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## An assessment of Norwegian and global sources and the Global Warming Potential

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# Summary

Worldwide a majority of the total $SF_6$ produced is used in and emitted from electrical equipment, mainly in Gas Insulated Switchgear (GIS). A more limited use is in degassing molten reactive metals. The major contributors to $SF_6$ emissions in Norway are the magnesium industry (22 800 kg in 1992), the aluminium industry (3 125 kg in 1992), the secondary foundries (780 kg in 1992) and leaks from electrical equipment (estimated to 2 230 kg in 1992).

Estimation of future $SF_6$ consumption in both the magnesium industry and the electricity supply is difficult. However, it is believed that most likely a reduction in both $SF_6$ consumption and emissions will take place in Norway. The only Norwegian primary foundry in the aluminium industry which contribute to the $SF_6$ emission today plans to substitute $SF_6$ with argon from 1994. There is today one operating secondary foundry in Norway using $SF_6$ as covergas, and two are presently being established. In addition there are four secondary foundries using $SF_6$ as refining gas.

There was an appreciable decline in the Norwegian emissions from 1991 (86 420 kg) to 1992 (28 935 kg). The relative consumption between the magnesium industry and the electricity supply in 1992 was about 40 to 60. However, the magnesium industry is the major source of $SF_6$ emissions in Norway (79 % in 1992).

*Table A: Estimates of emissions of $SF_6$ in Norway (kg).*

| Year | Magnesium smelters | Aluminium smelters | Secondary smelters (foundries) | GIS 145-420 kV | GIS 12-24 kV | Total |
|---|---|---|---|---|---|---|
| 1980 | | | | 390 | | 390 |
| 1981 | | | | 600 | | 600 |
| 1982 | 90 600 | | | 670 | | 91 270 |
| 1983 | 99 600 | | | 700 | | 100 300 |
| 1984 | 184 200 | | | 930 | | 185 130 |
| 1985 | 198 000 | | | 1 000 | 30 | 199 030 |
| 1986 | 238 800 | | | 1 070 | 60 | 239 930 |
| 1987 | 238 800 | | | 1 230 | 100 | 240 130 |
| 1988 | 222 000 | | | 1 350 | 140 | 223 490 |
| 1989 | 105 600 | | | 1 450 | 180 | 107 230 |
| 1990 | 89 400 | | 300 | 1 620 | 220 | 91 540 |
| 1991 | 84 000 | | 500 | 1 640 | 280 | 86 420 |
| 1992 | 22 800 | 3 125 | 780 | 1 890 | 340 | 28 935 |
| 1993 | 22 800 | 6 000 | 150 | 1 970 | 420 | 31 340 |

Global production and sale volumes of $SF_6$ have never been reported, but may roughly be estimated to 5 000-8 000 tons per year. The global consumption of $SF_6$ is also dominated by the metal industry and GIS, where the latter accounts for about 80 %. The total global emission is highly uncertain, but could be about 50 % of the production. The global emission from the magnesium industry is estimated to 930 tons (1991).

The amount of $SF_6$ accumulated in GIS is significant. To avoid major $SF_6$ emissions in the future it is important to have efficient equipment for handling and storage of gas removed from gas compartments when GIS units are taken out of service.

A narrow band, a broad band and a correlated k-distribution radiative transfer model have been used to calculate the radiative forcing due to $SF_6$ using available spectroscopic data. The effect of spectral overlap with other atmospheric species has been taken into account, and is shown to be of some importance for $SF_6$. Recommended value for the radiative forcing for $SF_6$ is 0.602 $Wm^{-2}$/ppbv. The uncertainty is estimated to be at least 20 %. Estimates for Global Warming Potentials (GWPs) relative to $CO_2$ are 14 100, 19 000, and 31 000 on the 20, 100 and 500 years time horizons respectively showing that $SF_6$ is an extremely potent green-house gas. GWPs are calculated based on the Intergovernmental Panel on Climate Change (IPCC) methodology.

*Table B: Global Warming Potentials (GWPs) for $SF_6$. Numbers are given relative to $CO_2$.*

| Time horizon (years) | 20 | 100 | 500 |
|---|---|---|---|
| Relative to $CO_2$: | 14 100 | 19 000 | 31 000 |

Combining the assessments of emissions and GWP for $SF_6$ yields that $SF_6$ makes a small, almost negligible, contribution to the greenhouse effect on a global scale. The contribution of $SF_6$ is about 0.2 % of the anthropogenic emissions of $CO_2$. In Norway, the contribution is more significant, and was equivalent to about 5% of the $CO_2$ emission in 1990 when wheigted by the GWP for a 100 year time horizon.

$SF_6$ is very stable in the atmosphere. Its lifetime is estimated to be 3 200 years. Any changes in the radiative forcing due to emissions of $SF_6$ can therefore impact the earth's climate on a very long time scale.

# $SF_6$ as a greenhouse gas:

## An assessment of global and Norwegian sources and the Global Warming Potential

## 1. Introduction

There has been a growing concern that the build up of certain trace gases in the atmosphere can result in an increase in the greenhouse effect, and thereby give rise to a global warming. Anthropogenically emitted $CO_2$ is thought to cause the largest problem, but a range of other trace gases are believed to be potential contributors to future climate change, depending on their future man made releases. Some of these gases absorb very effectively in the infrared region. Among these are some components, e.g. $SF_6$, $CF_4$ and $C_2F_6$, with extremely slow atmospheric removal. They can add up to significant atmospheric amounts over decades and centuries, despite relatively moderate emissions, and have the potential to cause climate change over hundreds and thousands of years.

The present report is an assessment for the Norwegian State Pollution Control Authority (SFT). It contains a review of national (Norwegian) and global consumption and emission of $SF_6$ as well as new calculations of the greenhouse effect due to $SF_6$.

## 2. Consumption and emission of $SF_6$ in Norway

### 2.1. Norwegian import of $SF_6$

There is no $SF_6$ production in Norway. The worldwide commercial market for $SF_6$ is small, and there is competition between suppliers. There are only three Norwegian suppliers of $SF_6$. They all want their sales figures to be treated confidentially.

About half of the $SF_6$ consumed in Norway is supplied by the three Norwegian dealers. The Norwegian magnesium industry imports most of their $SF_6$ directly from foreign suppliers.

*Table 1: Norwegian import of $SF_6$.*

| Importer of $SF_6$ | Import of $SF_6$ 1991 kg | Estimated import of $SF_6$ 1992 kg | Estimated import of $SF_6$ 1993 kg |
|---|---|---|---|
| Magnesium industry | 84 000 | 19 200 | 30 000 |
| Dealers | 16 750 | 21 700 | 26 120 |
| TOTAL | 100 750 | 40 900 | 56 120 |

## 2.2. Fields of $SF_6$ application

The main use of $SF_6$ in Norway are in the magnesium industry and in gas insulated switchgear (GIS). In addition some $SF_6$ is used in the aluminium industry, secondary foundries, insulated glass production and in medical applications. A brief description of the various applications are given in this section.

### *2.2.1. Magnesium industry*

$SF_6$ is used as cover gas in the primary foundry in magnesium production. $SF_6$ prevents oxidation of magnesium metal and also prevents the equipment from catching fire in the founding process. There is only one magnesium producer in Norway. It converted from $SO_2$ as cover gas to $SF_6$ in the period 1979-1982.

### *2.2.2. Gas insulated switchgear and circuit breakers*

$SF_6$ is used as insulation medium in the electricity supply. In Norway $SF_6$ has been used for this purpose since 1973. $SF_6$ enables building of more compact enclosed high tension installations. It replaces air as insulating medium. Some switchgear and circuit breakers are delivered prefilled while others are filled with $SF_6$ during commissioning. Some refilling of $SF_6$ is, to a small extent, done as a part of equipment maintenance. The main Norwegian operator of high-tension installations assumes that the total amount of $SF_6$ contained in high voltage switchgear in Norway today is about 200 000 kg.

### *2.2.3. Aluminium industry*

$SF_6$ can be used as cover gas in primary foundries in the aluminium industry. There is only one Norwegian primary foundry using $SF_6$ today.

### *2.2.4. Secondary foundries*

Some $SF_6$ is used as cover gas and refining gas in secondary aluminium and magnesium foundries. $SF_6$ is often mixed with argon and chlorine. There are a number of different gas mixtures, and the $SF_6$-content varies from 1-2 % to 90 %. $SF_6$ gas is expensive. For economic reasons, therefore, the foundries try to keep the $SF_6$ consumption as low as possible.

### *2.2.5. Insulated glass*

A mixture of $SF_6$ and argon has been used as insulating medium in sound insulating glass for the last 15-20 years and its use has increased the last 5-10 years. There is one dominating Norwegian producer of sound insulating glass using $SF_6$.

### *2.2.6. Other applications*

$SF_6$ is used for medical purposes, for example for blowing up collapsed lungs. The consumption of $SF_6$ in the health service in Norway is minimal and will not be estimated.

Another application is $SF_6$ used as a trace gas to study dispersion of pollutants. The consumption is negligible in this field.

## 2.3. Consumption of $SF_6$

The $SF_6$ consumption in Norway in 1990, 1991 and 1992 is presented in Table 2, along with estimates for 1993. The numbers are based on information from the major consumers.

*Table 2: $SF_6$ consumption in Norway.*

| Consumers | $SF_6$ consumption 1990 (kg) | $SF_6$ consumption 1991 (kg) | $SF_6$ consumption 1992 (kg) | Estimated $SF_6$ consumption 1993 (kg) |
|---|---|---|---|---|
| Magnesium Industry | 89 400 | 84 000 | 22 800 | 22 800 |
| Aluminium industry | - | - | 3 125 | 6 000 |
| Secondary foundries | 765 | 550 | 830 | 1 610 |
| GIS 145 kV, 300 kV, and 420 kV installation | 16 875 | 1 875 | 25 625 | 7 500 |
| GIS 12 kV and 24kV installation | 4 500 | 5 700 | 6 760 | 7 760 |
| Sound insulating glass | * | 300 | 700 | 500 |
| TOTALT | 111 540 | 92 425 | 59 840 | 46 170 |

* The consumption is not estimated.

### *2.3.1. Magnesium industry*

The consumption of $SF_6$ in magnesium industry has been reduced significantly from 1991 to 1992. The reduction is not a result of converting to a new found and cover gas technology. It is caused by changes in types of products produced and in production volume. There has also been some changes in type of equipment being used and production procedures. The consumption of $SF_6$ in 1993 is assumed to be of the same magnitude as in 1992. In the 1980'ies (Table 3) the consumption increased, reaching a maximum in 1986 and 1987.

### *2.3.2. Gas insulated switchgear*

i) 145 kV, 300 kV and 420 kV installations

The $SF_6$ consumption in the largest installations of gas insulated switchgear has increased significantly from 1991 to 1992 (Table 2) because of a greater extention rate of the electricity supply in Norway. The $SF_6$ consumption in such installations is assumed to drop significantly from 1992 to 1993. The consumption, reflecting the building of new high-tension transmission lines and transformer stations, has varied considerably over the years, since $SF_6$ was first applied in 1973. A small, but not quantified, amount of $SF_6$ is deposited in spare bottles placed in electricity supply installations.

Table 1 and 2 show that the estimated $SF_6$ consumption for 1992 and 1993 are below the estimated import. This could be explained by the fact that $SF_6$ is not necessarily consumed in the year when it has been purchased. One should also notice that there are $SF_6$ consumers not covered in this survey.

*Table 3: $SF_6$ consumption (kg) and accumulated consumption in Norway, given for applications with major contributions.*

| | Consumption | | | Accumulated consumption | |
|---|---|---|---|---|---|
| Year | Magnesium industry | GIS 145-420 kV | GIS 12-24 kV | GIS 145-420 kV | GIS 12-24 kV |
| 1973 | | 6 250 | | 6 250 | |
| 1974 | | 1 250 | | 7 500 | |
| 1975 | | 2 500 | | 10 000 | |
| 1976 | | 9 375 | | 19 375 | |
| 1977 | | 0 | | 19 375 | |
| 1978 | | 10 000 | | 29 375 | |
| 1979 | | 3 750 | | 33 125 | |
| 1980 | | 6 250 | | 39 375 | |
| 1981 | | 20 625 | | 60 000 | |
| 1982 | 90 600 | 6 875 | | 66 875 | |
| 1983 | 99 600 | 3 125 | | 70 000 | |
| 1984 | 184 200 | 22 500 | | 92 500 | |
| 1985 | 198 000 | 7 500 | 2 500 | 100 000 | 2 500 |
| 1986 | 238 800 | 6 875 | 3 000 | 106 875 | 5 500 |
| 1987 | 238 800 | 16 250 | 4 000 | 123 125 | 9 500 |
| 1988 | 222 000 | 11 875 | 4 000 | 135 000 | 13 500 |
| 1989 | 105 600 | 10 000 | 4 000 | 145 000 | 17 500 |
| 1990 | 89 400 | 16 875 | 4 500 | 161 875 | 22 000 |
| 1991 | 84 000 | 1 875 | 5 700 | 163 750 | 27 700 |
| 1992 | 22 800 | 25 625 | 6 760 | 189 375 | 34 460 |
| 1993 | 22 800 | 7 500 | 7 760 | 196 875 | 42 220 |

ii) 12 kV and 24 kV installations

The $SF_6$ consumption in the smaller installations of gas insulated switchgear is assumed to increase slightly from 1991 to 1993. 12 kV and 24 kV installations are placed nearby transformers all over the country. $SF_6$ was first used in this application in Norway in 1985. 12 kV and 24 kV switchgear are produced in Norway as well as imported from foreign producers. The Norwegian producer exports more than half of the switchgear produced. The numbers in Table 2 and Table 3 include the GIS that are installed in Norway.

### *2.3.3. Aluminium industry*

The only primary foundry in the Norwegian aluminium industry which use $SF_6$ as covergas did not use it until 1992. Their consumption of $SF_6$ increased from 1992 to 1993. However, the company plans to substitute $SF_6$ with argon from 1994.

### 2.3.4. *Secondary foundries*

One operating secondary foundry uses $SF_6$ as covergas. In addition there are four secondary foundries which use $SF_6$ as refining gas only. Two new secondary foundries are presently being established. They both plan to use $SF_6$ as cover gas.

### 2.3.5. *Sound insulating windows*

The $SF_6$ consumption in sound insulating windows is based on information on the $SF_6$ consumed by the dominating producer. The $SF_6$ consumed in this field of application has increased from 300 kg in 1991 to 700 kg in 1992. The estimate for 1993 is 500 kg.

## 2.4. Emissions of $SF_6$ in Norway

Table 4 presents and overview of the estimated $SF_6$ emission in Norway since it was first used in 1973. According to this table the emissions peaked in 1987 with about 240 ton/year. Since then, the main contributor, the magnesium industry, has decreased its emissions considerably.

*Table 4: Estimates of emissions of $SF_6$ in Norway (kg)*

| Year | Magnesium smelters | Aluminium smelters | Secondary smelters (foundries) | GIS 145-420 kV | GIS 12-24 kV | Total |
|---|---|---|---|---|---|---|
| 1973 | | | | 60 | | 60 |
| 1974 | | | | 80 | | 80 |
| 1975 | | | | 100 | | 100 |
| 1976 | | | | 190 | | 190 |
| 1977 | | | | 190 | | 190 |
| 1978 | | | | 290 | | 290 |
| 1979 | | | | 330 | | 330 |
| 1980 | | | | 390 | | 390 |
| 1981 | | | | 600 | | 600 |
| 1982 | 90 600 | | | 670 | | 91 270 |
| 1983 | 99 600 | | | 700 | | 100 300 |
| 1984 | 184 200 | | | 930 | | 185 130 |
| 1985 | 198 000 | | | 1 000 | 30 | 199 030 |
| 1986 | 238 800 | | | 1 070 | 60 | 239 930 |
| 1987 | 238 800 | | | 1 230 | 100 | 240 130 |
| 1988 | 222 000 | | | 1 350 | 140 | 223 490 |
| 1989 | 105 600 | | | 1 450 | 180 | 107 230 |
| 1990 | 89 400 | | 300 | 1 620 | 220 | 91 540 |
| 1991 | 84 000 | | 500 | 1 640 | 280 | 86 420 |
| 1992 | 22 800 | 3 125 | 780 | 1 890 | 340 | 28 935 |
| 1993 | 22 800 | 6 000 | 150 | 1 970 | 420 | 31 340 |

### *2.4.1. Magnesium industry*

The Norwegian producer of primary magnesium has been assessing whether $SF_6$ used as cover gas reacts with other components in the furnace. Results so far indicate that $SF_6$ used as cover gas is relatively inert. For the time being it will therefore be assumed that all $SF_6$ used as cover gas is emitted to air. The consumption figures in Table 3 are therefore used as emission estimates in Table 4.

### *2.4.2. Gas insulated switchgear*

$SF_6$ is in this field of application used in enclosed installations. Emission from these installations will only occur as a result of leakages or accidents, or if installations are destroyed without capturing the $SF_6$ gas. Enclosed high-tension installations are now delivered with a leakage guarantee of less than 1 % per year. This applies to all the GIS, both in the 12-24 kV and the 145-420 kV groups. The real leakage may be as low as 0.1 % of the total amount of $SF_6$ in the installations in some cases.

On the other hand, emissions larger than 1 % per year may occur in accidental releases. It is therefore not possible to give accurate figures for the $SF_6$ emissions from the GIS in Norway. It has been assumed that 1 % per year will give the best estimate of the emissions.

All installations have been assumed to leak with 1 % per year throughout their lifetime. The accumulated consumption figures from Table 3 are therefore used to estimate the emissions in Table 4. More accurate figures for emissions from the largest installations (145-420 kV) could be obtained, if records were kept for the refilling of the $SF_6$ gas in the installations.

The amount of $SF_6$ accumulated in the electricity supply is significant as seen in Table 3. At present, the amount of $SF_6$ accumulated used in GIS is about 239 ton, which corresponds to the emission in one year when the emission peaked in 1987. Even though the present emissions from $SF_6$ installations are relatively low, major emissions may occur in the future if the equipment for handling and storage of gas removed from gas compartments in connection with destruction of these installations is not used.

### *2.4.3. Aluminium industry*

$SF_6$ used as cover gas in the aluminium industry is assumed to be inert. Consequently, the $SF_6$ emission equals the consumption.

### *2.4.4. Secondary foundries*

$SF_6$ used as refining gas in secondary foundries is assumed to react chemically with the melting mass and to a large extent be eliminated as source of emission. $SF_6$ used as cover gas is inert and consequently the $SF_6$ emission equals the consumption.

### *2.4.5. Other $SF_6$ consumers*

Sound insulating windows have an estimated average lifespan of 25-30 years. The emission due to diffusion in this application is negligible. However, all $SF_6$ contained in the windows will be released when the glass is broken, or the windows taken out of service. The contribution to $SF_6$ emission from this source is probably small compared to the actual emission from the magnesium industry and the potential future emission from the electricity supply. Because of the low consumption of $SF_6$ the emission from the health service is disregarded.

## 2.5. Future consumption and emission of $SF_6$

### *2.5.1. Magnesium industry*

The magnesium industry claim to have no basis for estimating their $SF_6$ consumption in the years 2000 and 2030. A drastic increase in their $SF_6$ requirements seems highly unlikely, however. $SO_2$ has previously been used as cover gas, but with the present foundry equipment and demands for working environment and product quality this is no longer a viable alternative. A probable trend is that $SF_6$ will have to be used but that the consumption will decrease due to development of new equipment and methods which require less $SF_6$ gas.

### *2.5.2. Gas insulated switchgear*

The future use of $SF_6$ in the electricity supply is highly dependent on the extension rate of new installations. The extension rate is very low at the moment and will depend on future political decisions. It is therefore difficult to estimate the future consumptions of $SF_6$ in the electricity supply, but the trade agrees that the number of new $SF_6$ installations will decrease in the years to come and stabilize well below the level in the eighties which was 11 000 tons on a yearly average. However, this will imply a slow, but steady, increase in the emissions, since the emissions are calculated from the accumulated consumption.

The lifespan for $SF_6$ installations has constantly increased. The first Norwegian $SF_6$ installation was established in 1973. The lifespan for $SF_6$ installations has increased from 10 years in 1973 to 30 years today. It is assumed to be 40 years in year 2000. The next generation of $SF_6$ installations will be more compact, reducing the $SF_6$ requirement per installation. Because of the long lifespan for $SF_6$ installations, the electricity supply business has not to any detail considered the problems involved in equipment destruction. It is possible to extract $SF_6$ when equipment is destroyed, and the necessary equipment exists.

### *2.5.3. Aluminium industry*

The one primary foundry in the aluminium industry which uses $SF_6$ today plans to substitute it with argon from 1994. The secondary foundries have no plans to change their use of $SF_6$.

### *2.5.4. Insulated windows*

Future demands to indoor quality may result in extended use of sound insulating windows and consequently an increased use of $SF_6$.

## 3. Estimate of global consumption and emission of $SF_6$

The dominating use of $SF_6$ worldwide is in gas insulated switchgear (GIS), in blanketing or degassing molten reactive metals, e.g. aluminium, (Mac Neal et al., 1990) and magnesium production. According to estimates of emission for the period 1953-1974 (Krey et al., 1976), emission increased from 10 tons/year in 1953 to 1180 tons/year in 1974. Emissions since then have not been reported.

According to estimates by gas manufacturers, the worldwide production of $SF_6$ is presently between 5000 and 8000 tons (1990). The production of $SF_6$ in Europe in 1991 is estimated by one of the producers to 3000 tons. About 80 % of the total $SF_6$ produced is used in heavy electrical equipment, such as GIS and substations (Niemeyer and Chu, 1992). The remaining 20 % is mainly used in the metal industries.

The current emission may be significantly smaller than the production, as a substantial part of the produced $SF_6$ is contained in electrical equipment. The recent improvement in equipment and gas recycling presumably yields that a decreasing fraction of the $SF_6$ produced is released to the atmosphere. The amount of $SF_6$ banked in electrical equipment has not been thoroughly investigated. Ko et al. (1993) argue that as much as 50 % of current productions are banked, yielding global emissions in the range 2 500-4 000 tons/year.

The worldwide production rate of $SF_6$ has approximately risen linearly since 1970 and is expected to rise to about 10 000 tons/year in the year 2010 (Niemeyer and Chu, 1992). On the other hand, improved electrical equipment and recycling practicies will limit the emissions to the atmosphere. Emissions to the atmosphere will most likely grow at a slower rate than the production, and may even stabilize.

The $SF_6$ consumption in magnesium industry worldwide can be from 1 kg to 5 kg per ton magnesium produced, but exact data has not been found. All the magnesium producers in the west use $SF_6$ as cover gas but some producers in eastern Europe and Russia probably still use $SO_2$. A global $SF_6$ emission has been estimated based on average $SF_6$ consumption of 3 kg per ton magnesium produced (Table 5). About 15 % of the magnesium produced is processed in secondary foundries. The consumption and emission of $SF_6$ in secondary foundries is considerably smaller than in the primary foundries, and is therefore neglected.

*Table 5: Global $SF_6$ emission from the magnesium industry.*

| Geographical area | Production of magnesium in 1991 Tons/year | $SF_6$ emission factor kg/ton | $SF_6$ emission Tons/year |
|---|---|---|---|
| USA/Canada | 167 000 | 3 | 501 |
| Western Europe | 69 000 | 3 | 207 |
| Russia/China | 65 000 | 3 | 195 |
| Asia | 11 000 | 3 | 33 |
| The rest of the world (Brasil) | 8 000 | 3 | 25 |
| TOTAL | 320 000 | | 930 |

# 4. Actions to reduce $SF_6$ emission

## 4.1. Magnesium industry

The Norwegian magnesium producer will continue to optimize casting machines and casting methods, in order to minimize $SF_6$ emissions.

## 4.2. Gas insulated switchgear

There is equipment for handling of $SF_6$ commercially available.

The equipment used for handling $SF_6$ and its operational decomposition products should ensure fast emptying and filling procedures to minimize outage time. The handling equipment should also ensure the storage, processing, transport and reuse of gas taken from equipment and in addition efficient and safe processing of solid waste.

In view of the cost and complexity of gas handling equipment, it is generally not feasible to equip each GIS with all the required facilities. For this reason mobile units have been developed.

The handling unit should contain the following equipment:

a) Gas service and storage facilities equipped with adequate filters for gas cleaning
b) High efficiency vacuum cleaner equipped with a paper absorbent capable of trapping particles in the micron range. It should also have a non metallic open ended nozzle
c) Gas checking equipment
d) Disposible cleaning materials
e) Decomposition product neutralizing equipment and materials

Today the handling equipment is mainly used for maintenance purposes, but it can also be used to remove $SF_6$ from gas compartments in connection with destruction of $SF_6$ installations. The storage of the removed $SF_6$ gas can be made to an installed tank, a separate tank or in $SF_6$ gas bottles. In this way the handling equipment contribute to reduction of $SF_6$ emission from gas insulated switchgear.

## 4.3. Sound insulating windows

There are today no alternative gases to $SF_6$ for use in sound insulating windows. New and more expensive types of windows are being devoloped which require less gas to give the same insulation effect. $SF_6$ will however still be used to give the best insulating product.

# 5. Radiative Forcing Due to $SF_6$

## 5.1. Introduction

Several highly fluorinated species have been proposed as possible future greenhouse gases due to anthropogenic emissions. A few studies have considered the greenhouse effect from $SF_6$. Ramanathan et al. (1985), who studied the radiative effects of a wide range of species, mentioned $SF_6$ as a possible candidate for global warming, although they did not present any radiative model calculations for this species. Recently radiactive model calculations and GWP estimates have been published by Ko et al. (1993). The present study also include calculations of GWP for $SF_6$. The methodology of a recent study of the radiative forcing and greenhouse warming potential of the fluorocarbons $CF_4$ and $C_2F_6$ (Isaksen et al, 1992) is closely followed.

## 5.2. Models and absorption data

Three different models have been used in this study of radiative effects of $SF_6$. The main characteristics of the models are described in Section 5.2. The most detailed models are a narrow band model developed at the University of Reading (UoR) and a correlated k-distribution model, which has been developed at the Lawrence Livermore National Laboratory (LLNL). In the present work the UoR model has been run at NILU. A broad band NILU model has also been used in this study.

Line data for $SF_6$ are only reported for the $\nu_3$ band (the HITRAN91 data base, Rothman et al., 1992). Hot band contributions to the radiactive forcing can be estimated to be approximately three times the contribution from the $\nu_3$ band (Fox and Person, 1976). In the present report three different models have been used. One of them (the LLNL model) depends on line data. A detailed intercomparison between the three models has therefore been performed for the $\nu_3$ band only. An earlier study based on another of the models (the NILU model, Stordal and Myhre, 1991b) only considered the $\nu_3$ band, yielding a GWP value of $SF_6$ which represented a considerable underestimate.

In the present study, radiative calculations including all $SF_6$ bands have only been performed with the two band models (the UoR and NILU models). These models have also been run for a range of latitudes and various seasons, and also including clouds. Globally averaged forcing has then been calculated to form the basis for the GWP estimates.

### *5.2.1. University of Reading (UoR)*

The UoR model is a standard narrow-band radiative transfer model, which resolves the thermal infrared spectrum between 0 and 2500 $cm^{-1}$ at 10 $cm^{-1}$ intervals (Shine 1991). The absorption bands due to water vapour, carbon dioxide, methane, nitrous oxide, CFC-11 and CFC-12 are incorporated from the HITRAN 1986 data base, containing spectral line data (Rothman et al. 1987). The water vapour continuum absorption is treated by the method developed by Clough et al. (1989). The model has about 20 atmospheric layers in the vertical in the calculations presented here.

$SF_6$ is included in the model using the weak limit approximation, which is appropriate for present concentrations. The flux transmittance is given by the expression exp(-2sx), where s is the absorption cross-section, x is the path length of absorber, and 2 is the diffusivity factor for optically thin gases.

### *5.2.2. Norwegian Institute for Air Research (NILU)*

A broad band model is adopted for calculations of the infrared flux changes caused by $SF_6$. The model formulation is based broadly on the work of Ramanathan (1976), as described in Stordal (1988). It has earlier been used to calculate GWP values for $SF_6$ (Stordal and Myhre, 1991b) as well as $CF_4$ and $C_2F_6$ (Stordal and Myhre, 1991a). Overlap by $H_2O$ vibrational rotational bands and continuum is included using values from Rodgers and Walshaw (1966). $CO_2$ overlap with water vapour is treated using a fit based on Kiehl and Ramanathan (1983). The vertical resolution is 1 km in the altitude range 0-60 km.

### *5.2.3. Lawrence Livermore National Laboratory (LLNL)*

A correlated k-distribution model (Grant et al., 1992, Grossman and Grant, 1992) for the atmospheric transmission of the major molecular species has been used to calculate the tropospheric radiative forcing of $SF_6$. Since spectral data have not been available to the hot bands, calculations have been performed only for the $\nu_3$ band. Flux calculations were performed on the altitude range 0-60 km. The wave number interval covered by these calculations was 940-955 $cm^{-1}$. The model uses the HITRAN91 data base for the line parameters, a version of the FASCODE2 code (Clough et al., 1986) to calculate a grid of line by line opacities, and a sorting code to calculate the k-distributions at each atmospheric level. The molecular vibration frequencies for $SF_6$ were obtained from McDowell et al. (1990) and Rinsland et al. (1976) and were inserted into the FASCODE2 for the opacity calculations. The altitude resolution is 1 km (0-20 km altitude) or 2 km (20-80 km altitude).

### *5.2.4. Absorption data*

As mentioned above only approximately one fourth of the infrared absorption by $SF_6$ takes place in the $\nu_3$ band. Only for the $\nu_3$ band spectral data are available in the HITRAN91 database. The integrated band strength for the $\nu_3$ band is $5.234 \times 10^{-17}$ $cm^{-1}$/molec $cm^{-1}$, or 1408 $cm^{-2}$ $atm^{-1}$.

Several measurements have been made of the $SF_6$ absorption in certain windows used in remote sensing (e.g. Varanasi et al., 1992) and of the total band strength of $SF_6$ including also the hot bands. For the total band strength we use the value 4800 $cm^{-2}$ $atm^{-1}$, recently obtained by Varanasi (1993). The same value was obtained in the early study of Schatz and Hornig (1953). Five studies have reported values 2 % or less different from 4800 $cm^{-2}$ $atm^{-1}$ (Schachtschneider, 1960; Brodbeck et al., 1980; Dunn et al., 1982; McDowell et al., 1986; Chapados and Birnbaum, 1988). However, another recent value (Ko et al., 1993) is 23 % higher than the Varanasi (1993) value, closer to the value given by Kim et al. (1980), being 27 % higher than the value used in this study.

The NILU model treats each absorbing band as an integral. The $\nu_3$ band of $SF_6$ is assumed to occupy 12 $cm^{-1}$, whereas 60 $cm^{-1}$ is adopted as the width of all the $SF_6$ bands.

### 5.3. Impact of $SF_6$ on clear sky irradiances, $\nu_3$ band only

Calculations of the effect of gases on the irradiance in a clear sky standard atmosphere have been performed, following the method of the International Intercomparison of Radiation Codes for Climate Models (ICRCCM) (see, e.g., Fels et al. 1991). In the following results and sensitivities are presented for the change in net thermal infrared irradiance at the tropopause due to $SF_6$ in the atmosphere. The calculations are performed for a one-dimensional profile, allowing several case studies, without high computational costs, with the UoR and NILU models, and a few calculations with the more computer time consuming LLNL model. Calculations including the $\nu_3$ band only are presented in this section, allowing a detailed intercomparison between the three models.

A standard ICRCCM mid-latitude summer atmosphere is used in the present study (McClatchey et al., 1972), specifying profiles for temperature, ozone and water vapour. The concentrations of other radiatively-active gases are taken from IPCC (Houghton et al., 1990): $CO_2$ 353.93 ppmv; $CH_4$ 1717 ppbv; $N_2O$ 309.68 ppbv; CFC-11 0.2800 ppbv; CFC-12 0.4844 ppbv. These are all well mixed in the troposphere. The mixing ratios are kept constant at the given levels in the troposphere as well as in the stratosphere. The tropopause is defined to be at 179 hPa, according to the ICRCCM standard.

A series of experiments have been performed adding 1 ppbv of $SF_6$ at all levels in the atmosphere in combination with a variety of other gases. The results of the various experiments are summarized in Table 6 showing the impact on the net tropopause irradiance for different combinations of absorbing gases. The effect of $SF_6$, like any other greenhouse gas which is well mixed in the troposphere, is to decrease the net upward irradiance at the tropopause. Table 6 shows values for this change, which can alternatively be expressed as an increase in the net downward irradiance. The $SF_6$ absorption band at 940-953 $cm^{-1}$ is most strongly overlapped by $CO_2$ and $H_2O$.

*Table 6: Increase in net downward tropopause irradiance in a clear sky mid-latitude summer atmosphere, due to 1 ppbv of $SF_6$, $\nu_3$ band only.*

| Case | Gases included | Irradiance Change ($Wm^{-2}$) | | |
|---|---|---|---|---|
| | | UoR | NILU | LLNL |
| 0 | None | 0.244 | 0.216 | 0.292 |
| 1 | $H_2O$ | 0.225 | 0.203 | |
| 2 | $CO_2$ | 0.237 | 0.216 | |
| 3 | $H_2O$, $CO_2$ | 0.220 | 0.203 | |
| 4 | $H_2O$, $CO_2$, $O_3$ | 0.220 | 0.203 | |
| 5 | $H_2O$,$CO_2$, $O_3$, $CH_4$, $N_2O$, CFC-11, CFC-12 | 0.220 | 0.203 | 0.263 |

The effect of overlap is significant, but moderate since the spectral region is in the atmospheric window region. The inclusion of $H_2O$ and $CO_2$ decreases the irradiance change from $SF_6$ by 8 and 3 % respectively in the UoR model (case 1 and 2 vs case 3). A similar effect of overlap with $H_2O$ has been found in the NILU model, which does not include overlap with the relatively weak $CO_2$ band near 948 $cm^{-1}$. The effects of $O_3$, $CH_4$, $N_2O$, CFC-11 and CFC-12 are negligible in both models. There is uncertainty in the precise overlap between $SF_6$ and the lines of $CO_2$ and $H_2O$, which we are unable to investigate in detail here.

The UoR model was used for a sensitivity study, as one of the experiments (case 4) was repeated with the $SF_6$ band strength increased and decreased by 10 %. The change in the net irradiance was directly proportional to the band strength changes. Since the NILU model spreads the effect of $SF_6$ and the overlapping gases over a wider spectral interval, another sensitivity study of case 4 was also performed with the UoR model with the cross-sections spread evenly over the 940-960 $cm^{-1}$ region, instead of using the observed distribution. The irradiance change increased modestly, from 0.197 to 0.202 $Wm^{-2}$, indicating that improvements in spectral resolution in models influence the results significantly.

The LLNL model calculates an irradiance change that is 20 % higher than the UoR model. The higher value is shown to result from $SF_6$ itself, rather than from overlap effects (see case 0). The UoR and the LLNL models are quite different in the way they treat the radiative transfer. The variation of 20 % difference between the results of the two models represent the uncertainty due to model formulations, which is thought to be of the order of 10-15 % for both models. The accuracy of the flux calculations in the LLNL model for a mixture of gases (case 5) without $SF_6$ is on the order of 10-15% when compared to line by line calculations. We assume that the $SF_6$ forcing value is also accurate to the order of 10-15 % for the correlated k-distribution model.

The LLNL, UoR and NILU values for the $SF_6$ forcing lie within the range of the error estimates. The modelling approach taken by the three methods to calculate the forcing are very different. The UoR and NILU approaches consider a weak line limit band model which easily lends itself to the analysis of the effects of the different species and physical parameters of the problem. The LLNL approach considers a very detailed, but time consuming, reduction of the line by line opacities using combined gas mixtures. As a result of the complexity of the LLNL calculation, a simple analysis of the effects of the variation of different parameters is much more difficult to obtain. For the $\nu_3$ band, we recommend an $SF_6$ forcing, in the ICRCCM approximation, of 0.240 $W/m^{-2}$ +/- 15 %.

### 5.4. Radiative Forcing

A proper assessment of the forcing, following the IPCC (Houghton et al., 1990; 1992) requires the inclusion of clouds and preferably also the effect of temperature variations with latitude and season. The forcing is usually calculated by including a process known as stratospheric adjustment (Shine et al., 1990, Isaksen et al., 1992), taking into account the changes in stratospheric temperature as a consequence of trace gas changes. As this effect has been shown to be small for other gases (Isaksen at al., 1992), it has been omitted in the present study.

Global mean forcing for $SF_6$ has been calculated in this study with the two band models (the UoR and NILU models). Calculations have been performed both for the $\nu_3$ band alone and for the total $SF_6$ absorption.

In the present study the global mean is calculated by taking into account the latitudinal and seasonal variation of temperature, $H_2O$, $O_3$ and cloudiness, using available climatologies. Results from the UoR model are shown in Figure 1 for a 1 ppbv increase of $SF_6$, for clear skies and average cloudy conditions for January and July in the Northern Hemisphere. Clouds reduce the outgoing infrared radiation and therefore decrease the effect of adding greenhouse gases. The actual reduction depends on the cloud amounts and distribution, which are not very accurately known. The variation of forcing with latitude is greater in January than in July. The amount of energy in the strong $SF_6$ band decreases with latitude, due to decreasing temperatures. This is counteracted, to a small extent by a decrease in water vapour with latitude, tending to increase the effectiveness of $SF_6$. The latitudinal gradient in the temperature, and therefore also in the radiative forcing, is less in July than in January.

A global averaged radiative forcing is obtained by area-weighting the January and July results from the Northern Hemisphere. This has been done since performing the above calculations with the UoR model globally for each month with such a high resolution radiation code was not practicable. The coarser and faster NILU model has the advantage that it allows inexpensive calculations using a finer resolution in latitude and season. The NILU model has been run for global (in latitude, resolution 10 deg.), and seasonal conditions (resolution 1 month). Again, observed climatological data for temperature, ozone and water vapour have been used. The net raditive forcing at the tropopause is shown in Figure 2 as a function of latitude and season. The results are similar to those obtained with the UoR model (Figure 1), but now the full seasonal cycle in the temperature and the radiative forcing can be followed. Furthermore, a more representative global and seasonal average can be calculated. However, the experiments with the NILU model have only been performed without clouds. The results from these two sets of experiments are summarized in Table 7.

*Table 7: Radiative forcing ($Wm^{-2}$/ppbv) for $SF_6$.*

| Present work: | $\nu_3$ band only (HITRAN91) | All bands (Varanasi, 1993) |
|---|---|---|
| UoR, with clouds | 0.174 | 0.602 |
| UoR, without clouds | 0.237 | 0.815 |
| NILU, without clouds | 0.203 | 0.681 |

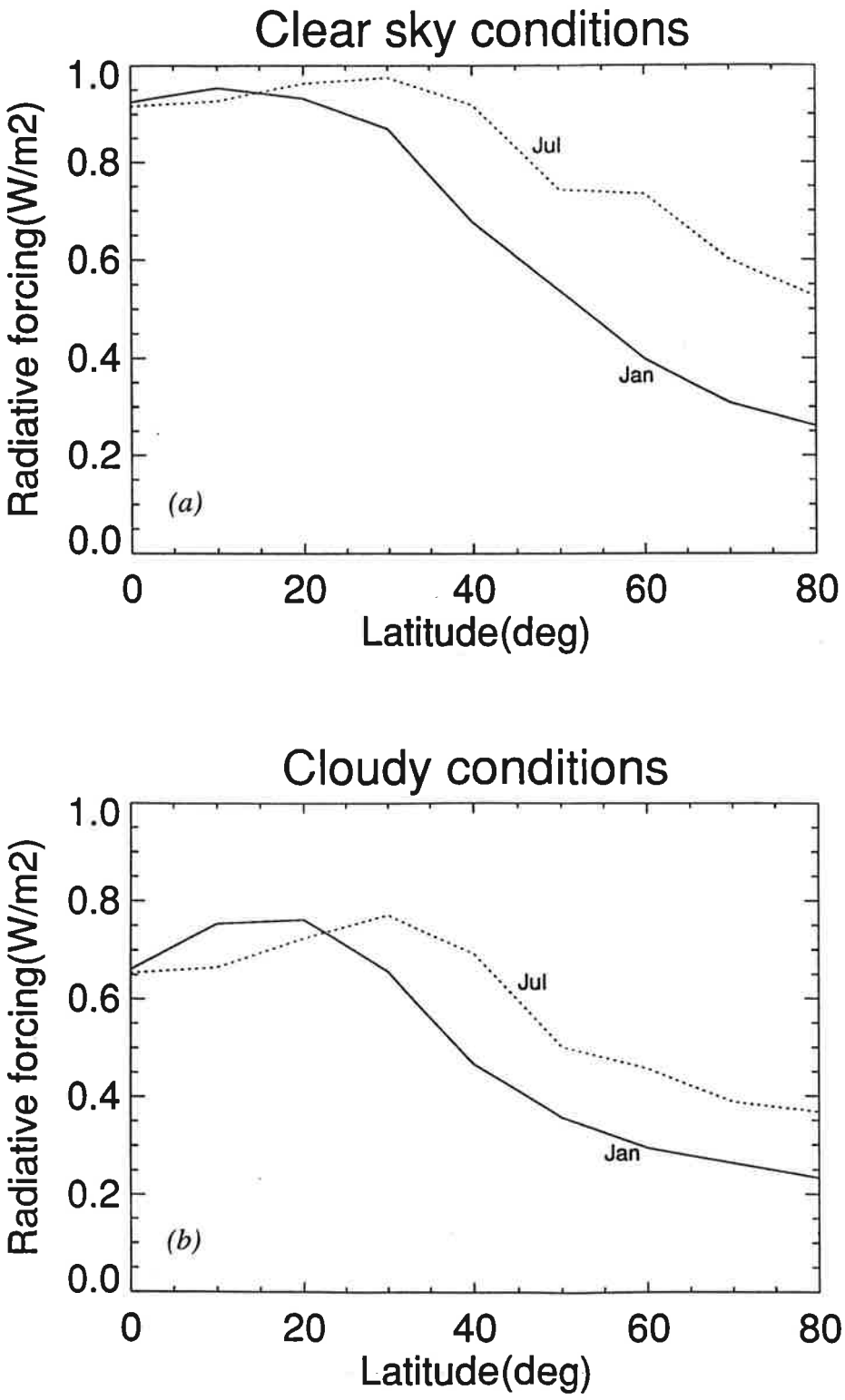


*Figure 1: Latitudinal variation of radiative forcing ($Wm^{-2}$) for a 1 ppbv increase in $SF_6$ concentration as calculated with the UoR model. (a) $SF_6$ forcing for the clear sky case for January and July (b) As (a) but for cloudy conditions. All calculations have been performed using the total $SF_6$ band strength reported by Varanasi (1993) and excluding stratospheric adjustment.*

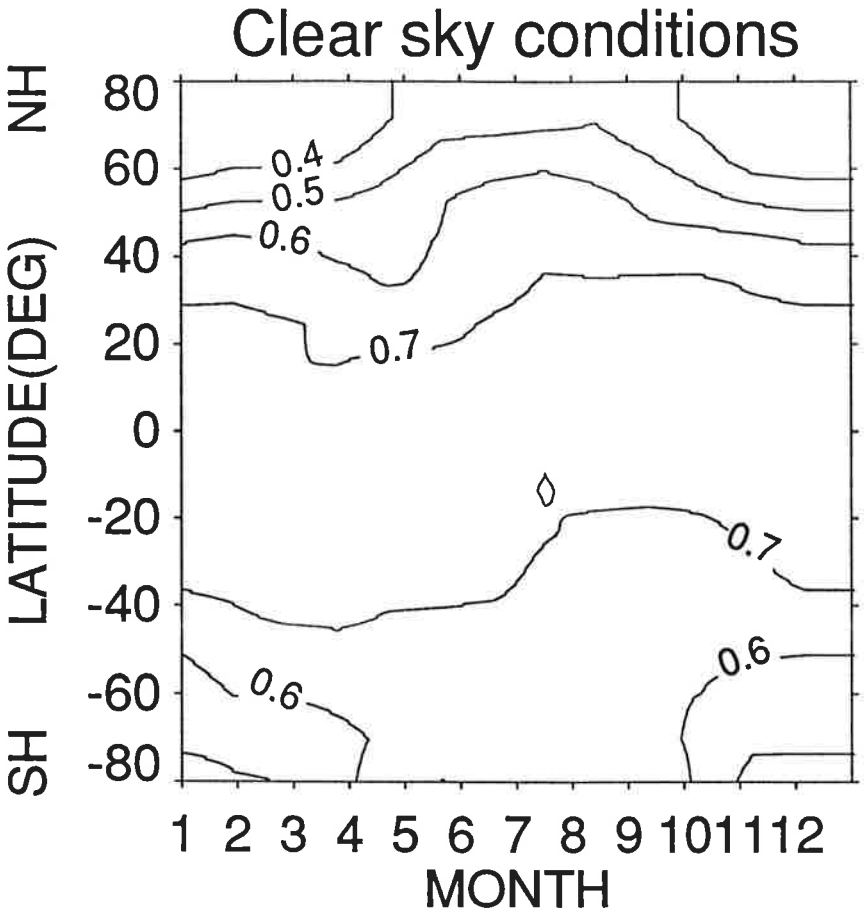


*Figure 2: Latitudinal and seasonal variation of radiative forcing ($Wm^{-2}$) for a 1 ppbv increase in $SF_6$ concentration as calculated with the NILU model using the total $SF_6$ band strength reported by Varanasi (1993). Clouds have not been included in the calculations.*

Results obtained with the broad band NILU model are lower than the ones from the UoR model (cloud free case). The difference is obviously in part due to differences in the radiative models (see Table 6). There is presumably a difference due to the differing global mean representations, as explained above. Some of the discrepancy could possibly also be explained by different values for the climatological data used, especially for temperature and water vapour (references to data used are given in Stordal, 1988 and Shine, 1991).

Since cloud effects are quite important, and has also been used in the IPCC studies, we recommend to adopt a value accounting for clouds in radiative forcing calculations for $SF_6$ forming the basis for GWP estimates. This value is 0.602 $Wm^{-2}$/ppbv for the UoR model when the total absorption of $SF_6$ has been taken into account. The error due to uncertainties in spectral resolution, the effect of overlapping gases and band strengths are, rather qualitatively, believed to be at least ± 20%. As explained above, the more detailed correlated k-distribution model yielded a forcing that was 20 % higher than the narrow band model in the clear sky case for the $\nu_3$ band. Clearly, the uncertainty in the globally averaged forcing described here is significant.

Adopting the value for $SF_6$ forcing recommended above, the strength of $SF_6$ relative to $CO_2$ and CFC-11, are given in Table 8. Values for the radiative forcing of $CO_2$ and CFC-11 have not been calculated with the models used in the present study, but rather been taken from Houghton et al. (1990, their table 2.3). Figures are given on both a per molecule and a per mass basis. For comparison, numbers are also given for the fluorocarbons $CF_4$ and $C_2F_6$, as reported by Isaksen et al. (1992).

*Table 8: Relative strength of $SF_6$, $CF_4$ and $C_2F_6$ compared to the IPCC values of $CO_2$ and CFC-11 (only direct radiative effects included), on a per molecule and a per unit mass basis.*

| | Relative strength per molecule | | Relative strength per unit mass | |
|---|---|---|---|---|
| Gas | $CO_2$ | CFC-11 | $CO_2$ | CFC-11 |
| $SF_6$ | 33 700 | 2.73 | 10 600 | 2.58 |
| $CF_4$ | 5 430 | 0.44 | 2 710 | 0.69 |
| $C_2F_6$ | 16 900 | 1.37 | 5 360 | 1.37 |

$SF_6$ is extremely potent as a greenhouse gas absorbing substantially stronger even than the efficient greenhouse gases $CF_4$ and $C_2F_6$. Large emissions should therefore be avoided, especially since the lifetime is very long.

## 5.5. Global Warming Potentials

The GWP has been developed as a tool to rank the effectiveness of climate gases in terms of the relative contribution of their emissions to the greenhouse effect. The GWP measures the warming potential of a climate gas relative to that of a reference gas (Houghton et al., 1990; 1992). It is defined to give the global and annually-averaged radiative forcing, as a cumulative measure over a specified time horizon, taking into account the decay of the atmospheric concentration following the emission of the compound.

The definition of GWP is given by the expression

$$GWP = \int_0^{t_h} a_i\, c_i\, dt \;/\; \int_0^{t_h} a_r\, c_r\, dt \qquad (1)$$

where $a_i$ is the instantaneous radiative forcing due to a unit increase in the concentration of trace gas $i$, $c_i$ is its concentration remaining at a time, $t$, after its emission. The corresponding values for the reference gas is given in the denominator. The time horizon, $t_h$, is the time period for the integration.

The cumulative effect of very stable gases, like $SF_6$, is larger for longer time horizons. This can clearly be seen from the expression for the GWP, which can be simplified when the lifetime is much larger than the time horizon:

$$GWP = a_i\, c_i\, t_h \,/\, \int_0^{t_h} a_r\, c_r\, dt \qquad (2)$$

Equation (2) is a very accurate measure of GWP for $CF_4$ and $C_2F_6$, with lifetimes expected to be larger than 10000 years. The lifetime of $SF_6$ is recently estimated to be 3200 years (Ravishankara et al., 1993). Equation (2) then underestimates GWP on the 500 years time horizon by 7 %, so that the following solution of Equation (1) is used instead:

$$GWP = a_i\, c_i\, \tau_i\, (1 - e^{-t_h/\tau_i}) / \int_0^{t_h} a_r\, c_r\, dt \qquad (3)$$

The reference gas used when defining GWPs is usually $CO_2$, the dominant contributor in the greenhouse gas problem. $CO_2$ is removed from the atmosphere by several processes at different time scales which are also somewhat uncertain. This has the disadvantage that the value of the denominator in the expressions is uncertain. We therefore also specify GWPs with CFC-11 as a reference gas (Table 9), since CFC-11 has a simple atmospheric decay. However, it has now been shown that CFCs may have large indirect radiative effects in addition to their direct greenhouse effect (Houghton, 1992). This is due to the loss of stratospheric ozone on a global scale, believed to accompany CFC emissions, since ozone is also a greenhouse gas. It has been shown that the ozone reductions may lead to a cooling that to some extent counteracts the warming from the CFC-11 molecule itself (Ramaswamy et al., 1992). The numbers given in Table 9, which only take into account the direct radiative effects of CFC-11, could therefore be somewhat misleading. In the computations, a lifetime of 55 yrs is used for CFC-11.

*Table 9: Global Warming Potentials (GWPs) for $SF_6$. Numbers are given relative to $CO_2$ and CFC-11. Radiative forcing and lifetimes for $CO_2$ and CFC-11 are taken from Houghton et al. (1990). Notice that for CFC-11 only direct radiative effects have been considered.*

| Time horizon (years) | 20 | 100 | 500 |
|---|---|---|---|
| Relative to $CO_2$: | 14 100 | 19 000 | 31 000 |
| Relative to CFC-11: | 3.24 | 5.84 | 23.1 |

Ko et al. (1993) recently estimated GWP for $SF_6$. As the lifetime of $SF_6$ is still somewhat uncertain, they estimated GWP values for a range of possible lifetimes. Their GWP value for a 100 year time horizon and a lifetime of 3 200 years is 21800, which is 15 % higher than the value recommended in this report. The desarepancy is probably largely due to the 23 % higher band strength used by Ko et al. (1993).

## 6. Contribution of $SF_6$ to global warming

One way of assessing the impact of $SF_6$ as a greenhouse gas is to compare its emissions weighted by its GWP, with emissions of other greenhouse gases, as e.g. $CO_2$. Such an assessment enlightens the accumulated effect of present day emissions over a time span which equals the time horizon for which the adopted GWP is estimated.

Although the current and the future emissions of $SF_6$ are somewhat uncertain, it seems likely that $SF_6$ gives a moderate, almost insignificant, contribution to the anthropogenically enforced increase in the greenhouse effect. The global emissions are relatively uncertain and are estimated to be in the range 2 500-4 000 tons in 1990. Applying a GWP of 19 000 on a 100 year time horizon (Table 9), the contribution is equivalent to 50-75 M $CO_2$ tons. In 1990 the anthropogenic $CO_2$ emissions were 27 G tons (Houghton et al., 1992). $SF_6$ thus contributed with about 0.2 % of the $CO_2$ emissions, or about 0.1 % of the total emissions of greenhouse gases in 1990, when the contribution of $CO_2$ emissions made about 60 % (Houghton et al., 1990) of the total anthropogenic effect.

In some countries, as e.g. Norway, $SF_6$ plays a more important role due to a highly developed magnesium industry. The emission in Norway was about 90 tons in 1990, or about 1.7 M $CO_2$ tons when applying the GWP on a 100 year time horizon. The Norwegian emission of $CO_2$ was 35 M. tons in 1990, consequently, in the Norwegian greenhouse gas budget of 1990, $SF_6$ contributed with about 5 % compared to $CO_2$. Since then the contribution has decreased markedly due to reductions in the emissions from the magnesium industry.

A different way of assessing the role of $SF_6$ is to evaluate the effect of its presently observed atmospheric content, weighted by its relative strength per atmospheric molecule (Table 9). Hougthon et al. (1990) performed such an evaluation and comparison of the effect of the changes in atmospheric composition from 1965 to 1990, and found e.g. that the CFCs then contributed with about 12 % of the increase in the total burden of greenhouse gases, or 20 % of the effect of the increased $CO_2$. The atmospheric concentration of $SF_6$ has been measured to be about 2 ppt (Rinsland et al., 1990). Weighting this amount with the relative greenhouse strength of $SF_6$ yields a contribution to the total increase in the greenhouse effect up to 1990 by about 0.05 %. In a scenario calculation Ko et al. (1993) estimated a possible contribution of 0.5% from $SF_6$ compared to the warming due to $CO_2$ increase in the year 2010. Since $SF_6$ does not contain chlorine, it does not influence stratospheric ozone. $SF_6$ therefore has no known indirect climate effect.

In conclusion, $SF_6$ at present plays an almost insignificant role in influencing the global climate. In Norway its contribution to the national total emission of climate gases is significant, although moderate. $SF_6$ is extremely potent as a greenhouse gas, and large emissions should therefore be avoided.

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ABSTRACT
Norwegian and global sources of $SF_6$ have been assessed, and GWP values have been calculated. It is found that on a global scale $SF_6$ plays a minor role in the currently increasing greenhouse effect. However, in some countries, as e.g. Norway, $SF_6$ plays a more important role due to a highly developed magnesium industry.

TITTEL $SF_6$ as a greenhouse gas:
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