substances.

The process is a procedure very similar to other procedures of disposal and the cost today is in the order of the price of new SF_6.

There are several incineration plants in different parts of the world that offer an SF_6 destruction service. The equipment manufacturers should assist SF_6 users in finding a suitable plant.

9 CONCLUSIONS

(1) In order to avoid contamination of the atmosphere, recycling of SF_6 is essential.

(2) Recycling equipment and procedures are available to allow, in the majority of cases, economically favourable recycling of SF_6.

(3) Properly recycled SF_6 is suitable for reuse in electrical power equipment.

(4) Final disposal, by conversion into environmentally disposable materials, is feasible.

(5) All SF_6 users should follow the recommendations for recycling.

(6) International standards need to be established to promote both recycling of SF_6 and use of recycled SF_6.

10 RECOMMENDATIONS

10.1 General Recommendations

(1) The deliberate release of SF_6 must be avoided.

(2) SF_6 shall be recycled, i.e. reclaimed, reused or disposed of in an environmentally compatible way.

(3) Purity standards for reusability have been proposed in this document and should be integrated into the revised Standard IEC 60480.

(4) Standards for the determination of low leakage rates shall be defined.

(5) National agreements comply with National Voluntary Agreements resulting from the “Kyoto Protocol”

10.2 Recommendations to Electrical Power Equipment Manufacturers

(1) Equipment manufacturers shall inform users on the recyclability of SF_6 and other materials contained within the equipment.

(2) Equipment manufacturers shall revise their statements to allow the reuse of SF_6 fulfilling the purity requirements according to the revised IEC 60480.

(3) Equipment manufacturers shall encourage the reuse of SF_6 and provide instruction and technical support to the users.

(4) Equipment manufacturers shall recommend adequate and user-friendly recycling equipment to the users.

(5) Gas checking techniques for the detection of leakage in service shall be developed to higher sensitivity.

(6) Records shall be kept of the SF_6 quantities purchased, delivered to customers, and returned to SF_6 manufacturers or recycling companies.

10.3 Recommendations to Electrical Power Equipment Users who handle SF_6

(1) Gas handling equipment or service contracts for gas handling shall be provided.

(2) Equipment users shall revise their operating instructions to allow the reuse of SF_6 fulfilling the purity requirements according to the revised IEC 60480.

(3) The electrical power equipment shall be operated and maintained according to both manufacturer specifications and state-of-the-art knowledge concerning best practice in SF_6 handling and recycling.

(4) Electrical power equipment with excess leakage shall be repaired or replaced.

(5) Records shall be kept of the installed SF_6 inventory and of the SF_6 quantities required for operation and maintenance during equipment lifetime.

(6) Final disposal of electrical power equipment containing SF_6 shall be given only to authorised enterprises.

10.4 Recommendations to SF_6 producers

(1) SF_6 gas that cannot be reused shall be accepted for further purification or environmentally correct final disposal.

(2) Records shall be kept of the SF_6 quantities produced, sold, recycled and finally disposed.

11 RECOMMENDED FURTHER WORK

(1) The revised IEC Standard 60480 should include the proposed purity requirements for SF_6 for reuse as proposed in this document. The standard should also discuss the measurement techniques by which the compliance of SF_6 with the standards requirements can be verified.

(2) A global SF_6 balance shall be set up.

(3) Appropriate test procedures should be investigated to prove leakage values lower than 0.5%/a in both routine and on-site testing.

(4) Standards for quantifying the performance of SF_6 recycling equipment shall be defined.

(5) Cost feasibility studies on environmental improvement for gas insulating electrical power equipment should be evaluated as a database for Life Cycle Costing (LCC).

12 REFERENCES

[1.1] "Radiative forcing of climate change", the 1994 report of the scientific assessment working group of IPCC, P.28.

[1.2] J. G. Owens, “Calculation of the global warming potential for sulfur hexafluoride using the updated Atmospheric lifetime from Moore, et al.” 9th Intern. Sympos. on Gaseous Dielectrics, Ellicott City MA, 2001

[1.3] CIGRE WG 23-02: "SF_6 and the global atmosphere", ELECTRA 164, (1996), 121 - 131.

[1.4] “SF_6 in the electric industry, status 2000”, ELECTRA, February 2002, pp. 16-25

[1.5] IEC Standard 60298 "A.C. metal-enclosed switchgear and controlgear for rated voltages above 1kV and up to and including 52kV".

[1.6] L. Niemeyer, "S_2F_{10} in SF_6 insulated equipment", 7th Intern. Sympos. on Gaseous Dielectrics, Knoxville TE, 1994.

[1.7] H. D. Morrison, V. P. Cronin, et al, "Production and decay of S_2F_{10} in a disconnect switch", pp 433-439 in Gaseous Dielectrics V11 ed LG Christophoron and D R James, Phenum Press New York 1994.

[1.8] "Investigation of S_2F_{10} production and mitigation in compressed SF_6 - insulated power systems", Final Report, Vol. 1 Executive Summary, Oak Ridge National Laboratory, Oct. 1995.

[1.9] F. Y. Chu, "SF_6 Decomposition in gas insulated equipment" IEEE Transactions on electrical insulation, Vol. EE-21, No. 5, (1986), 693-725.

[1.10] S. Tominaga, H. Kuwahara et. al., "SF_6 gas equipment", IEEE-PAS-100, (1981), 419-4206.

[1.11] C. Boudene, J.L. Clouet et al., "Identification and study of some properties of compounds resulting from the decomposition of SF_6 under the effect of electrical arcing in circuit breakers", Rev. Gen. d'Electricite, Special Issue June 1974, 45-78.

[1.12] M. Piemontesi and W. Zaengl, "Analysis of decomposition products of sulphur hexafluoride by spark discharges at different spark energies", 9th Internat. Sympos. on High Voltage Engineering, Graz 1995, 22-83.

[1.13] T. Nitta, Y. Shibuya et al., "Factors controlling surface flashover in SF_6 gas insulated systems", IEEE-PAS-97, 1978, 959-968.

[1.14] H. A. Stuckless, J. M. Braun, and F.Y. Chu, "Degradation of silica-filled epoxy spacers by arc contaminated gases in SF_6 insulated equipment", IEEE-PAS-104, 1985, 3597-3600.

[1.15] IEEE Standard 1125-1993 "Guide to Moisture Measurement and Control in SF_6 Gas Insulated Equipment".

[1.16] IEC Standard 60376-1971: "Specification and acceptance of new sulphur hexafluoride", including supplements A and B.

[1.17] IEC Standard 60694, 2.1 edition 2001 - 05 "Common specifications for high-voltage switchgear and controlgear standards".

[1.18] Draft IEC Standard 60480, Second edition - Fifth version "Guide to the checking and treatment of SF_6 taken from electrical equipment".

[1.19] IEC Standard 61634, First edition 1995 “High-voltage switchgear and controlgear – Use and handling of sulphur hexafluoride (SF_6) in high-voltage switchgear and controlgear”.

[1.20] “Report on the 2nd international survey on high voltage gas insulated substations (GIS) service experience”, CIGRE brochure N. 150

APPENDIX 1

FUNCTIONAL DETERIORATION BY CONTAMINANTS

A functional deterioration of SF_6 equipment by contaminants and the toxic health risk associated with them can be quantified with the help of the data given in **Table 8**. Estimated values are given in brackets. This data will be used to derive the maximum admissible concentrations of contaminants below which the various functions of the equipment are not degraded or toxic health risk can be excluded.

1 Toxic Health Risk

Limit concentrations to avoid a toxic health risk can be readily defined on the basis of the TLV (threshold limit value) concentrations of the toxic decomposition products, which have been set by governmental health authorities. They define the maximum admissible concentrations in the air for a regular 8 hours daily exposure in ppmv (parts per million by volume). These concentrations are listed in the column labelled TLV of **Table 8**. From this data the maximum admissible concentrations **inside** the equipment can be derived following reasoning proposed in [A1.1]. It is assumed, as a worst case, that the SF_6 together with its toxic contaminants is inadvertently released from the enclosure by an unnoticed leak. The toxic gas is then diluted together with the SF_6 in the air. The released SF_6 would trigger the alarm of an SF_6 detector when the SF_6 concentration in the air would exceed the TLV of SF_6 (1000 ppmv). In order to avoid toxic risk, the concentrations of the toxic decomposition products accompanying the released and diluted SF_6 must not exceed their TLV levels. With this criterion the maximum admissible concentrations of the toxic decomposition products inside the equipment (i.e.: before release) can be determined as

$$c_{max}\ [\text{ppmv}] = 10^6 \times \text{TLV (toxic decomposition product)/ TLV } (SF_6) - \qquad (A1.1)$$

These alarm levels are given in the second column of **Table 9** as maximum admissible levels inside equipment from a toxic risk point of view.

2 Corrosion

Corrosive activity is not an inherent property of a gas but depends on the reactivity of this gas with the materials to which it is exposed. In modern SF_6 equipment, materials are chosen such as to be resistant to corrosion by SF_6 decomposition products, even if these would be present in high concentrations.

The major primary gaseous decomposition products of high reactivity are SF_4, WF_6, and SOF_4. They readily hydrolyse with moisture H_2O via the hydrolytic reactions:-

$$WF_6 + H_2O \longrightarrow WO_xF_y + HF \qquad (A1.2)$$

$$SF_4 + H_2O \longrightarrow SOF_2 + 2\,HF \qquad (A1.3)$$

$$SOF_2 + H_2O \longrightarrow SO_2 + 2\,HF \qquad (A1.4)$$

$$SOF_4 + H_2O \longrightarrow SO_2F_2 + 2\,HF \qquad (A1.5)$$

These reactions continue until the available moisture H_2O in the system has been consumed. The hydrolytic reaction products SO_2 and SO_2F_2 are stable in the SF_6 environment so that the HF remains as the major corrosive compound.

HF (and SF_4 and SOF_4 to a lower degree) attacks metals and metal oxides transforming them into fluorides. The metal fluorides form thin coherent layers, which do not affect the functionality of the equipment. Dramatic destruction processes similar to rusting in air do not occur with the materials usually employed in the SF_6 environment.

The only corrosion problem that has been encountered so far in SF_6 insulated systems was related to polymeric insulators with silica filler. It will be discussed in detail in **Section 4** of this Appendix.

3 Gas Insulation Performance

The relevance of contaminants for the gas insulation performance can be judged on the basis of their critical fields E_{cr}, i.e. the threshold fields for ionisation avalanche growth. The relative critical fields are listed in the 3rd column of **Table 8** the values being referred to SF_6.

In order to determine how the dielectric strength of SF_6 is affected by a contaminant we use, as a first approximation, a linearly weighted mixing rule for the critical field:

$$E_{cr,\ mix} = (1 - c)\ E_{cr,\ SF6} + c\ E_{cr,\ cont} \qquad (A1.6)$$

where c is the concentration of the contaminant. This mixing rule was shown to be a good approximation for mixtures of fluorinated gases and a lower limit (i.e.: worst case) estimate for mixtures of strongly electronegative gases with non-electronegative gases [A1.1]. If the contaminant shall not reduce the dielectric strength by more than X [%], i.e. if

$$(E_{SF6} - E_{mix})/E_{SF6} < 0.01\ X \qquad (A1.7)$$

then the maximum admissible contaminant concentration results

$$c_{max} = 0.01\ .\ X /(1 - E_{cr,\ cont}/E_{cr,\ SF6}) \text{ if } E_{cr,\ cont} < E_{cr,\ SF6} \qquad (A1.8)$$

If $E_{cr,\ cont}$ / $E_{cr,\ SF6}$ > 1, i.e. if the contaminant is a better insulator than SF_6, the contamination level can be tolerated to take arbitrary values (of course only as far as insulation would be concerned).

For $E_{cr,\ cont}$ > 1, the quantitative value of the maximum tolerable contamination level depends on the choice of the acceptance level X for which we will take the value

$$X = 2\% \qquad (A1.9)$$

This is a conservative lower limit in that it is much lower than the statistical scatter of about 3 to 5% within which functional performance can be assessed experimentally.

Equations (A1.8) and (A1.9) have been used to determine the maximum tolerable contaminant levels with respect to gas insulation performance. They are given in the 3rd column of **Table 9**.

4 Surface Insulation Performance

The insulation capability of insulators (spacers, support insulators, insulating transmission elements etc.) can be deteriorated by contaminants if these create a surface conductivity of sufficient magnitude such as to cause a distortion of the electric field or thermal runaway heating by the surface leakage current [A1.2]. The three main mechanisms for the generation of surface conductivity are the condensation of a conducting liquid, the deposition of a conducting solid, and the creation of a conducting surface layer by corrosive attack of the insulator material.

4.1 Condensation of a Conducting Liquid

The only example of practical relevance is moisture condensing as liquid **water**. Moisture condenses as water when the water vapour pressure p_{H20} exceeds 611 Pa which corresponds to a dew point of 0^oC. At temperatures below the freezing point moisture condenses as ice, which does not deteriorate the insulation because it is non-conducting [1.15]. In order to safely exclude condensation of liquid water, the IEC standard 60694 [1.17] requires that the moisture level in equipment does not exceed 400 Pa (corresponding to a dew point of $– 5^oC$).

4.2 Formation of Conductive Surface Layers on Insulators by Corrosion

The most important example for this mechanism is the reaction of corrosive SF_6 decomposition products, mainly HF, with inorganic filler materials in polymeric insulators. The effect is most pronounced for silica SiO_2 which is attacked, according to [1.15], by the reaction:

$$4\ HF + SiO_2 \text{--->} SiF_4 + 2\ H_2O \qquad (A1.11)$$

The gaseous SiF_4 formed may further react with surface adsorbed water or water vapour to produce hydrated SiO_2 and the acid H_2SiF_6 :

$$SiF_4 + (x + 2)\ H_2O \text{--->} SiO_2\ x\ H_2O + 2H_2SiF_6 \qquad (A1.12)$$

These reactions consume SiO_2 from the filler grain surfaces thus creating interconnected internal interfaces between resin and filler. These interfaces are believed to adsorb H_2SiF_6 and other ionic contaminations from resin and filler that give rise to conductivity along the corroded interfaces. A similar effect, although substantially weaker, also has been observed with aluminium oxide-filled epoxy resin [1.15].

The weakly conducting surface of an insulator, when exposed to the electric field induces surface leakage currents, which may cause field distortion and ohmic heat dissipation. The latter may eventually lead to thermal runaway flashover. It was shown in [A1.2] that the critical surface conductivity $K_{s,cr}$ above which such runaway occurs depends inversely on the square of the applied electric field E with the approximate relation:

$$K_{s,cr} \propto \text{const}/E^2 \text{ with const } 100\text{W/m}^2 \qquad (A1.13)$$

As the design fields in gas insulated equipment usually do not exceed some 5 kV/mm one thus obtains a critical surface conductivity of the order:

$$K_{s,cr} \propto 4\ .10^{-12}\ S \qquad (A1.14)$$

The experiments reported in [A1.2] show that the corrosion induced surface conductivity of silica-filled epoxy resin increases approximately with the square of the partial pressure p of the corrosive gas.

$$_{s} \propto p^{2} - - - \qquad \text{(A1.15)}$$

For an SF_4 pressure of 10 kPa, surface conductivities of the order of 10^{-8} S were observed on silica filled epoxy resin. This finding is in order of magnitude agreement with the data reported in [1.14]. In the latter reference it was further shown that the surface conductivity of aluminium oxide filled epoxy results more than 2 orders of magnitude lower than for silica-filled material. From these data one can extrapolate, with the help of eq. (A1.15) the critical pressure p_{cr} above which the surface conductivity would exceed the limit of eq. (A1.14). This yields:

$$p_{cr} = 200 \text{ Pa for silica filled material} \qquad \text{(A1.16a)}$$

$$p_{cr} = 2000 \text{ Pa for aluminium oxide-filled material} \qquad \text{(A1.16b)}$$

As highly stressed SF_6 equipment always uses aluminium oxide-filled insulator materials the maximum tolerable contamination level of 2000 Pa has been entered into the **4th column of Table 9** for the corrosive gases HF, SF_4 and SOF_4.

4.3 Deposition of a Conducting Solid

Examples are conducting metal oxides or sulphides and carbon. The formation of such deposits is usually minimised by the choice of appropriate materials from which such compounds cannot be formed. Also, the presence of the SF_6 tends to suppress the formation of oxides and sulphides in favour of non-conducting fluorides. SF_6 also tends to suppress the formation of carbon from spark or arc eroded polymers, because it binds carbon as CF_4 by the reaction [A1.3]:

$$C + 2\,SF_6 \text{ ---> } CF_4 + 2\,SF_4 \qquad \text{A1.17)}$$

If conducting deposits should nevertheless occur for other reasons the only physically adequate specification of a level of acceptance would be a limit for the resulting surface conductivity of the contaminated insulator according to eq. (A1.14). This, however, is irrelevant for the scope of the present document.

5 Switching Performance

The switching performance of a gas is controlled by its dielectric [A1.4] and thermodynamic [A1.5] properties. With respect to the dielectric interruption performance the same reasoning can be applied as in **Section 3** for the gas insulation performance.

With respect to the so-called thermal interruption performance the thermodynamic properties of the gas enter in a much more complex way and require for their quantification sophisticated numerical simulations [A1.4]. Preliminary orientation is provided by comparative measurements of the thermal interruption capacity, which were carried out for various gases under short line fault conditions [A1.5]. These allow an approximate ranking of the thermal interruption performance of several gases relative to SF_6. These data are inserted into **Table 8** in the column "Thermal interruption capability" and have been used to assess values for gases that were not measured. It seems that the switching performance of complex fluorinated gas molecules is of the same order as for SF_6 whereas small or non-fluorinated gas molecules tend to perform much worse. It is therefore assumed, as a first approximation, that the more complex fluorinated contaminants (i.e.: CF_4, SOF_2 etc.) are about equivalent to SF_6 and that non-fluorinated gases (i.e.: air, H_2O) and HF are equivalent to air.

If we again apply the linearly weighted mixing rule eq. (A1.7) - (A1.9) and use the data from the **5th column of Table 8** we obtain the maximum admissible contamination levels given in **5th column of Table 9** as volume percentage concentrations.

6 Heat Transfer

In gas insulated equipment, the conductors and contacts are heated by ohmic losses. Part of this heat is transferred to the enclosure by the insulating gas via natural convection. This heat transfer is controlled, apart from the gas pressure, by the heat transfer coefficient [A1.6]

$$\alpha = \lambda \, [(\rho/p) / \eta]^{1/2} \qquad \text{A1.18)}$$

where λ is the thermal conductivity, (ρ/p) the pressure reduced density, and η the dynamic viscosity of the gas.

The values for the various contaminants are listed in column 6 of **Table 8**. They are in the range of 60 to 90% of the value for SF_6. Again the linear mixing considerations according to eqs. (A1.7) - (A1.9) can be applied to assess the maximum admissible contaminant levels which are given in the **6th column of Table 9** labelled "heat transfer", again in terms of volume percentage concentrations.

Table 8: Functionally Relevant Properties of Gaseous SF_6 Contaminants. Values in brackets are estimates.

Conta-minant	TLV Concentr. inside equipment [ppmv]	Insulation [Critical fields E_{cr} relative to SF_6]	Boiling Point at 1 bar [^oC]	Thermal interrupt. capability [relative to SF_6]	Heat Transfer [W/m^2K]	Reactivity in SF_6 environ-ment
SF_6	-	1.00	-64	1	$3.7 .\ 10^{-2}$	-
Air	-	0.38		0.2	$2 .\ 10^{-2}$	-
CF_4	1000	0.42	-128	0.6	$2.4 .\ 10^{-2}$	-
Moisture H_2O	-	(0.4)	+100	(0.2)		Hydrolysis
SF_4	0.1	(1)	-40	(1)		hydrolysis Me F*
WF_6	0.1	(1)	+18.5	(0)		Hydrolysis
SOF_4	0.5	0.75	-49	(0.5)		hydrolysis Me F*
SO_2F_2	5	(1)	-55	(0.5)		-
SOF_2	1.6	1.44	-43.7	(0.5)		Hydrolysis
SO_2	2	1.02	-10	(^{a} 0)	$2.3 .\ 10^{-2}$	-
HF	2	<<1	+ 19.4	(^{a} 0)	$2 .\ 10^{-2}$	Si F_4 Me F^1)

1) Me F: fluorination of metals and metal oxides

Table 9: Gaseous contaminants and their maximum levels in equipment up to which functional deterioration remains insignificant

Conta-minant	**Alarm level [ppmv]**	**Gaseous insulation**	**Surface insulation**	**Thermal arc interruption**	**Heat transfer**	**Minimum of columns 2-5**
Air	-	3.2% vol	-	2.5% vol	4.4% vol	2.5% vol
CF_4	-	3.4% vol	-	5.0% vol	5.7% vol	3.4% vol
H_2O	-	3.3% vol	611 Pa @ 0^oC	2.5% vol		611 Pa @ 0^oC
SF_4	100	arbitrary	2000 Pa	arbitrary		100 pppmv
WF_6	100	arbitrary		2% vol		100 ppmv
SOF_4	500	arbitrary	>2000 Pa	4% vol		500 ppmv
SO_2F_2	5000	arbitrary	arbitrary	4% vol		5000 ppmv
SOF_2	1600	arbitrary	arbitrary	4% vol		1600 ppmv
SO_2	2000	arbitrary	arbitrary	2% vol	5.3% vol	2000 ppmv
HF	2000	2% vol	>2000 Pa	2% vol	2.2% vol	2000 ppmv

7 References for Appendix 1

[A1.1] K. P. Brand and J. Kopainsky, "Model description of breakdown properties for unitary electronegative gases and gas mixtures", 3rd Internat. Sympos. on High voltage Engineering, Milan, 1979.31.05

[A1.2] B Brühl and L Niemeyer, "Monitoring of electrical properties of particulate filled epoxy resins under corrosive stress", Electrical / Electronic Insul. Conf., Chicago, 1993, 13-16

[A1.3] R. E. Wooton, R. W. Liebermann et. al., "Prediction of electrical breakdown carbonisation of gases and gas mixtures", 2nd Internat. Sympos. on Gaseous Dielectrics, Knoxville TE, 1980, 37

[A1.4] W. Hermann and K Ragaller, "Theoretical description of the current interruption process in HV gas blast breakers, IEE PAS-96, No. 5 (1977), 1546 - 1555.

[A1.5] G. Frind, E. Kinsinger, et al., "Fundamental investigation of arc interruption in gas flows", EPRI EL-284, 1977

[A1.6] W. M. Rohsenow, "Handbook of Heat Transfer", McGraw Hill 1973

APPENDIX 2

SF_6 QUALITY CHECKING EQUIPMENT

1 Moisture

Many different physical quantities and related measurement units are used to give the moisture contained in a gas. They are: volume concentration expressed in ppmv (parts per million in volume), mass concentration expressed in ppmw (parts per million in weight), dew point expressed in ^{o}C, relative moisture expressed in % (normally not used) and absolute moisture expressed in g/cm^3. Conversion among these units is provided in the IEEE Standard 1125-1993 [1.15]. The volume concentration in ppmv, which is used in the present document, is here suggested as reference unit for future standards on electric power equipment.

The concentrations are the only figures expressing the moisture content that do not vary when the gas pressure is changed. Thus when the moisture content is measured in a SF_6 insulated equipment, if volume (ppmv) or mass (ppmw) concentrations are used, then the value remains constant. This is also true in case of the actual pressure of the gas changes due to modifications of the ambient temperature (for example summer and / or winter). Hence the moisture content, measured as concentration expressed either in ppmv or ppmw, needs no reference pressure (i.e.: the pressure at which the measurement was performed).

The following measurement principles for moisture are presently used:

- Physical dew point meters;
- Electronic dew point meters;
- Chemical reaction tubes with visual indication.

1.1 Physical Dew Point Meters

Chilled mirror type instruments allow the sample gas to be passed onto a reflective part that is cooled during the measuring process. A light sensitive system is activated by the reflection from the mirror. Once the dew point temperature has been reached moisture fogs up the reflective mirror and the light sensitive device picks up the difference in reflection. As the temperature is recorded when this occurs, the dew point is then known. These instruments are commercially available; they tend to be more expensive but are more accurate when compared to other available dew point meters. They are however vulnerable to particle and/or corrosive gas damage.

Other physical types of dew point meters allow the user to watch a reflective mirror until fog can be seen to build up whilst the mirror is cooled down. These devices are commercially available, they typically require an external source for cooling material (i.e.: dry ice), use more gas than comparable electronic systems and the results are subjective to the user's skill and knowledge.

1.2 Electronic Dew Point Meters

This category refers to devices that use an electronic sensor to detect the dew point of the sample gas. Ceramic sensors and aluminium oxide sensors change capacitance with very small changes in water vapour. Changes in capacitance are converted to indicate the moisture content of the gas. These capacitance sensor based instruments are the most widely used types of moisture measurement instruments for SF_6. They are available from a wide range of manufacturers. The following is a list of features that are important in the selection of a suitable type:

- Response time;
- Gas release;
- Corrosion resistance;
- Life time of sensor;
- Calibration;
- Price.

Another type that would probably belong to this category are the electrolytic type instruments which measure the moisture content in the gas sample with a phosphorous-pentoxide film coated between two platinum electrodes in the electrolytic cell. The water vapour is dissociated into hydrogen and oxygen when direct current is applied, the amount of current used to dissociate the water being converted to a direct moisture content reading in ppmv.

Most recent dew point meters display the due point at atmospheric pressure as well as at the operating pressure in the power equipment.

1.3 Chemical Reaction Tubes with Visual Indication

The refrigeration industry uses a wide range of so called eyeglass - dew point indicators. They use a chemically reactive material that changes its colour at a certain dew point. The observer gets a general indication if the "freon" is dry or wet. Past trials of this technology with SF_6 gas have not been very positive as these indicators are pressure sensitive and readings vary with pressure.

1.4 Summary of desirable features of dew point meters:

- Measuring range 10 ppmv to at least 500 ppmv;
- Accuracy ± 20 ppmv;
- Sensor resistant to oil traces and corrosive gases;
- Permeation resistant connecting pipes using self-sealing valve connections;
- Portable;
- Calibrated or field calibratable;
- SF_6 gas release less than 1 bar litre (~ 6 g) per measurement;
- Average time to obtain result less than 5 minutes.

2 Reactive Gases (SF_6 Decomposition By-Products)

Reactive gaseous SF_6 decomposition products include various gaseous fluorides such as SF_4 and WF_6, oxifluorides like SOF_2, SOF_4, and SO_2F_2, the oxide SO_2, and hydrogen fluoride HF. All of these gases could principally be detected using gas chromatography or infrared spectrometers. However, low cost measurement devices are only available for SO_2 and HF. Devices for SO_2 are also found to be sensitive to SOF_2. The devices for HF are less sensitive than those for SO_2.

Because of the difficulty of measuring all reactive gases, it is recommended that one or two of them be selected as indicators for the total concentration of all reactive gases. The gases SO_2 and SOF_2 are particularly suitable because they make up a major fraction of all reactive contaminants, which may remain in reclaimed gas after filtering. Their relative abundance is determined by the stoichiometry of the reactions by which they are created and is approximately (SO_2 + SOF_2) / HF = 1:2 to 1:4, i.e. 1:3 on average. Therefore, if the sum concentration of SO_2 + SOF_2 is measured, the total concentration, including HF is about 3 to 4 times higher, e.g. a reading of say 12 ppmv would indicate a total concentration of SO_2, SOF_2 and HF of about 50 ppmv, this corresponds to the recommended level given in **Table 1** for reclaimed SF_6 to be reused. In order to account for this indicator function of SO_2 + SOF_2 an equivalent level has been included in the purity requirements (**Footnote 1 in Table 1**).

The present technology to detect SO_2 by a portable field instrument is to use so called detector tubes, which change their initial colour if SF_6 containing SO_2 or SOF_2 is fed through them. The device samples a small amount of SF_6 from the equipment (0.5 litres at 2 bar). This sample gas is then released through the test tube, thus a quantitative measurement is possible. Typical measuring range is 0 ÷ 20 ppmv.

Electronic and electro-chemical SO_2 sensors have been developed but have not yet been tested in SF_6 insulated power technology.

Desirable features are:

- Measuring range up to 20 ppmv;
- Calibration for SO_2 and SOF_2;
- Accuracy ± 10%;
- Decomposition product resistant connecting pipes using self sealing valve connections;
- Portable;
- SF_6 gas release less than 1 bar litre (~ 6 g) per measurement.

3 Non Reactive Gases (Air and CF_4)

These include mostly air (introduced by handling) and CF_4 (produced by arc erosion of polymers). Devices that compare the speed of sound or the thermal conductivity of the SF_6 gas mixture with pure SF_6 can measure the concentrations of these gases. Speed of sound based systems are fast (response time less than 1 min), accurate to ± 1% and do not need recalibration and use only minimal amount of gas. Their readout is the SF_6 concentration in % volume. They are mostly calibrated for mixtures of SF_6 and Nitrogen and/or air, but can also be calibrated for SF_6 / CF_4 mixtures. Devices measuring the concentration of the non-reactive gases (such as Oxygen sensors) and then calculate the % of SF should not be used, as different non-reactive gases such as Nitrogen (N_2) or CF_4 may be present.

Desirable features are:

- Accuracy better ± 1% vol;
- Response time < 1 min;
- No recalibration required;
- Separate calibration for air and CF_4 mixtures with SF_6;
- Portable;
- SF_6 gas release less than 0.5 bar litre (~ 3 g) per measurement.

APPENDIX 3

DESIGN CONSIDERATIONS FOR SF_6 RECYCLING EQUIPMENT

As a general philosophy the better the design and quality of the various components of an SF_6 reclaimer, the lower the probability of introducing undesired contaminants into the SF_6 gas. An investment in good quality equipment may thus be justified by the elimination of high cost special procedures, which may otherwise be required when recycling SF_6, refer to **Figure 2** and **Section 5.3**.

1 Pre Filter for Heavily Arced SF_6 Gas

Additional pre filters, as described in **Section 5.3**, are typically used between the SF_6 gas processing unit and the SF_6 insulated equipment in an attempt to keep contaminants of heavily arced gas from harming the processing equipment and from contaminating reclaimed SF_6 already stored in the gas cart's storage vessel.

The characteristics of pre filter units should be in accordance with **Table 3** and should not contain ingredients that form stable gases rather than absorbing SF_6 by-products. They should have self-sealing pressure and vacuum tight connections on both input and output points and should facilitate easy exchange of filter material (i.e.: cartridges), preferably without the need to remove any connections, thus reducing the possibility of leakage. They should be portable for ease of use.

Facilities must be available to allow the removal of air from the associated section of gas cart after exchange of filter material by means of its internal air evacuation system (vacuum pump).

Soda Lime $NaCO_3$ (soda ash) should not be used as a pre-filter material as it produces CO_2, which is a stable gas that cannot be removed from the SF_6. Similarly, a molecular sieve with pore size larger than 4 Angstrom should not be used as thermodynamic reactions can occur under certain instances, causing a burnout or melt down of the filter interiors.

2 Particle Filter

The particle filter should be placed at the input of a gas reclaimer. It should be capable of holding back particles larger than 1 micron in size, thus preventing particles from entering mechanical parts of the gas reclaimer and/or being discharged into the air via the vacuum pump. It should facilitate easy exchange of filter material (i.e.: cartridges), preferably without the need to remove any connections thus reducing the possibility of leakage.

Facilities must be available to allow the removal of air from the associated section of the gas cart after exchange of filter material by means of its internal air evacuation system (vacuum pump).

3 Vacuum Pump

The vacuum pump module is used to extract air from SF_6 insulated equipment and associated piping prior to refilling with SF_6 and for dehydration (removal of residual moisture). It is also used to remove air from various sections of the gas processing system itself, e.g. after maintenance work and after filter exchange. The vacuum pump section must be designed so that accidental back-flows of air and oil are prevented. As vacuum pumps are generally oil-lubricated, they should not be used for SF_6 processing.

4 SF_6 Vacuum Compressor

The SF_6 vacuum compressor module is used to recover SF_6 from gas insulated equipment and to assist the in series connected SF_6 piston compressor to achieve a good level of SF_6 recovery. Its function is to produce a vacuum as low as possible within the electrical equipment and to feed the SF_6 gas to the main compressor.

Note: A piston compressor alone can only achieve a certain pressure differential that would limit the residual recovery pressure dependent upon the gas pressure in the storage compartment. The use of both compressor systems in series will assure that the desired recovery pressure can be achieved.

The vacuum compressor should be dry running and hermetically sealed to prevent accidental oil or air contamination. It should also have a pneumatic control system that ensures its operation in accordance with the prevailing pressure conditions.

Some systems combine the SF_6 vacuum compressor module with the vacuum pump. In this case the combination must perform according to requirements for both devices and an automatic shutdown feature must be incorporated to prevent SF_6 from being discharged into the air as a result of operator error.

Dry running vacuum pumps have recently become available for SF_6 recovery. As they produce a higher vacuum degree compared to the vacuum compressors, the costs substantially increase. On the other hand, a higher recovery rate can be achieved (up to 50 times).

Note: Most vacuum pumps are oil lubricated and produce some oil mist at their exhaust. If used for SF_6 processing the elimination of the oil mist must be assured. Vacuum pumps also are generally not airtight when a vacuum exists at their discharge side. This is however often the case where vacuum compressor and vacuum pump are combined. The use of a vacuum pump in the SF_6 circuit of a gas processing system must ensure the air tightness between vacuum and compression section.

5 SF_6 Piston Compressor

This module is used to compress the SF_6 into a storage container. It commonly comprises a single or dual stage piston compressor. It should be dry running and hermetically sealed to prevent accidental oil or air contamination. Its pressure differential must be sufficient to achieve the maximum storage pressure required to adequately fill the storage container.

6 Gas/Moisture Filters

Filter elements should be adequately sized to remove moisture, gas by-products and particles larger than 1 micron in size (as a second means of trapping and larger particles, which may have been transmitted via a non-efficient particle filter). The filter should be a cartridge type and changed easily. The desiccant and decomposition filters should be placed between compressor output and storage section. Absorbent filters have better efficiency under higher pressures and elevated temperature.

Facilities must be provided to allow the removal of air from the associated section of gas cart after exchange of filter material by means of its internal air evacuation system (vacuum pump).

7 SF_6 Storage

The SF_6 storage module is used to store SF_6 processed by the reclaimer (see Section 6.1). It must have enough capacity to store the amount of SF_6 to be recovered. It can be an integral part of the gas reclaimer or it can be an external item. If used for liquid storage of SF_6 it must be rated for at least 50 bar. A net content weighing system should be available in order to determine the degree of filling of the container. If the reclaimer is intended to be transportable when containing gas within its storage containers it must comply with the local pressure vessel regulations (see Section 6.4).

8 SF_6 Re-filling

The SF_6 gas reclaimer must have provisions to allow refilling of the gas, from the storage vessel, into the electrical equipment. The refilling provisions will vary depending on the storage method. Means must be incorporated to ensure that the electrical equipment is not subjected to overpressure. The SF_6 compressor is generally used to transfer the gas from the storage vessel to the electrical equipment.

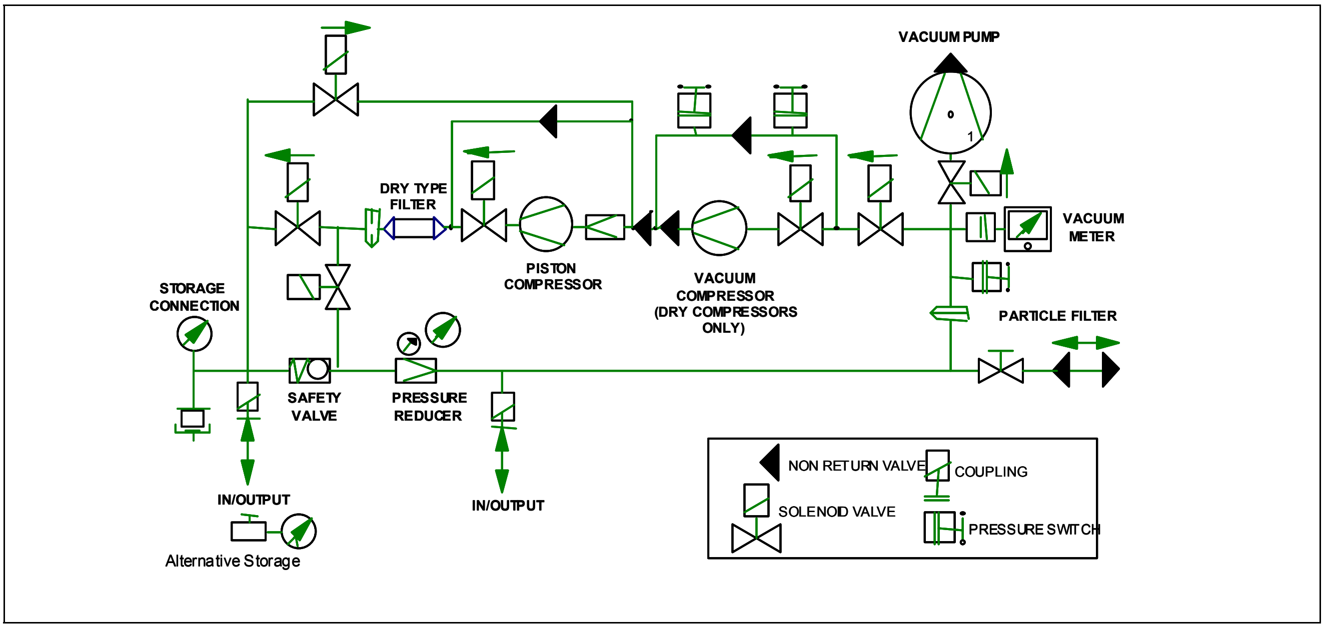
When the gas is stored in gaseous form it can be refilled by using a regulator and the compressor only.

When the gas is stored in liquid form it is necessary to control the temperature of the refilled SF_6 to ensure that freezing cannot occur in the system and that SF_6 is filled into the equipment in vaporised form only.

9 Design Example

The following Figure 6 shows the gas flow scheme of a general purpose SF_6 reclaimer designed for processing "normally arced gas".

Figure 6: Typical flow diagram for a general purpose gas reclaimer



Each of the various components shown here, has specific design considerations in regards to their ability to keep the SF_6 in a re-usable state, at acceptable cost, and to prevent accidental gas losses during handling.

Gas/hose connections should be self-sealing to prevent air and moisture from entering the gas reclaiming equipment. As the equipment will often be left in a state of vacuum and/or high pressure, these SF_6 valves need to be pressure and vacuum tight.

Gas piping and pipe unions used must be of high quality and preferably use a metal to metal re-usable sealing system, proven in its performance with SF_6 and its decomposition by-products. The following characteristics are essential:

- Pressure and vacuum tight;
- Vibration proof;
- Re-usable (indefinite refitting possible);
- Temperature change resistant.

All pipe-work should be of copper tubing silver soldered to tube unions. All components (gauges, valves, filters, etc.) should be securely mounted to the frame of the gas cart, such that pipe-work does not have to support them. This prevents stress cracks causing either gas losses or inadvertent gas mixtures. Heavy components (i.e.: compressors and vacuum pumps) should be "shock-proof" mounted and be connected to the fixed pipe-work via flexible connections.

Equipment used to process SF_6 (i.e.: compressors) should be dry running (oil less), of gas tight construction and should not contain any internal components that can corrode by being exposed to decomposition products (i.e.: galvanised metal).

Solenoid type valves that close automatically in case of a loss of power should be used to control the gas flow.

Vacuum pumps used to extract air and moisture from electrical power equipment or gas reclaiming equipment, should have an oil back flow prevention valve.

Storage tanks should not be internally coated.
SF_6 compressors must be pressure and temperature protected, and be able to shut solenoid valves in case of overload or failure.

Filter elements should be as described earlier in **Section 5.3**.

10 Safety Features

Operator safety features should be incorporated into gas reclaimers, in particular, systems to prevent operator errors. The following features will assist in achieving safe operation:

- Pressure relief valves at all critical sections;
- Automatic control of gas temperature;
- Check valves at critical points throughout the gas reclaimer;
- Appropriate wiring, screening of live components and grounding of all electrical equipment.

11 Ability to maintain original gas quality.

Important design features to ensure the conservation of gas quality are:

- Vacuum pump oil back flow prevention;
- Dry-running (oil-less) SF_6 processing components;
- Use of high reliability tubing and fittings;
- Gas tight compressor designs;
- Self sealing pressure/vacuum connections with minimum flow restriction;
- Vibration proof mounting of components.

12 Transportability

Transportability is an essential value for many applications. For small gas volumes assemblies that may be transported in a car, or small van, and set up on site may suffice. For large gas volumes a trailer mounted self contained assembly is required. Special considerations should be given to ensure that the storage vessel used could legally be transported when filled with SF_6

APPENDIX 4

MOISTURE

1 General

The issue of moisture in GIS has led to substantial confusion in the past, which seems to be partly due to the numerous measurement units in use and partly to the unfamiliar features of the subject. This appendix therefore summarises the measurement units and their conversion, dew point measurement practice and the mechanisms responsible for the establishment of a basic moisture level in gas insulated electric power equipment.

2 Moisture measurement units

The primary physical quantity characterising the moisture level in a volume is the partial **water vapour pressure p_{H2O}, [Pa].** It is a linear measure of the moisture level and is independent of the pressure of the background gas and of its composition.

Condensation of water vapour as liquid (droplets = dew) or solid (ice) occurs when the water vapour pressure p_{H2O} exceeds a critical level p_{H2Osat}, the saturation vapour pressure. ***It is important to note that the condensation only depends on p_{H2O} and the gas temperature whereas the pressure and composition of the background gas*** in which the moisture is contained as impurity, ***plays no role.***

The dependence of the saturation vapour pressure on temperature $p_{H2Osat}(T)$ is tabulated in IEC 60376. This relation defines another measure for moisture, which is equivalent to the water vapour pressure, namely, the **dew point T_d**. It is defined as the temperature below which a given water vapour pressure p_{H2O} causes condensation. Note that, different from the partial water vapour pressure, the dew point T_d is a *non-linear* measure for moisture, which has only been introduced because the observation of condensation is presently the mechanism underlying most moisture measurement devices (dew point meters).

The **conversion of partial water vapour pressure p_{H2O} to dew point T_d** can be carried out using the water vapour pressure curve $p_{H2Osat}(T)$ tabulated in IEC 60376.

A further measure for moisture is the **volume concentration c_{H2O} [ppmv] of the water vapour with respect to the background gas** (at pressure p). It is usually expressed in **ppmv** (= parts per million by volume) and is defined as the ratio

$$c_{H2O}\ [\text{ppmv}] = p_{H2O}/p \times 10^6$$

This measure has been recommended as preferential unit for moisture because of its practical advantages as discussed in Section 4.3.1.

A further moisture measurement unit in use is the mass concentration **c_{mH2O} [ppmw]**, which is defined by:

$$c_{mH2O}\ [\text{ppmw}] = \rho_{H2O}/\rho \times 10^6$$

where ρ_{H2O} and ρ are the mass density of the water vapour and the background gas, respectively. Note that the density ρ of the background gas depends on its composition so that mass related concentrations results differ for different SF_6 mixtures when the same absolute moisture level is present. This makes this unit difficult to handle for SF_6 mixtures.

The conversion rules between volume and mass concentration are:

c_{H2O} [ppmv] = c_{H2O} [ppmw] / (M_{cont}/M_0)
c_{H2O} [ppmw] = c_{H2O} [ppmv] (M_{cont}/M_0)

where M_{H2O} and M_0 are the molecular masses of water and of the background gas, respectively.

Specifically for pure SF_6 one has, with $M_{SF6} = 146 \times 10^{-3}$ kg/mol, $M_{H2O} = 18 \times 10^{-3}$ kg/mol

c_{H2O} [ppmv] = 8.1 c_{H2O} [ppmw]
c_{H2O} [ppmw] = 0.12 c_{H2O} [ppmv]

3 Moisture measurement practice

As already explained in Appendix 2, Section 1, the most common way to measure the moisture content of SF_6 if the measurement of the dew point. The dew point is the temperature at which the water vapour, which is in the gas mixture, starts to condense.
At this critical temperature, the partial pressure of water vapour is equivalent to the saturation vapour pressure. The relationship between the partial pressure of water at the temperature of the dew point can be found in table given by Annex A of IEC 60376 [1.16].

3.1 Influence of the pressure and temperature

In fact, the dew point of a gas depends on the pressure and on the temperature. Sometimes confusions are done between the Dew Point of a gas inside a container or equipment and the dew point measured.

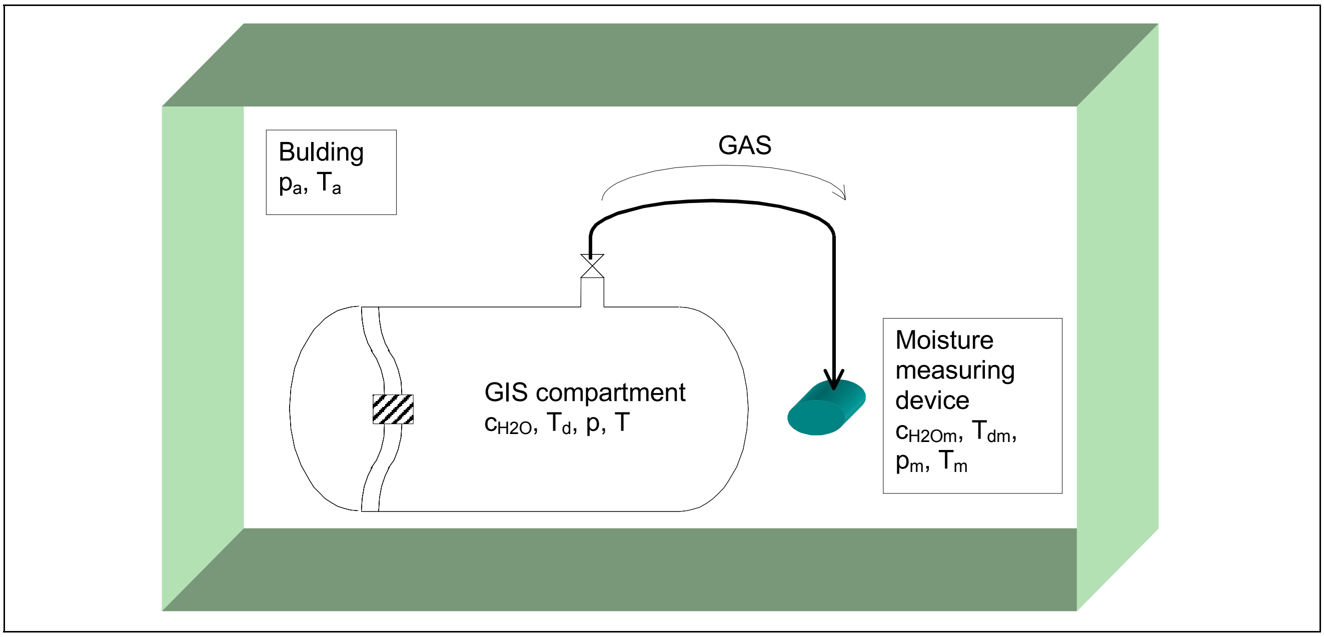
As it can be seen in Figure 7, the dew point of a gas inside a container or equipment T_d is the temperature at which the water vapour starts to condense in a gas at the compartment pressure p. From this dew point value, the moisture content c_{H2O} can be deducted (see next Section 3.2).
The dew point measured T_{dm} is the temperature at which the water vapour starts to condense in a gas at a lower pressure than the nominal pressure p_m. When the measuring device is working at atmospheric pressure p_a, then the measuring pressure p_m is equal to p_a. From this dew point value, the moisture content c_{H2Om} can be deducted (see next Section 3.2). c_{H2Om} is equal to c_{H2O}.

On the other hand, the moisture inside the compartment varies depending on the temperature of the gas inside the compartment T, as a consequence of sorption and desorption processes. This temperature is normally different from the ambient temperature T_a, due to the current flowing in the conductors and sometimes the sun heating on the electrical equipment. When the temperature rises, the moisture desorbs from the aluminium and polymeric walls of the electrical equipment, so that both the moisture content and the dew point of the gas increase.

Due to these different aspects, when the dew point T_{dm} of a gas is measured, some other information must be documented. They are:

- T: the temperature of the gas in the compartment;
- p_m : the pressure at which the dew point is measured

Figure 7: Measurement of the moisture content in a GIS compartment



- p_a is the ambient pressure and T_a is the ambient temperature;
- c_{H2O} is the moisture content of the gas, T_d is the dew point, p is the gas pressure, T is the gas temperature in the GIS compartment;
- c_{H2Om} is the moisture content of the gas, T_{dm} is the dew point, p_m is the gas pressure, T_m is the gas temperature in the measuring device.

3.2 Relation between the humidity contain and the dew point measurement

$$c_{H2O}\,[\text{ppmv}] = p_{H2O} / p_m \times 10^6$$

- p_{H2O} is the saturation vapour pressure at the dew point temperature (see Annex A of IEC 60376 [1.16]);
- p_m is the gas pressure in the measuring device;
- c_{H2O} [ppmv] is the volume concentration expressed in parts per million by volume.

4 Basic Moisture Level in Equipment

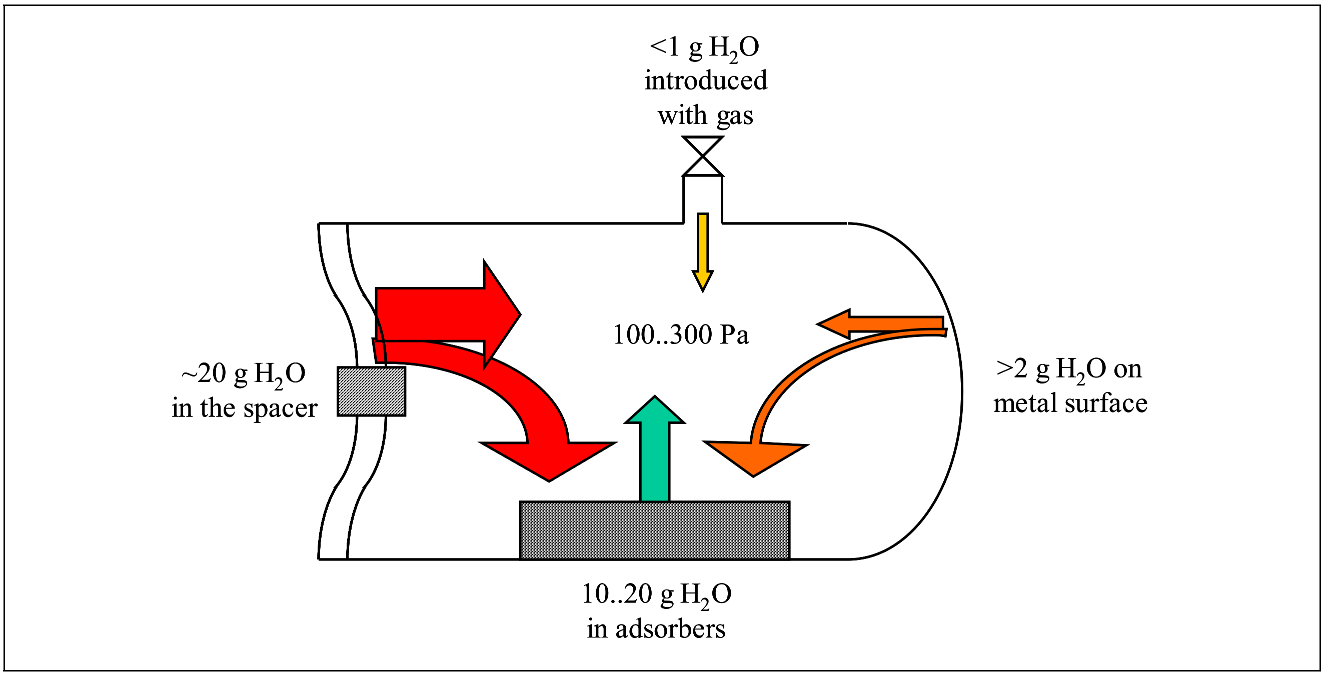
The moisture level in gas-insulated equipment is controlled by a number of different moisture sources, which include

(1) Moisture diffusing into the gas containment from the outside atmosphere through leaks and sealings;
(2) Moisture introduced by the moisture contained in the gas filled into the equipment;
(3) Moisture desorbed from inner metallic surfaces of the gas containment;

(4) Moisture desorbed from inner polymeric surfaces of the gas containment;
(5) Moisture desorbed from adsorbers placed the gas containment for moisture control and sorption of gaseous decomposition products.

As pointed out in [1.15] moisture diffusion from outside (1) is usually negligible for intact equipment. In order to assess the role of the remaining moisture sources it is instructive to carry out some order-of-magnitude estimates of the moisture inventory contained in a typical gas insulation compartment as shown in **Figure 8**.

Figure 8: Moisture balance in a gas insulation compartment in gas insulated power equipment



If gas contaminated with a partial water vapour pressure p_{H2O} = 150 Pa (corresponding to a dew point of –15 °C) is filled into the enclosure, the moisture imported with it m_{H2O} is:

$$m_{H2O} = \rho_{H2O}V = p_{H2O}\, M_{H2O} /(RT)$$

With $M_{H2O} = 18 \times 10^{-3}$ kg/mol, R = 8.3 J/K mol and T = 300 K one obtains for a typical volume of V = 0.5 m^3:

~ 0.5 g water imported into the enclosure when filling it with gas containing 150 Pa moisture

When the metallic surface consists of aluminium it is covered by an aluminium oxide layer, which, on a microscopic scale, has a spongy structure with an effective surface some n ~ 500 times higher than the geometric surface. It is known that such an oxide layer can accommodate about N ~ 20 molecular layers of water molecules. The moisture adsorbed at the aluminium surface per area thus is of the order

$$m_{met} = n\, N\, m_{H2O} / A_{H2O}$$

where $m_{H2O} = 3 \times 10^{-26}$ kg is the mass of a water molecule and $A_{H2O} = 10^{-19}$ m^2 its area. Thus, $m_{met} \sim 3 \times 10^{-3}$ kg/m^2 corresponds, in our example, to about

3 g water stored at the metallic surface.

The polymeric surface in contact with the gas volume usually has a moisture content of the order of c_{H2Ow} ~1 % wt. As the diffusion of moisture is a slow process only a limited depth of a few mm under the polymer surface is accessible for diffusing moisture. With a typical diffusion depth of d ~3 mm (corresponding to a diffusion time of several months) the water inventory of the polymer surface per area results $m_{poly} \sim d\ \rho_{poly}\ c_{H2Ow}$ so that with $\rho_{poly} \sim 1000\ kg/m^3$ and a surface of ~1 m^2 one has

~ 30 g water stored in the polymer surface.

The sorption performance of adsorbers are characterised by the sorption isotherm, a curve which relates the degree of adsorber charging to the residual water vapour pressure left in the gas. Typical molecular sieve type adsorbers leave very low residual water vapour pressures when they are completely uncharged but leave considerable residual water vapour pressures when they are partially charged. They typically have residual pressures of the order of 100 Pa when charged to 50 % of their capacity at an operating temperature of only 40 ^oC. Under these conditions, they contain about 0.1 kg moisture per kg adsorber material. The moisture inventory of a “half-filled” adsorber of typically 300 g would thus be about be 0.3 x 0.1 = 0.03 kg, i.e. there would be

~ 30 g water stored in the “half-filled” adsorber.

The comparison of the above order-of-magnitude estimates shows that the moisture inventory essentially resides in the spacer and in the adsorber whereas moisture imported with filling-in gas is negligible. As a result, the **basic moisture level in the equipment** is not determined by the moisture imported with the gas but mainly by the sorption equilibrium between polymer surface and adsorber. It thus depends, in a complex way, on such parameters as adsorber design, polymer surface treatment, temperature etc..

The order-of-magnitude of the basic moisture level can be inferred from sample moisture measurements in gas insulating equipment in service as reported in [1.15]. These measurements yield water vapour pressures in the range of typically **100 to 300 Pa**. As a consequence of that:

The choice of a maximum tolerable moisture level of 150 Pa (corresponding to a dew point of –15 ^oC) constitutes a safe criterion for the reuse of reclaimed gas.

Putting extremely high requirements on the “dryness” of the gas is a functionally unnecessary over-specification, which only causes cost without reducing the moisture level in equipment. It is not possible to dry out an enclosure by filling in extremely dry gas.