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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 SF₆ 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 SF₆ 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 SF₆ consumption in both the magnesium industry and the electricity supply is difficult. However, it is believed that most likely a reduction in both SF₆ consumption and emissions will take place in Norway. The only Norwegian primary foundry in the aluminium industry which contribute to the SF₆ emission today plans to substitute SF₆ with argon from 1994. There is today one operating secondary foundry in Norway using SF₆ as covergas, and two are presently being established. In addition there are four secondary foundries using SF₆ 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 SF₆ emissions in Norway (79 % in 1992).

Table A: Estimates of emissions of SF₆ 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 SF₆ have never been reported, but may roughly be estimated to 5 000-8 000 tons per year. The global consumption of SF₆ 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 SF₆ accumulated in GIS is significant. To avoid major SF₆ 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 SF₆ 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 SF₆. Recommended value for the radiative forcing for SF₆ is 0.602 Wm⁻²/ppbv. The uncertainty is estimated to be at least 20 %. Estimates for Global Warming Potentials (GWPs) relative to CO₂ are 14 100, 19 000, and 31 000 on the 20, 100 and 500 years time horizons respectively showing that SF₆ 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 SF₆. Numbers are given relative to CO₂.

Time horizon (years)	20	100	500
Relative to CO ₂ :	14 100	19 000	31 000

Combining the assessments of emissions and GWP for SF₆ yields that SF₆ makes a small, almost negligible, contribution to the greenhouse effect on a global scale. The contribution of SF₆ is about 0.2 % of the anthropogenic emissions of CO₂. In Norway, the contribution is more significant, and was equivalent to about 5% of the CO₂ emission in 1990 when weighted by the GWP for a 100 year time horizon.

SF₆ 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 SF₆ can therefore impact the earth's climate on a very long time scale.

SF₆ 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 CO₂ 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. SF₆, CF₄ and C₂F₆, 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 SF₆ as well as new calculations of the greenhouse effect due to SF₆.

2. Consumption and emission of SF₆ in Norway

2.1. Norwegian import of SF₆

There is no SF₆ production in Norway. The worldwide commercial market for SF₆ is small, and there is competition between suppliers. There are only three Norwegian suppliers of SF₆. They all want their sales figures to be treated confidentially.

About half of the SF₆ consumed in Norway is supplied by the three Norwegian dealers. The Norwegian magnesium industry imports most of their SF₆ directly from foreign suppliers.

Table 1: Norwegian import of SF₆.

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 SF₆ application

The main use of SF₆ in Norway are in the magnesium industry and in gas insulated switchgear (GIS). In addition some SF₆ 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

SF₆ is used as cover gas in the primary foundry in magnesium production. SF₆ 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 SO₂ as cover gas to SF₆ in the period 1979-1982.

2.2.2. Gas insulated switchgear and circuit breakers

SF₆ is used as insulation medium in the electricity supply. In Norway SF₆ has been used for this purpose since 1973. SF₆ 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 SF₆ during commissioning. Some refilling of SF₆ 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 SF₆ contained in high voltage switchgear in Norway today is about 200 000 kg.

2.2.3. Aluminium industry

SF₆ can be used as cover gas in primary foundries in the aluminium industry. There is only one Norwegian primary foundry using SF₆ today.

2.2.4. Secondary foundries

Some SF₆ is used as cover gas and refining gas in secondary aluminium and magnesium foundries. SF₆ is often mixed with argon and chlorine. There are a number of different gas mixtures, and the SF₆-content varies from 1-2 % to 90 %. SF₆ gas is expensive. For economic reasons, therefore, the foundries try to keep the SF₆ consumption as low as possible.

2.2.5. Insulated glass

A mixture of SF₆ 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 SF₆.

2.2.6. Other applications

SF₆ is used for medical purposes, for example for blowing up collapsed lungs. The consumption of SF₆ in the health service in Norway is minimal and will not be estimated.

Another application is SF₆ used as a trace gas to study dispersion of pollutants. The consumption is negligible in this field.

2.3. Consumption of SF₆

The SF₆ 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: SF₆ 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 SF₆ 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 SF₆ 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 SF₆ consumption in the largest installations of gas insulated switchgear has increased significantly from 1991 to 1992 (Table 2) because of a greater extension rate of the electricity supply in Norway. The SF₆ 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 SF₆ was first applied in 1973. A small, but not quantified, amount of SF₆ is deposited in spare bottles placed in electricity supply installations.

Table 1 and 2 show that the estimated SF₆ consumption for 1992 and 1993 are below the estimated import. This could be explained by the fact that SF₆ is not necessarily consumed in the year when it has been purchased. One should also notice that there are SF₆ consumers not covered in this survey.

Table 3: SF₆ consumption (kg) and accumulated consumption in Norway, given for applications with major contributions.

Year	Consumption			Accumulated consumption	
	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 SF₆ 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. SF₆ 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 SF₆ as covergas did not use it until 1992. Their consumption of SF₆ increased from 1992 to 1993. However, the company plans to substitute SF₆ with argon from 1994.

2.3.4. Secondary foundries

One operating secondary foundry uses SF₆ as covergas. In addition there are four secondary foundries which use SF₆ as refining gas only. Two new secondary foundries are presently being established. They both plan to use SF₆ as cover gas.

2.3.5. Sound insulating windows

The SF₆ consumption in sound insulating windows is based on information on the SF₆ consumed by the dominating producer. The SF₆ 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 SF₆ in Norway

Table 4 presents an overview of the estimated SF₆ 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 SF₆ 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 SF₆ used as cover gas reacts with other components in the furnace. Results so far indicate that SF₆ used as cover gas is relatively inert. For the time being it will therefore be assumed that all SF₆ 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

SF₆ 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 SF₆ 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 SF₆ 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 SF₆ 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 SF₆ gas in the installations.

The amount of SF₆ accumulated in the electricity supply is significant as seen in Table 3. At present, the amount of SF₆ 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 SF₆ 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

SF₆ used as cover gas in the aluminium industry is assumed to be inert. Consequently, the SF₆ emission equals the consumption.

2.4.4. Secondary foundries

SF₆ 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. SF₆ used as cover gas is inert and consequently the SF₆ emission equals the consumption.

2.4.5. Other SF₆ 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 SF₆ contained in the windows will be released when the glass is broken, or the windows taken out of service. The contribution to SF₆ 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 SF₆ the emission from the health service is disregarded.

2.5. Future consumption and emission of SF₆

2.5.1. Magnesium industry

The magnesium industry claim to have no basis for estimating their SF₆ consumption in the years 2000 and 2030. A drastic increase in their SF₆ requirements seems highly unlikely, however. SO₂ 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 SF₆ will have to be used but that the consumption will decrease due to development of new equipment and methods which require less SF₆ gas.

2.5.2. Gas insulated switchgear

The future use of SF₆ 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 SF₆ in the electricity supply, but the trade agrees that the number of new SF₆ 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 SF₆ installations has constantly increased. The first Norwegian SF₆ installation was established in 1973. The lifespan for SF₆ 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 SF₆ installations will be more compact, reducing the SF₆ requirement per installation. Because of the long lifespan for SF₆ installations, the electricity supply business has not to any detail considered the problems involved in equipment destruction. It is possible to extract SF₆ when equipment is destroyed, and the necessary equipment exists.

2.5.3. Aluminium industry

The one primary foundry in the aluminium industry which uses SF₆ today plans to substitute it with argon from 1994. The secondary foundries have no plans to change their use of SF₆.

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 SF₆.

3. Estimate of global consumption and emission of SF₆

The dominating use of SF₆ 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 SF₆ is presently between 5000 and 8000 tons (1990). The production of SF₆ in Europe in 1991 is estimated by one of the producers to 3000 tons. About 80 % of the total SF₆ 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 SF₆ is contained in electrical equipment. The recent improvement in equipment and gas recycling presumably yields that a decreasing fraction of the SF₆ produced is released to the atmosphere. The amount of SF₆ 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 SF₆ 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 practices 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 SF₆ 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 SF₆ as cover gas but some producers in eastern Europe and Russia probably still use SO₂. A global SF₆ emission has been estimated based on average SF₆ 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 SF₆ in secondary foundries is considerably smaller than in the primary foundries, and is therefore neglected.

Table 5: Global SF₆ 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 SF₆ emission

4.1. Magnesium industry

The Norwegian magnesium producer will continue to optimize casting machines and casting methods, in order to minimize SF₆ emissions.

4.2. Gas insulated switchgear

There is equipment for handling of SF₆ commercially available.

The equipment used for handling SF₆ 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) Disposable 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 SF₆ from gas compartments in connection with destruction of SF₆ installations. The storage of the removed SF₆ gas can be made to an installed tank, a separate tank or in SF₆ gas bottles. In this way the handling equipment contribute to reduction of SF₆ emission from gas insulated switchgear.

4.3. Sound insulating windows

There are today no alternative gases to SF₆ for use in sound insulating windows. New and more expensive types of windows are being developed which require less gas to give the same insulation effect. SF₆ will however still be used to give the best insulating product.

5. Radiative Forcing Due to SF₆

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 SF₆. Ramanathan et al. (1985), who studied the radiative effects of a wide range of species, mentioned SF₆ as a possible candidate for global warming, although they did not present any radiative model calculations for this species. Recently radiative model calculations and GWP estimates have been published by Ko et al. (1993). The present study also include calculations of GWP for SF₆. The methodology of a recent study of the radiative forcing and greenhouse warming potential of the fluorocarbons CF₄ and C₂F₆ (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 SF₆. 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 SF₆ are only reported for the ν_3 band (the HITRAN91 data base, Rothman et al., 1992). Hot band contributions to the radiative forcing can be estimated to be approximately three times the contribution from the ν_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 ν_3 band only. An earlier study based on another of the models (the NILU model, Stordal and Myhre, 1991b) only considered the ν_3 band, yielding a GWP value of SF₆ which represented a considerable underestimate.

In the present study, radiative calculations including all SF₆ 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 ν_3 band. Flux calculations were performed on the altitude range 0-60 km. The wave number interval covered by these calculations was $940\text{-}955\text{ cm}^{-1}$. 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 ν_3 band. Only for the ν_3 band spectral data are available in the HITRAN91 database. The integrated band strength for the ν_3 band is $5.234 \times 10^{-17}\text{ cm}^{-1}/\text{molec cm}^{-1}$, or $1408\text{ cm}^{-2}\text{ atm}^{-1}$.

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 $4800\text{ cm}^{-2}\text{ atm}^{-1}$, 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 $4800\text{ cm}^{-2}\text{ atm}^{-1}$ (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 ν_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, ν_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 ν_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 $940\text{-}953 \text{ cm}^{-1}$ 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 , ν_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	$\text{H}_2\text{O}, \text{CO}_2$	0.220	0.203	
4	$\text{H}_2\text{O}, \text{CO}_2, \text{O}_3$	0.220	0.203	
5	$\text{H}_2\text{O}, \text{CO}_2, \text{O}_3, \text{CH}_4, \text{N}_2\text{O},$ 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 H₂O and CO₂ decreases the irradiance change from SF₆ by 8 and 3 % respectively in the UoR model (case 1 and 2 vs case 3). A similar effect of overlap with H₂O has been found in the NILU model, which does not include overlap with the relatively weak CO₂ band near 948 cm⁻¹. The effects of O₃, CH₄, N₂O, CFC-11 and CFC-12 are negligible in both models. There is uncertainty in the precise overlap between SF₆ and the lines of CO₂ and H₂O, 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 SF₆ 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 SF₆ 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 SF₆ 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 SF₆ is on the order of 10-15% when compared to line by line calculations. We assume that the SF₆ 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 SF₆ 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 ν₃ band, we recommend an SF₆ forcing, in the ICRCCM approximation, of 0.240 W/m² +/- 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 et al., 1992), it has been omitted in the present study.

Global mean forcing for SF₆ has been calculated in this study with the two band models (the UoR and NILU models). Calculations have been performed both for the ν_3 band alone and for the total SF₆ absorption.

In the present study the global mean is calculated by taking into account the latitudinal and seasonal variation of temperature, H₂O, O₃ and cloudiness, using available climatologies. Results from the UoR model are shown in Figure 1 for a 1 ppbv increase of SF₆, 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 SF₆ 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 SF₆. 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 radiative 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 SF₆.

Present work:	ν_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

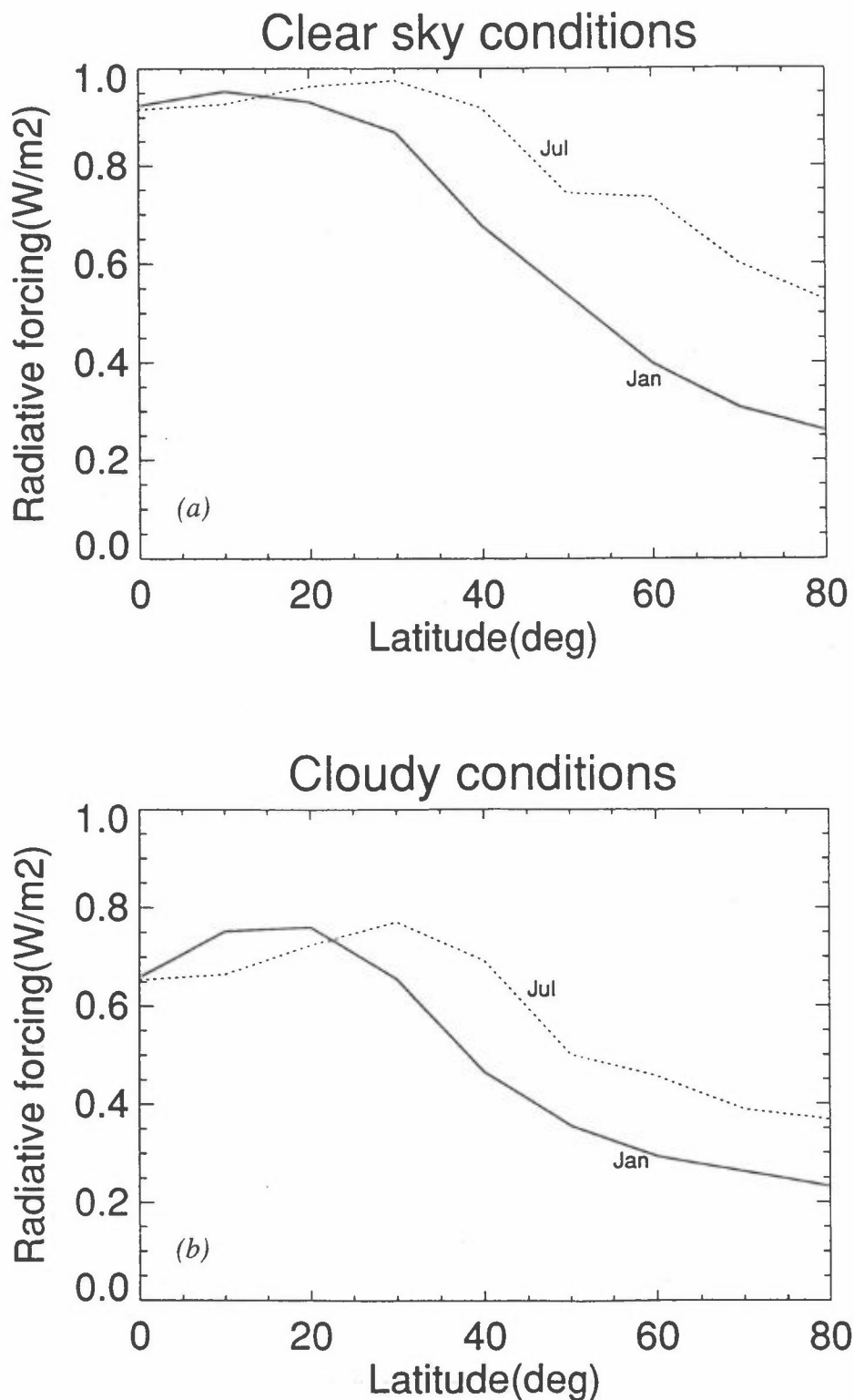


Figure 1: Latitudinal variation of radiative forcing (Wm^{-2}) for a 1 ppbv increase in SF_6 concentration as calculated with the UoR model. (a) SF_6 forcing for the clear sky case for January and July (b) As (a) but for cloudy conditions. All calculations have been performed using the total SF_6 band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

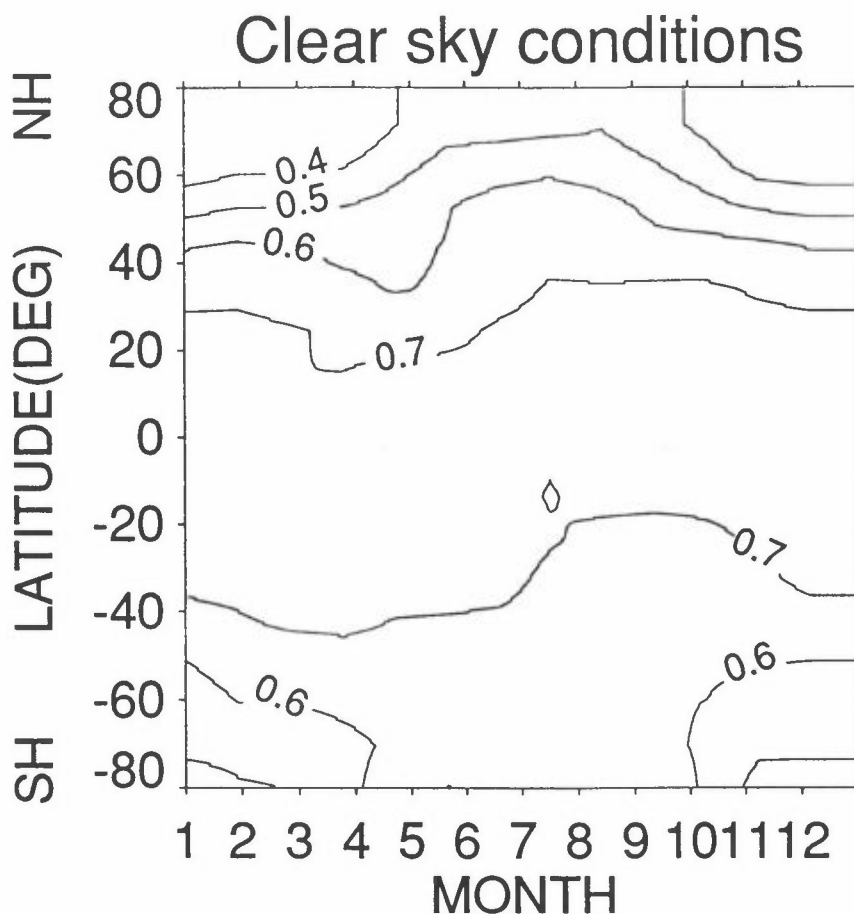


Figure 2: Latitudinal and seasonal variation of radiative forcing (Wm^{-2}) for a 1 ppbv increase in SF_6 concentration as calculated with the NILU model using the total SF_6 band strength reported by Varanasi (1993). Clouds have not been included in the calculations.

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 $0.602 \text{ Wm}^{-2}/\text{ppbv}$ 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 $\pm 20\%$. 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 ν_3 band. Clearly, the uncertainty in the globally averaged forcing described here is significant.

Adopting the value for SF₆ forcing recommended above, the strength of SF₆ relative to CO₂ and CFC-11, are given in Table 8. Values for the radiative forcing of CO₂ 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 CF₄ and C₂F₆, as reported by Isaksen et al. (1992).

Table 8: *Relative strength of SF₆, CF₄ and C₂F₆ compared to the IPCC values of CO₂ and CFC-11 (only direct radiative effects included), on a per molecule and a per unit mass basis.*

Gas	Relative strength per molecule		Relative strength per unit mass	
	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 ₂ F ₆	16 900	1.37	5 360	1.37

SF₆ is extremely potent as a greenhouse gas absorbing substantially stronger even than the efficient greenhouse gases CF₄ and C₂F₆. 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

$$GWP = \frac{\int_0^{t_h} a_i c_i dt}{\int_0^{t_h} a_r c_r dt} \quad (1)$$

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 SF₆, 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:

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

Equation (2) is a very accurate measure of GWP for CF₄ and C₂F₆, with lifetimes expected to be larger than 10000 years. The lifetime of SF₆ 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:

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

The reference gas used when defining GWPs is usually CO₂, the dominant contributor in the greenhouse gas problem. CO₂ 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 SF₆. Numbers are given relative to CO₂ and CFC-11. Radiative forcing and lifetimes for CO₂ 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 SF₆. As the lifetime of SF₆ 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 discrepancy is probably largely due to the 23 % higher band strength used by Ko et al. (1993).

6. Contribution of SF₆ to global warming

One way of assessing the impact of SF₆ as a greenhouse gas is to compare its emissions weighted by its GWP, with emissions of other greenhouse gases, as e.g. CO₂. 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 SF₆ are somewhat uncertain, it seems likely that SF₆ 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 CO₂ tons. In 1990 the anthropogenic CO₂ emissions were 27 G tons (Houghton et al., 1992). SF₆ thus contributed with about 0.2 % of the CO₂ emissions, or about 0.1 % of the total emissions of greenhouse gases in 1990, when the contribution of CO₂ emissions made about 60 % (Houghton et al., 1990) of the total anthropogenic effect.

In some countries, as e.g. Norway, SF₆ 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 CO₂ tons when applying the GWP on a 100 year time horizon. The Norwegian emission of CO₂ was 35 M. tons in 1990, consequently, in the Norwegian greenhouse gas budget of 1990, SF₆ contributed with about 5 % compared to CO₂. 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 SF₆ is to evaluate the effect of its presently observed atmospheric content, weighted by its relative strength per atmospheric molecule (Table 9). Houghton 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 CO₂. The atmospheric concentration of SF₆ has been measured to be about 2 ppt (Rinsland et al., 1990). Weighting this amount with the relative greenhouse strength of SF₆ 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 SF₆ compared to the warming due to CO₂ increase in the year 2010. Since SF₆ does not contain chlorine, it does not influence stratospheric ozone. SF₆ therefore has no known indirect climate effect.

In conclusion, SF₆ 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. SF₆ is extremely potent as a greenhouse gas, and large emissions should therefore be avoided.

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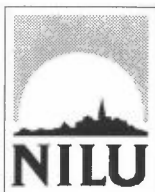
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ENTRY SF ₆	Emission assessment	GWP calculations	
ABSTRACT Norwegian and global sources of SF ₆ have been assessed, and GWP values have been calculated. It is found that on a global scale SF ₆ plays a minor role in the currently increasing greenhouse 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: An assessment of Norwegian and global sources and the Global Warming Potential			
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* Categories: A *Open - can be ordered from NILU*
 B *Restricted distribution*
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