Environmental aspects of the use of Sulphur Hexafluoride

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Summary

This report was commissioned by ERA Information Services to investigate environmental aspects of the use of sulphur hexafluoride and, in particular, to provide a preliminary assessment of the likely future trends in legislation or usage.

The report is based on a literature survey and provides information on the properties and characteristics of sulphur hexafluoride and its decomposition products that may arise during use as electrical insulation or in switchgear applications. Safety precautions that need to be taken are discussed, as well as considerations to be taken into account in respect of maintenance of equipment containing sulphur hexafluoride.

Environmental aspects discussed include ozone depletion and the greenhouse effect. Sulphur hexafluoride is a potent greenhouse gas. Recent developments suggest that there may be significant constraints imposed on the usage of sulphur hexafluoride in the years to come. It is therefore important for the electricity supply industry and other sectors using SF_6 to continually monitor best practice procedures in environmental management of equipment containing SF_6 and the regulatory controls that apply.

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1. Introduction

Sulphur hexafluoride (SF_6) is a man made gas that is extensively used in electrical equipment for the power transmission and distribution industry. Its principal uses are as an insulating and arc interrupting gas. Applications include gas-insulated circuit breakers, gas-insulated transmission lines, gas-insulated transformers, and gas-insulated substations. About 80% of the gas produced worldwide is used in the electrical industry (Ref 1). Circuit breaker applications account for most of the gas used.

Non-electrical uses include: air-sole shoes, thermal and sound insulation (e.g. double glazing applications), semiconductor processing, atmospheric trace gas studies, leak detection, ball inflation, blanket gas for magnesium refining, and reactive gas in aluminium recycling to reduce porosity. The highest volumes in non-electrical applications are used in the processing of magnesium and aluminium and in sound insulation.

SF_6 provides important advantages to the electrical industry allowing compact designs and a long prospective lifetime for components. This enables substations to be installed in cities very close to the loads. Power losses can be significantly reduced by the use of equipment using SF_6 and there are no fire safety problems.

Special handling and control procedures are required in dealing with the decomposition products developed in use, for example, products caused by electrical arcing or discharges. These decomposition products can be highly toxic and corrosive. Another concern is that SF_6 is a potent greenhouse gas and thereby contributes to global warming. There is now a worldwide movement to reduce the amount of greenhouse gases being released to the environment. It is therefore extremely important for the industry to continually monitor best practice procedures in environmental management of equipment containing SF_6 and the regulatory controls that apply. Also, alternative technologies need to be continually appraised to ensure sustainability and a commercial advantage in a competitive market that is likely to come under increasing pressure to reduce the use of this material.

SF_6, halogenated hydrocarbons and nitrogen, the most commonly used dielectric gases, are readily available from two or more sources each although the price of SF_6 is relatively high compared with most other dielectrics. Technologically it is still unsurpassed for most applications.

2. Properties and applications

2.1 Properties

SF_6 has been available commercially since 1947. In its normal state SF_6 is chemically inert, non-toxic, non-flammable, non-explosive and thermally stable (it does not decompose in the gas phase at temperatures less than 500^oC). It has a relatively high dielectric strength and good arc-interruption properties. SF_6 is strongly electronegative, i.e., electron attracting, both at room temperature and at temperatures well above ambient. Also, it has a fast recovery time and is self-healing when dissociated under high-pressure conditions in an electrical discharge or an arc. In addition, it has good heat transfer properties. SF_6 produces no polymerisation, carbon, or other conductive deposits during arcing and it is chemically compatible with most solid insulating and conducting materials used in electrical equipment at temperatures up to 200^0C. Most of its stable decomposition by-products do not significantly degrade its dielectric strength and are removable by filtering.

The electrical breakdown strength is normally two to three times higher than air at atmospheric pressure. However the breakdown voltage is sensitive to water vapour, conducting particles and conductor surface roughness.

SF_6 is usually transported in the liquid phase. The pressure required to liquefy SF_6 at 21^oC is about 2,100 kPa and it is easily liquefied by compression (below the critical temperature of 45.6 ^oC), which allows compact storage in metal cylinders.

A summary of properties is given in Table 1.

Particular characteristics of this gas are the high stability of SF_6 gas, which is due to the six covalent bonds of its molecule. These bonds are between the sulphur atom and the six fluorine atoms forming the points of an octahedron. Also the dielectric strength of SF_6 is superior to that of most insulating materials and SF_6 is therefore regarded as having superior properties as an insulating gas.

SF_6 also has a number of advantages as a breaking gas:

- High capacity for carrying the heat produced by the arc. The latter is strongly cooled by convection during arcing.
- High radial thermal conductivity and high electron capturing capacity. When the current passes through zero, the arc is extinguished by the combination of these two phenomena and permits rapid heat exchange from the centre of the arc towards the exterior.
- Fluorine atoms generated by arc discharge are highly electronegative and act as ‘traps’ for electrons, which makes the medium an insulant again.

As with other inert gases, oxidation is inhibited and abrasion of contact surfaces due to oxidation is consequently small when large currents are broken.

The gas properties that are most significant for different gas insulated systems will vary according to their function. A brief overview is given below of electrical applications in the context of the uses and important characteristics of SF_6 for the application. Non-electrical applications will be discussed in Section 7 of this report.

Table 1: Properties of Sulphur Hexafluoride

Property	Units	Value
Melting point	°C	-50.8
Sublimation temperature	°C	-63.8
Density (solid)	g/ml	2.51
Density (liquid)	g/ml	1.98
Density (gas)	g/l	1.329
Critical temperature	°C	45.6
Critical pressure	psia	540
Critical density	g/ml	0.755
Specific heat (25 °C)	cal/ml/ °C	7.09
Surface tension	dynes/cm	11.63
Coefficient of expansion	-	0.027
Thermal conductivity	cal/sec/cm^{-2}/°C/cm x 10^{4}	3.36
Viscosity (gas at 25°C)	poise x 10^{4}	1.61
Boiling point	°C	-63
Specific heat (30 °C)	cal/g	0.143
Relative density (air =1)	-	5.1
Expansion on melting	%	30
Vapour pressure	psig	150
Refractive index at 0°C	-	1.000783
Density at 20°C 760 mm Hg	lb/cu ft	0.406

2.2 Applications

Circuit breakers and switchgear

SF_6 first found commercial application in electrical circuit breaker applications as a dielectric and arc interrupting gas. For circuit breakers the excellent thermal conductivity and high dielectric strength, along with SF_6's fast thermal and dielectric recovery (short time constant for increase in resistivity), are the main reason for its high interruption capability. These properties enable the gas to make a rapid transition between the conducting (arc plasma) stage and the dielectric state of the arc and to withstand the rise of the recovery voltage.

Gas insulated transformers

For gas insulated transformers the cooling ability, compatibility with solid materials, and partial discharge characteristics of SF_6, added to its beneficial dielectric characteristics, make it a desirable medium for use in this type of electrical equipment. The use of SF_6 insulation has distinct advantages over oil insulation, including the avoidance of breakdown due to charge accumulation on insulators, no fire safety problems, high reliability, flexible layout, little maintenance, protected insulation, long service life, lower noise, better handling, and lighter equipment.

Gas insulated transmission lines

For gas insulated transmission lines the dielectric strength of the gaseous medium under industrial conditions is of paramount importance, especially the behaviour of the gaseous dielectric under metallic particle contamination, switching and lightning impulses and fast transient electrical stresses. The gas must also have high efficiency for transfer of heat from the conductor to the enclosure and be stable for long periods of time (say 40 years).

SF_6 insulated transmission lines offer distinct advantages: cost effectiveness, high current carrying capacity, low losses, availability at all voltage ratings, no fire risk, reliability, a compact alternative to overhead transmission lines in congested areas, and avoidance of public concerns with high-voltage overhead transmission lines.

Substation and system considerations

The principal aims of users of SF_6 equipment when changing from other types have been to reduce fire risk and to increase the number of short circuit operations possible without maintenance. Other requirements have been to minimise the number of components located in the tank, simple and accessible operating mechanism high breaking capacity, ability to withstand frequent switching for auto-reclose applications, and long contact life. Equipment life is estimated at a minimum of 20 years even on systems where the switchgear is in frequent use. This type of switchgear also has the advantages of requiring neither very little inspection nor special maintenance. This level of performance is most appreciated in public supply distribution substations.

Compact SF_6 encapsulated units have been available since 1967 and their space saving characteristics have also been a factor in making their installation popular throughout the world. The tendency to supply conurbations at high voltage and the fact that switchgear sites are becoming scarce make it likely that the demand for compact design switchgear will increase.

The factor of compactness has also been an advantage when designing switchgear units for installation inside small buildings or steel enclosures for protection against environmental effects such as salt deposits near coasts, industrial vapours, sandstorms and precipitation.

2.3 SF_6 and its decomposition products

Decomposition of SF_6 occurs when the gas is subjected to high temperature or an electric arc. The quantity and type of by-products generated depend on the types of material in contact with the SF_6 and also on the content and type of gas impurities (humidity, air etc.).

The most severe conditions arise when SF_6 is used as an arc interrupting gas. Decomposition can occur during electrical switchgear operation as a result of the energy released, for example, as a result of switching, faults, internal short circuit, partial discharges etc.

When the discharge is cleared the gas will recombine to a large extent but not entirely. Examples of by-products obtained by recombination of SF_6 itself are: SF_4, SF_2, SF, S_2F_{10}, F^{-ion}, F_2, and S_2. Reaction with impurities and humidity can form SOF_2, SOF_4, SO_2F_2, HF, S_2OF_{10}, and SO_2F.

By a reaction between SF_6 dissociated ions and the metallic fumes from the electrodes and metal walls: CuF_2, AlF_3, WF_6, can be formed. Reaction with insulating polymeric materials and inorganic compounds can produce: CF_4, and SiF_4; in addition by reaction with the compounds above mentioned: SO_2, H_2SO_3, H_2SO_4 CuO, Al_2O_3, WO_3, COF_2 and SiO_2 can arise. Toxic by-products will be produced.

Toxicity

Table 2 below illustrates the range of products formed as a result of decomposition and the Threshold Limiting Value (TLV) for each decomposition product. The value shown in the Table is the concentration to which a worker can be safely exposed during a forty-hour week.

Table 2: Threshold limit values of potential gaseous decomposition products of sulphur hexafluoride

Gas		Parts/million(vol) @ 25°C (76 cm Hg)
Sulphur hexafluoride	SF_6	1000
Sulfuryl fluoride	SO_2F_2	5
Hydrofluoric acid	HF	3
Sulphur dioxide	SO_2	2
Thionyl fluoride	SOF_2	1
Silicon tetrafluoride	SiF_4	0.6
Sulphur monofluoride	S_2F_2	0.5
Thionyl tetrafluoride	SOF_4	0.5
Sulphur tetrafluoride	SF_4	0.1
Tungsten hexafluoride	WF_6	0.1
Disulphur decafluoride	S_2F_{10}	0.025

Source: American Conference of Governmental Industrial Hygienists

It has been reported that the most abundant by-product is SOF_2 and that this dominates the overall toxicity of decomposed SF_6. This compound can be effectively removed by the presence of absorbent material placed in the equipment (Ref 2). In practice major hazards may reside in other materials. The highly toxic materials include: SF_4, S_2F_4, S_2F_{10}, SOF_2, SO_2F_2, HF, and SO_2. These compounds have an irritating action on the skin, the eyes and the respiratory mucous membranes (Ref 3).

Chemical and Thermal Stability

Gases used as dielectrics should be inert, non-flammable, and be chemically and thermally stable at room temperature and have a wide useful temperature range. Nitrogen, SF_6 and hydrocarbon gases are the most common dielectric gases used. These dielectric gases with the exception of hydrocarbon gases are considered inert, non-flammable and chemically stable at room temperature and atmospheric pressure. Hydrocarbon gases are inherently flammable. A feature of nitrogen is its chemical stability at all operating temperatures to which electrical apparatus could be exposed

All chemical compounds have temperature limits above which they are no longer chemically stable. The decomposition rates of dry SF_6 in contact with metals used in electrical equipment are shown in Table 3

Table 3: Decomposition rates of sulphur hexafluoride in contact with metals

Material	Decomposition %/year	
	@200 deg C	@250 deg C
Aluminium	-	0.0064
Copper	0.18	1.4
Silicon steel	0.005	0.01
Mild steel	0.2	2

Source: Chemical Sector Allied Corp

Decomposition rates increase significantly with higher concentrations of moisture and other contaminants. Tests by DuPont indicate that under certain conditions, Freon 116 (C_2F_6), which is also used as a dielectric gas, has somewhat higher thermal stability than SF_6. However, both gases exhibit significantly increased fluoride ion formation as moisture content rises, and this is the paramount factor in determining the thermal and electrical stability of both gases.

Decomposition under Spark Discharge and Corona Discharge

The toxic by-product generation rates strongly depend upon the type of the electrical stress (i.e. corona, spark discharge) and the overall operating conditions (i.e. humidity levels, nearby surfaces that can act catalytically, X-ray radiation, or high energy photons, surface to volume ratio, polarity effect). Typical net production yields for several SF_6 decomposition products formed during electrical discharges are shown in Table 4

Table 4: Net production yields for several SF_6 decomposition products formed during electrical discharges

Species	Corona Discharges (nmol/J)	Spark Discharges (nmol/J)
SOF_4	0.9	0.2
SOF_2	0.54	1-3
SO_2F_2	0.25	0.02
S_2F_{10}	0.5	0.04-0.37

Recent experimental work has established that the production yield of some of the contaminants (i.e. S_2F_{10} may be affected by the presence of water, oxygen, or even surface reactions originating from organic insulants present, for example, PTFE, under corona, spark, and arc discharges). In addition high-energy photons and high-energy x-rays lead to decomposition of gaseous SF_6 forming corrosive oxyfluoride by-products comparable to those arising during corona discharge activity.

3. Safety precautions and maintenance

3.1 Safety precautions

Sulphur hexafluoride is a very heavy gas, about five times as dense as air. This gives rise to a serious potential danger (Ref. 4). Equipment trenches, and similar enclosed spaces may remain full of gas, which if pure has no colour or odour which might warn personnel of the danger. Although sulphur hexafluoride is non-toxic, it will not support life, and personnel entering a sulphur hexafluoride filled enclosure, trench etc. will be asphyxiated. It is essential that personnel are made well aware of this danger, and equipment etc., should be adequately ventilated if it is to be entered without breathing apparatus. If there is any doubt, it is essential to verify the presence of sufficient oxygen, using, e.g. a portable oxygen analyser.

Sulphur hexafluoride is chemically inert in the pure state and is considered to be physiologically inert as well. However, as it is ordinarily available, it can contain variable quantities of the low sulphur fluorides. Some of these are toxic, very reactive chemically and corrosive in nature. These materials can hydrolyse on contact with water to yield hydrogen fluoride, which is highly toxic and very corrosive.

Although uncontaminated sulphur hexafluoride is non-toxic, some of the gaseous impurities produced by electrical breakdowns in the gas are toxic if inhaled in sufficient quantity, and the solid fluoride powders also produced by breakdown may cause skin irritation. If it is necessary to carry out work on equipment that involves contact with SF_6 or its decomposition products personnel must:

- Maintain a high standard of personal hygiene
- Not eat, drink or smoke
- Avoid wiping the nose, eyes or face other than with clean paper tissues

Equipment designed for arc interruption should only be opened by authorised personnel, or personnel working under the supervision of a suitably authorised person and wearing full face mask canister respirator and protective clothing including overalls, boots and gloves (Ref 6).

Special filters are fitted in certain sulphur hexafluoride filled equipment to absorb gaseous breakdown products. Before attempting to remove any such gas filters the operator should be familiar with the manufacturer’s instructions for doing this, together with his instructions for disposing of the used filter material, cleaning the container and re-charging it with new material (Ref 4).

After work has been completed following the removal of SF_6 gas and any decomposition products cleared from the work area, protective clothing and equipment should be cleaned off using disposable materials and/or an approved vacuum cleaner. Protective clothing and equipment may then be removed, preferably in the work area, if practicable (Ref 6). After treatment of disposable items, personnel should wash all exposed parts of the body as soon as possible after leaving the operational area.

3.2 Maintenance of SF_6 equipment and installations

One of the principle objectives of using sulphur hexafluoride gas or vacuum is to extend the life of the components associated with current interruption, often up to the anticipated economic lifetime of the equipment. For this reason many modern equipment types are not intended to be dismantled or overhauled. In the most onerous conditions of frequent switching (e.g. several operations per day) it is expected that overhaul will eventually be required for this type of equipment and the manufacturer should be consulted. With this class of equipment, periodic inspection and operational checks together with periodic measurement of the contact engagement, will give information to ensure that the contact components are in acceptable condition.

In the case of low maintenance equipment e.g. vacuum and SF_6 switchgear, post fault maintenance may not be required and the routine maintenance may be sufficient to ensure that the equipment is in a satisfactory condition.

For circuit breakers fitted with pressure gauges, a periodic checking and recording of SF_6 gas pressure and temperature together with a reference to the manufacturer’s handbook should indicate any leaks.

In equipment where the gas is used for arc extinction, molecular sieves, activated alumina or charcoal are provided, to absorb decomposition products. The solid products resulting from the decomposition of SF_6 exist in the form of a whitish powder that hydrolyses in the presence of moisture to form a sticky grey deposit. This powder has an irritating action on the skin, eyes and the respiratory mucous membranes.

Experience shows that in the rare event of any of these products being present in the atmosphere within a substation, warning indications will be apparent, at very low concentrations, in the form of a strong and nauseous odour. This will be evident well before any toxic effects can take place (Ref 5).

In the very unlikely event of a failure of an SF_6 switchgear enclosure as a result of an internal arcing fault there is a risk that some of the potentially toxic arcing products may be released into the substation. As mentioned above the presence of these products can be detected at levels of concentration well below the danger level and it is recommended that personnel who would be concerned with such a substation should be given the following advice.

- If a disagreeable smell is detected on opening the door of the premises or near the place where the plant is installed, the area should be thoroughly ventilated.

- As far as possible, entering the premises should be avoided until the ventilation has dispersed the nauseous products.

- When the area has been ventilated, it is possible to proceed with the removal of damaged equipment and the cleaning of the cubicle and its surroundings. However care should be taken to ensure that there is no risk of asphyxiation if SF_6 has leaked out of the damaged equipment.

Special filters are fitted in certain SF_6 *filled equipment to absorb gaseous breakdown products. Before attempting to remove any such gas filters the operator should be familiar with the manufacturer's instructions for doing this, together with his instructions for disposing of the used filter material, cleaning the container and re-charging it with new material.*

Many SF_6 equipment types are intended to be low maintenance and will not be designed for these operations to be carried out on site. Where examination and/or overhaul is intended to be a site operation, special precautions concerning the gas handling and entry to the equipment are required and the manufacturer's handbook should be consulted whenever the results of an initial inspection indicate that a more detailed examination would be desirable. (See also Ref 6).

Environmental factors

Controlling the water content of equipment in gas-insulated substations (GIS) is essential for reliable operation. GIS requires very little maintenance compared to traditional air-insulated equipment. Moisture levels however must be kept low. Water especially in the liquid phase affects the dielectric withstand capability of GIS adversely. Also water reacts with SF_6 arcing products and can form hydrofluoric acid, which is extremely corrosive.

Most manufacturers have guidelines on the maximum allowable levels to minimise both risk of flashover and long term degradation. The dew point (the temperature at which the vapour condenses to liquid or frost) should be low enough to keep the moisture in the vapour phase for all operating conditions. Different limits are often set for breaker and non-breaker chambers.

Trace quantities of water are present in SF_6 gas even at the time of manufacture but most come from other sources including:

- Inherent moisture contained in equipment components. This water can be either on the surface of the component (adsorption) or where the moisture is dispersed throughout the material (absorption). This water can then diffuse into the $SF_{6\,in}$ some conditions.

- Permeation, where moisture can pass through components. For example, polymeric shields such as O-rings.

- Leaks. Imperfections in the seals can result in tiny pinholes or cracks. When SF_6 leaks out moisture will enter the equipment.

Based on research, the IEEE's Insulated Conductor and Substation committees have established guidelines for moisture measurement and control. Tests indicate that absorbed moisture within epoxy spacers and rods is the most significant reservoir. Most of this water is contained within the components at the time of assembly; it does not enter the equipment during its service life.

Humidity in SF_6 refers to the momentary amount of H_2O molecules present among the SF_6 molecules. In addition humidity may be contained in the insulating spacers and on metal and varnished surfaces. It has been reported that the insulating materials can absorb 5 to 10 times more water per volume than the SF_6 gas. The amount of moisture that can enter the gas volume from the ambient is normally neglected in cold countries in the Northern hemisphere but it can be significantly higher in tropical environments, where ambient temperature and humidity are high, if proper precautions are not taken at the manufacturing and assembly stages.

Although SF_6 gas by itself is very stable and has very high insulation strength, the stability of the gas is disturbed when it contains moisture exceeding a certain concentration. The breakdown strength reduces considerably when moisture condenses on insulating spacer surfaces. As the partial pressure of humidity in SF_6 increases beyond the saturated vapour pressure of water at that temperature, the breakdown voltage across the insulator surface reduces and finally reaches a value that is only a small fraction of the original value.

In tropical environments it has been reported that the moisture content inside equipment can be much higher than the limits set in published standards. SF_6 decomposition in the presence of moisture leads to the formation of hydrogen fluoride (HF). Epoxy spacers used in equipment usually contain silica or alumina as fillers and the presence of HF and its absorption in the epoxy resin will greatly modify the surface resistance and ultimately lead to a drop in the impulse flashover voltage of the spacers.

In the case of silica samples, a 50% drop in withstand voltage and a corresponding drop of 5 orders of magnitude in surface resistance have been obtained after exposure to 6500 ppm of HF vapour for 72 hours.

Gaseous by-products have little effect on the insulation strength, although the gas can chemically attack solid insulating materials, which may eventually lead to reduction of the dielectric strength. Flashover on the surface of support insulators or spacers is a common cause of GIS failure in service.

Fluorides of metals in SF_6 filled apparatus will be formed as by products and will be present in the form of powder. The insulating spacers when by-products are present will be covered with a layer of white powder. When covered with powder the spacers have shown a reduction of up to 20% in dielectric strength. From the practical point of view the problems caused by the solid by-products are more severe because they cannot be easily removed from the system without opening the compartments.

Service experience and maintenance scheduling

CIGRE have researched the GIS maintenance practices of utilities. Their findings suggest that GIS technology can contribute very effectively to increasing the reliability of new substations and to improving the asset life cycle of existing ones. GIS reliability, economic advantages for life cycle cost and physical compactness have resulted in its widespread application at all levels for over 30 years.

The paper reveals how the pressure on utilities to work transmission plant harder is affecting the ways in which plant is managed and maintained. The majority of the utilities have GIS equipment that is 20-30 years old and only a very few utilities have GIS equipment that is over 40 years old. Equipment within the voltage range 50-199 kV is the oldest with an average age of 26 years. Equipment within the voltage ranges 200-349.kV and greater than 349 kV has an average age of 23 years and 18 years respectively.

Of the utilities that responded two thirds are government owned. In the majority of these utilities the intention is to meet fixed targets. In the majority of privately owned utilities the intention is to maximise profit.

Almost all utilities (92%) indicate that they have developed a long-range plan for equipment replacement. The time span of the range varies depending on the type of equipment and voltage level. The most important factor is the deterioration of the transmission system performance (to 91%) although there is a trend towards a decrease in this importance. Availability of capital is important to utilities in North America.

There is a trend towards maintenance and safety costs becoming more important criteria.

For most utilities, refurbishment (i.e., returning equipment to “as new”) is carried out before replacement. The survey indicated that public utilities consider refurbishment more than private utilities.

SF_6 leakage

At present, a gas leakage rate of 1% per year is specified for SF_6 insulated power equipment. Data from utilities (Ref 6) indicates that actual leakage rates in operating equipment are often substantially lower. Apart from some early poorly designed equipment, leakage rates below 1% are found for first generation equipment (before about 1985). Second generation equipment leakage rates are usually below 0.5% per year. For distribution applications, sealed-for-life equipment is being produced for which leakage rates below 0.1% per year are obtained. If the equipment is not sealed for life, built in and portable monitoring devices are available to detect gas leakage. SF_6 gas in electrical equipment is normally at a pressure of 0.1Mpa to 0.9Mpa absolute. The quantity varies approximately between 0.1 kilogram in one pole of a medium voltage switching device and several hundreds of kilograms in the largest compartment of a large high voltage GIS substation.

Abnormal leakage can occur as a result of a fault or as a result of damage. Internal faults can lead to pressure relief or burn through of the enclosure. There is also the possibility that damage to the enclosure can occur as a result of an external fire. Protective clothing will invariably be needed where there is internal access to SF_6 compartments (Ref 6).

SF_6 is an extremely potent "greenhouse gas" as discussed later in Section 5 and has been blamed as a major contributor to global warming (Ref 7). It is now widely acknowledged that the amount of leakage that does occur in practice must be reduced. As a result the US Environmental Protection Agency has recently asked electricity utilities to reduce leakage of SF_6 from their substations. In addition at the present time a compelling reason for many utilities to monitor their plants for any leaks of SF_6 is the high cost of replacing the gas. In the U.S., a replacement bottle of SF_6 costs around $1,500 (£938).

4. SF_6 and Ozone depletion

IEC and Australian Standards information on SF_6 gas suggests that SF_6 gas has a negligible impact on the environment in respect of ozone depletion (Refs 8 & 9). The standards do not consider SF_6 to be an ozone depletion gas because the catalytic reaction scheme associated with gases causing depletion is practically impossible for these two reasons:

1. Due to the structure of its ultraviolet absorption spectrum, SF_6 is not broken down by ultra-violet radiation in the critical ozone destruction altitude range between 32 km and 44 km, so that very little atomic fluorine is expected to come from SF_6.

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

Because of these two factors the standard IEC 1634:1995 concludes that:

'Taking account of the facts that one Cl atom can catalytically destroy 10,000 ozone molecules, that the concentration of SF_6 is 1000 times lower than that of CFC and that virtually no free fluorine is formed from SF_6 under the circumstances as described, it is clear that SF_6 does not contribute to the destruction of stratospheric ozone'.

5. The Greenhouse effect

5.1 General

Carbon dioxide and other greenhouse gases in the atmosphere are more transparent to shorter wavelengths of electromagnetic radiation than to some of the longer infrared wavelengths. The shorter wavelengths from solar radiation penetrate to the surface of the earth. The reflected radiation from the earth, which is substantially in the infrared region (around 10-20 μm), is trapped near the earth's surface by those gases in the atmosphere. As a result of this 'greenhouse effect' the earth's equilibrium temperature is higher than it would be without those gases. Water vapour and carbon dioxide are the most important of the greenhouse gases.

Data from the Goddard Institute (Figure 1) demonstrate the strong correlation between the temperature of the earth and the concentration of carbon dioxide. The temperature for each year is expressed as the differences from a base of years 1951-1980.

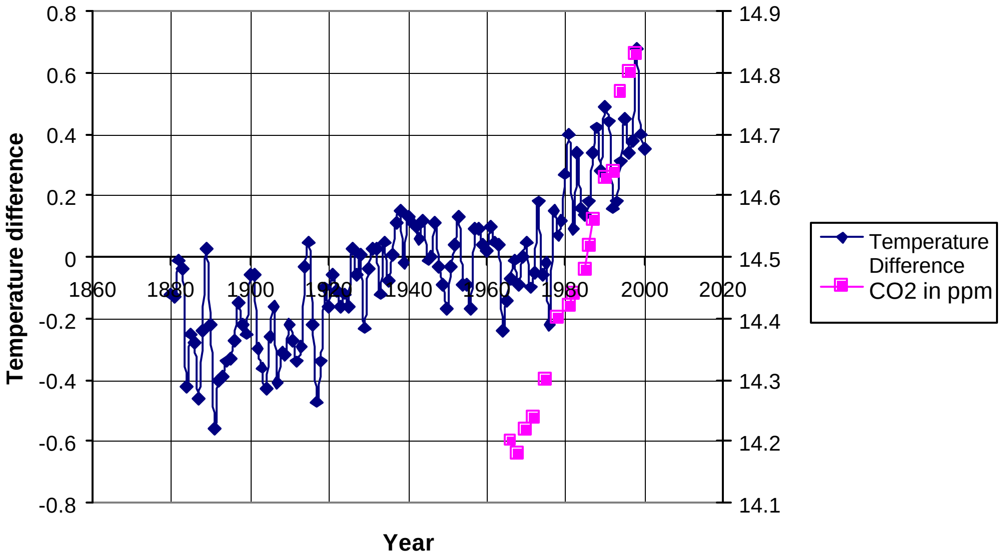

Figure 1: Annual Earth Temperatures and carbon dioxide concentration

Greenhouse gases occur naturally in the environment and are essential to maintain the narrow range of climates that allow life (Examples are H_2O, CO_2, CH_4, N_2O). The man-made contribution has been established as shifting the balance between the incoming and outgoing radiation in the direction of global warming by increasing the amounts of greenhouse gases in the upper environment. Man-made sources include fully fluorinated compounds (FFC); combustion products such as CO_2, nitrogen and sulphur oxides; and SF_6.

Sulphur hexafluoride is an efficient absorber of radiation, particularly at wavelengths near 10.5 µm (Ref 10). Additionally, unlike most other naturally occurring greenhouse gases (e.g. CO_2, CH_4,), SF_6 is largely immune to chemical and photolytic degradation and therefore its contribution to global warming is expected to be cumulative and virtually permanent. Estimates of the lifetime of SF_6 in the environment when estimated on the basis of the negative ion model are found to range between 800 and 3,200 years. The global warming potential of SF_6 for a 100-year horizon is estimated to be of the order of 25,000 times that of CO_2 the predominant contributor to the greenhouse effect (Ref 11).

5.2 Concentration of SF_6 in the environment

The atmospheric concentration of SF_6 was measured to be about 2.5 pptv (parts in 10^{12} by volume) in 1990 (Ref 12) and 3.2 pptv in 1995 (Ref 13). The amount of SF_6 present in the upper atmosphere has been quoted as being of the order of 10,000 metric tons. This reflects the fact that in the past a large quantity of SF_6 has been released due to lack of awareness of the environmental issue.

World production of SF_6 has increased steadily since the 1970s to 7,000 metric tons per year in 1993. In the ten years leading up to 1993 the amounts of SF_6 in the atmosphere have increased at a rate of about 8.7% per year from barely measurable quantities to reach 3.2 pptv in 1995. In many industrial applications SF_6 is not recoverable. Releases of SF_6 into the environment by the electrical power industry come from normal equipment leakage, maintenance, reclaiming, handling, testing, etc. Without disposal methods that actually destroy SF_6 some commentators suggest that it can be expected that all the SF_6 produced will eventually enter the atmosphere (Ref 1). In the near term the effect of SF_6 on global warming will be small.

The relative contribution of SF_6 to global warming at the present time is estimated to be only 0.01%. Because SF_6 is now extensively used concerns have been raised about its long-term environmental impact. If production and leak rates of SF_6 are maintained at current rates it is expected that in 100 years its relative contribution to global warming could become as high as 0.15 %.

High precision long-term observations were carried out in the Neumeyer Station, Antarctica and Izafia Observatory, Tenerife. According to these results the annual rate of increase for SF_6 between 1986 and 1991 was estimated to be 8.3%.

Shuttle flights of April 29 1985 and Nov 2 1994 enabled the comparative study of change in the concentration of each molecule in the lower stratosphere. During this period the annual rates of increase for SF_6 at altitudes between 17-30 km was 8.0 ± 0.7 %, the highest rate of increase found out of all of the examined ozone depleting or potent green house compounds.

Due to its enormous global warming potential, SF_6 is now being systematically monitored by a number of air sampling programmes.

A significant portion of the available literature limits any analysis to the short-term effect. The position stated in IEC and Australian Standards (Refs 8 & 9) is as follows: As a greenhouse gas SF_6 has negligible impact. Table 5 below reprinted from IEC 1634: 1995 and AS 2791-1996, compares SF_6 to the main recognised greenhouse gases.

Table 5: Relative Impact of Greenhouse Gases

Gas	**Concentration (ppbv)**	**Percentage Contribution**
CO_2	353000	60
CH_4	1700	15
N_2O	310	5
O_3	10-50	8
CFC-11	0.28	4
CFC-12	0.48	8
SF_6	0.002	.01

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

As a result these standards conclude that:

"The substantial amount of evidence available indicates that SF_6 has a negligible impact on the global environment' (IEC 1634:1995, P137)."

Also, Task Force 01 of working group 23.10 of CIGRE reported in 1996 that: "the contribution of SF_6 to the greenhouse effect due to losses from the electrical industry is negligible" (Ref 14).

By contrast, government and environmental protection agencies, and many electrical, chemical and other industries using or interested in the use of SF_6 have expressed concerns over the possible long-term environmental impact of SF_6.

World wide, sales of SF_6 have grown dramatically since 1972, when industrial production and use of the gas began to spread beyond the United States, where commercial use was pioneered in 1953. Scientists in the Max Planck Institute for Chemistry in Germany have shown that the growth in SF_6 sales correlates strongly with the increase in the accumulated atmospheric loading of the gas.

In 1995, U.S. manufacturers of electrical equipment purchased approximately 140 tons (130 metric tonnes) of SF_6 for new gas-insulated equipment, according to the National Electrical Manufacturers Association. NEMA also reported that in the same year, U.S. and Canadian electric utilities bought an estimated 700 tons (640 metric tons) for, among other uses, possible leakage replacement in existing power equipment with a total installed SF_6 capacity of 3500 tons (3200 metric tons). It is commonly estimated that directly or indirectly, electric utilities purchase some 80% of all SF_6 produced (Ref 15).

It was reported in 1998 that the electric power industry was responding to the need to control the use of SF_6 and to reduce its release into the environment. Such initiatives are leading to new and improved detection methods being developed for detecting leaks of SF_6 from equipment using laser-based imaging systems (Ref 17). Also, more emphasis is being placed on recycling of the gas.

5.3 The Kyoto Protocol

The greenhouse effect and its influence on world climate has been studied since the early 1800s. The first description of the greenhouse effect was established by Jean-Baptiste Fourier in 1827. In 1895 Svante Arrhenius linked global warming with the level of CO_2 in the atmosphere. Systematic measurements of CO_2 were begun in Hawaii and in Alaska in 1957. In 1967 estimates were made that there would be a doubling of the concentration of CO_2 in the atmosphere by the start of the 21st century and an increase in the mean temperature of 2.5 deg C over the same period.

The first world conference on climate change was held in 1979 and an intergovernmental group on climate change (GIEC, IPCC) was established in 1988.

Under the framework convention on climate change, agreed in Rio in 1990, the UK and other developed countries agreed a voluntary target of returning greenhouse gas emissions to 1990 levels by 2000.

At the UN Conference on climate change held in Kyoto Japan in December 1997 further actions were considered and as a result agreement was reached to reduce the emissions of greenhouse gases (Ref 18). Greenhouse gases with particular emphasis on CO_2 were addressed. Other naturally occurring gases discussed included nitrous oxide and methane. Manmade gases included hydrofluorocarbon gases, perfluorocarbons and sulphur hexafluoride. Carbon dioxide, methane and nitrous oxide together contribute over 99% of man-made global warming, with hydrofluorocarbons (HFCs) perfluorocarbons and sulphur hexafluoride making up the remaining 1%.

The protocol legally binds Annex I countries to reduce aggregate emissions of these greenhouse gases by at least 5% below 1990 levels from 2008 to 2012. Targeted percentages below 1990 levels are as follows: United States 7%; European Union 8%; Japan 6% and the Russian Federation 0%.

Initially the target proposed by the European Union's Council of Environment Ministers called for a 15% reduction in the emissions of greenhouse gases with a deadline in the year 2010. The final agreement sets differentiated timetables for developed countries, which in total amount to a global reduction of 5.2%, averaged over a commitment period of 2008-2012. Trading between individual gases is a feature of the approach.

The position at September 2001 is that discussions on detail are proceeding and it is not expected that ratification will occur before a further meeting in 2002. It is now widely accepted that the problem is more complex than at first envisaged. Topics such as land-use change and forestry are now being recognised as factors in the equation.

Sulphur hexafluoride is included in the basket of greenhouse gases due to its very high global warming potential. At present voluntary agreements are being established between the authorities and industry in the United States to reduce emissions of sulphur hexafluoride.

It is expected that controls will be introduced within the European Union concerning greenhouse gas emissions including sulphur hexafluoride. The Commission of the European Communities under Council Decision 1999/296/EC has issued a report concerning a monitoring mechanism of Community green house gas emissions (Ref 19).

5.4 Reducing emissions

The United States Environmental Protection Agency (EPA) started voluntary pollution prevention arrangements in October 1998 to reduce sulphur hexafluoride emissions. The programme aims to decrease emissions from industries that are associated with the biggest emission sources of SF_6 including magnesium casters, electric utilities and electronics manufacturers. Under the EPA effort, companies signing an EPA memorandum of understanding aimed at electric utilities would vow to annually report their emissions of SF_6, as well as pledge to create a corporate policy to handle the issue appropriately. The EPA calls for a commitment to reduce emissions to the extent that is economically and technically feasible as determined by the companies themselves (Ref 15).

Increasing the level of recycling and decreasing the rate of leakage are high priorities since they will reduce the volumes of SF_6 produced that will be potentially available for release into the environment. Recently increased efforts have been made by the electricity power industry to better monitor the gas present in SF_6 insulated equipment and the amount of SF_6 released to the environment (Ref 14). Improvements have included better methods to quantify and stop leakage, better standards for recycling, manufacturing more compact equipment, development of sealed for life electrical apparatus, and the gradual replacement of older equipment which normally leaks at higher rates.

In March 1999 the UK Department of the Environment, Transport and the Regions, published a study, which gives estimates of the national emissions of HFCs, PFCs, and SF_6 and assesses the technical feasibility and cost implications of potential methods to limit future emissions. The study was based on interviews with a wide range of UK suppliers and users of the fluids, supplemented by a review of the relevant literature (Ref. 20).

Under the framework Convention on Climate change the UK is committed to reducing the emissions of a basket of the six main greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6). The UK must achieve GWP (global warming potential) - weighted emission reductions of 12.5 % from 1990 levels by 2008 - 2012.

The technical and economic potential of various emission reduction options was considered by sector including the use of alternative fluids, not in kind technologies, and emission techniques. Future possible scenarios were then considered to reduce national emissions of HFCs, PFCs, and SF_6.

The estimates of the UK emission for the six greenhouse gases under consideration showed that HFCs, PFCs, and SF_6 represented 2.4% of total UK global warming emissions in 1995, with SF_6 representing 0.2%.

UK Current Use of SF_6 and Emissions

There are four main markets in which SF_6 is used or is likely to be used in the near future: electrical insulation, magnesium smelting, electronics and training shoes. Total use has remained approximately constant over the past decade at around 160 tonnes per year. SF_6 emissions from these end use markets are estimated to have been 1.2 Mtonnes CO_2 equivalent in 1995.

A business-as-usual scenario was developed to indicate likely future emissions assuming existing and agreed policies but no further intervention by government. This scenario predicted that the emissions of SF_6 would be expected to remain approximately constant to 2010.

In some markets it is clear that emissions will fall as industry responds to global warming issues. This aspect has been allowed for in the assessment of the likely change in future emissions in the business as usual scenario. This scenario assumes that there is no further market intervention by the government.

The end use assessment reported "Leakage from existing units during refurbishment has been reduced from 100% to less than 5% due to the development of fluid recovery equipment. This equipment extracts the SF_6 from the switchgear during the maintenance operation and subsequently fully recovers and re-uses it. The leakage rate during use has also been reduced considerably, to a current level of 0.1% per year. There is ongoing research to further reduce this leakage level."

The report concluded that the only alternative technology is to use vacuum devices, which can only be applied in low-to-medium voltage applications, i.e. up to 36 kV. For high voltage applications, vacuum is not viable and oils have both safety and environmental risks.

The best options for further reducing SF_6 emissions are to improve recycling/recapture rates on older equipment and to investigate the use of mixed gases such as SF_6/N_2. The electrical properties of such gas mixtures are discussed in Section 6.1.

If mixtures of SF_6 and N_2 are used, as described above, there will be significant reductions in the quantity of SF_6 consumed and emitted. The high price of SF_6 means that reducing its overall usage by utilising mixtures could result in substantial savings by the electric power industry.

In respect of control mechanisms, emission reporting mechanisms and end–use emission regulations, would be expected to provide good effectiveness. A high degree of effectiveness would be expected from voluntary agreements since only one grid operator and a few power generators operate in the UK.

Also in 1999 a report was issued by the European Commission (DGXI) concerning the reduction of emissions of HFCs, PFCs and SF_6 in the EU (Ref. 22). Following consultation with the Member States preliminary emission projections for 2010 for the European Community in terms of Mt CO_2 equivalents (business as usual) have been established. For SF_6 the year 2010 emission data set established the Mt CO_2 equivalent emissions as 12 Mt comprising electricity distribution 6 Mt and other 6 Mt (the latter estimate assumes 3 Mt related to noise isolating windows).

The options considered were:

- reduction and prevention of leakage during use (by better installations/materials, preventive maintenance) and during installation, maintenance and refill
- recycling/reuse of discarded agents
- application of alternative agents
- development of modified (components of) installations, using less or no SF_6
- Miscellaneous(e.g. incineration)

The relevant application of SF_6 was considered to be High (and mid) voltage switches. Leakage reduction modifications were estimated to have a potential for a 90% marginal emission reduction and a possible 100% reduction for recycling was estimated.

The report concluded that there is a substantial potential for reducing emissions of SF_6. Among the low cost options is leakage reduction and recycling of SF_6.

The impact of measures that can be taken are summarised in Table 6.

Table 6: Summary of measures and their impact

Name of measure	**Reduction**	**Remarks**
A. Leakage		
Reduction of leakage installations	Annual reduction from 2% to 0.4%	Leakage % in switches from 1970's; 0.4-0.5% in new generation switches
B. Recycling/reuse		
Recycling of SF_6 from discarded switches	100%	Solvay/Dio in Germany
C. Alternatives		
Use of liquid resin, air or oil in mid voltage switches	100%	No reliable alternatives for high voltage switches
D. modifications		
Improved pumps for handling SF_6 during testing and regeneration	5% or 15-20%	
Development of more compact switches	Annual reduction from 2% to 0.4% (see also *A. Leakage*)	Already limited quantity of leakage during use of switches

Source: reduction of emissions of HDCs, PFCs and SF_6 in the European Union Ref 20

Assuming improved leakage prevention due to new switches that will be installed after the year 2000 emissions will decrease. Until 2010 emissions will slightly rise due to an increase in the use of switches. Between 2010 and 2020 the first generation switches containing SF_6 will be removed. At least in some countries (the Netherlands, Germany) SF_6 from replaced switches will be collected and reused.

The generation installed in the seventies has an annual leakage percentage of 2%. From 2020, when all the first generation switches containing SF_6 have been removed, all new switches that are being installed will have an annual leakage of 0.4%. The international norm IEC 694 defines leakage standards of 3% for appliances older than 1979 and 1% for other appliances.

In Germany in 1996 the energy companies (VDEW and ZVEI) have obliged themselves to recollection and reuse of SF_6 from replaced switches in a "Statement on the use of SF_6 in electronic switches in Germany".

In general the report noted that greenhouse gas emissions in the European union have decreased by 2.5% since 1990. Whilst CO_2 emissions almost stabilised between 1990 and 1998 (+0.2%) CH_4 and NO_2 emissions decreased by 16.5% and 9.9% respectively. These figures suggest that in 1998, the European Union as a whole was in line with its target paths for both 2000 and 2008-2012.

5.5 Recycling

A recent CIGRE enquiry (Ref 14) has suggested that most users of SF_6 insulated power equipment have become aware of the environmental issue. They are ready to avoid the release of SF_6 into the atmosphere and to start to systematically recycle it on site. The toxic nature of decomposition products has been discussed earlier in this report. UNIPEDE have made recommendations in respect of hygiene and the protection of the safety of personnel working with SF_6 and concerning gas handling, storage, and transportation together with the disposal of clothing, filter and cleaning materials (Ref 6). Particular care is required in respect of the replacement and disposal of molecular sieve components designed to remove toxic materials.

CIGRE have produced an SF_6 recycling guide: Re-use of SF_6 in electrical power equipment and final disposal (Ref 17). The basic process of recycling involves the SF_6 being pumped out of the equipment through a filter into a storage tank. If the gas is known to be highly decomposed (e.g. after abnormal arcing) an additional pre-filter is used upstream of the pump. The gas in the storage tank is checked by an SF_6 quality detector. If it fulfils the purity requirements for reuse it can be refilled into the equipment, if not, it can either be subjected to an additional treatment in a special cleaning device or it can be disposed of as detailed below.

SF_6 can be destroyed by thermal decomposition in industrial waste treatment furnaces at elevated temperatures (> 1100 °C). In this process the constituents of SF_6, sulphur and fluorine, are transformed into naturally occurring materials $CaSO_4$, (gypsum) and CaF_2 (fluorspar). These materials can be land filled or possibly used as raw materials in other processes.

CIGRE recommendations (Ref 14) concerning environmental aspects of the use of SF_6 were:

1. SF_6 should not be released into the atmosphere.

2. SF_6 should be recycled.

3. SF_6 losses from electrical equipment should be further minimised by improving electrical equipment design and handling procedures.

4. All new SF_6 applications should allow for recycling.

5. Standards for recycling procedures and purity of SF_6 should be established.

6. The environmental statement proposed by CIGRE should be displayed in all substations.

The environmental statement includes the claim that ‘the present contribution to the greenhouse effect is negligible because its atmospheric content is low and will remain so until the end of the next century with minimised equipment leakage, diligent recycling and improved handling.’

6. Electrical application developments

6.1 SF_6 substitutes and alternatives

Vacuum

Over a limited range of applications vacuum can provide a viable alternative to SF_6. Much of the early development work on vacuum breakers was carried out in the UK and in the USA. The vacuum switching technique is used widely for circuit breakers and contactors in medium voltage applications. Vacuum is generally practical if impulse voltages are limited to 100 to 200 kV which corresponds to an insulation level required for voltage ratings of less than or equal to 36 kV.

Switching and protecting overhead line distribution networks is one such application. Both vacuum and SF_6 technologies provide adequate margins over and above the maximum required by the relevant standards and in normal practice.

Vacuum (and SF_6) breakers allow a large number of break operations without the need for inspection making it possible to design breakers requiring almost no inspection and needing no maintenance over the entire service life (about 20 years). Breakers of this type do not eject flames of gas or oil; the arc extinction and insulating media exhibit almost no wear or changes in their properties and there is no fire or explosion hazard.

Vacuum breakers are characterised by short travel of the moving contacts, low weight, relatively low break-speed and consequently, low dynamic loads, lack of restrictions in applications at low temperatures and the possibility of installation in any spatial position. SF_6 and especially vacuum breakers permit a significant reduction in the dimensions of equipment cabinets, an additional advantage and a positive economic incentive for their extensive utilisation.

In the USSR the extensive exploitation of areas of Siberia and the far east of the USSR for industrial and agricultural development have led to a large increase in the extent of 10-35 kV overhead lines. The low population density of these areas and the need to ensure reliability and uninterrupted electricity service demands breakers which need almost no maintenance over an extended period and allow multiple fast automatic re-closing when subjected to multiple lightning strikes. The breakers must be serviceable at temperatures down to –50°C to –60°C. In these conditions the additional expense of using vacuum breakers was easily out-weighed by the savings made on maintenance.

Suitable applications for vacuum technology include: switching the magnetising currents of unloaded transformers, motor switching, re-strike-free switching of capacitor banks, arc furnace switching, shunt reactors and railway traction. In the latter application both technologies are well suited;

however, in the case of low frequency (16.67 Hz) applications, vacuum breakers are to be recommended.

A particular feature of vacuum switching devices (contactors, circuit breakers and switches) is that they are likely to generate overvoltages when interrupting current in inductive circuits (e.g. in connection with a no-load transformer or a non-charged motor or motor in the start-up phase). Due to the special properties of vacuum these overvoltages can be of a different nature to those generated in the same conditions by switchgear that uses another type of medium (air, SF_6 oil etc.). In general the overvoltages do not pose a problem and do not need a special device (Ref 15). However, in the case of sensitive loads (for example motors) it is recommended that overvoltage limiting equipment be installed.

Neither of the technologies vacuum or SF_6 is generally better than the other where there is a choice and they are generally complementary from the application point of view. Economic factors, user preference, national traditions, competence, and special switching requirements are the decision drivers that favour one or other technology in this respect. Typical examples of such applications are given above. The need for soft switching can be an additional element influencing the choice.

Gas mixtures

Suggestions have been made repeatedly over the past two decades to use high pressure N_2 and mixtures of N_2 with SF_6 for insulation, arc quenching, and current interruption. The search for SF_6 substitutes dates back many years. Much work was done in the 1970s and the 1980s to find gases superior to SF_6. Since no single gas has emerged as an adequate replacement, the principal focus is on gas mixtures.

The Mean Breakdown Strength of a range of dielectric gases and binary gas mixtures with SF_6. (SF_6 = 100) are given in Table 7 overleaf

Table 7: Mean Breakdown Strength of a range of dielectric gases and binary gas mixtures with SF_6

	Formula	Unmixed	Percent of gas mixed with SF_6		
Chloropentafluoroethane	CF_3CF_2Cl	114	111	108	104
Sulphur dioxide	SO_2	102	111	116	108
Dichlorodifluoromethane	$CCl_2\ F_2$	100	108	107	106
Hexafluoroethane	CF_3CF_3	81	88	90	95
Chlorotrifluoromethane	$CCl_2\ F_3$	58	78	88	95
Chlorodifluoromethane	$CHCl\ F_2$	43	84	92	97
Carbon tetrafluoride	CF_4	42	63	78	89
Air	$N_2 + O_2$	37	78	85	94
Nitrogen	N_2	37	77	88	95
Carbon dioxide	CO_2	32	65	80	91

Source: EPRI EL-2620

For GIS a proposed alternative to the use of pure SF_6 under evaluation as an insulating gas is to use a mixture of SF_6 and nitrogen. A mixture of 40% SF_6 and 60% N_2 provides a gas with a dielectric performance of 85-90% that of pure SF_6. If a mixtures of SF_6 and N_2 is used it is possible to achieve a significant reduction in the quantity of SF_6 consumed and emitted.

There is also an interest in ternary mixtures composed of forty to sixty percent nitrogen, twenty to thirty percent SF_6, and as much halocarbon as permissible without condensation under operating pressures and low temperatures and without formation of carbon under arcing conditions. Such a mixture, if technologically acceptable to industry, would significantly decrease gas cost versus pure SF_6. For example, 50% N_2 + 40% SF_6 + 10% CCl_2F_2 has eighty five percent of the dielectric strength of SF_6 alone at approximately forty percent of the cost of SF_6 alone.

Simple replacement of pure SF_6 with a mixture would however require equipment certification and hardware changes for equipment already in use. New equipment designed specifically for use with SF_6 mixtures would be necessary for widespread insulation use. In any event even using a simple mixture could have a number of problems associated with it:

- More difficult gas supply, recovery and recycling procedures

- Monitoring and maintaining proper concentrations
- Unknown long term stability

Problems can however arise in recycling mixtures and where mixtures cannot be liquefied and must be transported in the gaseous phase. Pure SF_6 can easily be transported in liquid form and it can relatively easily be recycled for re-use.

The high price of SF_6 means that reducing its overall usage by utilising mixtures could result in substantial cost savings by the electric power industry.

6.2 Leakage Monitoring

In most practical applications in the electric power industry SF_6 gas will be pressurised to above atmospheric pressure. Preventing leakage will depend on the integrity of seals. In practice the number of linkages to the outer environment will be a factor. Where valves are incorporated, ageing is possible and the efficiency of the seal may deteriorate in the long term. In practice it is difficult to assess the pressure in the vessel without monitoring since in the absence of a fault current, switching is likely to be unimpaired. Significant leaks may go undetected. Clearly where the application concerns large numbers of small devices having a low volume of SF_6 it will be the total quantity of gas in all the devices and the integrity of the seals that will be important in determining the total leakage.

Traditional methods for detecting SF_6 leakage generally rely on monitoring the pressure in the SF_6 enclosure or the use of halogen detectors.

However with the growing awareness of the potential need to monitor emissions of SF_6 in the future and the rising cost of this gas, new methods are being established to detect emissions.

The GasVue camera uses a state of the art back scattering laser-based system developed with EPRI support by Laser Imaging Systems of Punta Gorda, Florida. The camera combines a carbon dioxide laser (tuned to an infrared absorption wavelength of SF_6) with an electronic imaging system. As leaking SF_6 absorbs some of the laser light that bounces off a background surface, and image of the gas is produced on the system's video display. The equipment is claimed to detect SF_6 leaks as small as 0.9 kg a year at distances of up to 18 m. The use of this type of equipment allows emissions to be detected without the need to de-energise the system.

6.3 SF_6 condition assessment

Ion mobility spectroscopy (IMS) has also been proposed as a method for onsite testing and monitoring of SF_6 decomposition in GIS systems. As well as the intermittent decomposition of the gas as a result of spark discharge and or power arcs laboratory experiments have shown that decomposition can also occur as a result of partial discharge activity. Due to long maintenance cycles, decomposition products may accumulate over long periods of time within switchgear. Thus a relatively small partial discharge activity may lead to a noticeable amount of corrosive by-products. These by-products are present continuously in the switches unless they are removed by filtering the gas with molecular sieves or similar preventive measures. Accordingly insulating spacers and other components may be exposed to a corrosive medium for a long time thereby suffering degradation. Thus the establishment of a diagnostic tool that allows on-site and on-line inspection of the insulating gas is of considerable interest for the user of SF_6 filled equipment.

Ion mobility spectrometry IMS, a low cost rugged and highly mobile technique for gas analysis, offers this possibility and this may help to reduce the costs for service and maintenance.

The method characterises chemical substances by detecting the gas phase mobility of ions in weak electric fields. Mobility is related to the collision rate with the gas molecules (reduced mass) the temperature, the dimensions of the ion (structure dependencies) and the collision integral is influenced by the size of ions or molecules, their structure and polarizability.

The technique was originally designed for the detection of trace compounds within a gas, for example gaseous pollutants in air. The working principle is based on the drift of ions at ambient pressure under the influence of an external field. Compared with mass spectrometry the mean free path of the ions is much smaller than the dimensions of the instrument. Therefore an ion swarm drifting under such conditions experiences a separation process that is based on different drift velocities of ions with different masses or geometrical structures. Collection of the ions on a Faraday plate delivers a time dependent signal corresponding to the mobility of the arriving ions. The characteristic trace of the drift times for reference SF_6 can be established in the data acquisition system and compared with the drift time of the SF_6 inside the circuit breaker during service. In general the peak positions of the traces are indicative of the levels of decomposition of the SF_6. The identity and origin of the by-products may be investigated using methods such as infrared spectroscopy. This technique is also used as a tool for electrical fault diagnostics in SF_6 insulated equipment.

It has also been reported that the condition of SF_6 insulated equipment can be monitored by systematic examination of certain by-product concentrations can be used as a maintenance prognosis tool (e.g. the presence of high CO_2 levels in the SF_6 matrix of a GIS plant singularly identifies filter absorption saturation, while the presence of metal fluorides possibly originating from the erosion of field smoothing devices should be immediately be removed as it may induce surface fatigue or damage of the insulants of the installation).

When SF_6 levels fall or conducting contaminants are present in the gas, partial discharge activity can be initiated. Such activity can be detected and monitored using sensors designed to pick up discharges from GIS systems (Ref 16).

Logging of the usage of SF_6 and monitoring equipment performance could provide valuable reference data essential to maintaining an effective defence strategy and competitive advantage in the industry in the face of the likely cost penalties which may be incurred as a result of increasing pressure to reduce emissions of SF_6. Possible approaches to this would be to record instances when the pressure in systems falls to the alarm levels and to log the usage of SF_6 on re-pumping. An indirect benefit of this procedure could be to distinguish between the performances of designs of different manufacturer's products.

6.4 Market factors

In March 1999 the Freedonia Group, INC predicted a rise in demand for high-power circuit breakers. Demand was projected to rise 5.3% per annum up to 2003. However an element of uncertainty had arisen with respect to environmental concerns over SF_6. While not expected to seriously affect high-voltage circuit breaker demand in the aggregate, such concerns will probably lead to an increasing specification of vacuum-based breakers over SF_6 insulated ones, a trend that already appears to be in place.

A follow up report in November 2000 by the Freedonia Group INC noted the EPA initiative in the United States and reported that 48 electric utilities had formed a partnership to reduce SF_6 emissions. Under this agreement, the participating utilities have 18 months from the date they join the partnership to develop feasible reduction goals and agree to develop strategies to replace older, leaky equipment and recycle SF_6. In July 2000, the EPA invited more than 1000 other utilities to join the partnership, and, as of October 2000, approximately 55 utilities were involved.

In addition to replacing older SF_6 equipment, which is more likely to leak, companies are developing alternatives to electric power equipment requiring SF_6. New vacuum designs have generally been developed to handle low to medium voltage levels. Attempts to produce a high-voltage version would be likely to cost more and result in a higher priced alternative.

KEMA Laboratories in the Netherlands is a Certification body for SF_6 and vacuum switchgear. In the period from 1985 to 1997 the ratio of the number of certificates issued for vacuum switchgear in the range 12-36 kV compared to SF_6 types was about 10 to 1. If this is representative of the relative activity of manufacturers then clearly they have been putting considerably more effort into vacuum interrupter type switchgear development than into $SF_{6.}$ However vacuum circuit breakers have for many years been popular at medium voltage. Applications where SF_6 is used as an insulator as opposed to those using SF_6 for interruption purposes appear to be finding a share in the available market (Ref. 23).

7. Non-electrical applications

Magnesium Smelting

SF_6 is used as a shielding gas in magnesium foundries, to protect the molten magnesium from re-oxidising whilst it is running to be cast in ingots. Process emissions are responsible for a large part of emissions in countries where these production processes are located.

SF_6 has largely replaced SO_2 in this application. Sulphur dioxide is a better shielding gas but has significant occupational health risks due to its toxicity. SF_6 is occasionally used in blends with SO_2 for certain high specification applications.

In Germany 40% of magnesium production uses SF_6. The demand for magnesium is expected to rise due to increased use for weight reduction of steel components in car manufacturing (50% of the magnesium production in Germany is processed for manufacturing). Overall within Europe, despite an ongoing increase in magnesium demand, total emissions from magnesium smelting are expected to fall between 1995 and 2005 due to a reduction of the emission factor on the one hand and the transition to using SO_2 for magnesium production on the other (Ref 22).

It is possible to redesign the production equipment to minimise losses and to maximise the potential to recover the SF_6 cover gas. Analysis suggests this as an extremely low profit sector and companies are unlikely to invest in any emission reduction technology unless forced to. Additionally, any enforced emission reduction measures that result in increased costs are likely to close plants and force production to countries with less stringent policies.

Aluminium smelting

SF_6 is used as a de-gasser in aluminium casting. It is used in combination with argon or nitrogen to improve the purity and strength of the metal by removing gas bubbles and solid particles from the molten metal.

For both aluminium and magnesium smelting the key factor derived from the work in the UK is the likelihood that these applications are expected to remain 100% emissive under a business as usual scenario in 2010. There is no expectation of investment to clean up technologies as the industry is only marginally profitable and it is unlikely that any funds would be available to implement emissions reduction unless these measures were imposed by legislation. It is estimated that a 90% emission reduction would be possible by process modifications.

Semiconductor Industry

Both PFCs and SF_6 are used within the semiconductor industry for the manufacture of chips and circuits. During these processes the gases are emitted to the atmosphere. At present little is done to reduce the amount emitted. Redesign of the process is possible and since the lifetime of a product is currently around 18 months this should be achievable.

Compared to the other SF_6 applications emissions from the semiconductor industry are very small and are expected to decrease further due to the use of systems for recollection of flue gases during production.

Cushioning in training shoes

Nike uses SF_6 in the 'Nike Air' range as the gas to fill a cushioning pocket in the sole of their training shoes. SF_6 was chosen because of the large size of its molecule. This ensures that the gas only diffuses slowly through the membrane, which makes it in effect a closed system until the shoe reaches the end of its life.

Nike has worked for several years to find an alternative to SF_6 that meets the customer's high athletic performance standards. Nitrogen was eventually selected as the alternative and by 1999, 25% of the footwear was filled with nitrogen. The changeover entailed a change in production methods and a change in the type of membrane used since the nitrogen molecule is significantly smaller than SF_6. The use of SF_6 in this application is expected to be fully phased-out in 2001 and replaced by nitrogen

For similar reasons SF_6 has also been used in tennis balls. Although the emissions from these sources are currently substantial it is likely that emissions during and after the Kyoto commitment period will be negligible.

A substantial bank of SF_6 has been created since 1978 when the shoes were first manufactured. Since the general public will have little awareness of this issue old trainers will be disposed of in landfill sites and will subsequently leak to the atmosphere. This process is estimated to take of the order of 8 years.

Windows

SF_6 is used in sound insulating windows. The use of a barrier gas between two sheets of glass rather than a partial vacuum results in more stable thermal and sound insulation properties for the window. Inert gases such as argon and krypton can also be used. SF_6 has better sound reduction properties, but noble gases generally have better thermal properties. Krypton is slightly radioactive and is banned in some parts of Germany. The proportion of barrier gas windows in the UK that use SF_6 is thought to be negligible (Ref 20).

Until 1995 the use of sound insulated windows in new houses in Germany was increasing. From 2000 these windows will be replaced, causing an increase in SF_6 emissions if no recollection and recycling measures are taken.

Use of SF_6 filled windows is increasing in the Netherlands due to noise regulations. However use is limited to extreme cases e.g. around Schiphol (Amsterdam airport)

Car Tyres

In Germany SF_6 is used for stabilisation purposes in the more expensive car tyres. According to Continental Tyres, SF_6 was added because it escaped less quickly from the tyres than air and tyre pressures were more reliable and needed checking less frequently. SF_6 also gave better shock absorption to the tyre. The high cost of SF_6 meant that it was only ever used under high performance conditions. Continental no longer use SF_6 since becoming aware of the high global warming potential of the gas.

Medical

SF_6 is used as an internal tamponade for plugging of the eye during retina operations. The gas remains in the eye while the retina heals. The type of gas used depends on the length of time that the gas needs to be contained within the eye; the use of SF_6 allows up to 10 days. There are no alternatives for these gases; the patients would otherwise go blind. Current use is around 1 tonne of SF_6 per annum.

Other Applications

There are also reports of SF_6 use in electron microscopes, Van der Graaf generators, aircraft radar and as a tracer gas.

Waveguides with SF_6 can transport seven to ten times more microwave power than with air or nitrogen at the same pressure, or the same power as with air or nitrogen at lower pressure. Similarly the ratings of both Van der Graaf and linear accelerators can be raised by using SF_6. The arc extinguishing ability of SF_6 is also important in these applications.

It can be seen from the above brief review of non-electrical applications for SF_6 that industry is now being made aware of the need to reduce emissions of SF_6 and that there is growing pressure to seek alternative solutions or to collect and dispose or recycle SF_6 to avoid increasing atmospheric loading.

8. Overview and conclusions

Sulphur hexafluoride (SF_6) is a man made gas, which is extensively used in electrical equipment for the transmission and distribution of electrical power. Its principle uses are as an insulating and arc interrupting gas. Applications include gas-insulated circuit breakers, gas-insulated transmission lines, gas-insulated transformers, and gas-insulated substations. About 80% of the gas produced worldwide is used in the electrical industry. Circuit breaker applications account for most of the gas used. SF_6 provides important advantages to the electrical industry allowing compact designs and a long prospective lifetime for components. This enables substations to be installed in cities very close to the loads. Power losses can be significantly reduced by the use of equipment using SF_6 and there are no fire safety problems. Although uncontaminated sulphur hexafluoride is non-toxic, some of the gaseous impurities produced by electrical breakdowns in the gas are toxic if inhaled in sufficient quantity, and the solid fluoride powders also produced by breakdown may produce skin irritation. Care should thus be taken during maintenance, particularly with circuit breakers, or equipment known to have sustained a severe interior flashover.

Many SF_6 filled equipments are of the low maintenance type and will not be designed for maintenance operations to be carried out on site. Where examination and/or overhaul is intended to be a site operation, special precautions concerning the gas handling and entry to the equipment are required and the manufacturer's handbook should be consulted whenever the results of an inspection indicate that examination would be desirable.

IEC and Australian Standards Information on SF_6 gas suggest that SF_6 gas has a negligible impact on the environment in respect of ozone depletion. However, SF_6 is a potent greenhouse gas and there is now a movement worldwide to reduce the amount of greenhouse gases being released to the environment. SF_6 is largely immune to degradation by either chemical or ultra-violet radiation; its contribution to global warming is therefore expected to be cumulative and virtually permanent.

At present the contribution of SF_6 to global warming is very low. However there is a need for controls. Improved handling, diligent recycling and minimising equipment leakage are essential.

The Kyoto Protocol has established a target for reducing emissions of greenhouse gases and targets have been set for the developed nations. Certainly from the year 2008 records of usage will be required by the authorities from users to provide the information needed to be able to quantify and control SF_6 emissions. Voluntary agreements are already being established between users and the EPA in the USA to decrease and monitor emissions. Legislative control is expected in the EU.

The Kyoto protocol does allow some trading between different greenhouse gases to minimise the cost of reducing emissions to the targets agreed. However, inevitably in the long term there will be an extra cost and administrative burden on the electricity supply industry associated with the use of SF_6. Alternative technologies need to be continually appraised to ensure sustainability and a commercial advantage in a competitive market likely to come under increasing pressure to reduce the use of this material.

In view of the above considerations it is therefore important for the electricity supply industry and those in other industries using SF_6 to continually monitor regulatory controls and best practice procedures in environmental management of equipment containing SF_6. Logging of the usage of SF_6 and monitoring equipment performance could provide valuable reference data essential to maintaining an effective defence strategy and competitive advantage in the industry.

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