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Recovery and regeneration of SF_6 at switchgear end of life is now a mastered industrial process

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Abstract

Sulphur Hexafluoride (SF_6) gas has been used since approximately 1960 in electrical equipment for energy transmission and distribution at rated voltages above 1000 V. It is recognized as an ideal insulating and breaking current medium for transmission and distribution equipment. However, SF_6 is a very long-lasting greenhouse gas having a very high global warming potential. Aware of this, the European electrical industry represented by the T&D Europe manufacturer association has reinforced its actions in different directions to drastically reduce SF_6 emissions. These actions are applied all along the life cycle of SF_6, from procurement, production, design and manufacturing of electrical switchgear, operational life in grids and at end of life treatment.
Electrical switchgear life time is around 30 years up to more than 40 years. The first SF6 High Voltage switchgear were installed in the sixties. Most of them are still in service. However, in some cases end of life treatment has now to be considered. Based on CIGRE studies and on IEC standards, efficient procedures have been developed to minimize SF_6 emissions when the gas is recovered either at site (usually for high voltage equipment) or at manufacturing plant (mainly for medium voltage equipment). The recovered SF_6 is generally re-used, either directly if it meets standard technical grades, or after reclaiming.
Based on these good practices, the European Union has initiated measures to minimise the emission of fluorinated greenhouse gases (F-gases) within the framework of the climate protection policy. They are stipulated in the EC Regulation No. 842/2006 and in other detailed additional regulations.
SF_6 from medium- and high-voltage switchgear must be recovered both during decommissioning work and major maintenance. During any work involving the recovery of SF6, it is mandatory that the personnel are certified. All recovered used SF_6 should be recycled, reclaimed for reuse where necessary or in exceptional cases destroyed. Recovery and reuse has been common practice for several years now.
The paper will describe practical operational processes that are now commonly used by manufacturers and industrial companies to recover SF_6 on site or at dedicated plant, to analyze it and to reclaim it for reuse, making the closed cycle principle a reality.

Keywords:
Switchgear end of life. Sulphur-hexafluoride. High voltage. Medium voltage.

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Introduction

SF6 switchgear appeared in the 1960's

Sulphur Hexafluoride (SF_6) gas was produced for the first time more than hundred years ago (1900) in the laboratory of Faculté de Pharmacie in Paris by Moissan and Lebaeau. The first patent concerning use of SF_6 in electrical apparatus was granted in 1939. In 1948 the industrial manufacturing commences and in 1960 the first high voltage SF_6-equipment arrives on the market. Since then, SF_6 technology has taken over as the leading technology for high voltage equipment and transformer stations in the transmission and distribution network at rated voltages above 1kV. Its predominance is clearly demonstrated by its particular and well known physical properties. SF_6 is recognized as an ideal insulating and quenching medium for energy transmission and distribution equipment. The favourable properties of SF_6 make it possible to design compact, cost effective and even environmentally preferable equipment [1].

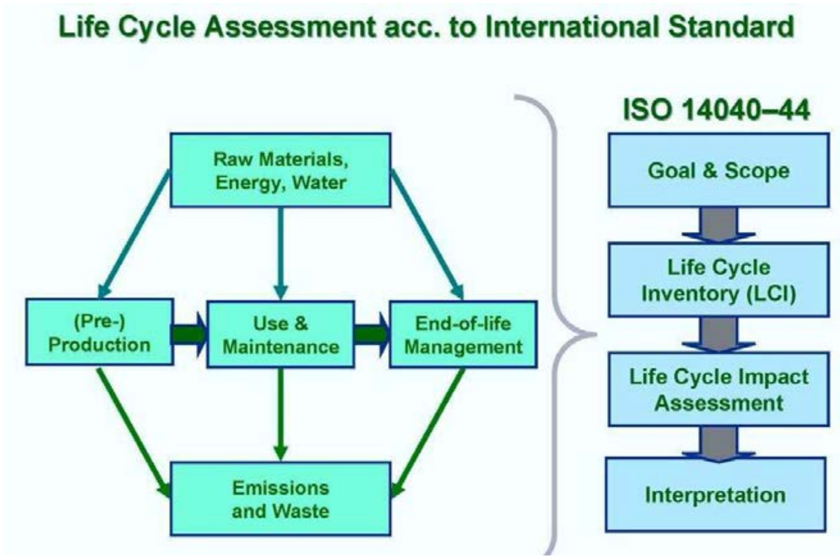
Questions about SF_6

As long as SF_6 has been used in electrical equipment its behaviour and use have been questioned, An early dominant motivation for research related to the toxicity of decomposition products and in particular to safety to humans. Although pure SF_6 is non-toxic there are by-products in few quantity which are not. In the 1990'ies, there was a paradigm shift in the motivation for research. This was ignited due to the increasing awareness of SF_6 as a highly potent and long lasting greenhouse gas with a global warming potential (GWP) of 22800 CO2 equivalences [2].

Actions to reduce SF_6 emissions along the life cycle

As historically, before 1990, SF_6 was often vented to the atmosphere for maintenance, the electrical sector and industry have taken from 1995 firm measures to mitigate SF_6 emissions to the atmosphere.
Being one of the active contributors, the European electrical industry represented by the T&D Europe manufacturer association has reinforced its actions in different directions to drastically reduce SF_6 emissions. These actions are applied all along the life cycle phases of SF_6, equipment from procurement, production, design and manufacturing of electrical switchgear, operational life in grids and at end of life treatment.
From a life cycle perspective measures have been implemented in the manufacturing-, use- (in operation) and decommissioning phase.

Figure 1
LCA Flowchart



Effective actions taken for the design and manufacturing phase yields a better performance ratio for the amount of SF_6 needed to perform a function so to minimise the accumulated amount of SF_6 banked in equipment as it is shown in Cigre brochure "SF_6 Tightness Guide" [3]. The quantity of gas providing same functionality in 1968 and today is significantly reduced. In addition the space requirement today is reduced to ca. 20%.

Tightness of equipment has improved and substantial effort has been taken by international standards working groups to set firm stricter tightness requirements for HV and MV sealed for life equipment to 0,5% p.a. resp. 0,1% p.a. as maximum permissible leakage rate [4].

The manufacturing process of electrical SF_6 equipment has become an automated precision processthat rewards a very low emissions contribution to each unit filled.

Figure 2
Filling and tightness testing tank

The emissions during the use phase has been minimised for HV-equipment that need servicing (needs to be opened) by matching the maintenance frequency with factual wear and by sectionising passive compartment from switching compartments. A recommended service interval is typically 25 years eg. only needed once in a lifetime.
Electrical switchgear life time is around 30 years or even more than 40 years for some high voltage equipment. Most of them are still in service. However, in some cases end of life treatment has now to be considered. Based on CIGRE studies [5] and on IEC standards [6], Members Companies of T&D Europe, Gas manufacturers and Gas Distributors have developed efficient procedures to minimize SF_6 emissions when the gas is recovered either at site (usually for high voltage equipment) or at manufacturing plant (mainly for medium voltage equipment). The recovered SF_6 is generally re-used, either directly if it meets standard technical grades, or after reclaiming.

SF_6 switchgear appeared in the 1960's

All these good practices have been developed in the continuity of the Kyoto protocol between 1995 and 2005. In the meantime, regulations have been put in place, all over the world, with the same objective. For example, the European Regulation 842/2006 [7] that regulates certain fluorinated greenhouse gases requires SF_6 recovery by certified personnel, dedicated labelling of SF_6 filled electrical equipment and reporting of some data.
The target of the European Regulation 842/2006 is to reduce the emissions of certain greenhouse gases including SF_6. The regulation applies during the whole life of a product, i.e. from design, type testing, manufacturing, operational life and end of life treatment.
The F-Gas regulation, aims to reduce 8% of the 1990's fluorinated gas emissions in the period 2008 to 2012, and 70% in the longer term. This means any emission of SF_6 should be controlled and monitored.
Several articles of the regulation require concrete measures, for labelling (Art. 7), reporting (Art. 6), training and certification (Art. 5). In line with the objective of emission reduction, one of the main points is that the regulation imposes the recovery of the gas

by certified personnel (article 4). There also are clear definitions of what is recycling and what is reclaiming.
The main regulation No 842/2006 was followed by other regulations providing detailed procedures.
Three of them apply to SF_6 switchgear and address reporting, labeling and training & certification.
The measures required in 842/2006 are described in detail in the Regulation 1494/2007 [8] establishing the form of labels and additional labelling requirements , 1493/2007 [9] establishing the format for the report, 305/2008 [10] establishing minimum requirements for training and certification of personnel.

Reporting: Regulation 1493/2007

This regulation complements the 842/2006 regulation, defining the format of the report that all producer, importer and exporter have to send to the Commission to summarize all SF_6 consumptions.
The reports shall be done by 31st of March of each year. As this reporting system only concerns SF_6 in bulks, member states are asked to get data in relation with FGHG emissions.

Labelling: Regulation 1494/2007

The purpose of this additional regulation No 1494/2007 [8] is to give clear information of what is banked in high voltage switchgear. It is obvious that the clearer the information is, the easier it is to deal properly with the gas contained in the switchgear, avoiding emissions. In order to get proper identification of the GHG contained in products or equipment, they shall be marked with a label containing the following information:
- the text ‘Contains fluorinated greenhouse gases covered by the Kyoto Protocol’;
- the abbreviated chemical names for the fluorinated greenhouse gases contained or designed to be contained in the equipment using accepted industry nomenclature standard to the equipment or substance;
- the quantity of the fluorinated greenhouse gases, expressed in kilograms;
- the text ‘hermetically sealed’ where applicable.

It must be fixed on the product or equipment next to the filling/emptying connection.

Training and certification

According to Regulation No 842/2006, only certified personnel can perform recovery of gas from equipment to ensure effective gas recover first and then either reclaiming and reuse or sound disposal.
Detailed provisions on how to establish in each Member State a training and certification system is described in the additional Regulation No 305/2008 [10]. Before the 4th July 2008, following the European Regulation, the Member States had to put in place their own system regarding training and certification of staff. The purpose was to provide the staff with the necessary skills to avoid SF_6 emissions during recovery together with practical handling of equipment with appropriate type and size. As stated in the regulation, companies involved in carrying out SF_6 handling can conduct such activities only if the staff is trained and certified.

Review process

It is planned in the Regulation No 842/2006 that on the 4th July 2011, the Commission will issue a report evaluating the impact of the regulation’s relevant application on annual and future emissions of FGHG and will review the cost/efficiency ratio of each provision.
The report will also:
- evaluate the efficiency of training and certification programs as well as all the burdens;
- assess the need for the development and dissemination of notes describing best available techniques and best environmental practices concerning the prevention and minimisation of emissions of fluorinated greenhouse gases.

Treatment process for recovering and reclaiming SF_6

SF_6 behavior in switchgear

When SF_6 has been used in an electrical switchgear, by-products may have been formed, leading to a lower purity of the gas.
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, decomposition by electrical discharges, secondary reactions of discharge decomposition products and mechanical generation of dust and particles.
Equipment are now often fitted with absorbers to remove the decomposition products (chemical, corrosive and toxic) and moisture. Therefore the level of decomposition in the equipment in operation 4 is very low. It appears that used SF_6 may be polluted by undesired products created in arcing conditions or corona discharge.
Here below is a scheme of the reaction that may occur to form by-products:

$$SF_6 \xrightarrow{\Delta E} SFx + (6-x)F,\ 0<x<6$$

The byproducts created can then react with Oxygen or moisture, and the main products to take into account in terms of toxicity are SO2, HF, and S2F10 (hardly created but very toxic) as described in IEC 60480 [11]. Other contaminants such as Air/CF4, Oil or metallic particles may also be present in used SF_6. These impurities may come from handling, switching arc erosion and mechanical erosion.

Table 1
Description of principal impurities (IEC 60480 Ed. 2 version 5, 5.1 Introductory remark)

SF_6 SITUATION & USE	SOURCES OF IMPURITIES	POSSIBLE IMPURITIES
DURING HANDLING AND IN SERVICE	Leaks and incomplete evacuation Desorption	Air, Oil, H_2O
INSULATING FUNCTION	Partial Discharges : Corona and Sparking	HF, SO_2, SOF_2, SOF_4, SO_2F_2
SWITCHING EQUIPMENT	Switching arc erosion	H_2O, HF, SO_2, SOF_2, SOF_4, SO_2F_2,CuF_2, SF_4, WO_3, CF_4, AlF_3
	Mechanical erosion	Metal dusts, particles
INTERNAL ARC	Melting & decomposition of materials	Air, H_2O, HF, SO_2, SOF_2, SOF_4, SO_2F_2, SF_4, CF_4 Metal dusts, particles, AlF_3, FeF_3 WO_3 CuF_2,

Certification of personnel in charge of SF_6 recovery

When electrical equipment has to be destroyed or maintained, several operations must be achieved.
These operations which start with the recovery of SF_6 from high and medium voltage equipment must be done by trained and qualified personnel. In fact, the European regulation N° 842/2006 imposes that the personnel shall be certified by an accredited centre. Even though, the regulation is European, agreements between countries allow granting personnel certification in a foreign country.
The minimum condition for granting a certificate to personnel shall be the successful completion of a theoretical and practical examination, able to verify the skills as precised in Annex of EU regulation No 305/2008.

Industrial process of SF_6 treatment

SF_6 Recovery

Here below are described the principal steps to recover SF_6 from high and medium voltage switchgear.
First of all, the equipment shall be dismantled, in order to give access to a valve or to the tubing in case of sealed equipment. This will allow recovering potentially degraded SF_6.
The dismantling of the equipment may be done either by the owner company of the switchgear or by treatment centres.

Figure 3
Connection to the HV cubicle

To recover SF_6, a device combining a compressor and a vacuum pump is used (Figure 3), (Figure 4).
After the recovery device has been connected to the valve, the compressor recovers SF_6 until atmospheric pressure or even below according to equipment. When the pressure inside the cubicle falls under atmospheric pressure, the vacuum pump starts and allows recovering the remaining SF_6.
The recovered gas is then compressed and cooled down to reach the liquefying pressure and is stocked in a packaging designed to contain used SF_6.

Figure 4
SF_6 recovery mobile equipment

IEC/TR 62271-303: Use and handling of sulphur hexafluoride (SF_6) [6] recommends recovering the gas until a remaining pressure lower or equal to 2 kPa abs. Nevertheless, there are now devices able to reach a pressure of less than 100 Pa, allowing the recovery of almost all remaining SF_6. Generally, HV switchgear are able to support this low residual pressure. Mechanical strength of the cubicle and timescale of the recovery operation are also of importance to choose the right level of remaining pressure to reach. The switchgear unit that is empty either can be refilled with new SF_6 or put at atmospheric pressure for maintenance operations.
In Medium Voltage equipment, the amount of gas contained is small and in most cases 1kg to 3kg. For these sealed (for life) units, it is not recommended to undertake evacuation on-site. This kind of equipment necessitates dedicated industrialised recovery processes for SF_6 and subsequent disassembly processes to assure optimal gas handling and payout of LCA results. Since these are sealed for a lifetime, the operator normally has no tools to access the SF_6 gas. If there is no access, for the recovery of gas, a specialized penetrating tool is needed. As the sealed units came on the market in

the mid-1980'ies and the vast majority was put in operation after 1995, we have a clear indication for when the industrialised recycling processes needs to be widely in place and that is by 2025 at latest.
We then take into account a lifetime expectancy of at least 30 years.

SF_6 analysis, reclaiming or destruction

The recovered SF_6 then undergoes gaseous phase chromatography analysis to determine the presence of impurities.This recovery process is used for all maintenance operations. Mobile recovery units can help recovering on site SF_6 from cubicles at end of life (Figure 4) and will ease their transport to a treatment facility. In fact, the equipment is empty; there is no risk of leakage from cubicle, no emission in atmosphere during transportation.
If the analysis shows that the recovered SF_6 respects certain maximum acceptable levels of impurity, it can be reclaimed and will go through specific sometimes patented treatment process (Figure 5). In some kind of process, it will then undergo series of filtration, and noncondensable gas (mainly CF4, air, nitrogen) will be removed. Analyses performed during the last four years showed that the treatment process allows to reach IEC 60480 requirements:

Table 2
Acceptable impurity level for reclaiming

Impurity	Maximum acceptable levels	
	Rated absolute pressure <200 kPa a	Rated absolute pressure >200 kPa a
Air and/or CF4	3 % volume b	3 % volume b
H2O	95 mg/kg c,d	25 mg/kg d,e
Mineral oil	10 mg/kg f	
Total reactive gaseous decomposition products	50 µl/l total or 12 µl/l for (SO2+SOF2) or 25 µl/l HF	

Figure 5
SF_6 regeneration unit

In case the used SF6 does not fit maximum levels of impurity before treatment process, it has to be destroyed by heating to above 1000 °C.

SF_6 gas emission reduction: The case of Norway

Configuration of Norway's network and switchgear infrastructure

Norway's power production enjoys a unique position. 99 percent of all power production comes from hydropower compared to the global average of around 16 percent. This is due to the country's topography and a good supply of waterways suitable for power exploration. As a result, Norway has become very dependent on medium and high voltage installations which contain SF_6 gas.
The majority of the power plants have been placed inside man-made mountain caverns. Initial expenses for these kinds of constructions are high, and they are near impossible to expand at a later stage. This means there is a need to build plants with compact

equipment. It is done by using switches with SF_6, among other things. Today there are just under 300 tonnes of SF_6 gas installed in medium and high voltage installations in Norway.

Configuration of Norway's network and switchgear infrastructure

Norway has ratified the Kyoto agreement and is committed to greenhouse gas emission reductions. Avoiding introducing a very high excise duty on SF_6 that would not have resulted in emission fall, an approach based on a voluntary agreement including all the stakeholders has been set up.

The most important element for making such an agreement work was the introduction in Norway of extended producers' responsibility for electrical and electronic products in 1999. This corresponds with the EU's WEEE Directive (Directive 2002/96/EC) which Norway is bound by through the EEA agreement. The WEEE Directive does however allow for individual member states, or EEA countries, to introduce regulations which are even more wide-ranging than what is being described in the directive. Norway has done this by introducing extended producers' responsibility on absolutely all kinds of electrical and electronic products. As a result a system and logistics for the collection and end treatment of medium and high voltage equipment - including installations with SF_6 - were already in place. But there was no formal requirement to drain sealed-for-life installations.

Voluntary agreement

The Users' Group for SF_6 Installations was established as early as 1991 (a cooperation body for owners and providers of SF_6-insulated installations). The Users' Group, in cooperation with the company responsible for the collecting and processing of waste products - entered negotiations with the authorities. In 2002 the authorities entered a binding agreement with importers, producers and users of SF_6 installations to implement systematic emission measurements and to introduce emission reduction measures. The agreement and arrangement also include better training for workers who handle gas and who are responsible for the running of the SF_6 installations. There is also a system for experience exchange between the users.

The agreement bound the parties to reduce emissions by 13 percent by 2005 and 30 percent by 2010 on 2000 levels.

Industrial organization for treatment

There are 15 plants for final treatment of electrical and electronic products. Guidelines were introduced for the recycling system to ensure all discarded SF_6 installations were sent to one of these end treatment plants.

At this stage there was no available technology or equipment to drain sealed-for-life installations of SF_6. But cooperation with an equipment provider resulted in the development of a special technique where SF_6 gas is sucked out of the installations and into gas cylinders.

A so-called pickler unit drills a hole in the installation. The drilling and draining happens simultaneously (Figure 6). The actual drilling unit is integrated in the unit which seals the area around the drill hole. This uses a powerful vacuum to get the gas into cylinders. The gas passes through several filters which remove impurities and particles.

Figure 6

Tight drilling

An employee is drilling a hole in a sealed-for-life unit, in order to drain it of SF_6 gas.

Photo: NorskMetallreturTønsberg

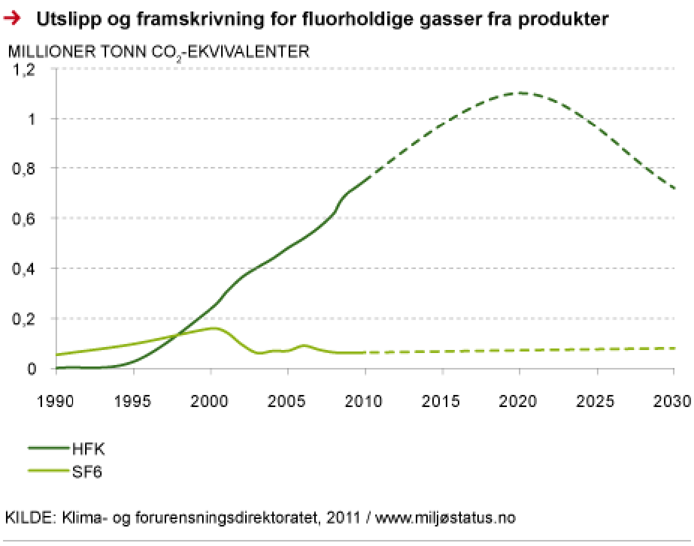
Gas cylinders with used/contaminated SF_6 gas from larger stationary SF_6 installations are also accepted. These cylinders are exported back to the gas producer together with gas drained from the sealed-for-life installations. This allows for a very good control of the treatment of used gas and creates an excellent basis for measuring atmospheric emissions. All registered imports, exports and emissions of SF_6 gas accounted for, must be approved by the authorities.

Main results in SF_6 emission reduction

The agreement between the authorities and the trade has already shown results. Emissions were down by 38 percent on 2000 levels already in 2006. On average the reduction on emission is 56 % over the period from 2002 until 2010.
2010 say the last measures for the original agreement on emission reductions. Norwegian authorities are so pleased with the results that they wish to carry the principles through to a new agreement. This is being developed and is expected to come into effect from 2011.

Figure 7

Emissions and projections for fluorine-containing gasses from products MILLIONS OF TONNES CO2 EQUIVALENTS Source: Norway's Climate and Pollution Agency, 2011 / www.environment.no



Conclusion

For many applications, SF_6 technology is the best solution without equivalent substitutes in terms of compactness, insensitivity to environmental conditions, low maintenance, cost-effectiveness and sustainability. From 1995, all the actors of the electrical sector have developped good practices to minimise SF_6 emissions. This has been done for every phase of the life cycle of switchgear. First actions have been implemented in gas production, switchgear manufacturing, operational life and end of life treatment.
As from now, more and more SF_6 switchgear will reach end of their life, it was time to industrialize the processes for SF_6 switchgear end of life treatment. As shown in the paper, there are different industrial processes able to properly manage the end of life operation on a large scale, keeping SF_6 emissions as low as possible from cradle to grave and making the re-use of SF_6 a reality.

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