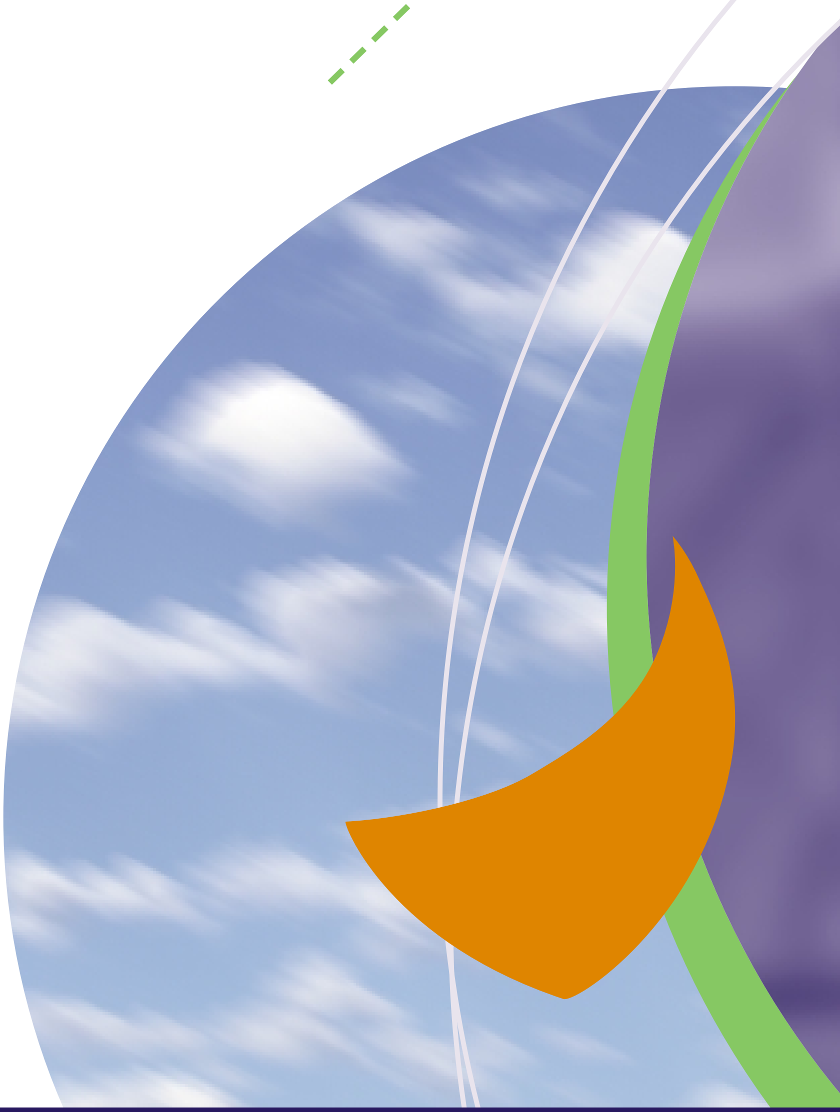
Australian Greenhouse Office
April 2000

Synthetic Gas Use in Non-Montreal Protocol Industries



AUSTRALIAN
Greenhouse
Office
The lead Commonwealth
agency on greenhouse
matters

prepared by
Burnbank Consulting

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Synthetic Gas Use in Non-Montreal Protocol Industries

Foreword

Although the full range of effects of increased greenhouse gas emissions in the Earth's atmosphere are not completely understood, the scientific evidence points to a discernible human influence on the global climate. While much of this influence is driven by the combustion of fossil fuels, a number of synthetic (ie industrially manufactured) gases have more recently been recognised as potent greenhouse gases. The global warming potency of these gases is, weight for weight, many hundreds or thousands of times more than carbon dioxide, and their use is increasing, particularly with the phase out of key ozone depleting gases.

Measure 7.2 of the National Greenhouse Strategy calls for the development of environmental management strategies for synthetic gases through coordinated action by all jurisdictions in consultation with industry. This report, which identifies current and likely future uses and emission sources of synthetic gases in the non-Montreal Protocol industries, lays the foundation for developing the environmental management strategies and initiates discussion on the range of technical response options for limiting emissions.

The Australian Greenhouse Office is pleased to present this study as a valuable contribution to the development of these strategies, and to the challenge faced by Australian industry and governments in collaboratively working to reduce emissions from the use of these potent gases. It is a difficult challenge, for the issues are diverse and complex.

I would like to commend the authors of the study, Burnbank Consulting, as well as acknowledge the contribution of industry and other stakeholders in the preparation of this report.

Gwenyth Andrews

Gwen Andrews
Chief Executive
Australian Greenhouse Office

April 2000

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Executive summary

This discussion paper is concerned with:

- A clear identification of the current use and emissions of synthetic gases in non-Montreal Protocol industries, including a life-cycle analysis on the use of synthetic gases, and their possible extension or further use by industry;
- A consideration of data collection regimes on synthetic gases in order to ensure that both the National Greenhouse Gas Inventory and emissions projections work adequately addresses the three gases;
- Identification of the widest range of possible response options.

Three main industries are identified that either emit synthetic gases as an incident to the production process or use and emit synthetic gases in Australia , namely:

- magnesium production;
- aluminium smelting; and
- electricity supply and transmission.

Magnesium production

Sulphur hexafluoride (SF_6) is the vital constituent in the cover gas used for magnesium casting, preventing reaction between the molten magnesium and air.

Magnesium producers that follow “best practice” in modern plants lose about 1kg of SF_6 to the atmosphere for every tonne of magnesium or magnesium alloy produced but forecast improvements will see this fall to about 0.5kg per tonne. Other sources of SF_6 are the casting of magnesium products (losses of 0.1 to 1 kg per tonne depending on the technology), and experimental work in magnesium casting.

To date, small quantities of SF_6 have been used from time to time in Australian processing of magnesium. They are used in experimental work on casting by CSIRO and the Cooperative Research Centre (CRC) for CAST Metals Manufacturing (CASTmm), Australia Magnesium Corporation’s (AMC) magnesium-metal demonstration plant at Gladstone, and by specialist Australian foundries when producing magnesium castings.

In the future, Australia has the potential to become a significant producer of magnesium. The ultimate implications for Australia’s SF_6 use depend on:

1. the likelihood of various projects proceeding; and
2. the usage of SF_6 by these projects.

The timeframe and success rate of the Australian projects will depend on growth in the world magnesium market, which in turn depends primarily on replacement of aluminium and steel automobile components by magnesium alloys. Lighter magnesium parts bring environmental benefits in the form of higher automotive fuel efficiency, and lower life-cycle greenhouse-gas emissions from automobiles, but only if SF_6 emissions can be reduced (Mellerud, 1999). Rapid replacement requires that the price of magnesium falls, and that actual and perceived disadvantages of magnesium are addressed by producers (Cole 1999).

Both of these preconditions are possible. The cash production cost estimates presented at the recent Inaugural Australian Magnesium Conference suggested the proposed facilities could undercut the current world price. This would generate the economic incentive for the global car companies to move more quickly towards magnesium components.

The International Magnesium Association (IMA) has advised member firms of the high GWP of SF_6 and provided them with technical information on how to reduce emissions. It is also co-ordinating efforts to develop SF_6-free magnesium production. Work is proceeding independently by at least four of the world magnesium players to develop solutions, with a variety of different approaches under examination.

Australia’s magnesium production is not necessarily tied to the use of SF_6. A new production technology being evaluated by one Australian magnesium venture may avoid the use of SF_6 cover gas. Other projects may choose to use SO_2, despite operational shortcomings, as a short-term solution. Australia’s primary magnesium producers could be SF_6-free by 2008, the start of the Kyoto Protocol commitment period. This outcome is probable and will depend on the results of current research on alternatives and the rate of diffusion of any new technology.

The magnesium companies have a keen interest in reducing and eventually eliminating SF_6 emissions. They recognise that they will be subject to increasing pressure to minimise emissions, particularly given that SF_6 is not the only greenhouse gas that will arise from magnesium production. In developing possible response options the following could be considered:

- The stand-back option. Do nothing for the present except maintain a watching brief being ready to take action if projects go ahead without appropriate technology. This approach is likely to be best if the pessimistic scenario for magnesium production and optimistic scenario for research into SF_6 alternatives eventuate.
- The keep-abreast of SF_6 research option. Do nothing except liase with the IMA and its SF_6 committee to keep abreast of the potential for SF_6 free production until more information comes to hand later this year. This will be advantageous if, as expected, feedback from the research becomes available before the projects become too advanced. It would allow government to specify what production technologies should not be allowed under EIS approval.
- Voluntary reporting by the proposed projects on projected greenhouse gas emissions. This could be part of the Greenhouse Challenge program. The advantage is that government objectives could be achieved without direct regulatory intervention.
- Mandatory reporting by the proposed projects. This would require some specification by government as to the detail of the report. It would be appropriate under the pessimistic scenario for research into SF_6 alternatives and the optimistic production scenario. This outcome would see a significant impact on greenhouse gas emissions, especially since some projects would generate significant process CO_2, and use large quantities of energy.

It is probable that Australia's magnesium producers will be SF_6-free by the commitment period. This will not obviate the need for monitoring greenhouse gas emissions from magnesium production. No detail is, as yet, publicly available on SF_6 alternatives, however, a cooperative approach should enable the Australian Greenhouse Office (AGO) to keep informed of developments in this area.

Aluminium smelting

Aluminium smelting gives rise to emissions of PFCs (CF_4 and C_2F_6) as a result of unwanted anode effects that occur in the production process. These emissions have been inventoried since the commencement of the compilation of Australia's national greenhouse gas inventory. The Australian aluminium industry has been at the forefront of research into controlling anode effects and reducing emissions of PFCs.

Since 1990, emissions of PFCs have declined by more than 70 per cent. Reporting of PFC emissions has been transparent. In addition, the industry has participated in the Greenhouse Challenge Program since 1996 and provides annual reports to the Australian Greenhouse Office on actions to reduce greenhouse gas emissions including emissions of PFCs.

The Australian aluminium smelting industry provides an example of "best practice" management in abating emissions of PFCs. This is reinforced by the information provided on other countries by Dolin (1999).

The voluntary agreements process under the Greenhouse Challenge Program is an example of a practice that has been adopted elsewhere, for example, the USA where the Voluntary Aluminium Industrial Partnership was implemented in 1998. So far the program has been successful and could be characterised as an example of "best practice'. The real test of voluntary programs and cooperation will come if there is a need to implement costly reductions in emissions.

Electricity transmission and distribution

Electricity transmission and distribution is a potentially significant area of SF_6 emissions where information for Australia is most deficient. Research into alternatives to SF_6 is being undertaken, but as yet SF_6 remains superior to the single gases and gas mixtures that have been investigated.

Attention has been focused on reducing emissions through improving the information on inventories of SF_6 used in equipment, monitoring the amount of SF_6 contained in equipment in service and leakage rates from equipment, improving seals and reducing leakage rates from new equipment, and recovery and recycling of contaminated SF_6.

Australia's electricity supply industry is understood to be addressing the issue of SF_6 through cooperative agreements under the Greenhouse Challenge Program. The discussion in the paper has highlighted several information deficiencies that need to be addressed in the context of framing a cooperative environmental management strategy. This includes acquiring information from electrical supply companies on:

- The equipment that includes SF_6, the quantity included in different types of equipment, and the number of units of equipment.
- The processes used for determining the quantities of SF_6 contained in equipment in service which in turn indicates leakage rates.
- The procedures used to determine quantities in equipment in service need to be clearly specified.
- The processes used for recycling normally arced and heavily arced gas, and the availability of reclaiming and recycling equipment.
- The rate of replacement of existing equipment, and the rate of increase in the installation of new equipment containing SF_6 including the quantities of SF_6 and number of units.
- The fate of SF_6 on decommissioning of equipment.

There is no formal data collection regime that ensures that both the National Greenhouse Gas Inventory and emissions projections work adequately addresses emissions of SF_6 from electricity transmission and distribution. The best and most desirable response option would be to obtain the cooperation of the electricity supply industry, preferably through the Electricity Supply Association of Australia, so as to answer the questions posed above. This would enable investigation into whether additional information is required, the type of additional information, and identification of areas where some assistance might be provided to the industry.

Without industry specific information it is impossible to determine whether substitutes for SF_6 should be encouraged, or whether more stringent policy approaches that would ensure curtailment of SF_6 emissions should be considered.

Other industries

No response options are suggested in respect of the other industries discussed because they are highly unlikely to become significant in Australia. Informal oversight of developments in the electronics industry could be considered so that the AGO is aware of any changes in the industry that could lead to the establishment of plants or commencement of activities using synthetic gases.

Information availability, data collection and verifiability

Difficulties with obtaining information and data have been highlighted. There is a need to overcome information deficiencies particularly in relation to the supply of synthetic gases and the use of SF_6 in the electricity supply industry.

It is essential that mechanisms be established to obtain the necessary information and data to facilitate proper planning within industries and enable effective implementation of domestic greenhouse gas policies. These mechanisms range from cooperative approaches with associated verification to more costly mandatory approaches enshrined in legislation. The former are preferable, but the latter could be inevitable in the absence of industry initiated actions to collect and make available the required information and data. One possible approach would be to have State agencies require reporting under the various licensing regimes that operate within each jurisdiction.

Irrespective of any reporting mechanisms, there will be a need for verification and validation of information. Because atmospheric fluxes of synthetic gases are entirely attributable to anthropogenic activities, reported emissions estimates can be compared with the emissions estimated from atmospheric concentrations. Significant divergence would indicate that reported emissions estimates are inaccurate. This can be used as an important approach to data validation.

Abbreviations

AE	*Anode effect*
AEEMA	*Australian Electronic and Electrical Manufacturers Association*
AGO	*Australian Greenhouse Office*
AMC	*Australian Magnesium Corporation*
ASIC	*Application specific integrated circuits*
ATV	*All terrain vehicles*
CAFE	*Corporate Average Fuel Economy*
CASTmm	*CAST Metals Manufacturing*
CF_4	*Tetrafluoromethane (perfluoromethane)*
C_2F_6	*Hexafluoroethane (perfluoroethane)*
CFC	*Chlorofluorocarbons*
CHC	*Chlorohydrocarbons*
Cl	*Chlorine*
CO_2	*Carbon dioxide*
CRC	*Cooperative Research Centre*
CVD	*Chemical vapour deposition*
DCITA	*Department of Communications, Information Technology and the Arts*
DISR	*Department of Industry, Science and Resources*
DSM	*Dead Sea Magnesium*
EMS	*Australian Electronics Industry Manufacturing Study*
FCCC	*See UNFCCC below*
Fe	*Iron*
GWP	*Global warming potential*
HFC	*Hydrofluorocarbon*
IC	*Integrated circuit (includes VLSI and ULSIs)*
IMA	*International Magnesium Association*
IPCC	*Intergovernmental Panel on Climate Change*
IR	*Infra red*
Kt	*Kilotonne*
Ktpa	*Kilotonnes per year*
MAC	*Magnesium Alloy Corporation*
MEPS	*Minimum Energy Performance Standard*
Mg	*Magnesium*
$MgCl_2$	*Magnesium chloride*
$MgCl_2.6H_2O$	*Magnesium chloride hydrate*
$MgCl_2.6NH_3$	*Magnesium chloride hexammoniate*
MPC	*Multi-polar cell*
Mt	*Megatonne*
MVEC	*Motor Vehicle Environment Committee*
NADCA	*North American Die Casting Association*
NAFC	*National average fuel consumption*
NECA	*National Electricity Code Administrator*
NGGI	*National Greenhouse Gas Inventory*
PCB	*Printed circuit board or Polychlorinated biphenols*
PFC	*Perfluorocarbon*
PNGV	*Partnership for a New Generation of Vehicles*
ppm	*parts per million*
R&D	*Research and Development*
RF	*Radio Frequency*
SA	*South Australia (or South Africa)*
SF_6	*Sulphur hexafluoride*
Si	*Silicon*
SMCBA	*Surface Mount and Circuit Board Association*
tpa	*tonnes per annum*
ULSI	*Ultra Large Scale Integrated Circuit*
UNFCCC	*United Nations Framework Convention on Climate Change*
USCAR	*United States Council for Automotive Research*
USGS	*US Geological Survey*
VLSI	*Very Large Scale Integrated Circuit*
VUT	*Victoria University of Technology*

1

Introduction

1 Introduction

1.1 Background

As a signatory to the United Nations Framework Convention on Climate Change (FCCC), which entered into force on 21 March 1994, Australia has accepted a range of obligations in respect of greenhouse gas emissions abatement. Included amongst these obligations are several measurement and reporting requirements for greenhouse gas emissions. The FCCC describes the emission target as, 'the aim of returning individually or jointly to their 1990 levels these anthropogenic of carbon dioxide and other greenhouse gases not controlled by the Montreal Protocol' (Article 4, paragraph 2, sub-paragraph (b)).

The Kyoto Protocol to the FCCC, which was agreed to on 10 December 1997 and was signed by Australia on 29 April 1998, crystallised the aim of the FCCC into quantified emission targets. Article 3, paragraph 1, of the Protocol states that:

'The Parties included in Annex I[1] shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts, calculated pursuant to their quantified emission limitations and reduction commitments inscribed in Annex B and in accordance with the provisions of this Article, with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012.'

The Protocol further states that:

'Each Party included in Annex I shall, by 2005, have made demonstrable progress in achieving its commitments under this Protocol' (Article 3, paragraph 2).

The quantified emission limitation or reduction commitment for Australia is 108 per cent of 1990 levels during the first commitment period, 2008 to 2012. That is, Australia's aggregate CO_2 equivalent emissions over the period 2008 to 2012 are to be no greater than 108 per cent of the CO_2 equivalent emissions for 1990 multiplied by five.

The Kyoto Protocol recognises that there are some greenhouse gases where a degree of flexibility in determining the base year is required. Article 3, paragraph 8 of the Kyoto Protocol states:

'Any Party included in Annex I may use 1995 as its base year for hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride, for the purposes of the calculation referred to in paragraph 7 above.'

The reason for allowing countries to use a base year other than 1990 for these gases is that implementation of the Montreal Protocol and subsequent amendments during the 1990s has resulted in the substitution of HFCs and PFCs (some of which are potent greenhouse gases) for CFCs and HCFCs (ozone depleting substances) in many applications including air conditioning and refrigeration. In 1990, actions to abate ozone depleting substances were of relatively recent origin.

The gases referred to in Article 3, paragraph 8 are collectively referred to as synthetic gases. The control regime for these gases in Montreal Protocol industries is administered by the Ozone Protection Section of Environment Australia and covers uses in refrigeration, air-conditioning, aerosols, fire extinguishers, foam blowing, metered dose inhalers (MDIs), and solvents. This discussion paper is concerned with the generation and use of these gases in non-Montreal Protocol industries. Despite the fact that the paper does not address Montreal Protocol industries, it is emphasised that emissions of synthetic gases from these industries are required to be included in the National Greenhouse Gas Inventory and in the development of environmental management strategies.

1.2 The National Greenhouse Strategy

The framework for Australia's response in meeting its commitments under the FCCC and Kyoto Protocol is the National Greenhouse Strategy (NGS). The Strategy extends the program of action launched by all Australian Governments in the 1992 National Greenhouse Response Strategy.

The NGS has been developed by the Commonwealth and all State and Territory Governments. The Australian Local Government Association, and industry and community consultations have made an important contribution. Further, in endorsing the Strategy, the Commonwealth, States and Territories demonstrate the commitment of governments to an effective national greenhouse response.

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[1] Annex I refers to those Parties named in Annex I of the FCCC. Annexes A and B are annexes to the Protocol.

The Strategy is comprised of a series of measures designed to reduce Australia's contribution to greenhouse gas emissions. For each measure, responsibility for implementation is allocated to particular levels of government. Measure 7.2 is concerned with environmental management strategies for synthetic gases. It states:

'Governments will work with industry to develop environmental management strategies for each of the synthetic gases included in the Kyoto Protocol – HFCs, PFCs and SF_6. The strategy for HFCs will address the use of HFCs in non-refillable containers.'

This discussion paper is a precursor to the development of relevant environmental management strategies. The NGS indicates that governments are to address this measure through coordinated action in partnership with industry.

1.3 Synthetic gases

The synthetic gases specified in the Kyoto Protocol are potent greenhouse gases. The GWPs for several of these gases are shown in table 1.1. As can be seen from the table, small quantities of emissions can lead to measurable growth in CO_2 equivalent emissions. Central to appropriate environmental management of these gases is to minimise emissions to the atmosphere and contribution to global warming, whilst exploiting the beneficial properties in many applications.

The synthetic gases have many desirable properties as substitutes for CFCs and HCFCs and in a range of other uses, the most important of which are discussed in detail in the following sections of the paper. Some are also emitted as by-products in the manufacture of other goods, such as the PFCs generated as a by-product of process upsets in aluminium smelting.

Table 1.1: Global warming potentials of synthetic gases

Gas	GWP (100 years)
HFC-23	11,700
HFC-134a	1,300
Perfluoromethane	6,500
Perfluoroethane	9,200
Perfluoropropane	7,000
Sulphur hexafluoride SF_6	23,900

Source: IPCC (1996; p. 22)

Research undertaken in the preparation of the discussion paper indicated that the main uses of SF_6 are in magnesium production, and electricity transmission and distribution. Use of HFCs and PFCs in non Montreal Protocol industries in Australia is minimal, although this could change in the future. Areas of possible growth are discussed briefly. Most attention has been paid to sulphur hexafluoride, a compound with many desirable properties that make it suitable for a variety of important commercial and research uses. It is chemically inert, non-toxic, non-flammable, non-explosive, and thermally stable. Possible applications are summarised in table 1.2.

1.4 Structure of the paper

The paper is structured as follows. Section 2 is concerned with the production of magnesium and alloys. This is an industry that has the potential to become an important source of SF_6 emissions. In section 3 aluminium smelting is discussed. Emissions of PFCs from aluminium smelters are due to anode effects in the pots and are a by-product of an unwanted event. This is followed in section 4 by a discussion of the use of SF_6 in electricity transmission and distribution. SF_6 is the preferred dielectric used in high voltage electrical equipment. Section 5 examines the use of synthetic gases in the electronics industry. The possibility for development of an electronics industry in Australia is analysed. Comment on various minor uses of synthetic gases is provided in section 6. Section 7 concludes the paper.

Table 1.2: Applications of sulphur hexafluoride

- Semiconductor processing.
- The active constituent in the cover gas (blanket gas or asphyxiant) for magnesium metal production and in magnesium foundries.
- As a reactive gas in aluminium recycling to reduce the porosity and maintain the structural integrity of the metal.
- Thermal and sound insulation.
- Aircraft tyres.
- "Air sole" shoes.
- Scuba diving equipment.
- Voice communication.
- Leak detection.
- Atmospheric trace gas studies.
- Ball inflation.
- Torpedo propeller quieting.
- Wind supersonic channels.
- Insulation for airborne warning and control system (AWACS) radar domes.

2

Metals processing — Magnesium and alloys

2 Metals processing - Magnesium and alloys

2.1 Introduction

Australia does not currrently have a magnesium industry, but it possesses world-class deposits of magnesium ore and cheap electric power, the two essential requirements for magnesium production. Proposals for nine magnesium plants are the subject of feasibility analyses and some analysts have predicted that Australia is poised to become the world's largest magnesium producer (Brown and Pawleck 1999; ACTED 1999).

Internationally, the magnesium industry is the second largest emitter of sulphur hexafluoride (SF_6). Only the electricity supply industry emits more SF_6. The International Magnesium Association (IMA 1999) estimated it used 7 per cent of the world's production of SF_6 in 1996. Given the world consumption of 7500 metric tonnes (Solvay 1999), primary production of magnesium (341,000 tons, USGS, 1998b) used about 525 metric tonnes of SF_6, generating about 1.54kg of SF_6 emissions per tonne of primary magnesium. While some of these emissions were generated by secondary processors of magnesium, primary producers generated over 1 kg per tonne.

Virtually all SF_6 used by the magnesium industry as a cover gas is emitted. Under the leadership of the IMA, the industry is seeking to reduce SF_6 emissions by improving operating practice and modifying plant design. Ultimately, the goal is to eliminate emissions by developing replacement and recycling options.

Given the prospect of Australia becoming a significant producer of magnesium and the importance of SF_6 to the magnesium production industry, the issue of emissions of SF_6 to the atmosphere from magnesium production is an important matter in the context of Australia's greenhouse gas policy.

This section describes the production processes for magnesium and changes occurring in the production technologies. The discussion includes a detailed description of the importance of SF_6 as a cover gas (asphyxiant) in large scale production processes. The factors driving the expansion of the international and Australian industries, new technologies that might eliminate or reduce SF_6 emissions, and the likely outcomes of efforts by the industry to reduce SF_6 emissions are examined. The international outlook for magnesium production is discussed. This is followed by a discussion of the eight Australian magnesium projects. Finally technical response options are discussed.

2.2 Magnesium production

2.2.1 PRODUCTION PROCESSES AND TECHNOLOGIES

Magnesium metal has been commercially important for over 50 years. Magnesium is abundant in the earth's crust. In low concentrations, it is widespread as a dissolved salt in oceans and underground brines, and in minerals and clays on land. Concentrations of magnesium occur in a range of ore bodies, including magnesite ($MgCO_3$), dolomite (($MgCO_3.CaCO_3$), magnesium oxide (MgO), and carnallite ($MgCl_2$). Magnesium is also contained in residues from other mining activity such as brines resulting from salt and potash extraction tailings from asbestos mining.

There are two principal routes for producing magnesium from the processed magnesium mineral — electrolysis and direct reduction. In the *electrolytic* process, molten magnesium chloride feedstock is broken down into chlorine (discharged as a gas at the anodes), and magnesium which separates as a molten metal. The electrolysis occurs from about 670 °C to 730 °C, a little above the melting point of magnesium (650 °C). A variety of electrolytic cells have been developed to suit the different feedstocks. Facilities being developed in the 1990s increasingly propose to use the Alcan cell, originally developed to recycle the magnesium reductant used to produce titanium from titanium tetrachloride feedstock. The Alcan cell requires a high-purity anhydrous magnesium chloride feedstock and new producers must develop or buy special feedstock pre-processing knowhow.

In the *direct reduction* process, a reactive element (carbon, silicon or aluminium) displaces some carbonate/oxide radicals from the magnesium mineral, thus generating elemental magnesium. The reaction typically takes place in a molten iron or slag solution at temperatures above the vaporisation point of the magnesium (1200 °C–2000 °C). Once displaced, magnesium vaporises from the melt, filling the vacuum or inert gas space above the retort before condensing as 'crowns' of powder or crystals in a cooling chamber off the retort proper. The most important direct reduction process is the *silico-thermal* process which uses silicon as the reducing agent (carbon is potentially deleterious due to the reactivity of molten magnesium). A typical feedstock for the silico-thermal process is a dolomite/ferro-silicon alloy mixture, and the typical residual, after the vaporisation of the magnesium, is calcium silicate slag and molten iron.

The silico-thermal and electrolytic processes are compared in table 2.1 below. The comparison points to the greater potential of the electrolytic process for large-scale continuous processing, with continuous casting of ingots of pure or alloyed magnesium. This potential depends, *inter alia*, on the low–cost production of high-purity anhydrous magnesium chloride feedstock.

The new large-scale plants (exceeding 10,000 tpa) use the electrolytic process. To compete with the older depreciated plants, they use new waste-reducing leaching and dehydration technologies to get economies in the pre-electrolysis processing of the mineral to a magnesium chloride feedstock. Chlorine generated by the electrolysis is recycled as hydrochloric acid to convert the oxide, carbonate or silicate ore to a magnesium chloride feedstock. In Canada, Noranda Inc's new Magnola project uses hydrochloric acid to extract the magnesium as the chloride salt, from silicates. In Australia, Australian Magnesium Corporation (AMC) uses hydrochloric acid to extract magnesium from carbonates. The recycling reactions take the following form:

$H_2 + Cl_2 = 2HCl$ and $MgCO_3 + 2HCl = MgCl_2 + CO_2$

Some new entrants to the industry — Dead Sea Magnesium (DSM) and Magnesium Alloy Corporation (MAC) — will use magnesium chloride as their source of magnesium. These producers do not need the chlorine gas from the electrolytic cell to convert the ore to the chloride form. They must on-sell the chlorine to downstream manufacturers, or otherwise use or dispose of it in a non-polluting way. In Australia, the use of by-product chlorine will be a consideration for the Pilbara Magnesium Metal Associates magnesium project at Dampier, WA.

Processes using the Alcan electrolysis cell remove calcium and alkali chlorides and all water of hydration from the magnesium chloride feedstock. This is difficult because anhydrous magnesium chloride reacts with its own water of crystallisation (hydrolysis), forming magnesium hydroxide and so reducing the purity of the anhydrous magnesium chloride. The available dehydration processes are generally patented. AMC will

Table 2.1: Comparison of the electrolytic and silico-thermal processes

Process name	Reaction	Feedstock	Advantages
Electrolysis	$MgCl_2$ + Energy = Mg + Cl_2	The magnesium ore must be converted to $MgCl_2$ before being fed into the cell.	Potential for large-scale low cost production.
Silico-thermal	($CaCO_3$ + $MgCO_3$) + FeSi = Mg(vapour) + CaSiO4 + $2CO_2$ + Fe	Complex pre-processing not needed for carbonate and oxide ores; calcium impurities need not be removed.	Although generally a low-scale batch process, it is suited to the refining of very pure magnesium.

use a patented process that converts the hexahydrate to a hexammoniate that converts easily to the required pure anhydrous magnesium chloride feedstock. Noranda and Magnesium Alloy Corporation (MAC) use a patented chlorine-based fluidised-bed technology.

An important property of magnesium is its reactivity. This complicates production management and is the reason for the use of a cover gas as discussed below. Reactivity is also a beneficial attribute leading to uses not only in incendiaries, but also in desulphurising steel, in sacrificial anodes that combat corrosion, batteries, and in producing other metals (mainly titanium). Engineering properties are equally important — it is light (one third lighter than aluminium) and has the highest strength-to-weight ratio of the common engineering metals. It is an important constituents of alloys, with about one-half of the present production used as an ingredient in aluminium alloys (table 2.2).

Table 2.2: Uses of primary magnesium

Use*	Primary production in 1998 (‘000tons)	Per cent of primary production
Aluminium alloying**	154	49
Die casting**	75	24
Desulphurisation of iron and steel	50	16
Nodular iron (ductile iron for pipe and automotive drive trains)	11	3
Electrochemical (corrosion protection, batteries)	10	3
Chemical (Grignard reagents to produce complex compounds used in a wide range of applications, e.g., lubrication oils, silicones, pharmaceuticals, vitamins.	7	2
Metal reduction (titanium, zirconium, hafnium, uranium, and beryllium, boron)	5	2
Wrought products (bakery racks, loading ramps, etc)	4.5	1

Source: Edgar (1999)

* Excludes other uses such as pyrotechnics and printing.

**The addition of a few percent magnesium to aluminium results in an stronger alloy with better corrosion resistance. Marine alloys contain up to 5.5% magnesium, aerospace alloys contain 3.5%, aluminium beverage cans have 4.5 per cent in the lid, and 1.1 per cent in the body.

***Die-casting covers a range of related casting technologies, for example, squeeze casting and semi-solid metal casting. Die cast magnesium alloy components are used in motor vehicle manufacture, chain saws, cameras and sporting goods, brackets, distributor parts, etc. Sand and permanent castings are used for larger components in aircraft engines and airframes for example, leading-edge flaps.

2.2.2 THE ROLE OF SF_6-COVER GAS TECHNOLOGIES

Magnesium’s reactivity requires that special techniques be used in its production, processing and working. Special adaptations are required when magnesium becomes hot during processing, for example, heating prior to shaping or during machining. The preventative solutions depend on the application, and are well established, but can adversely impact on cost and quality. One solution is to design magnesium alloys to have higher melting points and better high-temperature engineering performance. Oxidation during melting and casting is minimised by alloys containing a low proportion of beryllium (less than 0.003%). The reactivity of magnesium products in adverse environments can be controlled, if desired, by appropriate coating but these solutions cannot be applied to production processes used for pure magnesium.

For an engineering metal, it has a relatively low melting point (700 °C). When molten, its reactivity and tendency to vaporise are very high. Its high affinity for nitrogen, oxygen and water vapour causes burning in air. The reaction between air and molten magnesium in charging, holding and alloying furnaces, and during transfer of molten metal must be prevented. There are four broad approaches for this:

- Engineer appropriate enclosures that exclude air from contact with the molten magnesium surface (the molten magnesium contacts the enclosing metal surface rather than a cover gas).
- Replace air in an enclosed space above molten magnesium by a vacuum or inert gas.
- Cover the surface of the magnesium with a low-density, low-melting point flux to exclude air contact.
- Use reactive chemicals, such as sulphur powder, sulphur dioxide gas, or sulphur hexaflouride gas to form a stable protective film on the surface of the molten magnesium.

The first solution is used to varying extents in processes such as the die-casting of small magnesium components. Three properties of magnesium facilitate this approach. Its melting point is low relative to steel, its heat capacity is low, and, when molten, it has a low adhesion/reactivity with ferrous metals. In consequence, the molten metal can be transferred short distances in steel pipes with positive displacement heated pumps. This approach is best seen as part of a solution, as it is difficult to exclude all contact with the atmosphere. It is also expensive to apply this approach to large-scale production plants, or to the sand casting of large frames or assemblies such as used in transport equipment.

The second (inert atmosphere) approach is applied when magnesium is withdrawn from electrolytic cells (as liquid) or from thermal furnaces (as vapour). It is not good practice in casting housing and furnaces, because of the complexity of the engineering, a loss of magnesium vapour, and safety concerns – the fine magnesium metal powder that condenses on the internal furnace wall when magnesium is melted under a vacuum or inert gas (argon) can explode when the furnace is eventually opened. An *active* cover gas (for example, dilute SO_2) prevents vaporisation by forming a barrier film on the molten magnesium surface. It is more effective and far less hazardous than an *inert* cover gas for processes involving molten magnesium.

The solid flux approach was common in magnesium casting houses until the 1970s when it was replaced by the use of SF_6 cover gas. Special fluxes were developed to prevent burning during the melting of magnesium. A fluid flux of low melting point was used to prevent oxidation and local burning before melting was complete. A heavier refining flux was added to absorb the protective fluid flux, and any oxide and nitride inclusions, prior to casting. The approach has disadvantages: corrosive halide gases are generated and the partial adsorption of the flux by molten magnesium can adversely affect purity, casting quality, and its suitability for some applications. However it is still used where quality is less important than cost (e.g. the casting of sacrificial anodes), and where SF_6-cover gas does not provide sufficient protection (e.g. the re-melting of scrap, or 'dirty' recycle magnesium).

The reactive cover gas approach was first employed with sulphur dioxide as the reactive ingredient. It competed with the solid flux approach, and was arguably superior where high quality castings were required. Following the introduction of the sulphur hexafluoride cover gas in the 1970s, some magnesium foundries/casting houses replaced sulphur dioxide with sulphur hexafluoride, others continued with the SO_2 cover gas technology.

The SF_6-cover gas comprises a mixture of three gases. The main gases are dry air and carbon dioxide and N_2 (for some magnesium alloys, air and argon). These account for over 99 per cent of the cover gas. However, the critical constituent is the reactive gas, sulphur hexafluoride, present at less than 0.5 per cent by volume. Its role is to chemically modify the oxide film. Sulphur dioxide promotes film stability by adding sulphate ions to the oxide film — sulphur hexafluoride by adding fluoride ions. Unlike sulphur dioxide, SF_6 is not corrosive or toxic, and its use poses less risk to health and the immediate environment.

Cover-gas technology is simple, precise and relatively cheap, especially when applied to open containing vessels. The cover gas can be directly applied to the molten surface, via pressure lines and nozzles. No enclosures are required. The amount of the reactive gas constituent can be maintained at the optimum with gas mixing technology. There is little loss of magnesium to the atmosphere as the film acts a barrier preventing vaporisation from the surface. The process is relatively safe as the reactive gas can be kept to low concentrations.

The major disadvantage of using an SF_6 cover gas with a open vessel is the loss of the SF_6 to the atmosphere. Very little of the reactive cover gas is used to form the protective surface film — to ensure the film is maintained, excess SF_6 is applied. (About 0.06% of SF_6 provides a sufficient excess of SF_6 for film stability in the laboratory, but operational practice in magnesium furnaces requires 0.3 to 0.5 per cent. This higher level ensures the continuity of the minimum SF_6 concentration in the gas immediately above the molten surface). The consumption of SF_6 in magnesium production currently equates to the level of its SF_6 emissions.

2.2.3 INDUSTRY MANAGEMENT OF SF_6 EMISSIONS

In the 1970s, when the industry adopted the SF_6 cover gas approach as best practice technology, there was little appreciation of the impact of SF_6 on climate. It was only in the 1980s that the industry became aware of how its SF_6 emissions added to global warming.

Since then, the industry has been working to minimise environmental impacts with research results being published at various conferences (Couling *et al*, 1988). Research into the level of SF_6 emissions was undertaken by Norsk Hydro, the world's largest primary producer (Gjestland *et al*, 1996). Norsk Hydro and other researchers assessed the levels of SF_6 emissions from (1) primary production operations, and (2) secondary and product casting. In both areas, the rate of SF_6 usage varied widely, often appearing in excess of that required. The proportion of SF_6 in the cover gas was often higher than that required. Just as importantly, crucibles were generally not enclosed.

Recognising that emissions of synthetic greenhouse gases could harm magnesium's reputation as an environmentally-friendly metal, the IMA published a special page on its web site advising the industry on ways to safely reduce their SF_6 emissions. The technical advice is contained in a 10-page brochure (Erickson *et al*, 1996), and is freely downloadable from the site.

The brochure details engineering solutions for minimising cover gas loss. These include:

1. enclosing the charging and holding vessels;
2. choosing dimensions that minimise the ratio of surface area to volume; and
3. carefully designing the mechanisms for feeding the furnace and casting the melt.

The IMA also provides advice on how to overcome the problems that can arise when the crucible/furnace/melting chamber is enclosed. The risk of burning can be reduced by increasing the concentration of the SF_6 in the cover gas in enclosures, although the IMA warns that very high concentrations of SF_6 are hazardous in their own right and to be avoided in an enclosed furnace.

Progress has been made in implementing these design criteria, despite the difficulty in preventing the loss of a cover gas during such furnace operations as adding alloying ingots to molten magnesium. The consultants were advised that, with best practice in equipment design and operational procedures, the loss of SF_6 per tonne of magnesium can be reduced to 0.5 kg in primary magnesium production, and to 0.1kg in die casting.

The industry is searching for an environmentally-friendly SF_6 replacement. The research is being driven not only by environmental concern, but also by high prices for SF_6. Moreover, the industry is aware that regulators may require it to eventually eliminate all SF_6 emissions –Magnola's commitment to Quebec's Environmental Review Board to phase out SF_6 by 2005 at the latest is indicative of the direction of environmental regulation.

Bringing back solid fluxes is not an alternative – it would have adverse implications for output quality, and may give rise to health and environmental concerns through the release of halide gas.

The industry is seeking a new solution, ideally one that will eliminate any synthetic gas emissions. At least four production/research consortia are working towards a solution. The long term solution may be a new technology/equipment that:

- does not use a high GWP reactive material in the cover gas; or,
- can prevent the loss of the reactive cover-gas ingredient gas to the atmosphere by recycling/reclaiming the reactive cover gas.

In the short run, however, it does not appear possible to prevent some loss of SF_6-containing cover gas from existing magnesium furnaces, crucibles, melting pots, casting lines, etc. The best outcome may be to minimise the contribution to the greenhouse effect, by developing and using:

- a low GWP replacement for the SF_6 in the cover gas; and/or
- new technology that reduces the loss of cover gas and minimises the proportion of the SF_6 (or SF_6 replacement) in the cover gas.

The second option involves equipping all furnaces and casting crucibles with enclosing hoods, and designing the enclosures to minimise interference to the boundary layers between the cover gas and molten metal surface in charging, melting, and casting operations.

The solution presently favoured by Norsk Hydro is replacement of SF_6 by SO_2. However Australian researchers from AMC, CSIRO and the CRC for CASTmm have questioned the suitability of SO_2. They argue that although SO_2 cover gas was used commercially prior to the popularity of SF_6, it has severe drawbacks in some critical processes, even if used under best practice in well–designed plant. The use of sulphur dioxide in charging, alloying or holding crucibles is hazardous, because it forms reaction products on the crucible wall. These reaction products react vigorously with molten magnesium when dislodged from the crucible wall, causing the molten magnesium surface to erupt.

At its 1999 annual conference, the IMA established a technical committee to determine how SF_6 emissions could be eliminated or further reduced. Australia is represented on the committee by AMC. Other committee members come from Norway's Norsk Hydro, Canada's Noranda Inc. (Magnola) and Israel's Dead Sea Magnesium (DSM). This committee will consider a range of options ranging from engineering solutions that involve total recycle to the possibility of alternative reactive agents in the cover gas.

2.2.4 IMPLICATIONS FOR SF_6 EMISSIONS

Ongoing research to eliminate SF_6 emissions from primary production of magnesium is expected to succeed eventually. It is possible that, by the first commitment period, *new* technology for magnesium production might not generate SF_6 emissions. However, the cost of modifying or converting already established technology to SF_6-free status may be considerable, and may delay the phase-down to SF_6–free production. Nevertheless, it is likely that the average rate of emissions could fall to 0.5kg of SF_6 per tonne of primary production under industry management and environmental legislation.

The Magnola schedule for SF_6 phase-out is considered to be the worst-case template for all magnesium primary producers. From a commencement rate of about 1.5kg SF_6 emissions per tonne of magnesium, Magnola will, after 18 months, reduce emissions to an interim limit of about 0.6 kg/tonne (the Norsk Hydro rate). Complete phase out is required by 2005.

Producers that do not undertake activities such as alloying, where an interim use of SF_6 might be warranted on safety grounds, should do better than Magnola. Because of the confidential and developing nature of magnesium-metal technology, claims that new ventures can replace SF_6 with SO_2 cover gas technology should be supported. Data from pilot plant or from comparable existing installations would support assurances that claimed environmental outcomes can be fully met with confidence.

The move to develop SF_6-free production technologies is coming at a time of significant change within the magnesium industry. This is evidenced in the large number of new magnesium projects coming on stream or awaiting completion of feasibility studies. Nine Australian projects have ongoing feasibility studies. If the current expectations of these magnesium producers are met, primary magnesium production in Australia could reach 533.5 thousand annual tonnes (the optimistic scenario for magnesium). Then, even at the emission rate of 0.5kg of SF_6 per tonne, magnesium production would be a very significant contributor to Australia's annual greenhouse gases with 6.4 million tonnes of CO_2-equivalent emissions.

To better assess the likely outcome for Australia's SF_6 emissions, supply and demand developments internationally and within Australia need to be examined.

2.3 International outlook for magnesium production

2.3.1 DEVELOPMENTS IN MAGNESIUM-USING TECHNOLOGIES

The outlook for magnesium is changing under the combined influences of:

- An increasing demand for lighter, more environment-friendly products for transport and other industries;
- Expectations that emerging technologies for primary magnesium production will meet the increased demand for magnesium alloys, not only increasing magnesium supply, but also reducing its price; and,
- Expectations that emerging technologies for casting magnesium alloys will deliver the desired weight reductions to the automobile producers at reduced cost without performance penalties by improving overall production efficiencies.

Lighter materials allow efficiencies in transport, and when recycled, reduce waste. Aluminium is a major beneficiary from these factors. Magnesium benefits because it is an important ingredient in aluminium alloy. Magnesium also directly benefits through replacement demand, because (1) magnesium alloy has a higher strength to weight ratio than aluminium, (2) unit production costs for mass-produced magnesium components are much less than for steel, and potentially less than for aluminium, (3) magnesium framing complements aluminium sheeting to produce cost-effective weight-saving alternatives to steel assembles for transport equipment.

In the past, the high strength-to-weight advantage in structural and engineering applications has been offset not only by low corrosion resistance, poor creep properties at elevated temperatures, and some problems in metal-working, but also by a high price and uncertainly in supply. Of these disadvantages, the high price was arguably the most critical. It discouraged the development of appropriate alloys and processes to reduce magnesium's weaknesses and better exploit its strengths. For example, it may be that the capacity of magnesium components to dampen mechanical vibrations was not exploited due to its low creep resistance at engine temperatures (McGraw-Hill 1997, v10, p.298). In one instance, a price rise relative to aluminium contributed to the 'reverse' substitution of aluminium for a magnesium alloy automotive part. As discussed below, temporary price increases from uncertainty in supply are now less likely, with existing unused capacity setting a ceiling on prices.

Magnesium demand growth is driven primarily by the automobile industry as it replaces steel and aluminium with magnesium in order to meet legislated targets for fuel-efficient cars (USCAR 1998). Investors in new magnesium plants expect that advances in magnesium casting technologies (mainly die casting and its variants) will improve the price competitiveness and quality of mass-produced magnesium components used in structural and mechanical applications.

Leading US die-casters are actively promoting magnesium die-casting. Die-casting associations have published details of emerging technologies that allow light-metal castings to compete with steel assemblies in transport equipment. These include squeeze casting and semi-solid casting:

'Squeeze casting is a recently introduced high-pressure casting process, which through the use of very large gates and high hydraulic pressure can cast liquid metal without turbulence or gas entrapment. Production costs will be higher than conventional high-pressure die-casting, but squeeze-cast parts have qualified for replacing permanent mould and iron castings in high strength applications.

Semi-solid metal casting uses a special cast billet which is cut into heated slugs. The uniform globular semi-solid microstructure of the heated slugs provides superior flow characteristics capable of filling the casting under high pressure: gas entrapment is eliminated and solidification shrinkage reduced. Early qualification of parts for structural automotive applications has been successful. The process has proven suitable for use with both aluminium and magnesium alloys.'

Current development efforts in semi-solid metal casting are centred on the Thixomoulding, process being commercialised by Thixomat Inc. Thixomoulding, is the only available thixoforming process which offers a range of advantages for magnesium processing, combining elements of conventional die casting and plastic injection moulding (Hartmann, 1999).

Emerging surface-coating technologies can yield tailor-made design properties (appearance, corrosion resistance, dielectric strength, etc). These emerging technologies lower cost by high-speed mass-production processes that eliminate operations and improve component quality. For example, complex mechanical casting requiring holes may not require a secondary machining stage, the holes being made to specification in the die casting process.

Improved alloys complement the production technologies to improve the heat tolerance, corrosion resistance and surface finishing of cast magnesium alloy components. Special alloys used to resist high-temperature creep use zirconium, thorium and neodymium to expand the range of uses of magnesium, allowing it to compete more effectively with aluminium. These emerging magnesium alloys might eventually replace aluminium in automotive pistons, where low inertia (mass) and dimensional stability at operating temperatures are important properties.

The expected future growth would be from a low base. According to Wrigley (1997a), 'the average unit content of magnesium die castings in North American-built cars and light trucks will increase by 0.3 kilogram per vehicle from the 1997 model year to the 1998 model year. This increase represents an increase of 4,500 tons in total usage. The total magnesium content of each vehicle would average 2.9 kilograms'.

A move towards magnesium will improve environmental outcomes through direct and indirect effects. For example, 'Engineers are developing magnesium alloy heat-storage elements for a new generation of automotive catalytic converters. The variable-conductance-insulation converter is a leading candidate to replace conventional catalytic converters as hydrocarbon and carbon monoxide emission standards become more stringent. The new converter is based on technology developed by the U.S. Department of Energy, and commercial versions of the converter are being developed by Benteler Automotive Corp., Grand Rapids, MI, for introduction in 3 to 5 years. If the new catalytic converter is installed with magnesium alloy, which would replace aluminium as a heat storage and dissipating material, then each North American-produced vehicle would require 1.4 to 1.8 kilograms of magnesium' (Wrigley, 1997b).

Improved casting technologies for mass-production of high-quality magnesium components make these replacements affordable. Some existing component producers may be slow or reluctant to embrace alternative magnesium-based casting/production technologies. Initial resistance may be overcome by demonstration, regulation and technical and design assistance. If these pre-conditions are met, the rate of technology adoption may be very high, taking the form of the innovation S-curve.

Table 2.3 presents the optimistic scenario for magnesium growth. The die casting projection assumes a rapid take-up of new technologies for US and European automobile production under regulatory pressure from Corporate Average Fuel Economy (CAFE) standards, with continued US and international economic growth.

The growth projection for die casting assumes magnesium alloy prices fall relative to steel and aluminium. The new Australian projects boast low cash production cost estimates of about $US0.65 per pound. At 1998 year-end, the U.S. Western price was at a low of $US1.55, significantly down from the 1995 year-end prices of $2.09 (US Metals Week). The spot market price was much lower. Chinese magnesium at the Port of Tanjain was $US0.83 per pound at 1998 year-end, although the Chinese producers were endeavouring to establish a floor price of $US1.07 per pound. This was significantly lower than the corresponding 1995 price of $US1.88, pointing to the general decrease in prices.

Table 2.3: Optimistic outlook for world magnesium use

Year	Die casting	Desulphurisation of steel	Aluminium alloying	Total
1995	62,500	36,000	157,000	255,500
1996	72,300	39,000	138,200	249,500
1997	95,300	47,950	146,100	289,350
1998	110,100	48,200	154,000	312,300
2005	292,868	100,000	189,401	582,269

Use for desulphurisation of steel is projected to double to about 1000 tonnes per year in 2005 as Eastern European countries upgrade their steel making technologies. The demand for magnesium in the mature aluminium alloying market is projected to grow at 3 per cent a year. However, a rapid continued pick-up of Asian demand could increase the estimate by generating faster growth in the use of aluminium packaged goods, such as beverage cans.

With an assumed average annual growth rate of 39 per cent, the growth in magnesium demand will match the growth in supply under the optimistic supply scenario presented in section 2.3.2.

Under a pessimistic scenario, the technological and promotional hurdles confronting those developing and exploiting new technologies would persist for some time, price would not decline, and take-up rates of emerging technologies would be fairly slow.

A pessimistic scenario could still see magnesium grow by about 5 percent per year over the next decade, driven largely by growth of 15 per cent per year in die casting. This is consistent with the Norsk Hydro (1998) estimate for primary demand to reach about 500,000 tpa in 2007.

2.3.2 PRODUCTION

Advances in magnesium production technology will enable output to match the large increases expected in the demand for magnesium (Brown and Pawleck, 1999). New producers are combining emerging extraction technology, low-cost power and magnesium-rich sources to reduce cash production costs and so gain market share. Competition for market share has seen prices fall, and further price falls to stimulate the demand for magnesium are expected.

Table 2.4: Primary production outlook – optimistic scenario

Country	Present production	Production in 2003	Production in 2005
Republic of Congo	0	58,000	58,000
Canada	55,000	138,000	138,000
US	83,000	90,000	90,000
Brazil	9,000	18,000	18,000
Israel	25,000	35,000	35,000
Jordan	0	0	25,000
United Arab Emirates	0	0	20,000
China	100,000	200,000	200,000
India	1,500	3,000	3,000
Australia	0	266,000	533,500
France	18,000	22,000	22,000
Norway	52,000	60,000	60,000
Netherlands	0	40,000	40,000
Russia	26,000	65,000	65,000
Kazakhstan	10,000	10,000	10,000
Ukraine	10,000	10,000	10,000
Iceland	0	0	45,000
Albania	0	0	25,000
Serbia	3,000	3,000	6,000
Total	392,500	1,015,000	1,403,500
Capacity	536,000		

There is a tension between new and old producers. Some existing plants are old with low capital costs. New producers in most developed countries must submit an Environmental Impact Statement (EIS) or its equivalent, and have it approved — many existing plants would not meet the environmental standards imposed on new entrants. Existing producers can maintain prices through established relationships whereas new producers may have to cut prices to win market share. While existing producers protect their technological knowhow by patent and trade secrets, new entrants must license technology and/or develop new technologies and the associated operating practice. This, combined with the low capital costs associated with old written-down plants, can make it difficult for the new clean facilities to gain market share.

The dynamics of the magnesium market appear to have changed in the last few years. Prices have fallen since 1995, with the 26,000tpa expansion by Norsk Hydro and new plants in Israel (the 27,500tpa capacity Dead Sea Magnesium plant) and Canada (the Magnola plant). Table 2.4 shows the wide spread of the new ventures. Many of the new ventures are being supported by Russian know-how. Dow Chemical, one of the pioneers, has finally decided to quit the industry. Its 57-year-old, 65,000tpa seawater electrolytic plant at Freeport, Texas experienced flood damage last year. It is now selling its magnesium knowhow and plant.

Supply by new entrants, combined with cheap imports by former Eastern Bloc countries, may have weakened the competitive position of the US industry. China saw rapid growth in magnesium production in the last few years in response to supply shortages and price increases. The China Magnesium Association (CMA) boasted over 100 magnesium producers, although only 22 produced over 3,000tpa and all but 3 used high-cost silico-thermal processes. Many of these have closed following price falls in 1998. Nevertheless, the CMA is actively seeking foreign capital to help expand the industry to achieve world leadership. The modern electrolytic plant of Minhe Magnesium plans to increase capacity to 10,000 tpa by mid-1999.

In Canada, Noranda is proceeding with its Magnola project at Asbestos, Quebec. Its $US500m 58,000tpa is scheduled to commence production in 2002. The Magnola plant will exploit magnesium-rich asbestos mine tailings. Magnesium is leached from the tailings with hydrochloric acid, and the dehydrated magnesium chloride is converted by electrolysis to magnesium and chlorine. The chlorine is recycled as hydrochloric acid after reacting with hydrogen produced on site in a new $10 million BOC-owned and managed plant. Honeywell is working with Magnola engineers to develop a dynamic simulator that will ensure the plant operates according to specifications. The simulator will also be used to train operators to run the complex processes safely and in an environmentally friendly manner. The Magnola plant is being built by SNC-Lavalin Inc, Canada's largest engineering-construction firm. The process automation system is being supplied by the Foxboro Company. Foxboro, part of the Intelligent Automation Division of BTR Siebe London, claims to be the world's largest supplier of process automation equipment.

The original Magnola proposal was not approved. The primary concern was the SF_6-based design. A second concern was the disposal of small quantities of waste chlorohydrocarbons (CHCs). These were generated at the carbon anode of the electrolysis cell, adsorbed in particulate carbon from the anode, and filtered out as a residual.

It is understood that to obtain approval from Quebec's Environmental Review Board, Magnola made modifications to substantially reduce SF_6 emissions, and gave an undertaking to eliminate SF_6 emissions within 8 years.

Environmental associations criticised the plant as releasing 117 kg per year of PCBs, but Noranda rejected the allegations, stating the plant would generate only 3 kg of PCB annually, and another 1.3 kg contained in a residue storage pond.

The world's largest producer is a Norwegian company Norsk Hydro through its subsidiary, Hydro Magnesium. Hydro Magnesium produces 85,000 tpa of magnesium from two plants, the 1951 Portsgrunn plant in Norway, and the 1989 Becancour plant in Canada. It is increasing capacity to 110,000 tpa by expanding its Becancour plant to 68,000tpa in 2001. Its expansion is supported by a long-term contract with General Motors.

Dead Sea Magnesium, a joint venture between the Dead Sea Works (Israel, 65%) and Volkswagen AG (Germany, 35%) will produce 30,000 tpa in Sdom, Israel at the end of its first stage expansion.

In Africa, Magnesium Alloy Corporation (MAC) has a proposal, now at the final feasibility stage, to build a 60,000 tpa state-of-the-art plant at Pointe-Noire, Republic of Congo. It is to come on stream by 2002.

Some magnesium ventures appear to have been put on hold, for example, the Icelandic Magnesium Corporation's (IMC) proposal to establish a 50,000 tpa plant in Reykjanes. Australian Magnesium Investments Pty Ltd (AMI), the AMC holding company (95%), has become a major shareholder (40%, with an option to increase to 51%) in this venture. IMC is on hold pending support from a major customer, and a determination on whether the existing Ukrainian technology or the new Australian technology is most appropriate for Icelandic conditions.

2.4 Australian production of magnesium

Australia has no commercial magnesium metal plants at present. It does have:

- a 1500tpa-demonstration magnesium metal plant of AMC at Gladstone in Central Queensland;
- a few firms that produce magnesium and magnesium alloy die-castings;
- research into light-metal casting technology — magnesium research is a focus for CSIRO and the CRC for CASTmm.

This is expected to change, as commercial production of magnesium is established and grows in Australia. Downstream processing, especially die casting of automotive parts, may be expected to follow.

2.4.1 PRIMARY PRODUCTION OF MAGNESIUM METAL AND MAGNESIUM ALLOY

Australia has the major global share of new projects, eight in all (table 2.5). Brown and Pawleck (1999) have estimated that Australia could be producing 266 ktpa of magnesium by 2003, and 533 ktpa by 2008. If these production estimates are realised, Australia would be the world's largest producer of primary magnesium.

This analysis, and the following table, does not include the $1 billion Mt Margaret, Western Australia, magnesium project announced by Anaconda Nickel Ltd (ANL) on 28 July 1999. This venture is based on magnesium prospects that are within 30 km of ANL's Murrin Murrin lateritic nickel deposit. ANL have appointed ICF Kaiser International Inc to do a scoping study. However ANL states that the project is conditional on the price of energy being reduced, which in turn requires a gas pipeline from Geraldton to Mt Margaret. ANL, through an alliance with StateWest Power, have applied for a licence to construct and operate such a pipeline.

All Australian projects are based on large high-grade magnesium ore deposits. The challenge they face is developing and/or buying the technology to exploit the deposits. AMC is developing their own technology for production of feedstock for an Alcan electrolytic cell. Like Magnola, they are using a pilot plant to demonstrate and prove their technology. SAMAG have purchased Dow's magnesium technology and do not propose to develop a pilot plant. Mt Grace has a licence to use the yet-to-be-commercialised Heggie plasma arc technology. Crest has tasked MPL, a leading construction company, with the responsibility of establishing and commissioning the plant on a cost plus contract. Golden Triangle is exploring various licensing options.

Each of these proposals have merit and none can be ruled out on technical grounds. They all involve, however, some degree of technical and commercial risk due to issues of timing and possibly overly optimistic cost estimates.

Table 2.5: Australia's magnesium projects

Project Owner	Project Location	Nameplate Capacity (tonnes/yr in 2003)	Potential Installed Capacity in 2008
AMC	Kunwarara, Qld	96,000	96,000
Crest Magnesium	Author-Lyons River, Tas	95,000	190,000
Golden Triangle Resources	Main Creek, Tas	0	80,000
Golden Triangle Resources	Woodsreef, NSW	0	65,000
SAMAG (Pima Mining)	Leigh Creek, SA	0	52,500
Mt Grace Resources	Batchelor, NT	50,000	50,000
Pilbara Magnesium Metal Assocs	Dampier, WA	0	50,000
Hazelwood Power	Latrobe Valley, Vic	30,000	30,000
Total capacity (potential)		271,000	613,500
Estimated production		266,000	533,000

One of the uncertainties associated with the projects is the extent of SF_6 emissions. Some companies have stated they will use SO_2 as a replacement for SF_6. At issue is whether the commercial plant, when built, will be able to move away from the proven SF_6 technology. Should difficulties be experienced, what might the company do? The company's shareholders, employees and suppliers would want SF_6 used until problems with the SO_2 or alternative technology were resolved.

In this situation, the company's response to shareholder demands might depend on the regulatory and legislative restrictions imposed on it by the different levels of government. In the absence of any, it is likely to use SF_6 technology, thereby potentially shifting any costs that might arise from failure to meet Kyoto Protocol obligations from its shareholders to Australians generally. State restrictions are likely to be weak unless supported by an Australia-wide collective agreement on uniform or harmonised regulations. Such an agreement made before construction commences may assist regulators to maintain the agreed standard. In its absence, regulators may face localised pressure to grant (temporary) exemptions to a venture in its jurisdiction.

Technical response options would likely to have cross-jurisdictional support at this stage in the development of the Australian magnesium industry would:

- provide an incentive to reduce the use of SF_6;
- take into account that many of the proposed developments in Australia are speculative and are unlikely to be in production until 2003; and,
- not impose costs that would make projects in Australia less attractive than in less developed countries which have no incentive to reduce SF_6 usage.

Brief outlines of the other projects are provided below. For more detail, readers are advised to consult the papers presented at the Australian Journal of Mining's 'The Inaugural Australian Magnesium Conference: A New Industry for Australia', held in Sydney on the 30th June & 1st July 1999.

Australian Magnesium Corporation

Australian Magnesium Corporation (AMC) has demonstrated the technology and market links necessary to convert potential resources into commercial success. AMC's achievements to date include that it:

- operates a 1500 tpa demonstration magnesium metal plant;
- holds patents over important magnesium production technology;
- is undertaking state-of-the-art research into magnesium production and casting processes, including SF_6 replacement (through CSIRO and CAST);
- has world magnesium interests through part-ownership of Iceland Magnesium Corporation (IMC);
- has a working relationship and a long-term contract with the Ford Motor Company (Ford) for magnesium alloy; and,
- on current expectations, will submit an EIS for the project in November 1999.

AMC will exploit the world's largest deposit of cryptocrystalline magnesite, the 1.2 billion tonne Kunwarara deposit in Central Queensland. This deposit was discovered by Queensland Metals Corporation (QMC) in 1985. It is now being mined for production of dead burned magnesia, high-quality magnesite refractories, and magnesium hydroxide slurries used in environmental applications.
Following the discovery, QMC formed:

- A joint venture with CSIRO which developed and patented a low-cost environment-friendly technology for producing a pure anhydrous magnesium chloride feedstock suitable as feedstock for an Alcan electrolytic cell. The technology is called the Australian Magnesium (AM) technology.
- The Australian Magnesium Corporation (AMC) to use the AM technology to commercially produce magnesium and magnesium alloys. The AMC demonstration plant is now proving the technology for world-scale 90,000 tpa commercial production.

Construction of the commercial plant is planned to commence in the year 2000, and expected to be operating at capacity in 2004. It will be the largest plant in the world. Sale of 45,000 tpa is guaranteed under a long term contract with Ford. AMC might also supply ingot to the nearby aluminium companies. At present, Australian aluminium companies import the magnesium metal they need to produce magnesium-containing aluminium alloys.

Fluor Daniel, a major plant constructor, has earned a 5 per cent interest in AMC by developing and proving the technology. It operates the demonstration plant, and will construct and commission the commercial magnesium plant.

The raw materials consumed in the production of magnesium will be beneficiated magnesite ore (principally $MgCO_3$) and hydrogen (from the nearby Dennison coal-bed gas fields). The process uses recycled chlorine, water and low pressure process steam, and electricity. The steam and electricity come from a modern coal-based power station at Stanwell, adjacent to the plant.

The processes are:

- Leaching of the ore – the principal by-product is CO_2 gas, chemically generated:
  $MgCO_3 + 2HCl = MgCl_2 + CO_2 = H_2O$
- Leach solution purification – The residue (sand and clay containing iron, manganese and nickel hydroxides) is suitable for landfill. AMC expects approval by the relevant environmental protection agencies.
- Dehydration of the leach solution to get a pure dry magnesium chloride feedstock, the by-products being water vapour, and some impurities (calcium and alkali chlorides).
- Electrolysis of the magnesium chloride in an Alcan MPC cell to get chlorine gas and molten magnesium metal. The chlorine is recycled as hydrochloric acid. The reaction is:
  $MgCl_2 + Energy = Mg + Cl_2$
- The molten magnesium is cast into ingots, some pure magnesium, other as commercial alloys after the addition of alloying elements. AMC has committed to be SF_6 free prior to this stage, and is very active in the search for SF_6 alternatives for alloying and casting.

Crest Magnesium

Crest Resources (Tasmania) has the exclusive rights for Australia and New Zealand to purchase magnesium production technology for 20 years from the Ukrainian National Research and Design Titanium Institute and VAMI JSC. Its magnesium deposit is at Arthur-Lyons River, south of Burnie, Tasmania. The deposit can sustain production of 190,000 tpa for 100 years. The project cost was estimated at $A1billion for initial output in December 2002 of 95,000 tpa. Multiplex, a major Australian construction company, will supply 100 per cent of the finance for a 60 per cent interest in the project and has guaranteed to complete construction of the processing plant by December 2000.

The Tasmanian government has reportedly agreed to act as intermediary for the supply of all energy (gas, electricity and process steam) at the indicative price supplied by Duke Energy — this offer depends on the smelter being located in Tasmania. The cash cost is projected to be $US1.40/kg. Production is planned to begin in 2002. Projected output was increased to 190,000 in February 1999. Commercial feasibility may depend on, *inter alia*, support from a major long-term customer – General Motors (GM) has been suggested, although GM already have a long-term contract with Norsk Hydro and a five-year contract from 1996 with Russian Solikamsk Magnesium Works (SMW).

The project has been granted Major Project Facilitation status by the Federal Government. The Tarkine National Coalition is opposed to the project on the grounds of damage to a unique wilderness area.

Golden Triangle

Golden Triangle Resources NL has two magnesium ore bodies. One is a 47 million tonne, 43 percent magnesium oxide magnesite deposit at Main Creek, south of the Savage River Iron Ore mine in Tasmania. The second is the 24 million tonne asbestos tailings dump at Woodsreef, NSW, a body similar to Magnola's Canadian deposit currently being developed by Noranda. In August 1998, Golden Triangle announced a $US500 million project for the production of 80,000 tpa magnesium from its Main Creek, Tasmania ore body. Tasmania is the preferred location for its smelter but because of concerns about energy shortage in Tasmania, Golden Triangle has stated its intention to locate the smelter in Victoria's Latrobe Valley.

Golden Triangle gave details of both projects to 'The Inaugural Australian Magnesium Conference'. It has contracted Bateman Brown and Root (BBR) Asia-Pacific to develop its Main Creek Project. BBR are investigating alternative technologies as and when they become available. It sees three technologies as being potentially available for the preparation of an anhydrous magnesium chloride feedstock for an Alcan electrolytic cell:

- VAMI/UTI carnalite dehydration process. This is currently subject to an exclusive licence with Crest Magnesium in Australia. BBR has experience in the VAMI/UTI engineering through its associate Bateman Israel, which participated in the DSM project. It is understood that DSM use Alcan's electrolytic cell technology (Christensen *et al*, 1997).
- Noranda's Magnola process. BBP understand that Noranda will not make their technology available for licence until their plant has been commissioned.
- The Nalco/St Joe process. This ethylene glycol/anhydrous ammonia process is proposed by AMC (Roberts, 1999)

BBP have access to Alcan's alcohol/anhydrous ammonia process, a process that is somewhat similar to the Nalco/St Joe process. Both produce a magnesium chloride hexammoniate ($MgCl_2.6NH_3$) intermediate. The difference lies in how to prevent the $MgCl_2$ becoming contaminated by MgO produced by hydrolysis. In the Nalco/St Joe process the water produced when the $MgCl_2$ hydrate is converted to the ammoniate is distilled prior to the $MgCl_2.6NH_3$ crystalliser. In the Alcan alcohol/anhydrous ammonia process, the hydrolysis reaction is controlled in the crystalliser by the addition of ammonium chloride.

The development needs of the Alcan process may be significant - this technology was rejected by AMC to develop their own AM technology.

Clearly the Golden Triangle/BBP group has significant development work ahead and the proponent plans to construct a demonstration plant to resolve these technical hurdles. At this stage, it is unlikely that they could specify their choice of cover gas technology.

SAMAG

SAMAG (South Australian Magnesium Corporation) has a 388 million tonne magnesite deposit near Leigh Creek, and propose a $US400 million 52,500 tpa plant producing at $US0.61 per pound. Pima Mining NL is a minerals exploration company, and SAMAG is its 80 per cent owned subsidiary. SAMAG expects to complete a feasibility study by March 2000, and then build the commercial plant at Port Augusta in 18 months. A coal-fired power station already exists at Port Augusta. The SA government has given the project Major Development Status, and a joint venture of Sydney's Geo Processors and Japan's Takata Physics International Corp has built a $A3m pilot plant to test the ore.

SAMAG has (1) purchased Dow's magnesium technology, (2) will by-pass the pilot plant stage, and (3) has stated it will use an SO_2 in place of an SF_6 cover gas.

Mt Grace Resources' Batchelor Magnesite Project

Perth-based Mt Grace Resources NL will be the first company in Australia to evaluate and licence a process called the Heggie metallothermic technology for the production of magnesium metal (http://www.mtgrace.com/news.html). The Heggie process uses a plasma arc furnace. Plasma arc technologies are said to radically improve the silico-thermal process, although they are as yet to be commercialised. They are expected to be suitable for small-scale production, and may enable pure magnesium solids to be produced without an SF_6 cover gas.

The Heggie process is a variant of the silico-thermal process.` Dolomite and magnesite minerals pass through a precalciner to form the magnesia/lime feedstock used by the plasma arc furnace. Aluminium scrap replaces silicon as the reducing agent, with the dolomite beneficiated by flotation to yield less than 2 per cent silica prior to calcination.

Magnesium Developments International Pty Ltd (MDI) have purchased the right to commercialise/sub-license the Heggie process from its owners , LMA Pty Ltd. MDI will licence the technology to Mt Grace for use at Batchelor, make a 200 tpa pilot plant available for testing, and provide technical assistance. Under the licence agreement, Mt Grace will, inter alia, pay a royalty of 2.5 cents per pound of magnesium.

Mt Grace plans to use energy from a proposed development of Timor Sea natural gas. The capital costs are estimated at US $0.70 per annual pound, and operating costs are estimated to be $US0.70 per pound. Mt Grace is planning to commission its stage 1 (10,000 tpa) modules by June 2002, with the 50,000 tpa final stage production scheduled for 2005.

Hazelwood Power's magnesium from fly-ash project

Hazelwood operates a 1600MW brown coal power station in Victoria's Latrobe Valley. It has sufficient fly-ash to supply a 30,000tpa magnesium smelter for 30 to 40 years. Latrobe and HRL Technology Ltd are to investigate extraction of the magnesium as a magnesium chloride solution. Hazelwood's primary purpose is power generation. As an alternative to becoming a magnesium producer, Hazelwood sees its fly-ash potential as providing an incentive for a large-scale magnesium producer (Crest, Golden Triangle, or a new entrant) to co locate to gain synergetic benefits.

Pilbara Magnesium Metal Associates (PMMA)

The project would use technology similar to that used at Dead Sea Magnesium to convert magnesium–rich bitterns from Dampier Salt (Rio) to produce magnesium and chlorine. It is understood that Shell and Dow are considering an integrated chemical plant in the Dampier area, and could use the by-product chlorine as a chemical feedstock. A 50,000 tpa plant is planned.

2.4.2 ESTIMATING AUSTRALIAN PRODUCTION LEVELS

The projects could make Australia the world's largest magnesium producer. If the plants were to use existing practice, SF_6 emissions would add significantly to Australia's greenhouse gas emissions. The factors that will influence the outcome are:

- Whether annual growth in magnesium demand over the next decade is 15 per cent or higher on average, as expected by some commentators, or whether it will be 5 per cent or less.
- The impact on the market of many new companies that, with modern technology and low power costs, can cut production costs by up to 30 per cent
- Possible dumping on US and European markets of Russian, Ukrainian and Chinese magnesium.
- The extent of recycling of magnesium components.
- A possible withdrawal from the market of some of the older magnesium plants, following the closure of Dow's Texas plant last year. Nevertheless, if the plants are left on a care and maintenance basis,

the consequent excess capacity will add to existing unused capacity; for example, that in China and the Former Soviet Union. The excess capacity could be bought on stream if prices rise, placing a ceiling on potential price rises.

Under a pessimistic scenario, only one of the eight Australian ventures might be producing in 2003 and operating during the Kyoto Protocol commitment period. Under an optimistic scenario, most, if not all, of the eight projects would be producing over the commitment period.

The extent of downstream processing is likely to be low under the pessimistic scenario, but could be extensive under the optimistic scenario. In either event, casting, and particularly large scale casting, will require a cover gas. However, the level of SF_6 emissions from downstream processing is likely to be dwarfed by that from primary production. This is because (1) some magnesium ingot is exported and (2) cover gas is not needed in many downstream activities,aluminium alloying for example.

2.4.3 DOWNSTREAM PROCESSING

The advantages conferred by the advanced die-casting technologies have not yet been generally recognised in the wider Australian engineering community. This may change following the commencement of commercial magnesium production in Australia expected in 2003.

Australia has long been a major world producer of base metals, such as lead, zinc copper and silver, tin, aluminium and their alloys. It has added value to ingots that would otherwise be exported by casting and otherwise working the metals into components for domestic and foreign use. This value adding process has been greatly assisted by R&D into casting technology by CSIRO in joint ventures with Australian industry. CASTmm is presently conducting on-going research in this area.

CASTmm is a joint venture between CSIRO, the University of Queensland, Comalco Aluminium Limited, AMC, and the Australian Automotive Technology Centre. CASTmm's mission is to development and transfer technical know-how to the Australian light metals casting industry. It is a world class research body, with a net worth of $9 million, 80 CSIRO and University researchers, and significant business participants, including Capral Aluminium, Toyota Motor Corporation, Nissan Casting Australia Pty Ltd, Mitsubishi Motors Australia Ltd, Mett Diecasting, PBR, and Australian Die Castings. The development of an Australia magnesium plant should provide spillover benefits to Australia's mineral and light metal industries, and assist Australian foundries, particularly the casters of light metals.

Australia has a world-class downstream aluminium industry which exports aluminium die-castings, extrusions, and other products. The industry developed when Australia emerged as a major supplier of primary aluminium. Burnbank expects that downstream magnesium production will following the emergence of Australia as a world player in primary magnesium, and will extend and complement our aluminium capabilities. Thus, it is expected that Australia will have a downstream magnesium product industry well before 2008. This downstream industry will require an active cover gas, preferably one that replaces SF_6 and SO_2.

2.4.4 SYNTHETIC GAS EMISSIONS FROM A FUTURE AUSTRALIAN MAGNESIUM INDUSTRY

Elimination of SF_6 emissions from primary magnesium production does not yet appear feasible, although it can now be greatly reduced by use of an SO_2 cover gas in some operations, and by good operating practice and design.

We expect that the present industry research will lead to production free of SF_6-emissions. It is unclear whether such research will be available in time for those Australian projects that commence construction on time.

The pessimistic scenario for the magnesium industry's greenhouse gas emissions would combine the optimistic scenario for magnesium production with the pessimistic one for research into SF_6 alternatives. At a production level of over 500kt of magnesium, and the target best practice of 0.5kg of SF_6 per tonne, SF_6 emissions could total over 250 tonnes, equivalent to 5 million tonnes of CO_2-equivalent emissions, by 2008.

The optimistic scenario for the magnesium industry's greenhouse gas emissions would combine the pessimistic scenario for magnesium production with the optimistic scenario for research into SF_6 alternatives. At a production level of 100 kt of magnesium, and the best practice of say 0.1kg of SF_6 per tonne, SF_6 emissions would total about 10 tonnes, equivalent to about 200,000 tonnes of CO_2-equivalent emissions, by 2008.

The wide divergence in emission levels between the optimistic and pessimistic scenario reflects the present uncertainty in both the production outlook, and the research into SF_6-free production.

2.5 Technical response options

Australian greenhouse policy development needs to consider:

- The present uncertainty as to the outcome of efforts by industry players, coordinated by the IMA to develop SF_6-free magnesium production.
- The potential for the magnesium projects currently under study in Australia to greatly increase the level of Australia greenhouse gases going into the Kyoto Protocol commitment period.
- The approach to be taken in discussions with potential investors.

There are several options:

- The stand-back option. Do nothing for the present except maintain a watching brief being ready to take action if projects go ahead without appropriate technology. This approach is likely to be best if the pessimistic scenario for magnesium production and optimistic scenario for SF_6 research eventuate.
- The keep-abreast of SF_6 research option. Do nothing except liase with the IMA and its SF_6 committee to keep abreast of the potential for SF_6-free production. This will be advantageous if feedback from the research becomes available before the projects become too advanced. It would allow government to specify what production technologies should not be allowed under EIS approval.
- Voluntary reporting by the proposed projects on projected greenhouse gas emissions. This could be part of the Greenhouse Challenge program. The advantage is that government objectives could be achieved without direct regulatory intervention.
- Mandatory reporting by the proposed projects. This would require some specification by government as to the detail of the report. It would be appropriate under the pessimistic SF_6 research scenario and the optimistic production scenario. This scenario would have a significant impact on greenhouse gas emissions, especially since some projects would generate significant process CO_2, and use large quantities of energy.

2.6 Summary and conclusion

SF_6 is the vital constituent in the cover gas used for magnesium casting. The SF_6 prevents reaction between the molten magnesium and air. The SF_6 is used in low proportions, less than 0.5 per cent of the cover gas which is primarily dry air and/or carbon dioxide. SF_6 emissions arise when crucibles in which magnesium is melted or held for casting or alloying are not enclosed. Over the last five years, concern to reduce SF_6 emissions has seen crucibles enclosed, leading to declines in the SF_6 emissions.

Presently magnesium producers that follow good practice in modern plants lose about 1kg of SF_6 to the atmosphere for every tonne of magnesium or magnesium alloy produced. Under the oversight of environmental protection agencies, magnesium producers will reduce emissions to about 0.5kg per tonne through changes to their venting, continuous-casting, transfer and furnace technologies. The production of primary magnesium in large electrolytic plants is the major source of SF_6 emissions in magnesium production, with other sources being the casting of magnesium products (loss of 0.1 to 1 kg per tonne depending on their technology), and experimental development in magnesium casting.

At present, small quantities of SF_6 are sporadically used in magnesium-related activities in Australia. They are used in experimental work on casting by CSIRO and the CRC for CAST Metals Manufacturing, CASTmm, in metal production at the AMC magnesium metal demonstration plant at Gladstone, and by specialist Australian foundries when producing magnesium castings. However this could change with Australia having the potential to become the world's largest producer of magnesium. The ultimate implications for Australia's SF_6 use depends on (1) the likelihood of the projects proceeding, and (2) the usage of SF_6 by these projects.

The timeframe and success rate of the projects depend on growth in the world magnesium market, which depends primarily on replacement of aluminium and steel automobile components by magnesium alloy. Such replacement brings environment benefits in the form of higher automotive fuel efficiency, and lower life-cycle greenhouse-gas emissions, but only if SF_6 emissions can be reduced (Thorvald *et al*, 1999). Rapid replacement requires that (1) the price of magnesium falls relative to aluminium and (2) that actual and perceived disadvantages of magnesium are addressed (Cole 1999).

Both these pre-conditions are possible. The cash production cost estimates presented at the 'Inaugural Australian Magnesium Conference' suggests the proposed facilities could undercut the current world price. This would generate the economic incentive for the global car companies to move more quickly towards magnesium components. Work now being undertaken by the International Magnesium Association could see reduction and ultimate elimination of SF_6 emissions from magnesium production. For over 3 years the IMA has advised member firms of the high GWP of SF_6 and provided them with technical information on how to reduce emissions. It is also coordinating efforts to develop SF_6-free magnesium production — it has set up the 'Ad Hoc Committee For SF_6 Substitution' to report on this issue. In the interim, work is proceeding independently by at least four of the world magnesium players to develop solutions, with a variety of different approaches under examination.

The report provides an optimistic and pessimistic outlook for Australia's magnesium production. It does not tie this to the use of SF_6 for two reasons. A new production route (the Heggie plasma furnace) being evaluated by Mt Grace Resources may avoid the use of SF_6 cover gas. Other projects may choose to use SO_2, despite operational shortcomings, as a short-term solution. Norsk Hydro, the world's largest producer has recently announced it will adopt SO_2 as a short-term solution. At this stage, it is not possible to tie SF_6 usage to the Australian project proposals. A possible exception is AMC's Gladstone project for which an EIS is currently expected in November 1999.

The magnesium producers have a keen interest in first reducing and then eliminating SF_6 emissions. Until more information becomes available later this year, the stand-back watching brief may be appropriate. There appears no need for a government to institute a second level of management to overseas the management programs already instituted by the global players and their association, the IMA.

Several response options for managing greenhouse emissions from magnesium production are suggested ranging from informal monitoring to voluntary reporting arrangements to regulatory intervention. The best option will depend on the outcome of Australian and international research into SF_6 alternatives.

3

Metals processing — Aluminium production

3 Metals processing - Aluminium production

3.1 Primary aluminium smelting

Primary aluminium production involves the electrolysis of alumina (Al_2O_3) in a series of complex electrode reactions. The overall reaction results in aluminium being produced at the cathode and carbon dioxide at the anode:

$$\boxed{2Al_2O_3 + 3C \longrightarrow 4Al + 3CO_2}$$

The electrolysis process is conducted in carbon-lined steel pots containing high purity carbon anodes. The cell electrolyte consists of a molten bath of cryolite (Na_3AlF_6) to which varying proportions of aluminium fluoride, calcium fluoride or lithium fluoride may be added to lower the melting point, decrease the density of the electrolyte and improve energy efficiency (NGGIC, 1996; p. 16).

In addition to producing CO_2 from carbon anode consumption in accordance with the reaction shown, primary aluminium smelting gives rise to emissions of two perfluorocarbons, tetrafluoromethane (CF_4) (GWP of 6,500) and hexafluoroethane (C_2F_6) (GWP of 9,200). These gases are generated during anode effects (AEs). The AE is characterised by an increase in cell voltage as a result of the cryolite bath becoming deficient in alumina. Although the factors that determine the rate of formation of CF_4 and C_2F_6 are not well understood, the quantities emitted are accurately measurable (NGGIC, 1996; p. 17). There is a continuing research effort on AEs by the aluminium industry designed to increase the accuracy of measurement of PFC emissions and to improve process controls to reduce these emissions.

According to Grjotheim et al (1977) in contemporary practice one half to one AE per day per cell is considered to be normal, but in rare cases individual cells have operated for several weeks without AE. They note that frequent AEs are unwanted because of the extra energy consumption and possible overheating of the cells. They continue, 'On the other hand, the AE serves the purpose of keeping a check on the alumina content in the electrolyte, so that overfeeding can be avoided. If another means of alumina control is found, the AE may possibly be abolished altogether. It is commonly believed, however, that occasional anode effects have a favourable influence in "cleaning" the cell and particularly the anode surface, e.g. by bringing "carbon dust" to the surface of the melt. Laboratory experiments indicate that protruding particles on the anode are burnt away or become detached from the anode during AE. Samples of industrial anodes which were taken out immediately after AE, exhibited areas that were partly polished' (p. 240).

The idea of beneficial effects from AEs is no longer accepted. It is now accepted that any beneficial effects are outweighed by the disadvantages of extra energy consumption, overheating of cells, the need to take cells offline resulting in lost production, and the generation of potent greenhouse gases, namely, perfluoromethane (CF_4) and hexafluroethane (C_2F_6). Better process control and monitoring have enabled alumina content to be more accurately managed and AE frequency and duration to be substantially reduced.

3.2 Methods for estimating PFC emissions

The Intergovernmental Panel on Climate Change (IPCC) provides three methods for determining emissions of PFCs, referred to as Tier 1a, Tier 1b and Tier 1c (IPCC, 1997, Vol.2). Tier 1a requires emission data to be measured which would require continuous monitoring. This approach is not feasible given the costs of continuously monitoring emissions from each cell. Tier 1b refers to calculation of emissions using smelter specific measurements of operating parameters and emissions. Two approaches to calculation of emissions are used, the slope coefficient method and the Pechiney over-voltage method.

The equation provided by the IPCC is derived from the Tabereaux method. This method states that the generation of CF_4 in electrolysis cells follows Faraday's Law (the quantity of gas generated depends on the flow of electrical current in the cell). At 100 per cent efficiency, 13.68g of CF_4 is formed for every kiloampere-minute (kA min) duration of the AE. For example, CF_4 emissions for an aluminium smelter having an average percentage (p) of 16 per cent CF_4 in pot gas during AEs, 91 per cent current efficiency (CE) for aluminium production, 0.5 AEs per pot day (AEF), and anode effect duration (AED) of 2.5 minutes can be derived as follows:

kg CF_4/tonne Al = (kg CF_4/kA min) /kg Al/kA min) x (1000kg/tonne) x (p/CE) x AEF x AED

= (13.68/8.05) x (0.16/0.91) x (0.5) x (2.5)

= 0.373

The denominator in the first expression of the equation is not specified in the IPCC discussion (p.2.36). It refers to 8.05 g of Al per kA min, which is derived from Faraday's law which states that the number of moles of product formed by an electric current is stoichiometrically equivalent to the number of electrons supplied (Atkins and Jones, 1998; p.657). The expression can be reduced to an equation constant because the units of the numerator and denominator are identical and cancel.

The equation can be expressed as:

kg CF_4/tonne Al = 1.698 x (p/CE) x AEF x AED

where:

1.698 is the slope coefficient (equation constant approximately equal to 13.68/8.05)

p is the average fraction of CF_4 in the pot gas during anode effects (for prebaked anodes the fraction is 0.08 and for Soderberg anodes the fraction is 0.04)

CE is the current efficiency expressed as a proportion rather than a percentage

AEF is the frequency of anode effects per pot (cell) day

AED is the anode effect duration in minutes.

The slope coefficient method posits a relationship between AE minutes per cell-day and emissions of CF_4. A sample of measurements of CF_4 emissions are taken along with the AE minutes per cell-day. An ordinary least squares regression equation is estimated by regressing CF_4 emissions on AE minutes per cell-day.

The equation is:

kg CF_4 per tonne of aluminium = slope coefficient x AE minutes per cell-day

Using industry data of actual measurements from overseas plants with similar technologies to those used in Australia, the regression equation was:

kg CF_4 per tonne of aluminium = 0.18 x AE minutes per cell-day

In this estimation, the slope coefficient encompasses the equation constant and (p/CE).

An alternative Tier 1b method for calculating PFC emissions is the Pechiney over-voltage method. This method treats the anode effect over-voltage as the relevant process parameter. The relationship between anode effect over-voltage and PFC emissions was derived from measurements of PFC generation at smelters with Pechiney technology. The equation is:

kg CF_4/tonne Al = over-voltage coefficient x AEO/CE

where:

AEO is the anode effect over-voltage in mV/day

CE is the aluminium production process current efficiency in percent.

The Tier 1c method refers to estimated emissions data and is the least preferred. The IPCC states that the estimates should be used only where no measured data exist. Default emission factors relevant to particular technologies are provided expressed in terms of kg CF_4 per tonne of aluminium. Tier 1b methods also use default coefficients, although these are considered to be more accurate because they are derived from plant-specific measurements. In addition, AEF and AED are monitored and emissions are calculated using the monitoring data and the (default) equation constants.

3.3 Emissions of PFCs from Australian aluminium smelting

Australia's National Greenhouse Gas Inventory has included estimates of PFC emissions from the original compilation. A high level of cooperation has been provided by the Australian Aluminium Council and the aluminium smelters. Australian industry uses prebaked cell technology. Emissions of PFCs are estimated by individual producers using either the slope coefficient equation or the Pechiney anode effect over-voltage method. The majority of smelters use the slope coefficient equation. Anode effect frequency and duration are continuously monitored by the smelters (or the anode effect over-voltage), the results are entered into the relevant equation and emissions of CF_4 are derived. Emissions of C_2F_6 are estimated using the assumption that they are 10 per cent of the emissions of CF_4.

National emissions of CF_4 are estimated by summing the emissions from each smelter. An average emission factor for Australia is derived by dividing total CF_4 emissions by total aluminium output. The emission factor for C_2F_6 is 10 per cent of the CF_4 factor.

Tables 3.1 and 3.2 show emissions estimates for CF_4 and C_2F_6 from 1989/90. Better process control techniques have resulted in the emission factors falling by 75 per cent since 1989/90. Emissions of PFCs from aluminium production expressed in terms of CO_2 equivalents have declined by around 70 per cent since 1989/90, despite an increase in aluminium metal production of 13 per cent.

3.4 Management of PFC emissions by the aluminium industry

In recognition of the need to reduce the industry's emissions of greenhouse gases, particularly those gases with high GWPs, the Australian aluminium industry has been active in investigating PFC emissions and pursuing opportunities for reductions. This active approach has mirrored the approach of the aluminium industry worldwide. The International Aluminium Industry sponsored work by CICERO (Centre for International Climate and Energy Research, Oslo) in 1992 to determine the GWPs of CF_4 and C_2F_6. The International Primary Aluminium Institute organised a Workshop in March 1994, where industry experts presented measurement data on PFCs collected over a full range of smelter technologies. The fundamental strategy for reducing PFCs was to reduce anode effect frequency and duration.

A key factor from the perspective of the aluminium industry is that actions to reduce PFCs also improve process efficiency. Earlier it was commented that AEs were considered beneficial and played a role in monitoring alumina content of cells. Further research, some of which has been induced by the need to reduce greenhouse gas emissions, indicated that any beneficial effects were outweighed by the costs. In addition, computerised continuous monitoring systems mean that crude proxy variables such as an AE to signal alumina deficiency, are no longer necessary for process control. Essentially, improved process efficiency corresponds with reduced PFC emissions.

Table 3.1: Tetrafluoromethane (CF_4) emissions from aluminium production

Year	Amount of aluminium produced: (kt)	Emissions factor: (kg CF_4/t aluminium)	CF_4 emitted: (Gg)	CO_2 equivalent (Gg)
1989/90	1235	0.53	0.655	4255
1990/91	1236	0.53	0.655	4258
1991/92	1234	0.39	0.481	3128
1992/93	1301	0.33	0.429	2791
1993/94	1380	0.2	0.276	1794
1994/95	1285	0.15	0.193	1253
1995/96	1331	0.15	0.200	1298
1996/97	1395	0.13	0.181	1179

Source: NGGIC (various years)

Table 3.2: Hexafluoroethane (C_2F_6) emissions from aluminium production

Year	Amount of aluminium produced: (kt)	Emissions factor: (kg C_2F_6/t aluminium)	C_2F_6 emitted: (Gg)	CO_2 equivalent (Gg)
1989/90	1235	0.05	0.0618	568
1990/91	1236	0.05	0.0618	569
1991/92	1234	0.04	0.0494	454
1992/93	1301	0.03	0.0390	359
1993/94	1380	0.02	0.0276	254
1994/95	1285	0.015	0.0193	177
1995/96	1331	0.015	0.0200	184
1996/97	1395	0.013	0.0181	167

Source: NGGIC (various years)

The Australian aluminium smelting industry comprises six smelters: Bell Bay in Tasmania and Boyne Island in Queensland operated by Comalco; Point Henry and Portland in Victoria operated by Alcoa; Tomago in New South Wales operated by Pechiney; and Capral at Kurri Kurri in New South Wales operated by Capral. In recognition of the need to address greenhouse issues, the Australian Aluminium Council (formerly the Aluminium Development Council) signed a framework cooperative agreement under the Greenhouse Challenge Program in 1996. Supplementary Agreements incorporating detailed action plans for each smelter have subsequently been signed.

The 1998 report on the Greenhouse Challenge Program (Commonwealth of Australia, 1998; pp. 53-56) notes that significant progress has already been made by the companies in reducing greenhouse gas emissions over the period to 1995. Several initiatives undertaken by the industry are outlined, including major improvements in equipment performance and reliability, job redesign and training of smelter operators which have led to anode effect time being reduced to less than one-third of 1990 levels with corresponding reductions in PFC emissions.

In respect of future actions, the report describes a range of actions being pursued by the smelters. In particular, continued improvements in control of anode effects, and therefore release of PFCs, through refinement of automated control systems and further improvements in operator training to manage the systems. Continuing improvements in process control are reflected in the reductions in emissions of PFCs as shown in tables 3.1 and 3.2.

The active role of the Australian industry is reflected in the participation of industry representatives in the Workshop on Good Practice in Inventory Preparation for Industrial Processes and the New Gases held in Washington in January 1999. Discussions with the industry indicated that the equations used to estimate PFC emissions are being reviewed and the outcomes will be reflected in the inventory for 1998, and in the report on good practice. It is expected that the slope coefficient will be revised downwards. This will affect the estimated annual emissions, but not the percentage decline in emissions because each year's emissions will be reduced by the same factor.

Life cycle issues are not directly relevant to management of PFCs in aluminium smelting because they are a by-product of an unwanted event. That is, they are not deliberately introduced into the process nor are they deliberately produced. Investigation of the life cycle of aluminium, including aluminium recycling, would address incidentally the impact of recycling on emissions of PFCs. However, the aluminium life cycle is beyond the scope of this paper.

3.5 Aluminium outlook and PFCs

Australia's aluminium industry has been successful in significantly reducing emissions of PFCs. Further reductions are still expected although the limit to reductions is being approached. Existing technology is not expected to completely eliminate anode effects. This means that once the limit on emissions reductions per unit of output has been achieved, aggregate emissions will increase in direct proportion to any increases in output.

Projected output and PFC emissions are shown in figure 1. The projections have been derived on the assumption that there is no further reduction in emission factors (average emission factors for Australia of 0.13 kg and 0.013 kg per tonne for CF_4 and C_2F_6 respectively), and aluminium output increases at 2.2 per cent per year. This growth rate is consistent with industry advice that a 30 per cent increase in output by 2010 is considered reasonable.

Total CO_2 equivalent emissions of PFCs for 1990 are estimated to be 4823 Gg, compared with 1346 Gg in the latest 1997 national greenhouse gas inventory. Projected changes in aluminium output to 2012 and no further changes in emission factors result in emissions of 2079 Gg, substantially less than in 1990 despite the growth in output. Estimated aggregate CO_2 equivalent emissions for the period 2008 to 2012 (the first commitment period) are 9955 Gg, and five times 1990 emissions equate to 24113 Gg.

Even with 30 per cent growth in aluminium output from 1997/98 to 2010, and overall growth of around 36 per cent to 2012, aggregate emissions for the commitment period are 59 per cent lower than emissions in 1990 multiplied by 5.

Using the same growth rates as under the no change in emission factors scenario, and assuming that emission factors decline to 0.10 kg of CF_4 per tonne and 0.01 kg of C_2F_6 per tonne, aggregate emissions for the commitment period are estimated to be 7658 Gg of CO_2 equivalents. This compares with five times the 1990 value of 24113 Gg, and represents a decline in CO_2 equivalent emissions of 68 per cent.

3.6 Secondary aluminium production and foundries

SF_6 can be used for the purification of aluminium melts. Introducing SF_6/inert gas mixtures into the molten aluminium reduces the hydrogen content and removes oxides and solid inclusions.

Industry advised that SF_6 is not used for this purpose in Australia due to problems with containment and cost. Nitrogen is used to remove hydrogen, and potassium aluminium fluoride is used to remove oxides and solid inclusions.

Figure 1: Projected CO_2 equivalent emissions of PFCs from aluminium smelting assuming no further reduction in emission factors

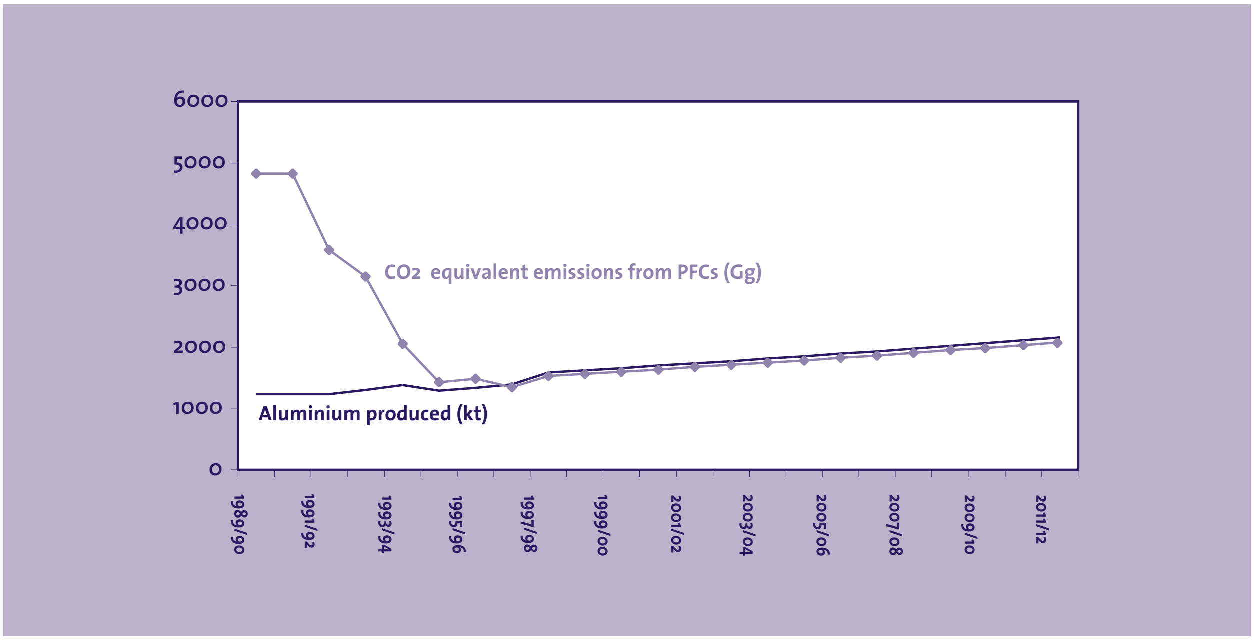
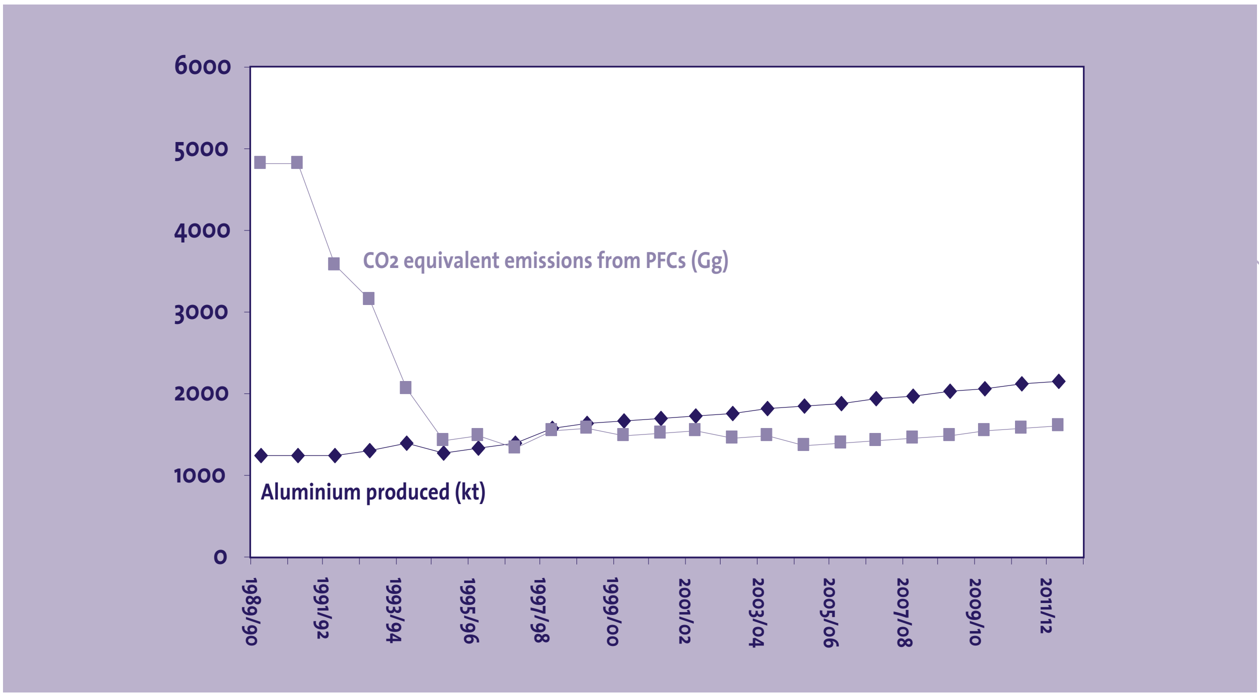


Figure 2: Projected CO_2 equivalent emissions of PFCs from aluminium smelting assuming a reduction in emission factors of 23 per cent by 2005



3.7 Summary and conclusion

Emissions of PFCs from aluminium smelting have fallen by more than 70 per cent from 1990 to 1997. Even with 30 per cent growth in aluminium production to 2010 and around 36 per cent growth in production to 2012, and no further reductions in average emission factors, aggregate emissions of PFCs over the commitment period (2008 to 2012) annual emissions are projected to be 59 per cent less than 1990 emissions.

The Australian aluminium industry has been at the forefront of investigation and implementation of better process control techniques to reduce anode effects (the cause of PFC emissions). All of the Australian smelters have compiled action plans appended to supplementary agreements under the Greenhouse Challenge Program. An important element of these plans is to further reduce anode effects and emissions of PFCs. These plans effectively represent detailed environmental management strategies for dealing with greenhouse gas emissions.

It is considered that Australian aluminium smelting industry provides an example of “best practice” management in abating emissions of PFCs. This is reinforced by the information provided on other countries by Dolin (1999). Dolin shows that the overall reduction in PFC emissions in Australia exceeds that in all other countries including Bahrain, Brazil, Canada, France, Germany, New Zealand, Norway, United Kingdom, and United States. In addition, the voluntary agreements process under the Greenhouse Challenge Program is an example of best practice which Australia adopted earlier than some other countries, such as the USA, where the Voluntary Aluminium Industrial Partnership was implemented in 1998.

The current environmental management strategies for aluminium are effective both in an absolute and comparative sense and any future measures should incorporate an understanding of the achievements of the industry. Although, it is noted that an important strategic issue for the industry and policy issue for government will arise once the limit to reducing PFC emissions has been reached. At this point, without changes in production technology, any increase in output will inevitably lead to an increase in emissions.

4

Electrical equipment

4 Electrical equipment

4.1 Overview

The main use of sulphur hexafluoride globally is in electricity transmission and distribution and accounts for approximately 80 per cent of the amount used each year. Christophorou, Althoff and Green (1997) provide detailed information on SF_6 and much of the following discussion is derived from their work. SF_6 is the electric power industry's preferred gaseous insulating medium for extra high voltage (above 100 kV) other than air. It is a strong electronegative (electron attaching) gas both at room temperature and at temperatures well above ambient, which principally accounts for its high dielectric strength and good arc-interruption properties. The breakdown voltage of SF_6 is nearly three times higher than air at atmospheric pressure.

In addition, it has good heat transfer (adiabatic) properties and readily reforms itself when dissociated under high temperature conditions in an electrical discharge or an arc (it has fast recovery and it is self-healing). Most of its stable decomposition by-products not significantly degrade its dielectric strength and are removable by filtering. It produces no polymerization, carbon, or other conductive deposits during arcing, and it is chemically compatible with most solid insulating and conducting material used in electrical equipment at temperatures up to about 200 °C.

Despite its efficiency as a dielectric, SF_6 does have some undesirable properties under certain stresses. It forms highly toxic and corrosive compounds when subjected to electrical discharges (for example, S_2F_{10}, SOF_2); non-polar contaminants (for example, air, CF_4) are not easily removed; its breakdown voltage is sensitive to water vapour, conducting particles, and conductor surface roughness. It also exhibits non-ideal gas behaviour in cold climatic conditions (about -50 °C), where it becomes partially liquefied at normal operating pressures. Attributes that make SF_6 useful for leak detection and as a tracer gas are its efficiency as an infrared absorber and chemical inertness, but these same attributes also make it a potent greenhouse gas which is the concern of this discussion paper.

The contamination products are formed when the SF_6 is partially decomposed by electric discharges (CIGRE, 1997). The four major types are partial discharges of the corona type, spark discharges, switching arcs, and failure arcs. Insulation defects cause partial discharges of the corona type. SF_6 is decomposed into SF_4 and F which further react with traces of oxygen, O_2, and water, H_2O, to form the compounds HF, SO_2, SOF_2, SOF_4 and SO_2F_2. Trace amounts of S_2F_{10}, S_2OF_{10} and $S_2O_2F_{10}$ are also formed. Spark discharges lead to the formation of the same substances as in partial discharges but the quantities are small. If severe insulation defects cause permanent spark-type discharge activity for an extended period of time and if no adsorbers are provided in the equipment, larger quantities can accumulate.

Switching arcs occur in load break switches and power circuit breakers. The high current flow leads to erosion of the contact and insulation materials by the hot arc. The erosion products react with fragments of thermally dissociated SF_6 and other trace gases such as oxygen and water vapour. The most important reactions are summarised as follows:

$$\mathrm{Cu + SF_6 \longrightarrow CuF2 + SF_4}$$

$$\mathrm{W + 3SF_6 \longrightarrow WF_6 + 3SF_4}$$

$$\mathrm{CF_2 + SF_6 \longrightarrow CF_4 + SF_4}$$

The source of copper (Cu) and tungsten (W) is the eroded material from the sacrificial arcing contacts. The last reaction leading to the generation of tetrafluoromethane (CF_4) is due to eroded PTFE (a CF_2 polymer) which is employed in switchgear to contain the arc (CIGRE, 1997; p. 8). CuF_2, SF_4 and WF_6 are the primary products generated, with the gases SF_4 and WF_6 being very reactive. CF_4 may affect the gas insulation capability and the circuit-breaker switching performance if present in too high concentrations. In addition, it may have an influence on the convective heat transfer by the insulating gas. The reaction product of most interest is the perfluorocarbon, CF_4, given that it has a global warming potential of 6,500. If the gas is present in quantities greater than trace amounts, both the quantity and fate need to be accounted for in the estimation of greenhouse gases from electricity supply.

4.2 Transmission and distribution equipment

The process of electricity supply is usually divided into generation, transmission and distribution. The majority of electricity is produced at large power stations from coal, natural gas, oil or hydro. The electricity is transported from the generator to the point of distribution using high voltage transmission lines. The electricity is then transformed to a lower voltage for distribution to the final consumer, household and smaller industrial power users. Although generation is referred to separately, transmission to the power station boundary uses similar equipment as is used in transmission for distribution. This means that in the discussion the reference to SF_6 used in transmission equipment also includes some equipment used by generators in the process of transmitting power offsite. Importantly, the life-cycle of SF_6 use in electrical equipment can begin at the power station in the generation circuit breaker. It is used almost exclusively for transmission circuit breakers and has very limited use in distribution.

Sulphur hexafluoride is the electric power industry's preferred gas for electrical insulation and for arc quenching and current interruption equipment used in the transmission and distribution of electrical energy. The four major types of electrical equipment where SF_6 is used are gas-insulated circuit breakers (GCBs) and current interruption equipment, gas insulated transmission lines (GITLs), gas-insulated transformers (GITs), and gas-insulated substations (GISs).

In GCBs, the excellent thermal conductivity and high dielectric strength of SF_6, along with its fast thermal and dielectric recovery (short time constant for increase in resistivity), are the main reasons for its high interruption capability.

With GITs the cooling ability (adiabatic properties), compatibility with solid materials, and partial discharge characteristics of SF_6 – added to its beneficial dielectric characteristics – make it a desirable medium for use in this type of electrical equipment. The use of SF_6 insulation has distinct advantages over oil insulation, including none of the fire safety problems or environmental problems related to oil, high reliability, flexible layout, little maintenance, long service life, lower noise, better handling, and lighter equipment. However, these environmental problems will in the future need to be balanced against the greenhouse impacts of SF_6 use. GITs have not penetrated the Australian market and significant use is not expected.

For GITLs the dielectric strength of the gaseous medium under industrial conditions is of paramount importance, especially the behaviour of the gaseous dielectric under metallic particle contamination, switching and lightning impulses, and fast transient electrical stresses. The gas must also have a high efficiency for transfer of heat from the conductor to the enclosure and be stable for long periods of time (perhaps, 40 years). SF_6-insulated transmission lines offer distinct advantages: cost-effectiveness, high carrying capacity, low losses, availability at all voltage ratings, no fire risk, reliability, and a compact alternative to overhead high-voltage transmission lines in congested areas that avoids public concerns with overhead transmission lines.

In GISs, the entire substation (circuit breakers, disconnects, grounding switches, busbar, transformers, etc., are interconnected) is insulated with the gaseous dielectric medium and all of the properties of the dielectric gas referred to are significant (Christophorou et al, pp.2-3).

Christophorou and Van Brunt (1995; p.952) comment that gas-insulated systems are now a major component of power transmission and distribution systems all over the world. They offer significant savings in land use, are aesthetically acceptable, have relatively low radio and audible noise emissions, and enable substations to be installed in cities very close to the loads. Virtually every substation now being built uses SF_6 circuit breakers, and every GIS and GITL relies on SF_6 insulation.

4.3 Management of SF_6 in the electricity supply industry

The electricity supply industry overseas is acutely aware of the need to improve the management of SF_6, both to reduce greenhouse gas emissions and to reduce costs. Substantial research has been undertaken on alternatives to SF_6, and SF_6 combined with other gases. In Discussion Group B of the Eighth International Symposium on Gaseous Dielectrics (Christophorou and Althoff, 1998) it was commented that, 'According to the Kyoto Protocol, a total emission reduction of 5.2% is demanded for the period 2008-2012 based on 1990 or 1995 levels. This can easily be realized if the following measures are taken in the electric power industry:

- a reduction of the leakage rate from the usual 1%/annum today to 0.5%/a;
- a reduction of the gas handling losses to 2.5%/annum by the new CIGRE recommendation (Task Force 23.10.01, CIGRE, "SF_6 recycling guide – Re-use of SF_6 gas in electrical power equipment and final disposal", Electra, No 173, 1997, p.43);
- improvement of the tightness in old designs in North America, Europe, and Japan or their exchange by modern equipment.

The CIGRE publication reviewed all significant aspects of the recycling of SF_6 gas used in electrical power equipment. A questionnaire circulated to equipment manufacturers and utilities resulted in 50 responses. Based on the survey CIGRE concluded that (p. 3):

1. There is presently little common consistency in the approach to handling and recycling SF_6 in practice.
2. Only high voltage gas insulated switchgear (GIS) users recycle systematically. For other electrical power equipment using smaller quantities of SF_6 recycling is frequently not applied.
3. The reasons for not recycling SF_6 are equipment and manpower costs, and the extremely stringent purity requirements imposed by the standard IEC 376, for new gas, which was specified by some manufacturers to guarantee equipment performance.
4. SF_6 handling and recycling equipment is commercially available ranging from the very basic to very sophisticated.
5. Presently applied handling and recycling procedures vary widely and are partly inconsistent.
6. The purity criteria applied for the recycled gas vary over a wide range.
7. The quantitative knowledge on actual leakage and handling losses is frequently insufficient.
8. The estimated costs/benefits of recycling varied extremely widely.

The major conclusion of CIGRE is that the need for recycling SF_6 has been recognised, but comprehensive guidelines for handling and recycling are urgently needed, along with realistic purity standards for reclaimed SF_6 to be reused in electrical power equipment.

Although leakage rates for equipment are stated to be less than 1 per cent and as low as 0.5 per cent, the CIGRE report (p. 5) comments that:

'Since it is difficult, due to variations in temperature between different parts of operating equipment, to monitor gas content with an accuracy of better than several per cent, commonly used gas monitors provide an alarm after 5 to 10 per cent of the gas has leaked out. The equipment is designed to operate correctly with this loss of gas, and still have a margin to lose more gas. This means that in most cases the gas monitors are not very efficient for checking for leakage of equipment in service. Gas monitoring that continuously measures the SF_6 gas content (density), rather than just giving an alarm after a certain amount of gas is lost, could provide leakage rate information which would allow leaks to be detected after little gas loss. Effective techniques have been developed using microprocessors which allow to measure in service (sic) leakage rates of 1% per year.'

- CIGRE state that efficient reclaiming and reuse of SF_6 on-site requires:
- Electrical power equipment designed to allow for the reuse of SF_6.
- Adequate reclaiming equipment.
- A purity standard for the reusability of reclaimed gas.
- Quality checks of reclaimed gas.
- Gas handling procedures.

Design features of gas insulated equipment contribute to the ready application of successful gas recycling as follows:

- The removal of decomposition products and humidity by internal adsorbers keeps the contamination levels in the gas very low and thus eases the cleaning of the gas during recycling.
- Minimising the gas volume and pressure reduces the quantity of gas to be recycled.
- Subdivision of the equipment in sealed compartments limits the quantity of the gas to be recycled, particularly in the of failure arcing where severely contaminated SF_6 has to be treated.
- Sealing systems that are designed to withstand both pressure and vacuum which will occur during gas removal/filling avoid the possible contamination of SF_6 with air.
- SF_6 specific gas connections and self sealing valves prevent accidental gas loss or contamination with air by false handling.
- Avoiding external gas pipe work minimises leakage from corroded or mechanically deteriorated materials and connections.
- Minimising the use of oil and grease as lubricants in the equipment excludes the possibilities of contamination in the gas with lubricant oil which is difficult to remove.

These features are considered to be state-of-the-art in most new equipment, and older equipment can be retrofitted at the time of maintenance at relatively low cost (CIGRE, 1997; p. 6).

There are four categories of gas – new gas, non-arced gas, normally arced gas, and heavily arced gas. New gas should comply with stringent manufacturer's specifications. Non-arced gas contamination may be air and humidity. Normally arced gas is gas recovered from switchgear after normal switching operations. Contaminants include air, humidity, CF_4, corrosive gaseous SF_6 decomposition products referred to earlier, and solid decomposition products, mainly metal fluorides and tungsten oxifluorides, usually referred to as switching dust.

CIGRE indicate that non-arced gas is to be expected at insulation testing in the factory, insulation testing on-site during erection/commissioning of equipment, routine maintenance of insulation compartments, repair of insulation compartments after malfunction without arcing, retrofitting of insulation compartments, and decommissioning of insulation compartments in which arcing has not occurred. Normally arced gas is to be expected at maintenance and repair of switching devices after normal (load or fault) operation, switchgear development tests, and decommissioning of switchgear. Heavily arced gas is to be expected at repair of circuit breakers after interruption failure, repair and insulation components after internal arcing failure, and decommissioning of equipment after any kind of arcing failure.

Equipment for reclaiming SF_6 has been available since the introduction of SF_6 technology. The basic operations in reclaiming are the recovery of the gas including filtering and compression, and reuse where the gas is used to refill equipment with separation of recovery and refill pipes recommended to avoid particulate contamination of the cleaned gas.

CIGRE (p. 26) concluded that:

- In order to avoid contamination of the atmosphere, recycling of SF_6 is essential.
- Recycling equipment and procedures are available to allow, in the majority of cases, economically favourable recycling of SF_6.
- The quality of properly recycled SF_6 is suitable for reuse in electrical power equipment.
- Final disposal, by conversion into environmentally disposable materials, is feasible.
- All SF_6 users should follow the recommendations for recycling.
- International standards for recycling of SF_6 need to be formulated.
- Further improvements shall be pursued and introduced.

CIGRE also framed a series of recommendations directed at equipment manufacturers, equipment users and SF_6 producers. In respect of equipment manufacturers they recommended that:

- Equipment manufacturers shall inform users on the recyclability of SF_6 and other materials contained within the equipment.
- Warranty statements shall be revised to allow the reuse of SF_6 fulfilling the proposed purity requirements.
- Equipment manufacturers shall encourage the reuse of SF_6 on-site and provide instruction and technical support to the users.
- Equipment manufacturers shall recommend adequate and user-friendly recycling equipment to the users.
- Gas monitoring techniques for the detection of leakage in service shall be developed to higher sensitivity.
- Records shall be kept of the SF_6 quantities purchased, delivered to customers, and returned to SF_6 manufacturers or recycling companies.

The recommendations to equipment users comprise:

- Gas handling equipment or service contracts for gas handling on-site shall be provided.
- The electrical power equipment shall be operated and maintained according to manufacturer specifications.
- Electrical power equipment with excess leakage shall be repaired or replaced.
- Records shall be kept of the installed SF_6 inventory and of the SF_6 quantities required for operation and maintenance during equipment lifetime.

Although the CIGRE recommendations were prepared in 1997, it is understood that they remain in draft form. Nonetheless, the content of the recommendations would seem to provide a strong indicator as to the environmental management issues that need to be addressed within the electricity supply industry. In particular, it appears that SF_6 specifications for equipment can limit the use of reclaimed SF_6 for refilling equipment, detailed knowledge of state of equipment in service is probably deficient due to the difficulties in detecting losses of less than several per cent, inventories of SF_6 could be improved, and recycling of SF_6 may not be common practice when equipment is serviced. A further issue in the context of this research is the fate of the non-reactive contaminant, CF_4.

The electricity supply industry (including equipment manufacturers) has been involved in research on alternatives to SF_6. The initial research effort was directed at finding substitutes for SF_6 that were superior dielectrics (Christophorou et al, p.27). This effort is now driven by the need to minimise the environmental impact of SF_6. The main substitutes that have been investigated are pure nitrogen (N_2), SF_6 and N_2 mixtures, and SF_6 and helium (He) mixtures. Other single gases that could have potential at high pressures for insulation purposes are CO_2, N_2O and SO_2. Mixtures for arc and current interruption that could be suitable include SF_6 and argon (Ar), SF_6 and CF_4, SF_6 and C_2F_6, and He. Combinations of gases for insulation include N_2 and SO_2, N_2 and c-C_4F_8, SO_2 and SF_6, SF_6 and CO_2, and N_2O and SF_6. Of these gases and combinations of gases N_2, He and Ar are not included as greenhouse gases, and the radiative forcing effect of SO_2 remains undefined. All of the other gases are greenhouse gases with significantly lower global warming potentials to SF_6.

Christophorou et al. (p. 29) observe that various gas mixtures show considerable promise for use in new equipment, particularly if the equipment is designed for use with a gas mixture:

- Mixtures of nearly equal amounts of SF_6 and N_2 exhibit dielectric properties that suggest that they could be used as a "universal application" gas for both electrical insulation and arc/interruption purposes. In this connection, standard procedures for mixture handling, use, and recovery would need to be further developed.
- Mixtures of low concentrations (<15%) of SF_6 in N_2 show excellent potential for use in gas insulated transmission lines, although further work on their in performance in practical systems is necessary.
- Pure high pressure nitrogen may be suitable for some electrical insulation applications. Consideration of the use of such environmentally friendly gases should be investigated and promoted.
- A mixture of SF_6 and helium has shown promise when used in gas insulated circuit breakers, and should be investigated further.

An important issue in relation to the development of alternatives to pure SF_6 is the fate of mixtures or single gas substitutes over the full life-cycle of the gas. The search for substitute gases is substantially driven by environmental concern, namely, the release of a potent greenhouse gas into the atmosphere. All other things equal, any substitute, even a mixture including SF_6, will reduce the greenhouse impact from charging of new equipment, leakage from equipment in service, and recharging of equipment in service. When the gas reaches the end of its life cycle and needs to be replaced, the ease with which gas mixtures can be recovered and reused is crucial. The removal of contaminants from mixtures to enable reuse or disposal of contaminated mixtures is an issue that needs to be addressed. If mixtures prove difficult to recover and reuse, the lower emissions during charging and servicing delay rather than abate emissions.

The attitude of the electricity supply industry overseas is reflected in the comments of Morrison et al. from Ontario Hydro Technologies, 'Managing our investment in SF_6 provides direct economic and environmental benefits. Voluntary controls on emissions may be cheaper to implement than regulatory controls, especially if it extends the useful life of SF_6-filled equipment. The simplest form of control is the development of handling procedures to minimize losses, and their careful implementation by proper training to ensure the desired results are achieved. Reclaiming used SF_6 for reuse is a standard practice to prolong the use of SF_6 indefinitely, and minimize expenditures for new gas' (p. 562). Further, 'Ultimately, what must be answered is the loss of SF_6, which should be reported as a fraction of installed inventory as well as an absolute quantity. The SF_6 emissions may then be assessed with respect to the total emissions of greenhouse gases' (p. 572).

4.4 Use of SF_6 in Australia's electricity supply industry

The Australian electricity supply industry comprises a large number of power stations, along with extensive transmission and distribution infrastructure. There are in excess of 80 substations of 220 kilovolts (kV) and above, and more than 240 substations of 132 kV and below. Extensive transmission networks at operating voltages above 110 kV require SF_6 for use in switchgear and circuit breakers. Australian Standard AS2791/1996 is concerned with high voltage switchgear and control gear – use and handling of sulphur hexafluoride. It is expected that procedures in Australia comply with this standard although Australian Standards are not mandatory. Development of high voltage transmission networks as a result of adaptation to the changes in the Australian electricity market is likely to result in increased use of SF_6 insulated equipment.

In conducting the research for this paper various utilities (Transgrid, NSW; Energex, Queensland; Energy Australia, NSW; GPU PowerNet, Victoria; CitiPower, Victoria; Powerlink, Queensland) and the industry's association (ESAA) were consulted. The utilities consulted were selected based on the advice of the ESAA. Powerlink, Queensland, and CitiPower, Victoria, responded to the request for information.

The National Greenhouse Gas Inventory includes leakage of SF_6 from switchgear and circuit breakers (electrical transmission and distribution). In 1996, estimated use in switchgear was estimated at 140 tonnes and the leakage rate was 0.2 per cent. This resulted in estimated emissions of 280kg. Original data for the Australian industry, however, is scarce. Comparison of this estimate of emissions from electrical transmission and distribution with estimates for the USA raises serious concerns about its accuracy. Burnbank believes that this estimate is too low.

The US Greenhouse Inventory for 1996 (US EPA, 1998; p. 3 27) comments that, 'To explore emission rates from electrical equipment, the EPA examined atmospheric concentrations of SF_6. Assumptions were made to estimate historical worldwide SF_6 production. An atmospheric mass balance was then calculated and compared with production of SF_6. The conclusion drawn by the US EPA was that most of the SF_6 produced worldwide since the early 1950s must have been emitted. Thus, it was concluded that emission rates from equipment must be higher than had been claimed.

It was assumed that roughly three-quarters of SF_6 production was used in electrical equipment and that equipment leaked at a rate much higher than proposed by industry'.

In view of the concerns about the original estimate and the absence of information for Australia, the original estimate of emissions of SF_6 has been revised. Estimates from 1990 have been derived based on the assumption that Australia's emissions per capita are likely to be similar to those in the US given both are developed countries with sophisticated electricity transmission and distribution infrastructure and a range of energy intensive industries. These top down emission estimates are shown in table 4.1.

It is recognised that the estimated emissions provided above are likely to be too high and it is expected that they will be revised in future national inventories. In the European Union, SF_6 emissions from the manufacture and use of high voltage switchgear are estimated to be 274 tons per annum in 1995 (Electricity Association, 1999). Estimated emissions in 1997 for the United Kingdom are around 11 tonnes, with 500 tonnes contained switchgear. The population of the United Kingdom is about 58 million, approximately 22 per cent of the US population, yet, based on this data, SF_6 emissions are one per cent of US emissions.

The ESAA has information of the situation within individual companies, but not for the industry overall. This information allowed the aforementioned bottom-up estimate of SF_6 emissions from this industry to be made. This estimate has a significant degree of uncertainty and includes some interpolated figures. The scale of the ESAA estimate is markedly lower than the top-down estimate based on extrapolated US figures. At this point, it is impossible to reconcile these two estimates. The ESAA appropriately asserts that:

'ultimately, more reliable and current data will need to be obtained from the holders of SF6 in the Australian Electrical Supply Industry.'

Table 4.1: Emissions of sulphur hexafluoride from electricity transmission and distribution

Year	Population: USA (millions)	SF_6 emissions: USA (tonnes)	Population: Australia (millions)	SF_6 emissions: Australia (tonnes)	CO_2 equivalent emissions: Australia (Gg)
1989/90	249.44	859	16.96	58	1396
1990/91	252.12	902	17.18	61	1469
1991/92	255	945	17.39	64	1540
1992/93	257.75	988	17.58	67	1611
1993/94	260.29	1031	17.76	70	1681
1994/95	262.76	1074	17.95	73	1754
1995/96	265.18	1074	18.19	74	1761
1996/97	267.64	1074	18.43	74	1768

Source: US EPA (1998); US Bureau of the Census (1998, Internet Release); ABS 3101.0 (various issues).

The majority of electricity utilities have signed or are involved in preparing cooperative agreements with Greenhouse Challenge. Cooperative agreements require an inventory of emissions which suggests that those utilities participating in the process would have compiled an inventory of SF_6 contained in equipment. These action plans could include an assessment of future developments in SF_6 management such as recovery of SF_6 and an increase in SF_6 contained in installed equipment. Information on this topic has not been included in this report.

Table 4.2: Energy Consumption 1989-90 to 2011-2012

Year	Electricity consumption (PJ)
1989-90	558.1
1998-99	718
1999-00	733.6
2000-01	752.3
2001-02	760.4
2002-03	774.7
2003-04	787.2
2004-05	803.6
2005-06	815.9
2006-07	827.8
2007-08	839
2008-09	847.4
2009-10	857.4
2010-11	867.3
2011-12	878.8

Source: ABARE (1999)

4.5 Future use and management of SF_6

ABARE regularly produce projections of energy demand in Australia. The latest projections were published in 1999 and examine energy market developments and projections to 2014-15. Projections for electricity consumption are shown in table 4.2 for 1990, and the period 1999 to 2012. This period covers the base year under the FCCC and Kyoto Protocol (1990), the time at which demonstrable progress is required to have been made under the Kyoto Protocol (2005) and the commitment period under the Kyoto Protocol of 2008 to 2012.

Electricity consumption has increased by 28.7 per cent since 1990 and is projected to increase from 1990 levels by 57.5 per cent by 2012 (table 4.2). If greenhouse gas emissions due to electricity consumption grow at the same rate as consumption, it is clear that there will be significant issues to be addressed in the context of Australia meeting its obligations under the Kyoto Protocol.

It is unlikely that SF_6 use and emissions will increase in direct proportion to electricity consumption. Given that all new equipment is expected to contain SF_6 and there are developments in other applications of SF_6 such as gas insulated transmission lines, it is possible that the quantity of SF_6 contained in equipment will increase. Another influence on the quantity of SF_6 is the age of existing equipment and the rate of replacement of that equipment. Newer equipment has more efficient seals, lower leakage rates and smaller quantities of gas. If older equipment is replaced, this will reduce future emissions from equipment in service. It could also reveal that losses from existing equipment are much higher than suggested, given that it is designed to function adequately with losses of 5 to 10 per cent compared with the previous estimate of 0.2 per cent referred to earlier.

There remain several unanswered questions with respect to the management of SF_6 in the Australian electricity supply industry. In order to answer these questions, information is required on:

- The electricity supply equipment that includes SF_6, the quantity included in different types of equipment, and the number of units of equipment.

- The processes used for determining the quantities of SF_6 contained in equipment in service (indicates leakage rates). This is an important issue given the observation of CIGRE that it is difficult to monitor gas content with an accuracy of better than several per cent because equipment continues to function properly even when 5 to 10 per cent of SF_6 has leaked out. Consequently, the procedures used to determine the quantities of SF_6 currently used in equipment need to be clearly specified.
- The processes used for recycling normally arced and heavily arced gas, and the availability of reclaiming and recycling equipment.
- The rate of replacement of existing equipment, and the rate of increase in the installation of new equipment containing SF_6 including the quantities of SF_6 and number of units.
- The fate of SF_6 on decommissioning of equipment.

The involvement of the electricity supply industry in the Greenhouse Challenge Program may become an important element of an environmental management strategy. Voluntary programs have been implemented in the United States (Dolin, 1998) and are currently favoured approaches both domestically and internationally. Options that could be considered are:

- Use information provided by the industry to the Greenhouse Challenge Program to monitor progress in managing emissions of SF_6 by the industry.
- Establish an independent reporting regime requiring industry participants to report on all equipment containing SF_6, annual quantities of SF_6 used and the environmental management strategies that are in place to minimise emissions of SF_6.
- Establish a formal mandatory reporting regime requiring industry participants to report on all equipment containing SF_6, annual quantities of SF_6 used and the environmental management strategies that are in place to minimise emissions of SF_6.

The proposed options do not define a process that would displace any strategies that are implemented through the Greenhouse Challenge Program. They are intended to indicate the direction that government monitoring of environmental management of SF_6 could take over the life cycle of the substance. Effective environmental management of SF_6 requires cooperation between equipment manufacturers and suppliers, equipment users, and recyclers of SF_6. Although the electricity supply industry as users of equipment are vitally important, a comprehensive approach would also include manufacturers and recyclers (including manufacturers of recycling equipment).

4.6 Summary

The effectiveness of SF_6 as a dielectric means that it will continue to be used in the electricity supply industry for some time. Research into alternatives is being undertaken, but as yet SF_6 remains superior to the single gases and gas mixtures that have been investigated. The central issue to be addressed by the industry is the environmental impact of SF_6 resulting from its high global warming potential. Attention has been focused on reducing emissions through improving the information on inventories of SF_6 used in equipment, monitoring the amount of SF_6 contained in equipment in service and leakage rates from equipment, improving seals and reducing leakage rates from new equipment, and recovery and recycling of contaminated SF_6. Ontario Hydro noted that the simplest form of control is the development of handling procedures to minimize losses and their careful implementation by proper training to ensure the desired results are achieved.

Australia's electricity supply industry is understood to be addressing the issue of SF_6 through cooperative agreements under the Greenhouse Challenge Program. Original data on the amount of SF_6 used in Australia, releases of SF_6, and information on reclamation and recycling practices are not available. Estimation of emissions has relied on US data and it is conjectured that the estimate is too high, particularly when compared with European data. Appropriate judgement on this issue will require more detailed information from the industry. Importantly, the discussion has highlighted several information deficiencies that need to be addressed in the context of framing a cooperative environmental management strategy.

5

Electronics industry

5 Electronics industry

5.1 Introduction

SF_6 is used in the electronics industry. According to BOC Gases (1999), 'Sulphur Hexafluoride is used by the semiconductor industry for plasma etching prior to chemical vapour deposition (CVD). These processes include oxide etching, nitride etching, and wafer cleaning. SF_6 gas, which is itself inert, dissociates in the presence of an RF field to form reactive fluoride ions. These highly reactive ions are excellent for etching Tungsten and Tungsten silicide films. Reaction products formed are carried off in the exhaust gas stream. Oxygen can be injected into the SF_6 inlet gas stream to react with the sulphur in the plasma to form volatile Sulphur/Oxygen gases that will also exit the process equipment in the exhaust stream.'

A range of very pure gases ('five-nines' or 99.999% pure) are used for semiconductor manufacture. These include bulk (shielding) gases such as hydrogen, helium, argon, nitrogen and oxygen) and speciality gases (silicon precursors, dopants, etching gases and reactant gases). SF_6 is one of the etching gases. Other etching gases include PFCs and HFCs (these replace the CFC etchants banned under the Montreal Protocol) and halogen sources such as nitrogen trifluoride, boron trifluoride, chlorine trifluoride and hydrogen bromide. Other etchants are tetrafluorosilane, chlorine and hydrogen. SF_6 is a key etchant in certain semi-conductor manufacturing processes because it has a selectively high etch rate of silicon relative to SiO_2 and SiN_2.

The SF_6 etchant must be very pure, with low ppm of HF and CF_4. BOC Gases supply a '4-nines' VLSI 4.6 grade (99.996% pure). To eliminate impurities, the gas is supplied in specially passivated steel cylinders with particularly designed connectors. In Australia, BOC Gases (Australia) has been the main supplier of SF_6, although there are now new suppliers. BOC Gases also advertises a '2-nines' Electronic 2.8 grade (99.8%) which is unsuitable for manufacture of Integrated Circuits (ICs), but satisfactory for use in the manufacture of other electronic components.

At issue is whether the Australian electronics industry uses either high purity or commercial grade SF_6, or HFCs, perhaps as CFC substitutes.

5.2 The semiconductor industry

Three semiconductor technologies are used today, namely: silicon-based semiconductors; compound semiconductors; and amorphous a-silicon based semiconductors.

The silicon-based technology uses crystalline silicon as the basis for fabrication of integrated circuits such as in computer chips, computer peripherals and telecommunications. They represent the bulk of the semiconductor industry. The most dominant transistor type in ICs is the metal oxide semiconductor (MOS). Etching is an important process in silicon fabrication, and the use of SF_6, PFCs and HFCs in the etching of ICs is described below.

Compound semiconductors are based on compounds such as GaAs, CdS, $ZnSiP_2$, Ga_2Se_3 that crystallise in the zinc blend cubic structure and are of commercial importance in electronic and photonic device applications. The original applications of compound semiconductors were in the development of microwave power and oscillator applications, but now Field Effect Transistors (FET), Hetero-junction Bi-polar Transistors (HBT) and Quantum Effect Devices (QED) are more important forms taken by compound transistors.

Compound transistors are uniquely suited for photonic devices, devices that generate, amplify, detect, propagate, transmit or modulate light. This includes the infra-red spectrum essential in night-vision devices which use arrays of compound transistors as detectors. Compound transistors are important in systems using light-emitting diodes (LEDs), lasers (solid state), optical amplifiers, detectors, waveguides (optical fibres, lenses), and optical modulators. In these areas, they extend the scope of semiconductor technology beyond the limits possible with silicon-based transistors. Semi-conductor lasers are used in CD players, CD-ROM drives, bar-code scanners and data-communication systems such as telephone systems. LEDs based on CSs are utilised in multi-colour displays, automobile indicators, and traffic lights. The recording device in the Sony Recordable MiniDisk Walkman, for example, uses a GaAlAs-based

Table 5.1 Synthetic gases used for plasma etching

Material being etched	Synthetic gas used for etch
Polysilicon	SF_6 or CF_4 (or non-synthetic gases such as Br_2, HBr, Cl_2, BCl_3, $SiCl_4$)
Tungsten	SF_6 (or NF/Cl_2)
Single crystal Si	CF_3Br or HBr/Cl_3
SiO2	CCl_2F (a replacement for CCl_2F_2)
SiO2	CHF_3/CF_4 (a replacement for CF_4)
SiO2	CHF_3/O_2 (a replacement for C_2F_6)
SiO2	CH_3CHF_2 (a replacement for C_3F_8)
Si3N4	CF_4/O_2, CF_4/H_2, CHF_3, CH_3CHF_2 (replacements for CCl_2F_2)

semiconductor. The etching systems used in compound semiconductors differ from those used in silicon-based ICs and are described below.

Amorphous silicon technologies are being used/developed for flat panel liquid-crystal displays, solar panels, flash memories, and power semiconductors. They further extend the capability of the semi-conductor devices, again using somewhat different fabrication technologies.

5.2.1 The etching of ICs based on silicon-based metal-oxide semiconductors (MOS)

After a resist layer is patterned on a wafer, the exposed substrate is removed by etching. Subsequently the resist is removed, leaving a desired pattern in a functional layer of the IC. In IC fabrication, a number of materials are patterned by etching. They include polysilicon, metal layers, and oxide and nitride layers. The etching process for each material is different and adapted to substrate properties. The aim in producing MOSs is creating precisely patterned geometries that have vertical profiles as undercutting of the substrate below the resist must be avoided. The etching must not remove the resist layer and act uniformly over the exposed surface.

The etching may be done chemically or physically. Physical removal of substrate (spluttering) works by accelerating energetic chemically inert ions such as Ar+ or Xe+ to the wafer where they eject material from the surface. Chemical removal works by subjecting a halogenated hydrocarbon to a plasma to generate a reactive ion, for example fluorine, which chemically reacts with the substrate, forming a volatile reaction product carried away in the gas flow. For example, CF_4 disassociates into CF_3 and F in a plasma, the CF_3 reacts with the shielding oxygen gas, the F atom reacts with a Si or SiO_2 substrate to form volatile SiF_4. The reaction products are removed in the exhaust gases. Typically the gases used for etching have included some CFCs, PFCs and HFCs ($CFCl_3$, CF_2Cl_2, CF_3Cl, CF_4, CHF_3, C_2ClF_5).

In Reactive Ion Etching (RIE), the wafer becomes the radio-frequency driven electrode instead of the grounded electrode. Its advantage is higher bombardment energy, with a larger grounded surface and lower pressures, leading in turn to greater wafer uniformity.

Etching technology is continuing to evolve, with new etching gas mixtures being developed to meet the needs of small chip fabrication and to comply with the Montreal protocol (Table 5.1). Smaller faster chips, fabricated with submicrometer processes, cannot get vertical profiling by the use of passivating gases (CCl_4, CF_4, $CHCl_3$ or CHF_3) in the etch gas. The replacement processes currently being developed for small chips use greater selectivity and higher etch rates to get the desired profiling.

The CFCs used for etching ($CFCl_3$, CCl_2F_2, CF_3Cl and CF_3Br) are being replaced to comply with the Montreal protocol. The replacements are:

- fluorine-based gases such as SF_6, NF3 and SiF_4 for tungsten etch;
- chlorine-based gases such as Cl_2, BCl_3 and $SiCl_4$ for aluminium etch; and,
- bromine-based gases such as Br_2 and HBr.

5.2.2 ETCHING IN FABRICATION OF COMPOUND-SEMICONDUCTOR DEVICES

Etching is extensively used in the fabrication of compound-semiconductor devices. Uses include active area definition, gate recess etching, and waveguide formation. Wet and dry etching technologies are used. Wet etching typically uses mineral acids, often in combination with hydrogen peroxide, or alkalis, depending on the purpose of the etch and the composition of the layer being etched. Wet etching does not use synthetic gases, and is not further discussed.

A wide range of gases can be used for dry etching, the choice depending on the semi-conductor and the etch method. The methods include chemically assisted ion-beam etching (CAIBE), reactive ion-beam etching (RIE), and electron cyclotron resonance (ECR). The CFC CCl_2F_2 has been used for ECR etching of GaAs and AlGaAs and GaN, InN and AlN as well as the hybrid ECR etching of GaSb. SF_6 and other synthetic gases can also be used as a source of F ions, when these are useful.

5.2.3 ELECTRONIC ASSEMBLY

Transistor devices are critical components in a wide range of appliances and equipment produced by the electronic industry. High-tech equipment containing semi-conductor devices is produced for a range of industries, including medicine, telecommunications, computing, and equipment for chemical analysis and environmental testing. The properties of SF_6 and other synthetic gases are not only used for the production of the chips, but also can be of use in the equipment. For example, the performance of the equipment, including the equipment used to manufacture the semiconductors, can be improved through the high InfraRed (IR) absorption of SF_6, as well as its plasma control, electrical insulation and cooling properties.

5.2.5 ISSUES

Specific research issues regarding use of SF_6, PFC or HFCs are:

- Does the Australia electronic component manufacturing use these synthetic gases in the manufacturing processes?
- Does the Australian industry use imported components that contain SF_6 , PFCs or HFCs?
- Is the Australian industry likely to use these gases in the future?
- Would Australian industry be affected by broadly based pre-emptive or reactive policies restricting or eliminating the use of SF_6? Is there a need for a special policy to meet the specific needs of the Australian electronics industry?
- Electrical equipment and power generation and transmission are not treated as part of the electronic industry – they are separately treated above. However components that are made by the electronics industry for use in power generating and transmission equipment are considered part of the electronic industry.

5.3 Approach

Information on the Australian industry was sought from the Department of Communications, Information Technology and the Arts (DCITA) and the Australian Electrical and Electronic Manufacturers Association (AEEMA). AEEMA sent information to their 'printed circuit board (PCB)' members asking for responses. AEEMA's study, the *Australian Electronic Manufacturing Study (EMS)*, originally due in May, was awaited in the expectation that it might indicate the current structure and future outlook for the Australian industry. Neither outcome came to fruition — an extension has been sought for the EMS, and AEEMA suggested direct consultation with its PCB members on synthetic gas use.

As a result, the 149 corporate membership list of the Surface Mount and Circuit Board Association (SMCBA 1999) was used. The list contained the major manufacturers identified in previous studies of the Australian industry (OECD 1990), the corporations represented in the EMS study, and electronics companies that had recent news releases (Blue Gum Group, Alcatel, Robert Bosch).

Table 5.2: Companies approached for information

Classification	Company
IC manufacturing	Integrated Electronic Solutions
PCB manufacture	Morris Productions, Precision Circuits
Electronic Contractors	Blue Gum Group
Other component manufacturers	Philips
Electronic assemblies	Varian

Table 5.3: Global manufactures of semiconductor chips by chip type

Chip type	Global Manufacturer
Memory Chips	Samsung
Computer CPUs	Intel
Telecommunications	Motorola
Consumer products	Philips

For the purposes of covering all uses of SF_6, the industry was divided into 5 groups:

- Manufacturers of thick or thin film integrated circuits (ICs) (including any silicon fabricators);
- Manufacturers of raw printed circuit boards(PCBs);
- Contract Electronic Manufacturers (Populators of PCBs);
- Other electronic component manufacturers (transistors, diodes, regulators, thyristors, etc); and
- Manufacturers of electronic assemblies.

At least one company was contacted in each group (table 5.2). The approach was by telephone. The contact position varied, but included Manager, Technical Manager, or Purchasing Officer, and Environmental and Safety Officer. In addition research establishments (CSIRO) and universities (VUT) were contacted.

5.4 Current industry structure

Discussions with the industry suggest that the present and future structure of the industry will be determined by global factors. The market and the main participants are global companies – economies of scale are very high. For example, there are four types of ICs where significant quantities of SF_6 could be used in etching prior to CVD. For each IC type, there are typically only a limited number of manufacturers (table 5.3).

Within Australia, manufacturing activity by global producers has declined over the last decade. The AWA chip plant has closed. Philips, IBM, Plessey and Alcatel have sold their major manufacturing facilities. Ericsson Australia (Broadmeadow), NEC Australia (Mulgrave), Fujitsu (Dandenong), Siemens (Bayswater) have wound down or closed manufacturing establishments. Through takeovers, contract manufacturing is becoming increasingly concentrated, with the Blue Gum Group the largest operator. Typically a manufacturing contract would specify imported raw printed circuits and imported chips. On the other hand, Robert Bosch Australia (Clayton) has gone against the trend and increased Australian production.

It is the sole supplier of an automotive diode to the world, a producer of other household and automotive electronic products, and has expanded Australian production.

Despite the Robert Bosch example, it appears that siting of electronic manufacturing plants is increasingly driven by globalisation dynamics. Australia's advantage appears to lie mainly in the design skills area. A silicon fabrication plant could cost up to $1billion to establish, and most observers contacted considered it extremely unlikely that Australia could attract one of these plants, despite the best endeavours of DISR's *Invest Australia* program.

The world outlook is for computer chips to play an increasing role in global industry. Innovation is proceeding and global demand is growing. The Business Communication Company describes the developments, claiming that 'New film technology to produce designer materials is revolutionising many industries.' (Buscom 1996, DFT96, p.1). Because of the unique properties of SF_6 and the other synthetic gases, use in these industries may increase. However, because manufacture involves large-scale investment in plant, know-how and design, with large economies of scale, and a small number of producers serving global markets, Australia's role in this technology is not expected to extend to manufacturing.

5.5 Current and future synthetic gas use

None of the companies reported using synthetic gases (although some did not respond). This is due to three factors:

- Products whose manufacture uses synthetic gases are not made in Australia – they may be imported.
- Processes that use synthetic gases are not used because alternative processes are available and preferred
- The owners of equipment that contain synthetic gases may not be aware of the fact - just as owners of sports shoes may not be aware of a SF_6 impact-absorbing cushion in the sole.

The first factor explains why SF_6 is not used in chip manufacture, the second why synthetic gases may not have replaced CFC in cleaning, and the third why no evidence of SF_6 use in electronic equipment could be found. To summarise:

Chip manufacture using SF_6: Integrated Electronic Solutions, the new owner of the Philips Australia plant at Hendon SA, is the only commercial chip manufacturer in Australia. It makes thick film hybrids, where an existing IC is customised — additional functions using a ceramic substrate. The process does not require SF_6.

Synthetic gases substitutes for CFCs previously used in the electronics industry: The finished PCBs, once cleaned with CFCs, now use de-ionised water. PFCs and HFCs do not appear to have been substituted.

SF_6 used in electronic equipment: It is possible that small quantities of SF_6 could be enclosed within a part of technical equipment without users' knowledge.

5.6 Conclusions

The findings are summarised in table 5.4. In respect of the issues listed in the table, it would seem sensible to cooperate with other countries to seek agreement in international fora. This is particularly so where cooperative solutions would assist identification and prevention in international trade.

Table 5.4: Synthetic gas use in the electronics industry

Issue	Finding
Does the Australian component manufacturing industry use synthetic gases?	No
Does the Australian industry use imported components containing SF_6?	Unknown
Is the Australian industry likely to use synthetic gases in the future?	No
Would Australian industry be affected by broadly-based preemptive or reactive policies restricting or eliminating the use of SF_6?	No
Is there a need for a special policy to meet the specific needs of the Australian electronics industry?	No

6

Other industries

6 Other industries

6.1 Sporting goods

Shoeworld (1999) claims that, 'Sulphur hexafluoride (SF_6) is the name of the gas contained within the air bubble on 'Nike Air' shoes' (http://www.shoeworld.co.uk/protest).

The technology and evidence is explained by Perrin (1999). Essentially, the large size of the SF_6 molecule prevents it from permeating through the polyurethane membrane. Over time, the smaller oxygen and nitrogen molecules will permeate though the membrane to top up the pressure, which could otherwise fall as the shape of the membrane enclosure degrades with use. The use of SF_6 or alternative dense gas is covered by Nike patent 4219945 that expired in 1997. An alternative mentioned in the Nike patent is the PFC, ethane hexafluoride (C_2F_6). Shoeworld (1999) claim that Nike want 18 months to 2 years to develop and use a replacement technology.

The use of SF_6 to increase the shelf life of recreational products such as tennis balls has also been protected by patent. The mechanism is similar to that patented by Nike for shoes. It is not known if imported tennis balls or other recreational balls use SF_6 or ethane hexafluoride in this way.

Evidence from the UK suggests that sporting shoes may have been a significant source of their SF_6 emissions, but that under this use has been phased out, and such emissions are now negligible.

6.2 Tyres

It is known that SF_6 is used in high-performance tyres. A new South African supplier, SA Industrial Solutions (1999), claims that SF_6 is used in the filling of elastomers to preclude pressure loss in tyres of high performance vehicles.

The impact-cushioning properties of pressurised SF_6 in polyurethane would be useful in some tyres, for example, aircraft tyres, tyres of All Terrain Vehicles (ATV), or tyres on high performance (Formula One) vehicles. Moreover, filling high performance tyres with SF_6 could have other benefits – the tyres could run cooler, and in accidents a burst tyre would assist to extinguish rather than fan a fire.

Bridgestone Australia has experience in the supply of high-performance tyres. In 1997, it supplied race tyres to four Formula One teams. It continued that support into 1998 when race regulations changed to see Formula One cars race on grooved tyres (Bridgestone 1998). They advised that nitrogen is used to inflate Formula One tyres. The RAAF and Qantas advised that aircraft tyres are also inflated with nitrogen.

It is possible that SF_6 has been or is used in tyre construction. Bridgestone Australia imports speciality tyres such as Formula One tyres. They do not use SF_6 in their Australian manufacture, and had not heard of it being used elsewhere.

However, they did advise that it was possible it could be used in "Run-Flat" tyres now gaining in popularity in the US. Once the province of high-performance cars, with special wheels and rims, Run-flat tyres are gaining in popularity for risk-free motoring on US freeways. They have also been designed for All Terrain Vehicles (ATVs).

Bridgestone/Firestone, a US-based subsidiary of Bridgestone Corporation of Japan, the world's largest and tyre and rubber company, first introduced the Run Flat tyre in 1992. In 1998, they announced a new range of Run Flat tyres, the Firehawk SH30 RFT, designed to travel with no air pressure for 80 km at up to 90 kilometres per hour, using conventional rims on a wide variety of today's vehicles (Bridgestone/Firestone 1998).

Two other tyre makers, Goodyear (1999) and Michelin (1997) have also introduced Run Flat tyres for conventional rims. The technical challenges of preventing rim roll-off (where the tyre's bead becomes unattached from the rim) has been overcome by using a specially designed rim-guard, and by engineering of the bead cable. The tyres also have an advanced tread and wall design, based on composites of special materials. These include special forms of carbon black that absorbs and spreads road stress over a larger area to resist cracking.

The use of advanced material engineering techniques, with final construction of tyres combining already complex textile, metal and compound materials, makes determining the original input materials somewhat more difficult. Firestone also produces industrial fibres and textiles, synthetic rubber, and air springs.

The construction of these tyres has been described, and comparison testing undertaken (The Auto Channel 1999). The reports do not indicate the use of SF_6-containing elastomers. However, Firestone does use special 'long-linked' carbon black in the tyre sidewall to strengthen it under zero pressure, and the tread has special construction.

The Partnership for a New Generation of Vehicles (USCAR 1998) considers the technologies that underlie the Run Flat tyre will eventually be used in the new mid-size super cars that meet the fuel-efficient target of 80mpg (over 25km/litre). The PNGV alliance, established in 1993, combines the resources of 7 US Federal agencies, laboratories, universities, suppliers with the resources of the United States Council for Automotive Research (USCAR), a co-operative, pre-competitive research effort between Chrysler Corp., Ford Motor Co. and General Motors Corp. (PNGV, 1999). Since the PNGV aim is an affordable, fuel-efficient, and low-emission vehicle, it would be contradictory if the design used components that had harmful life-cycle environmental impacts.

Several tyre technologies have been tried. For example, the Lifeguard Racing Shield 'tire-within-a-tire' technology still used today in NASCAR stock car racing series. It is possible that some of these tyre technologies may use SF_6. However, according to SA Industrial Solutions, SF_6 appears to be permanently encapsulated within the tyre construction. There is no evidence of these tyres being manufactured in Australia — if they are used, the SF_6 is probably contained within the tyre, and so not captured in the import statistics.

Burnbank understands that the SF_6 has been used as the inflation gas for high-performance tyres in some countries, particularly Germany. Such use is expected to be phased out.

6.3 Leak detection and tracer gas

According to Solvay Fluor Und Derivate, SF_6 is detected at very low concentration levels by modern halogen leak detectors. It is increasingly used as a test gas for detecting leaks in boilers, fuel tanks, pneumatic devices, pipe-line systems, plastic tubing, and containers for carrying radioactive materials and many other vessels.

In addition, SF_6 is used as a tracer gas for meteorological measurements. When added in measured quantities at an emission source, the distribution of the emitted substances can be determined even at relatively long distances. High stability and low solubility in water are of particular advantage for these uses.

In Australia and elsewhere the use of SF_6 for these purposes is minor and is not expected to increase. Air 57 studies use an alternative method for determining the rate of dispersion of gases of interest, referred to as ratioing.

7

Conclusion

7 Conclusion

This discussion paper identifies three main non-Montreal Protocol industries that emit synthetic gases, namely, aluminium smelting, magnesium production, electricity supply and transmission. These industries are addressed in turn.

7.1 Magnesium production

SF_6 is the vital constituent in the cover gas used for magnesium casting, preventing reaction between the molten magnesium and air. It is used in low proportions, less than 0.5 per cent of the cover gas which is primarily dry air and carbon dioxide. Formerly, the crucibles where the magnesium is melted or held in molten form for casting or alloying were not enclosed. The need to reduce SF_6 emissions led to enclosed crucibles. Magnesium producers that follow "best practice" in modern plants lose about 1kg of SF_6 to the atmosphere for every ton of magnesium or magnesium alloy produced but forecast improvements will see this fall to about 0.5kg per ton. The production of primary magnesium in large electrolytic cells is the major source of SF_6 emissions in magnesium production. Other sources are the casting of magnesium products (losses of 0.1 to 1 kg per ton depending on the technology), and experimental work in magnesium casting.

At present, only negligible quantities of SF_6 are used in magnesium production in Australia. These are used in experimental work on casting by CSIRO and the CRC for CASTmm, the AMC magnesium metal demonstration plant at Gladstone, and by specialist Australian foundries when producing magnesium castings. This could change in the future with Australia having the potential to become the world's largest producer of magnesium. The ultimate implications for Australia's SF_6 use depend on (1) the likelihood of the projects proceeding, and (2) the usage of SF_6 by these projects.

The timeframe and success rate of the Australian projects will depend on growth in the world magnesium market, which in turn depends primarily on replacement of aluminium and steel automobile components by magnesium alloy. Lighter magnesium parts bring environmental benefits in the form of higher automotive fuel efficiency and lower life-cycle greenhouse-gas emissions, but only if SF_6 emissions can be reduced (Mellerud, 1999). Rapid replacement requires that (1) the price of magnesium falls relative to aluminium and (2) actual and perceived disadvantages of magnesium are addressed (Cole 1999).

Both these preconditions are possible. The cash production cost estimates presented at 'The Inaugural Australian Magnesium Conference' suggested the proposed facilities could undercut the current world price. This would generate the economic incentive for the global car companies to move more quickly towards magnesium components.

Work now being undertaken by the International Magnesium Association could see SF_6 emissions from magnesium production reduced or eliminated. For over 3 years the IMA has advised member firms of the high GWP of SF_6 and provided them with technical information on how to reduce them. It is also coordinating efforts to develop SF_6-free magnesium production — it has set up the 'Ad Hoc Committee For SF_6 Substitution' to report on this issue. In the interim, work is proceeding independently by at least four of the world magnesium players to develop solutions, with a variety of different approaches under examination.

The discussion paper provides an optimistic and pessimistic outlook for Australia's magnesium production. It does not tie this to the use of SF_6 for two reasons. A new production route being investigated by one Australian magnesium venture may avoid the use of SF_6 cover gas. Other projects may choose to use SO_2 as a short-term solution, despite operational shortcomings. Norsk Hydro, the world's largest producer has recently announced they will adopt SO_2 as a short-term solution. At this early stage, it is not possible to tie SF_6 usage to the Australia project proposals. A possible exception is AMC's Gladstone project for which an EIS is currently expected by November 1999.

It is unnecessary to predict the time scale of Australia's primary magnesium projects if Australia's primary magnesium producers are SF_6-free by 2008, the start of the Kyoto Protocol commitment period. This outcome is probable but will depend on the results of current research on alternatives, and the rate of diffusion of any new technology.

The magnesium companies have a keen interest in reducing and eventually eliminating SF_6 emissions. They recognise that they will be subject to increasing pressure to minimise emissions, particularly given that SF_6 is not the only greenhouse gas that will arise from magnesium production. In developing possible response options the following could be considered:

- The stand-back option. Do nothing for the present except maintain a watching brief being ready to take action if projects go ahead without appropriate technology. This approach is likely to be best if the pessimistic scenario for magnesium production and optimistic scenario for SF_6 research eventuate.
- The keep-abreast of SF_6 research option. Do nothing except liase with the IMA and its SF_6 committee to keep abreast of the potential for SF_6-free production. This will be advantageous if feedback from the research into SF_6 alternatives becomes available before year-end. It would allow governments to specify which production technologies should not be approved.
- Voluntary reporting by the proposed projects on projected greenhouse gas emissions. This could be part of the Greenhouse Challenge program. The advantage is that government objectives could be achieved without direct regulatory intervention.
- Mandatory reporting by the proposed projects. This would require some specification by government as to the detail of the report. It would be appropriate under the pessimistic SF_6 research scenario and the optimistic production scenario. This scenario would have a significant impact on greenhouse gas emissions, especially since some projects would generate significant process CO_2, and use large quantities of energy.

Although it is probable that Australia's magnesium producers will be SF_6-free by the commitment period, this will not obviate the need for monitoring greenhouse gas emissions. No detail is available on the alternatives being investigated, however, a cooperative approach should enable the AGO to keep informed of developments in this area.

7.2 Aluminium smelting

Aluminium smelting gives rise to emissions of PFCs (CF_4 and C_2F_6) as a result of unwanted anode effects that occur in the production process. These emissions have been catalogued since the commencement of the compilation of the NGGI. The Australian aluminium industry has been at the forefront of research into controlling anode effects and reducing emissions of PFCs. Since 1990, emissions of PFCs have declined by more than 70 per cent. Reporting of PFC emissions has been transparent. In addition, the industry has participated in the Greenhouse Challenge Program since 1996 and provides annual reports to the Australian Greenhouse Office on actions to reduce greenhouse gas emissions including emissions of PFCs. Industry research on PFCs is continuing with the representatives from Australia participating in the IPCC's workshop on good practice in inventory preparation for industrial processes and the new gases.

It is considered that Australian aluminium smelting industry provides an example of "best practice" management in abating emissions of PFCs. This is reinforced by the information provided on other countries by Dolin (1999). Dolin shows that the overall reduction in PFC emissions in Australia exceeds that in all other countries including Bahrain, Brazil, Canada, France, Germany, New Zealand, Norway, United Kingdom, and United States. In addition, the voluntary agreements process under the Greenhouse Challenge Program has been successful and can be characterised as an example of 'best practice'. The real test of voluntary programs and cooperation will come if there is a need to implement costly reductions in emissions.

7.3 Electricity transmission and distribution

Electricity transmission and distribution is a potentially significant area of SF_6 emissions where information for Australia is deficient. The effectiveness of SF_6 as a dielectric means that it will continue to be used in the electricity supply industry for some time. Research into alternatives is being undertaken but as yet SF_6 remains superior to the single gases and gas mixtures that have been investigated. Attention has been focused on reducing emissions through improving inventories of SF_6 used in equipment, monitoring the amount of SF_6 contained in equipment in service and leakage rates from equipment, improving seals and reducing leakage rates from new equipment, and recovery and recycling of contaminated SF_6.

The discussion in the paper has highlighted several information deficiencies that need to be addressed in the context of framing an environmental management strategy as follows:

- The electricity supply equipment that includes SF_6, the quantity included in different types of equipment and the number of units of equipment.
- The processes used for determining the quantities of SF_6 contained in equipment in service which in turn indicates leakage rates.
- The processes used for recycling normally arced and heavily arced gas, and the availability of reclaiming and recycling equipment.
- The rate of replacement of existing equipment, and the rate of increase in the installation of new equipment containing SF_6 including the quantities of SF_6 and number of units.
- The fate of SF_6 on decommissioning of equipment.

At this stage there is no formal data collection regime that ensures that both the National Greenhouse Gas Inventory and emissions projections work adequately addresses emissions of SF_6 from electricity transmission and distribution.

The most desirable response option would involve obtaining the cooperation of the electricity supply industry, preferably through the Electricity Supply Association of Australia, so as to acquire the information referred to above. This would enable investigation into whether additional information is required, the type of additional information, and identification of areas where some assistance might be provided to the industry. Without industry specific information it is impossible to determine whether substitutes for SF_6 should be encouraged, or whether more stringent policy approaches that would ensure curtailment of SF_6 emissions should be considered. Australia's electricity supply industry is understood to be addressing the issue of SF_6 through cooperative agreements under the Greenhouse Challenge Program.

Options that government could consider are:

- Use information provided by the industry to the Greenhouse Challenge Program to monitor progress in management of SF_6 by the industry.
- Establish a reporting regime independent of Greenhouse Challenge requiring industry participants to report on all equipment containing SF_6, annual quantities of SF_6 used and the environmental management strategies that are in place to minimise emissions of SF_6.
- Establish a formal mandatory reporting regime requiring industry participants to report on all equipment containing SF_6, annual quantities of SF_6 used and the environmental management strategies that are in place to minimise emissions of SF_6.

7.4 Other industries

No response options are suggested in respect of the other industries discussed because they are unlikely to become significant in Australia. Informal oversight of developments in the electronics industry could be considered so that the AGO is aware of any changes in the industry that could lead to the establishment of plants or commencement of activities using synthetic gases.

7.5 Information availability, data collection and verifiability

The research necessary for the preparation of the discussion paper revealed that information availability and data accessibility varied greatly across the different industries. This appears to be attributable to information deficiencies rather than an unwillingness to cooperate. Information on the aluminium industry and the fledgling magnesium industry was readily accessible with a high degree of cooperation from industry participants and researchers associated with the industry. These industries have recognised the importance of greenhouse issues in planning for the future. The aluminium industry has been involved in voluntary government programs and is familiar with the information and data collection requirements for reporting. Some of the potential magnesium producers have also made themselves aware of greenhouse policy and are integrating the implications of greenhouse policies into their planning.

The electricity supply industry and significant suppliers of synthetic gases do not appear to have the data necessary to enable informed decisions to be made on the management of synthetic gases. All significant suppliers of synthetic gases were contacted. Responses were received from a small number of companies that supply gases to Montreal Protocol industries, and one response was received from a major supplier to both Montreal Protocol and Non-Montreal Protocol industries. It is essential that mechanisms be established to obtain the necessary information and data to facilitate proper planning within industries and enable effective implementation of domestic greenhouse gas policies. These mechanisms range from cooperative approaches with associated verification to more costly mandatory approaches enshrined in legislation. The former are preferable, but the latter could be inevitable in the absence of industry initiated actions to collect and make available the required information and data.

An option for reporting that is worth exploring is for relevant State agencies to require reporting under licensing regimes that operate within each jurisdiction and for consolidated reports to be passed to the Australian Greenhouse Office. This would enable State agencies to monitor synthetic gas emissions as part of their environmental policies. A caveat on this approach is that ownership of information would need to be clearly specified from the beginning so as to avoid any dispute relating to accessing and using the information.

Regardless of the approach, there is a need for adherence to good practice in inventory estimation and independent verification of estimation methodologies and emissions estimates. The IPCC is preparing guidelines on good practice in inventory preparation and is addressing the issue of uncertainties and cross-cutting issues (estimation of uncertainties, monitoring, verification, and quality assurance and quality control) in inventory management. It is expected that guidelines will be issued in 2000. An important approach to ensuring confidence in inventory is the application of a reputable validation method. Measurement of atmospheric fluxes of synthetic gases is a valuable monitoring and validation approach. Synthetic gases do not occur naturally in the atmosphere. Atmospheric concentrations result from anthropogenic emissions. Consequently, where these concentrations are not in accord with estimated emissions, it is clear that emissions are underestimated. For example, a global verification experiment conducted by the US EPA on the atmospheric content of SF_6 demonstrated that most of the SF_6 produced in the world must have been released. This demonstrated that leakage rates for SF_6 containing equipment were much higher than previously estimated.

Whatever system is implemented to provide data on synthetic gas emissions, it is essential that there are associated verification procedures. These do not need to be particularly onerous and would not place an additional responsibility on the emitting industries. At a minimum, periodic reviews should be conducted to ensure that atmospheric fluxes are consistent with estimated emissions.

Appendix 1: Terms of Reference

The Terms of Reference for the project specifies the purpose of the project as to conduct research on current and likely expected patterns of emissions, production, use and disposal of synthetic gases (HFCs, PFCs and SF_6) in non-Montreal Protocol industries in Australia.
The objective of the project is to contribute to the preparation of environmental management strategies for synthetic gases.

The outcomes required from the project are specified as:

- A clear identification of the current use and emissions of synthetic gases in non-Montreal Protocol industries, including a life-cycle analysis on the use of synthetic gases, and their possible extension or further use by industry;
- A consideration of data collection regimes on synthetic gases in order to ensure that both the National Greenhouse Gas Inventory and emissions projections work adequately addresses the three gases;
- Identification of the widest range of possible response options and recommendations about "best practice" management options.

Attachment A to the terms of reference lists the industry sectors and indicates the relevance of particular gases for Montreal Protocol industries and non-Montreal Protocol industries as summarised in the following table.

Industry sector	HFCs	PFCs	SF_6
Traditional Montreal Protocol Industries			
Refrigeration and air conditioning	X	X	
Fire suppression	X	X	
Foam blowing	X		
Aerosols (MDIs)		X	
Solvent cleaning	X	X	
Non-Montreal Protocol Industries			
Metal processing			X
Electrical (switchgear and circuit breakers)			X
Aluminium production		X	
Magnesium die casting			X
Other Industries Requiring Investigation			
Sports gear			X
Radar equipment and night vision goggles			X

Consultation

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