

Prepared for European Commission, DG Environment

**Service contract to assess the feasibility of options to
reduce emissions of SF₆ from the EU non-ferrous metal
industry and analyse their potential impacts**

Final Report

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Acknowledgements

A Project Expert Group consisting of selected experts with many years of experience in the non-ferrous metal sector in Europe has provided technical input in this study (see annex III to this report):

Executive Summary

The European Council and Parliament adopted Regulation (EC) 842/2006 on certain fluorinated greenhouse gases (the F-Gas Regulation) which entered into force on 4th of July 2007. Inter alia, the use of SF₆ in magnesium die-casting is prohibited as of 1 January 2008, except where the quantity of SF₆ involved is below 850 kg per year (Art 8(1)). Art 10(2) of the Regulation requires the European Commission to assess whether the substitution of SF₆ in gravity casting (e.g. sand casting) is technically feasible and cost-effective, and to review the 850 kg-threshold in die-casting with regard to available alternatives. The Commission has hence launched this study to assess options for the reduction of SF₆ emissions from the non-ferrous metal industry. The study deals with the sectors of magnesium die casting and magnesium sand casting, which are explicitly addressed in Art 10(2), but recycling (re-melting) of magnesium and the production of aluminium alloys are also included. Primary magnesium production does not take place in the EU.

The study was carried out from December 2008 to October 2009 in collaboration with a Project Expert Group consisting of selected experts with many years of experience in the non-ferrous metal sector in Europe (see annex III to this report).

1. In 2006, the EU non-ferrous metal industry consumed quantities of SF₆ with a global warming potential of 3 million t CO₂ equivalent: 1.8 million t CO₂ eq. in the production of secondary aluminium and 1.2 million t CO₂ eq. in the magnesium casting and recycling sector. While in the magnesium industry SF₆ consumption is considered equal to SF₆ emissions, only 1.5% of the applied SF₆ quantities are considered emissions in the aluminium industry. The total global warming emissions of SF₆ from the NF metal industry thus amounted to 1.22 million t CO₂ eq. (thereof 0.04 million t CO₂ eq. from the aluminium sector). The use prohibition under Art 8(1) of the F-Gas Regulation should, as of 1 January 2008, have already eliminated 0.7 million t CO₂ eq. in magnesium die casting (foundries with SF₆ consumption > 850 kg/a). The remaining sectors of the magnesium industry include die casting companies with SF₆ consumption < 850 kg/a, sand casting foundries, and recycling plants. The total amount of SF₆ consumed/emitted was 0.5 million t CO₂ eq.

2. In the magnesium industry (die casting, sand casting, recycling), the surface of the hot metal melt must be protected against oxidation by cover substances. The gases SO₂ and SF₆ allow good protection up to temperatures of 800 °C of the liquid metal. SF₆ has a high global warming potential (GWP) of 22,800, and the chemical industry developed substitutes containing fluorine with GWP substantially lower than that of SF₆. In the EU, HFC-134a became the most accepted new alternative to SF₆, aside from the well-established cover gas SO₂. Another new-developed cover gas, FK 5-1-12 (Novec-612TM), started being used in industrial applications in the USA and in Japan in 2008.

3. In the aluminium sector, only one smelter in Europe is using SF₆, though not as a cover gas but as a degassing agent to help eliminate impurities from the molten metal in the production of one special alloy. In 2008, the SF₆ consumption of this plant amounted to 100 t/a. The operator claimed more than 98.5% decomposition of the gas in the hot melt, thus only the remaining 1.5% is released un-destroyed to the atmosphere. Waste gas measurement carried out in the course of this study confirmed the 1.5% emission factor.

4. A survey on the use of SF₆ as cover gas in the EU magnesium industry and as degassing agent in the EU aluminium industry showed that 19 of the overall 53 magnesium die casting foundries used SF₆ in quantities < 850 kg/a, causing emissions of 135 kt CO₂ equivalent in 2008. In magnesium sand casting, SF₆ is still the gas commonly used because of the extremely high melting temperatures and the open operation which require extra stable and non-toxic cover gas. In sand casting SF₆ emissions were 228 kt CO₂ eq in 2008, thus higher than emissions from die casting. In magnesium recycling, the mostly used cover gas for normal die casting alloys is SO₂ with only one recycling plant still applying SF₆ for normal die casting alloys in a quantity of 3,000 kg/a. Another recycler, who relies on HFC-134a for normal die casting alloys, uses also SF₆ (3,000 kg) for the special alloys for which extremely high melt temperatures are needed. Thus, total SF₆ emissions from recycling amounted to 137 kt CO₂ eq. in 2008. In the production of one special aluminium alloy, the European plant, mentioned above, uses undiluted SF₆ as degassing agent of the melt. Their SF₆ emissions amounted to 3,000 kg (68 kt CO₂ equivalent) in 2008.

5. There are several policy options, both regulatory and voluntary, to reduce cover gas emissions. In addition to the option of no action (business as usual), options of containment/recovery, partial or full prohibition of use, voluntary agreements, joint implementation mechanism come into question. Screening the options for technical feasibility reveals that containment and recovery, which were the basic options followed by the F-Gas Regulation for the main F-Gas using sectors (stationary refrigeration, air conditioning, fire protection etc), are not feasible solutions in this sector. This is because the foundry equipment of the EU non-ferrous metal industry already represents state-of-the-art technology, and further containment measures would not be effective. From a technical point of view, the only possible choice to further reduce emissions is substitution of SF₆, i.e. by conversion of the plants to use cover gases SO₂ or HFC-134a in die casting and recycling of die casting alloys. In sand casting and recycling of special magnesium alloys, the melting temperature is too high for the use of HFC-134a, whereas SO₂ cannot be applied in such open application either because of its toxicity. The third alternative cover gas, the fluorinated ketone FK 5-1-12 (Novec-612TM), showed promising results at high temperatures in laboratory trials but is not yet commercially available in Europe. As a consequence, at present, the replacement of SF₆ is not feasible in sand casting and

recycling of special magnesium alloys. This is also true for the use of SF₆ as a degassing agent in secondary aluminium production.

6. The conversion of magnesium die casting foundries subject to the 2006 F-Gas Regulation has proved that SF₆ replacement by one of the two available alternative cover gases is technically feasible in this application. The lessons learned are that conversion to SO₂ requires extensive technical restructuring of the gas delivery system because of the toxicity and corrosiveness of the gas. When changing to HFC-134a, normally the existing gas delivery system can be re-used, and only a few adjustments must be made (at gas mixing station and furnaces). In exceptional cases, however, it can be necessary to stabilise the surface of the melt additionally by means of special devices (converters) for ingot feeding. In these cases, conversion to HFC-134a is more complex and costly than conversion to SO₂.

Therefore, the study is discussing and refining only policy options that are based on replacing SF₆ as a cover gas in die casting and in recycling of normal die casting alloys.

7. The following seven policy options are qualified for substitution of SF₆ by conversion to SO₂ or HFC-134a and are selected for more in-depth analysis of their environmental, economical and social impacts.

Option 1: No policy action for magnesium and aluminium industry

Option 2: Full SF₆ prohibition in magnesium die casting

Option 3: Revision of the 850 kg/a threshold in Mg die casting (reduction to 100 kg/a)

Option 4: Joint implementation mechanism for magnesium die casting

Option 5: Full prohibition of SF₆ in recycling of magnesium die casting alloys

Option 6: Voluntary agreement to replace SF₆ in recycling of die casting alloys

Option 7: Joint implementation mechanism for recycling of die casting alloys.

In die casting, the technical choices HFC-134a or SO₂ exist within each option. Operators will have to decide for conversion to either one of these two cover gases. In recycling, only the technical solution SO₂ is considered as the operator rejects conversion to HFC-134a as an alternative to SF₆.

8. Assessment of the environmental impacts of the policy options reveals several aspects:

- Without political action, SF₆ emissions from the NF metal industry will increase at a growth rate of 1% per year from 570 to 640 kt CO₂ equivalent by 2020.
- All reduction options have the potential to cut SF₆ emissions at a range of 212 to 229 kt CO₂ eq. by 2020. This amount translates into about one third of the no-action SF₆ emissions from the NF metal industry in 2020.

- The reduction potential achieved by substituting SF₆ with SO₂ is higher compared to HFC-134a. The use of HFC-134a (GWP=1,430) would also create global warming emissions in the range of 6% of SF₆ emissions.
- All options for SF₆ replacement cause emissions of acidic waste gas (SO₂, HF). As these emissions range below the legal threshold for waste gas concentration limits, considering the high environmental benefit of the replacement SF₆ for climate protection, they are considered acceptable.

9. Based on technical experiences gained by die casting foundries subject to the 2006 F-Gas Regulation within the conversion, the study estimates the annual additional costs (vs. SF₆) arising from conversion to HFC-134a or SO₂ in the 19 die casting foundries which consume < 850 kg SF₆ per year, and from conversion to SO₂ in the only recycling plant of die casting alloys. Conversion to SO₂ generally requires new equipment so that the investment costs are high compared to conversion to HFC-134a. In contrast, the gas costs are lower when using SO₂. Assessment of the economic and social impacts shows:

- The additional annual costs to be paid by the plants range from 0.0 to 0.5% of their annual turnover from magnesium products. This financial burden is considered acceptable for the industry.
- As a consequence, the expenses for new equipment, gas, and the license fee in case of HFC-134a do not cause job risks in the plants, but.
- New employment positions at equipment manufacturers, gas distributors, and the license holder would not be created either.

10. All options analysed are consistent with the EU policy on fluorinated greenhouse gases, and do not imply notable economic and social trade-offs. The specific abatement costs for the analysed reduction options vary between a minimum of -0.39 €/t CO₂ eq. and a maximum of only 0.91 €/t CO₂. The absolute abatement costs are very low in each case and the options do not significantly differ in efficiency (cost effectiveness).

The options are equivalent in coherence and cost effectiveness. Reliability of one particular option to reduce emissions hence becomes the key criterion for ranking. In this perspective, the non-regulatory policy options are ruled out. Full ban of the use of SF₆ in both die casting and recycling of die casting alloys are the most effective policy options. The study recommends these two reduction options to policy makers.

11. With regards to technical choices for implementing those options, HFC-134a solutions are shown to be less effective in emission reduction than the application of SO₂. The GWP of HFC-134a is relatively high (1,430), the potential of the HFC-134a solution to reduce emissions hence decreases. The relatively high costs for

conversion result from the fee that users have to pay to the license holder of HFC-134a.

Sensitivity analysis reveals that the disadvantage of HFC-134a in emission reduction considerably decreases if the destruction of the gas over the melt is taken into account. When taking into account decomposition during the process, the GWP of HFC-134a after use would effectively drop to around 400. Furthermore, the disadvantage in annual costs significantly is balanced if the license fee is lowered. The conversion to HFC-134a would be more cost effective than conversion to SO₂ if the license fee was reduced to half of the amount currently charged per tonne of magnesium produced. In contrast, it cannot be excluded that the propensity of operators of large magnesium foundries to choose HFC-134a as technical alternative to SF₆ is lowered as a consequence of increasing prices of HFC-134a.

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Introduction

SF₆ emissions from NF metal industry in EU-27

In the EU non-ferrous metal industry considerable quantities of SF₆ are applied. In the magnesium sector, SF₆ is used as a cover gas in the casting process of parts or ingots; in the aluminium industry SF₆ is used as a degassing agent for the refining of a special alloy. In 2006, global warming emissions amounted to 1.22 million t CO₂ equivalent from the two sectors, 1.18 million from the magnesium industry (own data) and 0.04 million from the aluminium industry (own data). This equalled almost 20% of the total SF₆ emissions in the EU.

It must be mentioned that in the magnesium sector all consumption of SF₆ is considered equal with emissions (emission factor 100%). This is done in accordance with the IPCC Guidelines of 1999 and 2006. The Guidelines, however, do not provide guidance for the emission factor in the aluminium sector, where SF₆ is used as a degassing agent in the production of one special alloy. In this study, the equation consumption = emission, which was formerly used for the aluminium industry in the EU emission inventory, is no longer maintained. This study relies on new measurements carried out in the course of the study by the only European aluminium smelter using SF₆. The measurements resulted in the finding that only 1.5% of the SF₆ quantity applied is released to the atmosphere.

The Regulation (EC) 842/2006 on certain fluorinated greenhouse gases (F-Gas Regulation) prohibits the use of SF₆ in magnesium die-casting as of 1 January 2008, except where the quantity involved is below 850 kg per year (Art 8(1)). According to a survey carried out in the course of this study, this provision covers already 0.7 million t CO₂ equivalent or 58% of the 2006 emissions from the entire EU magnesium sector.

The remaining 42% (0.5 million t CO₂ eq.) of SF₆ emissions from the magnesium sector arise from gravity (sand) casting, recycling, and from die casting in foundries with SF₆ consumption below the 850 kg/a threshold. These three sub-sectors of the magnesium industry are subject of this study which examines if technically feasible, effective and cost-effective options to reduce emissions could be considered for the upcoming revision of the F-Gas Regulation. Primary magnesium production does not take place in the EU.

Chapter 1 describes the magnesium casting technologies in use in the EU, and presents the established substances used for melt protection. Technical and environmental characteristics of the established cover gases, SO₂ and SF₆, and of available alternatives, HFC-134a and FK 5-1-12 (Novec-612), are discussed.

Chapter 2 covers the aluminium sector, in which only one aluminium smelter uses (undiluted) SF₆ as degassing agent for the production of a special alloy. SF₆ is not a cover gas, but is distributed in the melt by impeller technology. It is discussed to which degree the gas is decomposed in the melt and to which degree it causes global warming emissions.

Chapter 3 presents the results of a comprehensive survey on the use of SF₆ in the non-ferrous metal industry of the EU including the sectors of magnesium die casting, magnesium sand casting, magnesium recycling, and degassing of aluminium. The plants that used SF₆ in 2008/2009 are identified. The indicators include inter alia number of plants, metal input and output, equipment, applied gases, annual SF₆ consumption, etc. The chapter describes the trends in the use of cover gases in magnesium die casting as a result of the F-Gas Regulation.

Chapter 4 lists several possible policy options, not covered by the Regulation, to reduce SF₆ emissions in the magnesium and aluminium industry. It identifies possible technical measures to implement such options and screens them by assessing their technical feasibility.

Chapter 5 considers the existing experience with cover gas conversion in EU magnesium die casting, and describes the technical implications of converting to SO₂ and HFC-134a for the magnesium die casters with SF₆ consumption < 850 kg/a.

Chapter 6 estimates, based on technical data, the additional annual costs (vs. SF₆) arising from conversion to HFC-134a or SO₂ to the affected die-casting foundries, and the recycling plant for die casting alloys.

Chapter 7 identifies and refines, based on the assessments of chapters 4-6, the technically feasible policy options to reduce SF₆ emissions. Regulatory policy options discussed include the full ban of the use of SF₆, and ban of the use in foundries with SF₆ consumption over 100 kg/a, instead of 850 kg/a. The analysis of non-regulatory options includes voluntary agreement and application of the joint-implementation mechanism.

Chapter 8 contains the impact assessment. In addition to the no-action option, three policy options with emissions reduction potential are analysed for die casting, and another three for recycling, with the technical choices SO₂ and HFC-134a under each option. The analysis considers environmental impacts (global warming emissions, emission of acidic waste gas), social impacts (job and health risks), and economic impacts (direct costs to foundry operators, indirect effects on equipment manufacturers, gas distributors, and license holder).

Chapter 9 ranks the analysed policy options by the three evaluation criteria coherence, efficiency, and effectiveness. Two options are recommended to policy makers, one for die casting, and another one for recycling of die casting alloys.

Chapter One

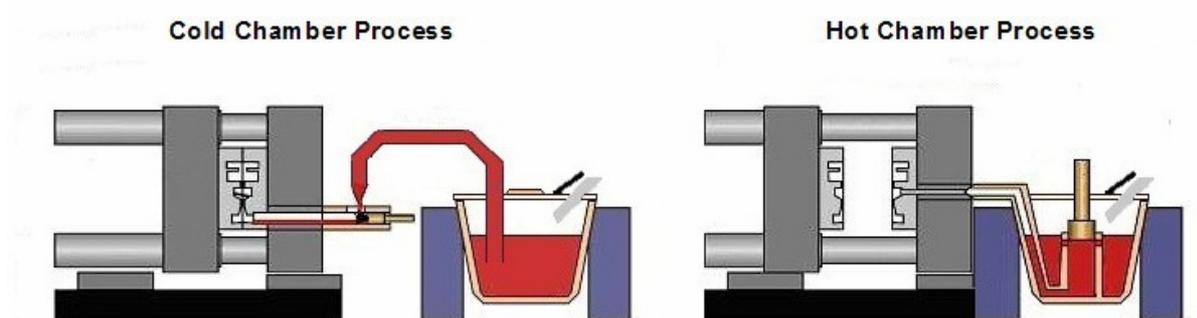
SF₆ and available alternative technologies for melt protection in magnesium casting in Europe

This chapter outlines the different casting technologies of magnesium, and discusses various substances for melt protection presently used in Europe in magnesium casting. Secondary casting of magnesium (die casting, gravity casting, recycling) is based on a liquefaction process by melting the metal at temperatures over 600 °C before casting it into moulds as parts or ingots. Primary production of magnesium does not currently take place in the EU, as the only primary producer shut down in 2000.

1. Casting technologies in the EU

Die casting (high-pressure die casting) is by far the most widespread processing technology for magnesium. It is applied in mass production of identical parts. Liquid metal is instantaneously filled into a steel die under high pressure. After cooling down, the part is ejected and the mould is closed again.

Technologies can be distinguished into cold chamber technology and hot chamber technology. In cold chamber casting (fig. 1), the metal is molten in a furnace, transferred to the casting machine, and filled into (cold) casting chambers. The liquid metal is filled into the die via a plunger.



In hot chamber casting technology, the pressure and melt temperature are lower, and the produced parts are smaller. The injection unit of the casting machine is immersed in the molten metal of a furnace tightly adapted to the machine. The metal is directly forced into the (warm) casting chamber. The machine is installed in a slightly inclined manner to allow the excess metal to flow back into the furnace after solidification of the shot.

Sand casting. Much smaller metal quantities are processed by sand-casting which is the only gravity casting process of economic relevance. Due to its own weight, liquid

metal flows through a gating system into a hollow mould made of sand. The mould is destroyed after solidification of the part. This technology is used for unique copies (prototypes) and small type series. As sand-cast prototypes often precede large-scale die-casting, both technologies are closely related to each other.

Normally, sand casting is an open application. The magnesium alloy is molten in a covered crucible, and then the crucible is carried manually to the casting place where the liquid metal is manually poured into the hollow moulds.

Recycling (melting, alloy making and ingot casting). In the foundries, gatings, feeders, sprues etc. are removed from the parts after casting, and large quantities of scrap arise. As a rule of thumb, one part of product requires two parts of raw material. Specialised recyclers (re-melters) melt the scrap, add primary metal and cast new ingots of alloys of the desired composition and in high-purity quality (i.e. very low levels of impurities like iron, copper and nickel). Only a minority of foundries recycles the returns in house.

2. Necessity of melt protection

Due to the high reactivity of molten magnesium with oxygen and humidity from the atmosphere, special measures must be taken to protect the hot melt from rapid oxidation and ignition in all three technologies described above. To avoid excessive oxidation and ignition, the film of magnesium oxide (MgO) on top of the melt has to be stabilised and separated from atmospheric oxygen and humidity. Both may be achieved by cover gases or layers of liquid salt. The MgO film, however, is regularly destroyed by ingot feeding or cleaning activities, and has to be renewed frequently. Furthermore, magnesium has a very high vapour pressure which allows the metal to escape through tiny defects within the film so that metal vapour passes and finally oxidises to white powder or even ignites.

In die casting, only the metal in the crucible of the melting and dosing furnaces has to be protected. In sand casting, the melt in the crucible must be protected within the furnace and on its way to the casting place, as well as during pouring the metal into the open moulds. In recycling, both melting processes and ingot-casting need protection.

3. Substances for melt protection in the EU

Several substances for melt protection are in use in sand casting, die casting and recycling.

3.1 Cover salts (fluxes)

One of the oldest methods widely used in all casting technologies before the end of the 1960s, is the application of cover salts (fluxes) which are mostly mixtures of chlorides on the basis of salt systems like magnesium chloride (MgCl₂), potassium chloride (KCl), and sodium chloride (NaCl). These mixtures of alkaline and earth alkaline chlorides, which are added as a powder onto the metal surface, show a melting point lower than that of the metal and create a thin, liquid layer of chloride on the surface of the melt. [Emley 1966]

Disadvantages of this measure include the possible contamination of the molten metal with chlorides causing corrosion of cast parts, and the formation of hydrochloric acid from exposition to humid air. Another problem is associated to flux fumes and flux dust, which can cause corrosion in a foundry. These by-products caused the abandonment of cover salts in die-casting. Today they are only used in sand casting, recycling processes (of low quality scrap) and exceptionally in small-scale die-casting.

3.2 Inert gas: Argon

The protection of the liquid metal under an atmosphere of inert gas, usually argon, is based on the displacement of oxygen. Argon, as an inert gas, does not react with the metal and, consequently, does not form a protective film over the melt. Therefore, it cannot prohibit evaporation of hot magnesium so that metal vapour reaches the atmosphere above the melt. This creates the risk of explosion especially when air enters the furnace on opening a lid. [Ditze/Scharf 2008] Like cover salts, argon is only used in some sand casting plants today, where the working temperatures are moderate (it is not applied at high temperatures above 720 °C).

3.3 Established reactive cover gases: SF₆ and SO₂

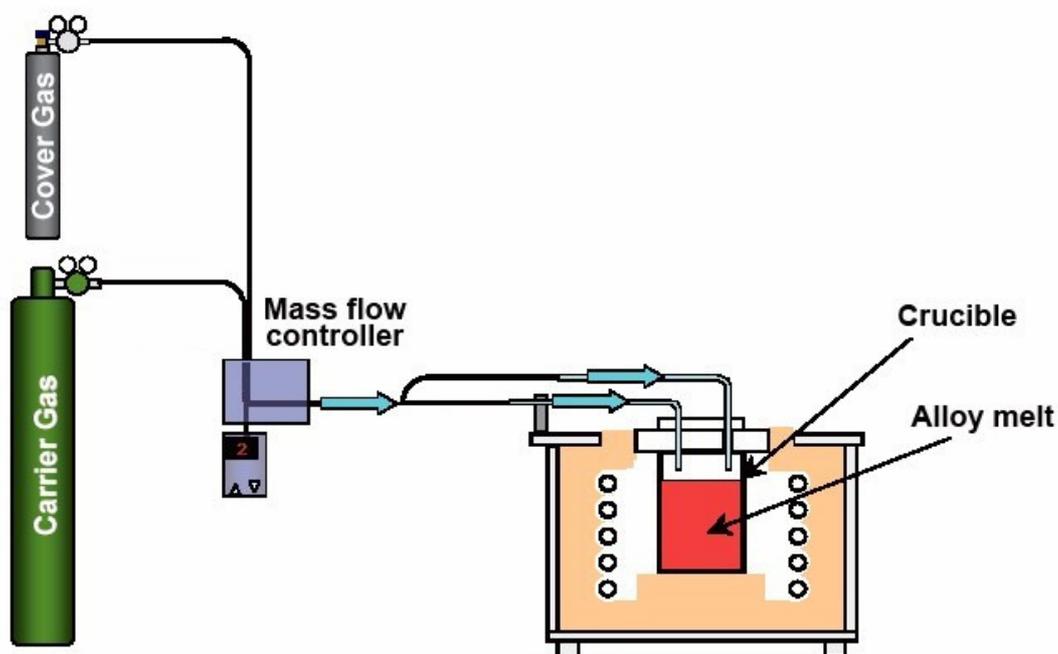
Since the 1970s, two different cover gases have been applied in die-casting: SO₂ and SF₆. Both gases are not inert, but interact to some extent with the melt surface. At high temperatures (above 600 °C), fractions of the gases do not only undergo thermo-degradation but also react chemically with the melt and create a thin film on the melt surface, which consists (in addition to MgO) of magnesium-fluoride (MgF₂ from reaction with SF₆) or magnesium-sulphur compounds (MgS and MgSO₄ from reaction with SO₂). Some authors assume that in addition to a chemical reaction, physical absorption of un-destroyed cover gas molecules into the porous MgO layer also takes place. [Gjestland/Westengen 1996; Ditze/Scharf 2008] Under the condition that the gas is

dosed at proper concentration and flow-rate, the resulting film is dense and stable enough to protect the hot metal from contact with oxygen.

The two active gases are applied in blends with non- or low-reactive carrier gases such as nitrogen (N₂) or carbon dioxide (CO₂), with or without dried air¹. The concentration of SF₆ in the gas mixture is 0.1-0.5%, and the concentration of SO₂ is four or five times higher (1.5-2.5%). [Hanawalt 1972] In the hot chamber process, a typical flow rate of the cover gas blend is 3 to 6 l/min being blown over a melt surface of 0.5 m².

Both reactive cover gases provide good protection for melting temperatures of up to 740 °C. Protection still exists beyond 740 °C, but performance gradually decreases. In die casting incl. recycling, temperatures above 720 °C are rarely needed. In sand casting, however, the melt temperature often reaches up to 800 °C.

Delivery System of Cover Gas Mixture



Source: KAMADO et al. :Internl. Sympo. on Mg Tech. in Glob.Age; Oct.1-4,2006

Figure 1. Cover gas delivery system in magnesium casting.

¹ In EU magnesium casting, cleaned dried air (CDA) is not used as carrier gas, according to our survey.

Sulphur dioxide SO₂

SO₂ forms a highly effective protective film on the melt surface by the formation of MgS and MgSO₄ in addition to the MgO film. [Gjestland/Westengen 1996]² However, the gas is characterized by two disadvantages: it is both corrosive and toxic.

While SF₆ acts corrosive in the furnace especially when overdosed (1%) [Bartos 2007], SO₂ is corrosive itself when in contact with humidity at low temperature³ via the decomposition product HF (hydrofluoric acid) in contact with humidity. When using humid SO₂, not only steel in the furnace might be corroded but also the entire gas piping system including the gas blending equipment. Therefore, piping and the gas mixing unit must be adapted to the cover gas (stainless steel instead of mild steel), which requires high investments.

As SO₂ is toxic, the user must make sure that the workers are not exposed directly to the gas. While the furnace was very leaky or even open in the past so that the occupational exposure limits (maximum acceptable concentration values) were exceeded frequently, decrease of emission was achieved due to various technical measures in recent years:

- The tightness of the furnaces has been improved. The refractory seal between the crucible and the lid prevents gas from escaping, and material charging is fully automatic and continuous, and passes through a lock system.
- During periodic phases for melt cleaning (manual removing dross on top of the melt) concentration and flow rate are automatically adopted to the needs of an open crucible (no longer adopted manually), thus avoiding high exposition of the worker to the gas.
- Use of protective masks additionally decreases the risk for gas exposition.

As a consequence to technical mitigation measures which allow safe handling⁴ the use of SO₂ has gained weight in recent years, particularly because SF₆ was increasingly criticized for global warming issues. SO₂ is not an IR absorber and therefore has no global warming potential. Nevertheless, it should be kept in mind that SO₂ is subject to

² When sulphur powder (elemental sulphur) is used as a protective agent (which is rarely the case in die-casting) it reacts with air creating SO₂ and can prevent the melt from burning like gaseous SO₂. [Ditze/Scharf 2008].

³ Destruction by-products from SO₂ by conversion from the conditions in the casting space environment virtually do not arise; H₂SO₄ was not found under these conditions. [Bartos 2007]

⁴ Bartos (2007) measured the air near the ingot loading area of the crucible in a modern cold-chambered die-casting plant in USA (Lunt Manufacturing). He found an average SO₂ value of 0.14 ppmv which was much below the permitted concentration of 2 ppmv.

other forms of air and safety regulation, and when released to the atmosphere contributes to acidification of soil and aqueous ecosystems.

Sulphur hexafluoride SF₆

Like SO₂, SF₆ has become an almost universal cover gas for magnesium processing. SF₆ forms a highly effective protective film on top of the melt by adding fluorine (mainly as MgF₂) to the MgO structure and thus stabilizing it. [Gjestland/Westengen 1996; Cashion 1998; Cashion et al. 2002a, 2002b] The advantage of SF₆ over SO₂ is that the gas is not toxic and its use does generally not result in strong corrosion of steel equipment when applied in concentration below 1%. [Cashion et al. 1998; Fruehling 1970] There is no need for stainless steel for piping and gas mixer.

The crucial disadvantage of SF₆ is the extremely high global warming potential (GWP) which is 22,800 times that of CO₂.⁵

As only a fraction of the cover gas undergoes chemical reaction and thermal degradation above the hot melt, SF₆ emissions from the melting furnace through leakages and openings (for ingot feeding and metal discharging) are equated to the gas input to the furnace. The equation became relevant for the estimation of global warming emissions of SF₆ for national greenhouse gas inventories required under the UNFCCC. The position of experts [Gjestland et al. 1996]: "In the magnesium industry all SF₆ used in production is released to the atmosphere" found its way into the IPCC Good Practice Guidelines 1999. The emission factor of 100% is also applied in the 2006 Guidelines.⁶

3.4 Alternative reactive cover gases: HFC-134a, FK 5-1-12

HFC-134a (AM-cover)

In the face of the high GWP of SF₆ scientific search for a "drop-in replacement" for SF₆ with no GWP or with a GWP lower than that of SF₆ had been ongoing for some years, since the end of the 1990s. Two fluorine-containing products became important as

⁵ In the 2001 IPCC Third Assessment Report the GWP value was changed from 23,900 (1995 IPCC Second Assessment Report), to 22,200, which in turn was updated to 22,800 in the 2005 IPCC/TEAP Special Report: Safeguarding the Ozone Layer and the Global Climate System. The latter value (22,800) was confirmed in the 2007 IPCC Fourth Assessment Report. The 22,200 GWP value from the 2001 IPCC Third Assessment Report underlies the EU F-Gas Regulation from 2006.

⁶ Bartos et al. [2003] found 10% average decomposition of SF₆ in die casting under certain circumstances. Similar findings are reported by Tranell et al. [2004]. The authors of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories doubt the emission factor of 100% saying "There is a level of uncertainty associated with the assumption that 100 percent of the SF₆ used is emitted". [IPCC 2006] However, the emission factor of 100% has not been changed in the new Guidelines.

alternative cover gasses for magnesium melt protection in industrialized countries, namely HFC-134a and the fluorinated ketone FK 5-1-12⁷. In Japan, another low GWP HFC is being tested: HFC-1234ze, which is a by-product of the production of HFC-245fa which is used for foam blowing.

The usage of the well known refrigerant HFC-134a for magnesium melt protection has been investigated by the Cooperative Research Centre for Cast Metals Manufacturing (CAST) in Australia. To date, this gas is the only new SF₆ replacement of importance in Europe. Five foundries in Germany and a UK-based recycler have converted to HFC-134a. In USA, another die casting foundry uses HFC-134a. Some more EU companies intend such conversion in the future. The GWP value is 1,430 and although still very high, it is about 16 times lower than that of SF₆. The application technology of HFC-134a is patented⁸ and is being marketed under the brand AM-cover. [Ricketts/Cashion 2000; 2001; Ricketts et al. 2003]

All fluorine-bearing cover gas mixtures protect molten magnesium by adding magnesium fluoride (MgF₂) to the magnesium oxide layer on the melt surface. When using cover gas mixtures containing HFC-134a, Cashion [1998] found that the surface film contains up to 50% MgF₂, which is much more than the 13% MgF₂ when using SF₆. This finding supported the expectation that the protection film is sufficiently dense and tight.

In real application, HFC-134a has been shown to provide effective protection of the melt without changing the existing mixing and gas distribution equipment ("drop-in replacement"). Even the HFC concentration above the melt and the carrier gases⁹ can be the same as before (~ 0.2%). In the best case only new pressure control installations are required to compensate for the low vapour pressure of HFC compared to SF₆. It should be noted that the protective effect of HFC-134a quickly diminishes above 720 °C so that HFC-134a can hardly be used in sand-casting. In die casting, temperatures above 720 °C are rarely needed.

In comparison to SF₆, the GWP value 1,430 of HFC-134a is lower. It is even lower when looking at the effective emissions from magnesium casting after use. In die casting, Bartos [2007] observed destruction rates over the melt averaging 79%. (Destruction rates on the order of 10% were measured for SF₆, in previous research). Applying the destruction rate, the GWP value of 1,430 for HFC-134a can be reduced to an effective

⁷ The latter has been developed by 3M and was traded as Novec-612. Presently it is marketed as MTG Shield (Novec 612) by Matheson Tri-Gas (MTG), a subsidiary of Taiyo Nippon Sanso Corporation.

⁸ Users of the AM-cover technology in Europe have to pay a license fee of 10 €/t Mg output.

⁹ In Europe, only nitrogen and carbon dioxide are applied. Both of them can be used for the dilution of HFC-134a (AM-cover) (Christian Kettler, pers. comm., 5th August 2009).

GWP of approx. 400 after use¹⁰. The 2006 IPCC-Guidelines do not present GWP default values for HFC-134a after use. Apparently, this is due to the fact that the conditions of application of HFC-134a differ widely by temperature, concentration, carrier gas mixture, etc. In this study the full GWP of HFC-134a is used when estimating HFC-134a emissions. The effective value is discussed in the sensitivity analysis in annex 1 to this report.

The backside of the much better climate performance of HFC-134a against SF₆ is the comparably low thermodynamic stability. HFC-134a reacts extensively in the contact with liquid and gaseous magnesium, leading to the production of HF (and other decomposition components) to a much higher extent than SF₆ does. Bartos [2007] measured HF concentrations from 448 to 1,199 ppmv when using HFC-134a of initial concentration of 4,200 and 3,600 ppmv¹¹ compared to HF concentrations of 1 to 49 ppmv when using SF₆ at similar concentration and with cleaned dry air as carrier gas. This finding confirmed the concern that HF gas may affect workers safety and accelerate corrosion of equipment [Cashion et al. 2000].

Practical application experience with HFC-134a

In Germany, after conversion from SF₆ to HFC-134a slightly stronger corrosion of crucible walls was detected while corrosion of metering pump and furnace lid remained at the same level. [Umweltbundesamt 2008] Furthermore, measurements of the HF concentration workers are exposed to on opening the crucible lid showed a temporary short-term rise to the 40 fold of the German Maximum Workplace Concentration (AGW) value of 0.83 mg/m³ / 1 ppmv (which, of course, is an 8-hour weighted average value). [Kettler 2008] Adverse health effects can be avoided by protective masks for the workers.

The conversion of several large cold chamber furnaces in Germany caused more serious problems. Under the HFC-134a containing atmosphere increase in dross, formation of smoke, and even ignition of the metal surface were observed. These phenomena could be eliminated by

- (1) air-tight sealing of the furnaces;
- (2) Providing a completely even gas distribution;

¹⁰ Destruction is defined as the percentage of base cover gas consumed by the process, whether by breakdown to a magnesium fluoride (MgF₂) film and subsequent chemical by-products, or by direct conversion to by-products from the thermal conditions and chemistries residing in the casting space environment. Bartos estimates the "normalised" or "composite" GWP of HFC-134a at 2% of that of SF₆, and the GWP of FK 5-1-12 at 1% of that of SF₆ – the latter is the result of high-GWP by-products.

¹¹ In the same study concentrations of COF₂ were found ranging from 16 to 59 ppmv.

(3) Installation of a device for controlled and smooth ingot feeding (e. g applying "converter" technology). [Umweltbundesamt 2008; Fehlbier/Lueben 2008]

The three measures have in common that they restrict movements and vibrations of the melt surface and of the protection film. Obviously, the latter is not as stable to external negative effects as the former SF₆ film.

The higher sensitivity of the protective film in HFC-134a based cover gas systems requires a set of complementary measures to maintain the protective effect against oxidation. As far as we know today, leak-tight furnaces with small surface area of the melt do not need additional safeguards. The vulnerability of the protection film seems to grow with the size and leakiness of the furnaces.

Table 1: Comparison of cover gas active components; *density 15 °C				
Gas/Substance	boiling pt. °C / density kg/m ³	concentration in blends vol.%	carrier gases	application
SF ₆	-63.8 (subl.)/ 6.18*	0.1-1	N ₂ , CO ₂ , Ar, dried air	industrial
HFC-134a (AM-cover) C ₂ H ₂ F ₄	-26/ 4.415	0.1-1	N ₂ , CO ₂	industrial in Europe and USA
HFC-125 C ₂ HF ₅	-48.5/ 4.14	unknown	unknown	industrial in Italy
FK 5-1-12 (MTG Shield Novec 612) C ₃ F ₇ C(O)C ₂ F ₅	49/13.6 (1 bar) 1.62 g/cm ³ (20 °C liquid)	0.05-0.15	N ₂ , CO ₂ +1-5% air	industrial, not sold in Europe
HFC-1234ze CF ₃ CH=CFH	-19/ 1.098 (48 °C)	0.1-0.4	N ₂ , CO ₂	industrial tests, only in Japan
SO ₂	-10/ 2.9	0.5-1.5 100	N ₂ , CO ₂ , Ar, air	industrial
Ar	-186/1.67*	100		sand casting
Frozen CO ₂	-78.5/solid	100		industrial tests

Source: Ditze/Scharf 2008 (updated).

So far, no coherent explanation for the reduced stability of HFC-134a based protection films has been given. Possibly, it is a result of the extensive decomposition of HFC-134a over the hot melt.

FK 5-1-12 (MTG Shield – Novec-612)

The US Company 3M has developed a fluorinated ketone to provide a protective gas for magnesium casting. The trade name of this ketone is Novec-612. As a fluorine-containing chemical with very low GWP it features properties similar to HFC-134a. In tests, however, it shows higher stability at temperatures beyond 720 °C.

Tests with Novec-612 also showed that it is able to effectively protect molten magnesium [Milbrath 2002; Milbrath/Owens 2002, 2005; Argo/Lefebvre 2003] at lower concentrations (less than a quarter of the SF₆ or HFC-134a quantity), using the same gas dilution, distribution equipment and flow rates. However, this fluid is not exactly a "drop-in replacement" because it is a liquid and needs a special device to be evaporated prior to use.

Table 2: Advantages and Disadvantages of Magnesium Cover Gases		
Active substance	Disadvantages	Advantages
SF ₆	expensive, GWP 22,800, corrosive >1%, HF production in the presence of humidity	non-toxic, stable at high temp., excellent protection up to high temperatures
HFC-134a (AM-cover) C ₂ H ₂ F ₄	corrosive via HF, HF and COF ₂ decomposition products, sensitive film, high GWP before use (1,430)	non toxic, GWP much lower than that of SF ₆ , good protection in many applications < 720 °C
HFC-125 C ₂ H ₅ F	comparable to HFC-134a, the GWP is higher with 3,500 vs. 1,300	comparable to HFC-134a
FK 5-1-12 (Novec 612) C ₃ F ₇ C(O)C ₂ F ₅	CO, CO ₂ , HF formation in the presence of humidity*; High-GWP by-products CHF ₃ , C ₂ F ₆ , C ₃ F ₈ .	non-toxic, GWP 1 before use (after use ~400), protection possible > 720 °C
HFC-1234ze CF ₃ CH=CFH	HF emission in the presence of humidity	non-toxic, GWP 9
SO ₂	toxic, corrosive, complex installation for gas supply	cost-effective, no GWP, no HF formation, good protection up to high melting temperatures
Ar	bad protection: Mg evaporation may occur	non-toxic
Frozen CO ₂	complex installation for supply	non-toxic, GWP 1 or 0

Source: Ditze/Scharf 2008 (updated).

* HF formation was denied by the 3M representative at the stakeholder meeting in May 2009.

The environmental advantage of this protection fluid is the GWP which is equal to 1¹² [3M 2002]. The problem rather is the thermal degradation products produced which is still an issue to be studied. Bartos (2007) showed that the toxic and corrosive breakdown product HF arises to a somewhat higher percentage than from HFC-134a, with 30-40% of the inlet concentration of the cover gas. As the inlet cover gas quantity of Novec-612 was only a fifth of that of AM-cover (HFC-134a) the actual production of HF is much lower with Novec-612. On the other hand, Novec-612 produces also extremely high GWP gases like C₂F₆, C₃F₈, and CHF₃ (HFC-23) with a share of 3 to 5%¹³ so that the effective GWP of the Novec-612 emissions is not only 1 but of the same order of magnitude as the GWP of the actual HFC-134a emissions. Bartos [2007] estimates the composite GWP of Novec-612 at 1% of that of SF₆.

In Europe, for commercial reasons, Novec-1230, which is chemically identical to Novec-612, is registered under REACH as a fire extinguishing agent, but Novec-612, is not registered as a cover gas for magnesium casting. At the occasion of the Brussels stakeholder meeting to this study, the potential value of Novec-612 as a cover gas was expressed. In a series of laboratory trials, this fluid had provided good melt protection at high temperatures common in sand casting, for which alternatives to SF₆ are not yet available. As a consequence, the representative of 3M concluded that his company would have to re-evaluate the potential of Novec-612 on the market for use as a cover gas in European magnesium casting, in particular in sand casting and recycling of sand casting alloys.

To date, FK 5-1-12 (Novec-612) has not been made available again in Europe.

As a consequence, practical experience with this fluid cannot yet be reported from foundries in EU-27.

Outside Europe, Novec-612 is no longer marketed by 3M but is now marketed by Matheson Tri-Gas, which is a US-based subsidiary of the Japanese Company Taiyo Nippon Sanso. The brand name of the technology is "MTG Shield (Novec 612)". At the beginning of 2009, MTG Shield was industrially used by one Japanese magnesium die casting company and by one US die casting company. Both of them have completely replaced SF₆ in 2008.

¹² The GWP value of FK 5-1-12 is not identified in the IPCC Third Assessment Report (IPCC, 2001), but it is estimated to be similar to that of CO₂ according to the producer of this gas.

¹³ Perfluoro-iso-butylene (PFIB), an occupational hazard and primary by-product of concern, was monitored in the 2008 study (Bartos 2008) but not detected during this study.

Chapter Two

SF₆ as degassing agent for secondary aluminium

In secondary aluminium production, SF₆ is not used as a cover gas but for refining. It serves as a degassing agent which helps to eliminate impurities from the molten metal. These impurities mostly consist of hydrogen which is the only gas soluble in molten aluminium and, hence, leads to porosity of the castings. Impurities may also result from alkali metals, as well as from alkaline earth metals and solids.

1. SF₆ as an additive to inert gas

Commonly used degassing agents are inert gases such as argon and nitrogen without any further additives. Small bubbles of the inert gas are dispersed into the aluminium melt by impellers. Hydrogen is removed from the melt as it joins the bubbles of the inert gas due to its physical characteristics.

In a number of secondary aluminium smelters, the degassing system is based on inert gas, and SF₆ is added in concentrations of 1 to 5% as a reactive component (substituting CFCs or elemental chlorine) in order to improve and accelerate the refining process. While the use of SF₆ as a degassing additive is still common¹⁴ in North America, it was stopped in Europe at the end of the 1990s.

2. Use of undiluted SF₆

Today, one aluminium smelter in Europe is still using SF₆ for the refinement of a special aluminium alloy. They started to use SF₆ in the late 1990s when the other aluminium smelters completed their phase out.

The plant, located in Germany, is using SF₆ not as an additive to inert gases but applies undiluted SF₆. Consequently, the annual SF₆ consumption of this smelter has rapidly increased and amounted to 100 t/a in 2008.

The management of the smelting plant claims that it was necessary to use SF₆ in the production of a special alloy for the automobile industry. They underline that their company holds the patent for this special alloy and is de facto the single source. The desired high grade of purity and the specific elasticity of the alloy could be obtained by using pure SF₆ as degassing agent only. Other degassing agents including chlorine or argon had been tested but did not result in these quality characteristics.

¹⁴ In North America, Linde offers SF₆ mixed with argon or nitrogen at 2.5 or 5% under the brand "Linde Mix 14". http://www.linde.com/international/web/lg/us/likelgus30.nsf/docbyalias/nav_industry_alum_stir.

3. Emission factor of SF₆ in aluminium smelting

Since 1999, the full consumption of SF₆ in the non-ferrous metal industry has been counted as emissions (emission factor 100%) in the emission inventory of the German Federal Environmental Protection Agency (German EPA, i.e. Umweltbundesamt).

In magnesium casting, this emission factor is applied according to the IPCC Guidelines of 1999 and 2006. The Guidelines, however, do not provide any details on the emission factor for the aluminium sector. As reliable data on the degree of SF₆ destruction during the melting process in the German plant had not been available, the emission factor of 100% (consumption equals emissions) had been applied to secondary aluminium production, too.

In 2007, in a letter to the German Umweltbundesamt, the aluminium plant claimed a decomposition rate of minimum 97% of the amount of SF₆ applied. This rate was based on their own measurements of the composition of the waste gas carried out in 2004.

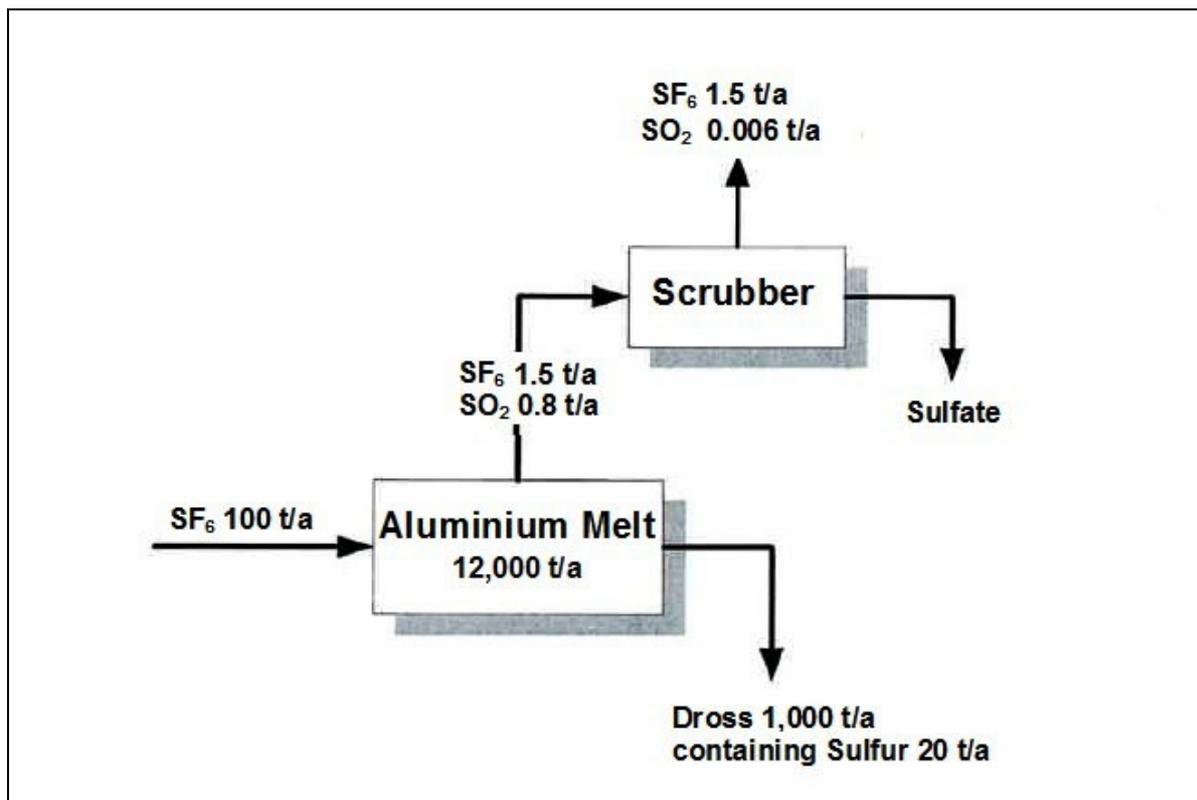


Figure 2: Mass flow of SF₆ used for degassing of the aluminium melt as presented by the plant operator in 2009. A quantity of SF₆ of 100 t/a is applied to 12,000 t/a of aluminium alloy. The flue scrubber removes about 0.8 t/a of sulphur dioxide (SO₂) which is transformed into sulphates. A quantity of 1.5 t/a of un-destroyed SF₆ gas passes the scrubber and is emitted. The dross (1,000 t/a) is considered to contain the decomposition products, fluorine and sulphur, of the applied quantity of SF₆ (100 t/a).

In 2007 the delivery mechanism of SF₆ to the aluminium melt was improved, leading to a decrease in the specific SF₆ consumption.

In April 2009, the measurement was repeated on request of the European Commission and the German Umweltbundesamt. From the measurement protocol (handed to the Umweltbundesamt in September 2009) follows a significant reduction of the emission factor: The applied quantity of SF₆ was 7,000 g/h, the waste gas stream contained 101 g/h SF₆ at the maximum (1.44%).¹⁵

The technical experts of the plant explained to the German EPA (Umweltbundesamt) and the authors of this study that the temperature of the aluminium melt amounted to about 680 – 710 °C. At such temperatures, SF₆ was decomposed into sulphur and fluorine almost completely. Especially through formation of various fluorides, the aluminium melt is cleaned from impurities. Fluorine compounds and sulphur compounds of the aluminium alloy remained in the dross, which is removed occasionally from the surface of the melt. Consequently, at most 1.5% of the amount of SF₆ initially applied to the melt was measured in the waste gas. Hence only this quantity could be considered as emissions of pure SF₆.

Based on the company information an emission factor of 1.5% is used in this study.

¹⁵ Pers. Communication Gabriele Hoffmann (Umweltbundesamt) to Öko-Recherche, September 2009.

Chapter Three

SF₆ use in EU non-ferrous metal industry: magnesium die casting, sand casting, recycling, and aluminium degassing

The empirical data of this study derive from a survey conducted in February 2009 in 53 magnesium die casting companies, 12 magnesium sand casting foundries, seven magnesium recycling companies, and one aluminium smelting plant in the EU. From the beginning the survey was supported by sector experts (see annex III for expert list and annex IV for the questionnaire used in the survey). In this chapter, we present the current state of cover gas application in the magnesium industry and of the use as degassing agent in secondary aluminium production.

1. Magnesium Die Casting

1.1 Cover gases used in magnesium die casting in the EU

At the beginning of 2009, 53 magnesium die casting companies were operating in eleven countries of the EU-27. The die casters were applying three different types of cover gases for melt protection: 22 foundries deployed SF₆, and almost the same number (23) used SO₂. Six die casters used HFCs - five of them HFC-134a, one HFC-125. Two very small casting foundries applied sulphur. See table 3, col. 2.

All of the six users of HFCs had consumed more than 850 kg SF₆ per year before the 2006 F-Gas Regulation. Among the users of SO₂ two had replaced SF₆ > 850 kg/a¹⁶.

Table 3: Magnesium Die-Casting Foundries in EU-27, by Protective Agent, Number, and Metal Consumption, 2008

Protective agent	Number of foundries	Metal consumption 2008	
		tonnes	percent
SO ₂	23	72,000	59.0
HFC (134a/125)	6	25,200	20.6
SF ₆	22	24,000	19.7
<i>SF₆ <850kg/a</i>	19	13,000	10.7
<i>SF₆ >850kg/a</i>	3	11,000	9.0
Sulphur	2	500	0.4
Total	53	122,000	100.0

Source: Öko-Recherche survey 2009.

¹⁶ One of the two foundries in Sweden had consumed > 850 kg/a of SF₆ in 2007; to date, it has replaced it partly by SO₂ in order to undercut the 850kg/a threshold. In 2004, this company had successfully tested AM-cover (HFC-134a) (Blomdahl et al. 2006) but did not adopt it. The replacement by SO₂ is expected to be completed by 2009. In this study, this foundry is treated as one of the 19 SF₆ users with consumption < 850kg/a. This is also the way we deal with another foundry which has been using SO₂ as the primary melt protection agent for several years but still needs 350 kg SF₆ per year in the plant.

The relative importance of the different cover gases cannot be assessed by direct comparison of the required quantities (in kg) because their concentration on application varies extremely. Instead, it can be measured by comparing the quantity of metal (in tonnes) which is protected by the one or the other cover gas on melting.

In 2008, the 53 die casters consumed about 120 thousand tons of metal and produced 70 to 80 thousand tons of magnesium parts. The arising scrap of approx. 50 thousand tons was mainly recycled by the seven external specialised re-melters (see over next section of this chapter) for re-use by the die casting foundries.

Classifying the processed metal (incl. in-house recycling) by different cover substances the following segmentation arises in percent (s. table 3, col. 3 and col. 4). SO₂ was applied to 59% of the metal quantity, followed by HFCs (21%) and SF₆ (20%). Sulphur was used for only 0.4%¹⁷ (see Diagram 1).

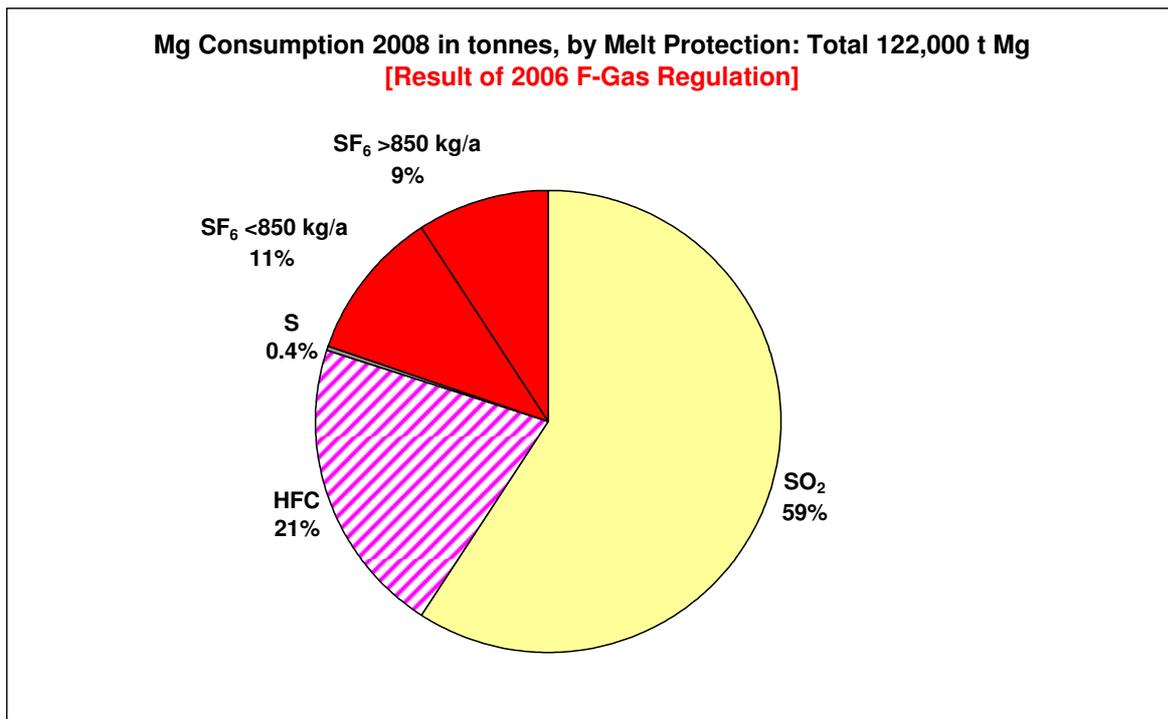


Diagram 1: In order to conform with the F-Gas Regulation, HFCs have been applied as new cover gas systems to 21% of the metal consumption by the die casting industry, thus reducing SF₆ (red sections) to half its former importance (20%). However, 9% of the molten metal is still covered by SF₆ in foundries with an annual SF₆ consumption over 850 kg (small red section). 11% of the overall metal consumption is melt protected by SF₆ in foundries with a gas consumption of less than 850 kg/a. SO₂ has become by far the most important cover gas (59%).

¹⁷ It should be noted that at the beginning of 2009 a small die caster (user of SO₂) had not yet completed the conversion of one hot chamber machine from flux salts (MgCl₂) to SO₂.

It is shown that, following the F-Gas Regulation, today no longer SF₆ but SO₂ is the most widespread cover gas in magnesium die casting. In Poland, Austria, and the Netherlands SO₂ is used even exclusively as cover gas in contrast to Italy where SO₂ has not yet been in use so far.

To date, cover gases other than HFCs and SO₂ do not play a role in SF₆ replacement in the EU. Certainly, the application of HFC-125 is worthy of mention. HFC-125 is similar to HFC-134a in its physical properties, but there is one additional fluorine atom in the molecule, which is likely to provide more fluorine to the melt surface. The GWP of HFC-125 is 3,500 and thus significantly higher than that of HFC-134a.¹⁸

1.2 Replacement and continued use of SF₆ since F-Gas Regulation

In connection with the 2006 F-Gas Regulation, eight die casters substituted SF₆ by HFCs or SO₂. Seven have completely phased-out SF₆, and one replaced only a part of this gas to undercut the consumption threshold of 850 kg/a. The eight foundries are listed in table 4 with the summarised quantities of SF₆ replaced.

Table 4: EU Mg Die Casting Foundries formerly using SF₆ > 850 kg/a by Substitutes and by replaced SF₆ Quantities in kg/a		
Foundry	Substitute	Replaced SF ₆ in kg/a
GE-11	HFC-134a	20,604
GE-12	HFC-134a	
GE-13	HFC-134a	
GE-14	HFC-134a	
GE-15	HFC-134a	
IT-11	HFC-125	
SW-11	SO ₂	3,780
SW-12	SO ₂	
Total		24,384

The names of the foundries are not given here for confidentiality, but are communicated to the European Commission, separately.

The replacement measures of the eight foundries have led to an overall decrease in annual SF₆ consumption by more than 24,000 kg/a (see Diagram 2). Hence, the 2006 F-Gas Regulation has successfully contributed to reduction in SF₆ consumption in Europe.

¹⁸ HFC-125 as a cover gas for magnesium is hardly dealt with in technical literature. One of the very few exemptions is: Guoqiang You, Siyuan Long, Rongfei Li: Effective protection of magnesium melt surface from oxidation using HFC125-containing shielding gas, Materials science forum, 2007, vol. 546-49 (1), pp. 119-122.

The replaced global warming potential of this SF₆ quantity amounts to 556 kt CO₂ equivalent, not accounting for the emissions of the HFC substitutes¹⁹.

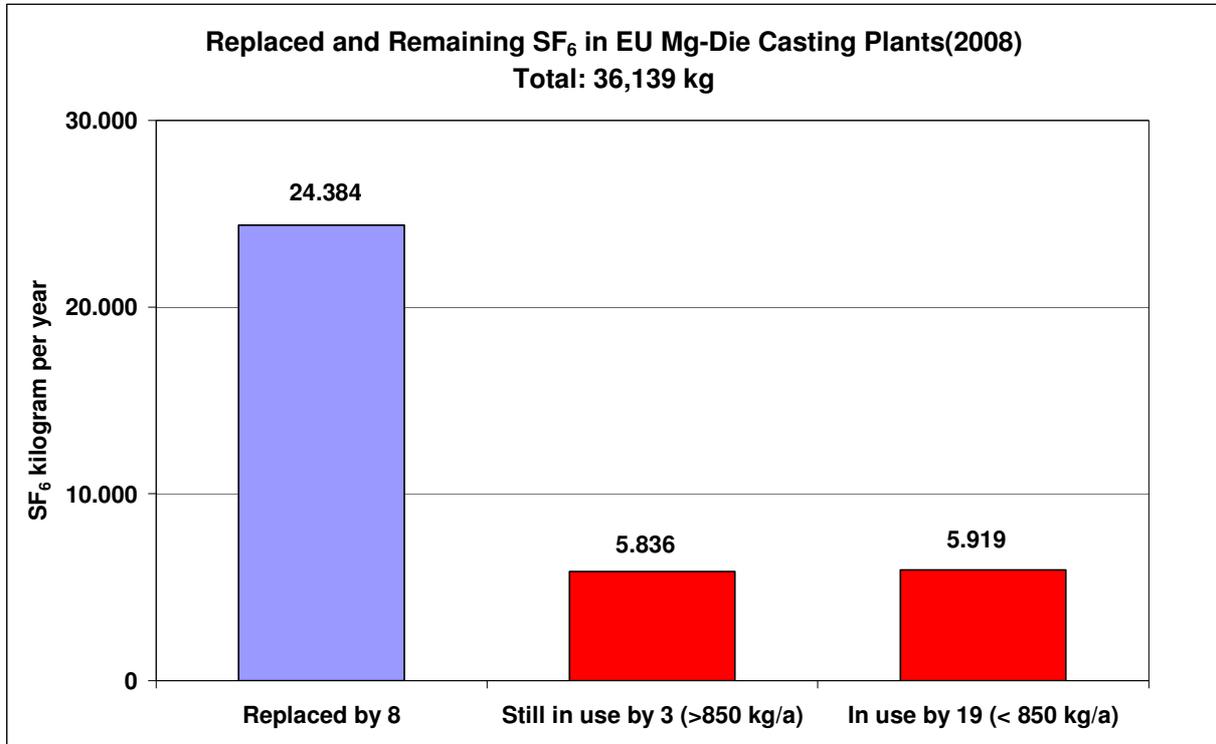


Diagram 2. In 2008, eight foundries with former SF₆ consumption >850 kg/a replaced 24,384 kg of SF₆ (left bar). Three foundries which are also subject to the 2006 F-Gas Regulation went on using 5,836 kg/a SF₆ (central bar). The nineteen foundries with annual SF₆ consumption of less than 850 kg applied a total of 5,919 kg (right bar).

In 2008, 22 magnesium die casting foundries in the EU still used a total quantity of 11,755 kg SF₆. Almost half of this quantity (5,836 kg) was applied by three foundries with SF₆ consumption > 850 kg/a (see Diagram 2).

These foundries with high annual SF₆ consumption are already subject to the F-Gas Regulation in its current version and should have replaced SF₆ by January 1st, 2008. This study primarily explores the possible impacts of a review according to Art 10(2) of the F-Gas Regulation, i.e. of a potential inclusion of the nineteen die casting foundries consuming less than 850 kg SF₆ per year in an amended Regulation. It is outside of the scope of this study to criticize the three foundries presently still using SF₆ in excess of 850 kg/a.

¹⁹ When assessing the actual emission reduction effect, new emissions of substituting HFCs have to be considered. This is done in the impact assessment of this study (chapter 8), and in annex I.

The nineteen foundries below the 850 kg/a threshold still used 5,919 kg SF₆ in 2008 (Diagram 2, right bar). This is 16% of the overall SF₆ quantity of 36,139 kg/a that could be replaced in magnesium die casting in the EU.

1.3 The nineteen foundries with SF₆ consumption below 850kg/a

The nineteen die casting foundries below the 850 kg/a threshold are located in six member states, half of them in Germany where also half of the cover gas SF₆ is applied (see table 5).

Table 5: Die Casting Foundries SF₆ < 850 kg/a, by EU Member States, Number and Gas Consumption in kg/a, 2008		
Germany	9	3,024
Italy	4	1,080
Sweden	2	825
Romania	1	420
UK	1	350
Spain	2	220
Total	19	5,919

Size and SF₆ consumption of the foundries vary widely. The annual SF₆ consumption ranges from 40 kg (one bottle) to 800 kg. Based on common features the foundries can be classified in three categories or types (see table 6).

Type 1. Five foundries are small SF₆ users with an average quantity of 56 kg/a. They are small-scale experts for NF metal casting with focus on aluminium, and cast magnesium only discontinuously. The number of employees is below 50.

Table 6: The Three Types of Magnesium Die Casting Foundries < 850kg/a SF₆			
	Type 1	Type 2	Type 3
Economic characterisation	Small sized NF-foundry Al-Mg	Medium sized NF-foundry Al-Zn-Mg	Mg foundry integrated in large firm
Number in EU	5	8	5
SF ₆ Consumption	Ø 56 kg/a	Ø 325 kg/a	Ø 600 kg/a
Employees company	< 50	50 -250 (Ø 200)	> 250
Metal processed	Ø 92 t/a	Ø 564 t/a	Ø 3,000 t/a
Series	small	large	very large
Equipment	1 hot chamber	2 hot 1 cold chamber	4 cold chamber
Utilisation machines	discontinuous	continuous	continuous
Max. temp. of melt	< 690 °C	< 690 °C	< 690 °C

Source: Öko-Recherche survey 2009.

Type 2. Eight foundries are medium-scale SF₆ consumers with an average quantity of 325 kg/a. They are medium-sized specialised companies for NF metal casting and process magnesium in addition to aluminium or zinc. The number of employees is between 50 and 250.

Type 3. Five foundries are large SF₆ consumers with an average quantity of 600 kg/a. They exclusively process magnesium on very large scale and are integrated into large firms who directly process the cast pieces. The number of employees of the company the foundry belongs to significantly exceeds 250.

One additional user of SF₆ does not match this classification. It is the light-metal test department of a German car manufacturer who applies approx. 40 kg/a SF₆ to one cold chamber machine. Although it is parts of a large firm, the discontinuous operation and small-series production distinguishes this foundry from type 3.

Table 6 shows typical or average values for the SF₆ consumption. The individual consumption values are presented in Diagram 3, where also the country of location is listed (y-axis).

On the very left, the test foundry of the German car maker (GE1) can be seen.

Next, the five foundries of type 1 are shown with uniformly low SF₆ consumption from 40 to 75 kg/a.

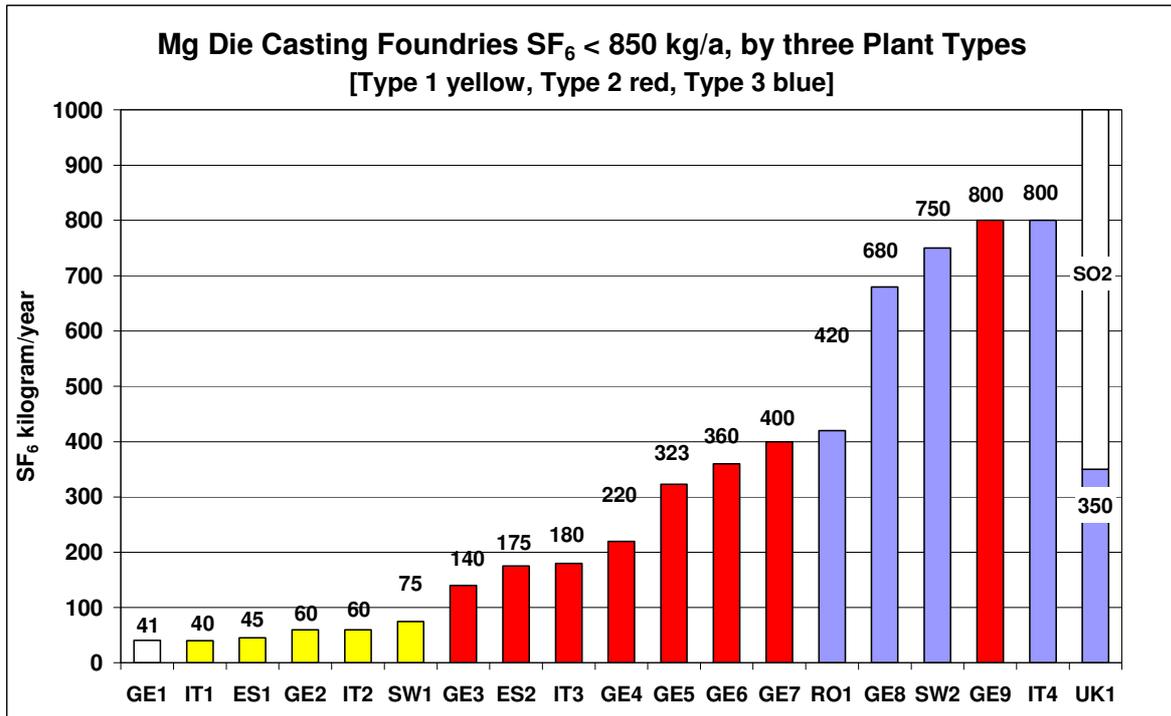


Diagram 3: The three types of die casting foundries < 850 kg/a SF₆. Type-1 foundries (yellow bars left) show consumption values from 40 to 75 kg - averaging 56 kg/a. Type-2 foundries (red bars, centre) range from 140 to 800 kg/a – averaging 325 kg/a. Type-3 foundries range from 350 to 800 kg/a – averaging 600 kg/a. For details see text.

The eight foundries of type 2 (red bars, centre) show the greatest variation in SF₆ consumption. The biggest consumer of this group (GE9) uses even 800 kg/a and thus more than the foundries of type 3 (right bars).

The foundry UK1 (last bar on the right) consumes only 350 kg SF₆ per year but it belongs to type 3. UK1 uses SF₆ only for secondary processes, its primary cover gas is SO₂ (indicated by the white bar above the blue section).

2. Magnesium Sand Casting

While die casters produce magnesium parts in very large series, sand casting is used for unique pieces (prototypes) and very small type series. In contrast to die casters which produce large numbers of identical parts mainly for the automotive industry, sand casters chiefly supply the defence and aerospace industries, motor sports etc, where identical parts are used only in small numbers but in high quality. Consequently, the quantity of metal consumed by sand casters is comparably small.

As outlined in the first chapter of this report, sand casting is characteristically based on manual mode of operation and carried out in open application. A small, mostly covered, crucible with hot melt of magnesium alloy is carried by workers to the remote casting place where the liquid metal is manually poured into hollow moulds.

The melt needs protection from oxidation in three sections of the process typically. Firstly, above the crucible while heated in the furnace, secondly during the manual transfer to the casting place, and finally in the casting process when the melt is poured into the mould which has to be protected by a cover gas itself. Often a worker applies cover gas manually from a lance onto the liquid metal and into the moulds. This manner of melt protection implicates the use of high amounts of cover gas. In fact, the relative gas consumption expressed as kg SF₆ per t magnesium parts amounts up to 20 to 50 while in automatic die casting less than 0.5 kg SF₆ per t magnesium output are typically used.

In our survey, we identified twelve sand casting plants based in six EU member states. Six of them specialise on aluminium and produce magnesium parts only occasionally. They do not use SF₆ but flux salt and/or Argon. The other six sand casters produce comparably large quantities of magnesium parts (together more than 600 t/a), and use high amounts of SF₆. Data on the twelve sand casting foundries are shown in table 7.

Table 7 shows that the six major sand casting plants consume approx. 10,000 kg/a SF₆, which is almost twice the quantity used by the nineteen EU magnesium die casters below the 850 kg/a threshold. For comparison: the metal consumption of those six sand casting foundries amounts to only 3% of the die casters' quantity.

Table 7: Magnesium sand casting plants in EU-27 by metal consumption (t), metal product (t) and melt protection, 2008					
Country	Company	Mg input	Mg output	Protection	SF ₆ kg/a
Germany	1 plant	620	260	SF ₆	10,000
France	1 plant				
UK	1 plant				
Italy	2 plants				
Sweden	1 plant				
Germany	3 plants	80	40	Ar	
Denmark	1 plant			MgCl ₂	
UK	2 plants			salts	
		700	300		10,000

Source: Öko-Recherche survey 2009.

For confidentiality, the names of the plants are not disclosed; data of the plants are summed up.

In the survey, the sand casters justified the high SF₆ cover gas quantities by two characteristics of the production process: open application instead of closed systems, and gas concentrations higher than in die casting, to the point of repeatedly using undiluted gas. The use of SF₆ as cover gas is justified by the particularly high temperatures of the liquid metal of up to 800 °C at which no other gas is stable enough, so far.

Three reasons for the extremely high temperatures of the melt were named:

1. The liquid metal cools down quickly on the way from the furnace to the casting place. Thus, it must be overheated to a certain degree in order to keep sufficiently high temperature and viscosity when filled into the moulds.
2. The cold moulds themselves cool off hot metal. When poured into moulds for thin-walled parts or parts of complex geometry, the metal must be kept liquid long enough to fill all cavities on time before solidifying.
3. Several special magnesium alloys for exclusive use in sand casting feature melting points higher than common die casting alloys, and, thus, require particularly high temperatures of the melt irrespective of the cool-down effect outside of the crucible.

The small magnesium sand casters in the survey do not use SF₆ but only Argon or cover salts. However, from this fact it cannot be concluded that SF₆ is principally unnecessary in sand casting. In some cases, also the large magnesium sand casters apply the cheaper Argon gas or cover salts instead of SF₆. This depends on the alloy and on the quality and complexity of the cast parts. In interviews, the smaller sand casters did not fundamentally exclude the use of SF₆ in their own plants in the future.

3. Magnesium Recycling (Re-melting)

Seven magnesium recyclers in the EU re-melt approx. 60,000 t/a scrap from die casting foundries, and cast the metal again in ingots of several alloys for die casters (closed loop). In addition, one of the six recyclers produces a certain amount of special sand casting alloys.

Common die casting alloys do not require higher temperatures for re-melting by recyclers compared to melting by die casters (< 720 °C). This is why both, SF₆ and SO₂, can be used as cover gases in normal concentrations.

Five of the seven recyclers have been deploying exclusively SO₂ for die casting alloys in their plants for a long time. At the required temperature level (< 720 °C), HFC-134a is also applicable and has been used by the company UK-R1 in the UK for the major part of their production since 2000.

Only one EU-based recycler continues using (until today, September 2009) SF₆ for re-melting and ingot casting of die casting alloys. In 2008, his annual consumption amounted to 3,000 kg.

The seven recyclers, their magnesium processing capacity and the cover gas in use in 2008 are shown in table 8.

Table 8: Magnesium recyclers/re-melters in EU by metal processed and cover gas in use, 2008			
Country	Company Code	Metal in t	Cover gas
Hungary	HU-R1	60,000	SO ₂ 10 t HFC-134a 6 t SF ₆
Czech Republic	CZ-R1		
Austria	AT-R1		
Germany	GE-R1		
Germany	GE-R2		
UK	UK-R1		
France	FR-R1		

Unlike recycling of die casting alloys, recycling of special alloys for use in sand casting requires specific characteristics of the cover gas. This issue has already been mentioned in the previous section on magnesium sand casting. According to UK-R1, no substance is available to date which could replace SF₆ at temperatures of 750-800 °C. This is the technical reason why the plant operator applies both HFC-134a and SF₆ in one of their three production lines in the UK plant, alternatively, depending on the melting point of the alloy. The plant consumes approx. 3,000 kg SF₆ per year, in addition to 10,000 kg HFC-134a. According to UK-R1 the UK plant is the only European

producer of special alloys in addition to common die casting alloys, and thus is in need of a limited quantity of SF₆.

The other six plants process scrap of common die casting alloys exclusively for which SO₂ is technically sufficient. This was confirmed in the survey by representatives of these six magnesium recycling plants, five of whom have been using SO₂ as the cover gas for many years.

4. Aluminium Smelting

In the EU, only one aluminium smelter uses SF₆ for the refinement of special aluminium alloy. The plant is located in Germany and does not apply SF₆ as an additive to inert gases but in undiluted form. Consequently, the annual SF₆ consumption of this smelter has increased in the period 1999-2008 from 10 t/a to 100 t/a. This quantity equals five times the quantity used by the entire EU magnesium industry.

In the aluminium plant, SF₆ is not applied as a cover gas to protect the melt from oxidation, but it serves as a cleaning agent to remove impurities, especially hydrogen, from the melt. The temperatures of the molten aluminium metal in the furnace do not differ significantly from the temperature of the metal melt in magnesium casting, ranging from 680 to 710 °C. There is, however, a substantial difference in reactivity.

In magnesium casting, a very small amount of SF₆ reacts on the melt surface only and forms a thin protective film. In this way, the quantity initially delivered is almost completely released to the atmosphere.

In aluminium smelting, SF₆ gas bubbles are finely dispersed in the melt by impeller technology. SF₆ is largely decomposed in the hot metal and broken into sulphur and fluorine compounds. As a consequence, only 1.5% of the SF₆ consumption is considered to be global warming emissions. In 2008, emissions amounted to 1,500 kg (34.2 kt CO₂ equivalent).

Chapter Four

Policy options to reduce SF₆ emissions from NF metal industry and associated technical measures

The following possible policy options have been identified at this stage. These options will be subject to screening and further refinement and where relevant to assessment of their impacts:

1. No policy action for magnesium and aluminium industry
2. Mandatory or voluntary containment and recovery
3. Full or partial SF₆ prohibition
4. Joint implementation mechanism for the non-ferrous metal industry
5. Voluntary agreement to replace SF₆ in the magnesium and aluminium sector

All of these options rely on three possible technical measures: 1) containment of the SF₆ during its application, 2) recovery of the SF₆ and 3) substitution by alternative gases. In the following sections of this chapter the technical feasibility of those technical measures is considered.

1. Containment

The facilities and processes of the non-ferrous metal industry (Mg die casting, Mg sand casting, Mg recycling, Al degassing) do not constitute closed systems. Additional containment measures cannot be implemented in the same way as in the refrigeration or air conditioning sectors.

1.1 Magnesium die casting

Melting furnaces are not entirely tight. The cover gas is fed into the head space over the melt. Although the crucible is covered by a lid, some cover gas permanently diffuses through unintentional leaks. Therefore, cover gas is continuously recharged into the crucible. The furnace is not under vacuum, which could prevent cover gas from diffusion, but under pressure in order to prevent influx of air and, thus, oxidation.

Significant improvements to minimise quantity of the cover gas have been made since 1995:

- The tightness of the furnaces has been enhanced. The refractory seal between the crucible and the lid prevents gas from escaping, and material charging is fully automatic and continuous, and passes through a lock system.
- The dosage of the gas is controlled electronically (gas mixture, flow rate, and supply pressure) and adapted to the state of the melt.
- During periodic phases for removing dross on top of the melt, gas concentration and flow rate are automatically adapted to the needs of an open crucible (no longer opened manually), thus avoiding high temporary release of cover gas.

As a consequence of these technical mitigation measures, the flow rate of the cover gas (reactive component and carrier gas) has decreased considerably. The specific consumption of SF₆ per tonne of produced magnesium parts dropped from more than 4 kg/t Mg (1995)²⁰ to less than 1 kg/t Mg (2008). In the 19 EU foundries with SF₆ consumption < 850 kg/a, the average coefficient in 2008 is 0.73 kg/t Mg.

According to our interviews with the leading suppliers of melting equipment, further technical improvement in leak tightness is presently not feasible. The members of the project expert group to this study agree that the coefficient "cover gas per metal product" will be stable in the foreseeable future, because the minimum coefficient has been technically achieved. Considerable differences in cover gas consumption of identical equipment between individual users still do exist. To a minor degree this results from differences in leak tightness subject to accuracy in handling. Predominantly, the specific cover gas consumption varies as a result of the heterogeneity of casting conditions which require higher or lower specific cover gas dosage (flow rate and SF₆ concentration in carrier gas), and in exceptional cases even the use of undiluted SF₆.

1.2 Magnesium recycling and sand casting

In magnesium recycling, the tightness of the melting furnaces has been improved to an extent comparable to die casting.

In sand casting, virtually all applications of the cover gas are open. Containment is not possible because the technology has to rely on the flexibility of manual application.

²⁰ This was the average coefficient of the foundries in Germany, in 1995. Communication by Cornelia Elsner, German Umweltbundesamt, March 2009.

1.3 Degassing of secondary aluminium

The potential for containment of SF₆ used as degassing agent in aluminium industry is different from the magnesium industry. The emission factor is not 100% but 1.5% only. This percentage of un-destroyed SF₆ is released from the melt, collected, and emitted in the flow of waste gas. The plant operator does not consider further containment measures technically possible for the time being. Destruction of downstream SF₆ by abatement systems in the exhaust gas, as it is state of the art in semiconductor industry, is neither considered technically feasible. This is because the waste gas mass flow of one melting furnace exceeds 2,000 m³ per hour, while in semiconductor manufacture only 50 m³/h are typical values, making effective waste gas treatment possible.

In this context, a plant-specific reduction measure in 2007 should be mentioned which has improved the delivery of SF₆ to the aluminium melt. Distribution of the gas bubbles in the melt was improved highly from ca. 47.5 kg dispersed by two impellers in one hour to 75 kg dispersed by three impellers within half an hour. In this way, the consumption of SF₆ has been reduced to 37.5 kg per treatment. This measure constitutes a relative reduction of SF₆ consumption of 21%. The operator does not consider further reductions of relative SF₆ consumption to be possible in the foreseeable future.

2. Recovery

Several factors prevent recovery of SF₆ used as a cover gas or as a cleaning agent.

- Firstly, emissions from the magnesium furnaces are extremely diffuse and can hardly be collected.
- Secondly, pure SF₆ is only used in exceptional cases in magnesium casting, while diluted cover gas mixtures with concentrations of SF₆ ranging between 0.2% and 1.0% are common.

Selective recovery of SF₆ contained in the high quantity of carrier gas, which in turn is diluted in the ambient air, might be possible in specialised laboratories but not in foundries. Experiments on recovery of SF₆ in magnesium foundries are not known.

The same is true for aluminium smelting plants, where the exhaust gas contains used SF₆ in concentration of 25 mg per m³ (Measurement Report 2009). This is far below realistic limits for the recovery of SF₆.

3. Substitution by alternative gases

Screening for technical feasibility of replacement of SF₆ by alternative cover gases is carried out for

- Magnesium die casting,
- Magnesium sand casting
- Recycling of common magnesium die casting alloys
- Recycling of special magnesium alloys,
- Production of one special aluminium alloy.

3.1 Magnesium die casting

Experts interviewed in the course of the survey stated that the technical problems arising at large consumers of SF₆ in connection with the introduction of alternative cover gases hardly differ from those at medium and small sized SF₆ users. Consequently, the successful conversions from SF₆ to HFC-134a or SO₂ in foundries with prior SF₆ consumption > 850 kg/a subject to 2006 F-Gas Regulation (see chapter 3.1.2) demonstrate the technical feasibility of the application of alternative cover gases to die casting foundries with SF₆ consumption < 850 kg/a (types 1-3).

3.2 Magnesium sand casting

Sand casting is carried out in open application and at high temperatures of the liquid metal, ranging to 800 °C. Both characteristics prevent cover gases other than SF₆ from application so far. In the survey, it was reported that tests with HFC-134a failed because HFC-134a decomposes at temperatures above 720 °C. SO₂, which may be stable enough, cannot be applied in open applications because of its toxicity.

The replacement of SF₆ could be possible in the future. Promising tests of special sand casting alloys with Novec-612 have been stopped reportedly because the fluid was no longer available. At the occasion of the Brussels stakeholder meeting in May 2009, several representatives of sand casting companies stated the need for further investigation on the potential use of Novec-612, and expressed their willingness to change to this fluid in case it turns out to be suitable for sand casting at high temperatures.

It is concluded that in foreseeable future a technically equivalent and more climate friendly alternative to SF₆ might be available for sand casting. This matter is urgent as

sand casting is now the largest single application of SF₆ in the EU magnesium industry. At present, however, conversion from SF₆ to other cover gases is technically not feasible.

3.3 Recycling of die casting alloys

Recycling of common die casting alloys does not rely on SF₆ as cover gas. This is clearly demonstrated by six plants in Europe which have successfully applied SO₂ for many years. Consequently, the continued use of approx. 3,000 kg/a of SF₆ by one European recycler cannot be justified by technical feasibility reasons.

At the time of the survey, the plant, which is in need of major modernisation, changed ownership. The new owner stated that he was aware of the problems related to the use of SF₆. He would replace it when stipulated by law, and convert to SO₂ which he considers a cost-effective technical solution.

Evidently, replacement of SF₆ is technically feasible in recycling of die casting alloys.

3.4 Recycling of sand casting alloys

The reasons for the application of SF₆ in the recycling of special alloys differ from the reasons for the use of SF₆ for common die casting alloys. Like sand casting itself, re-melting and production of sand casting alloys is carried out at high temperatures, ranging up to 800 °C. HFC-134a cannot be applied then because it decomposes above 720°C. The use of SO₂ is basically possible at these temperatures; however concentrations in the gas mixture would have to be higher than allowed by existing occupational exposure limits. In addition, corrosion could not be controlled then.

The only EU based recycler has already tested a number of potential alternatives to SF₆, and found Novec-612 to be the most suitable substitute (applicable up to 800 °C). However, as previously explained, Novec-612 cannot be purchased in Europe presently. They are willing to replace SF₆ as soon as Novec-612 (or another fluid) is available and has proved its ability to sufficiently protect the magnesium melt at high temperatures. As long as no suitable substitute for SF₆ is available for the recycling of special magnesium alloys, they will continue using SF₆ as the production of these special alloys could not proceed otherwise.

3.5 Degassing of secondary aluminium

As mentioned in chapter 2, the management of the relevant German aluminium plant claims undiluted SF₆ to be indispensable for the production of a special alloy for the

automobile industry. The required high grade of purity and the specific elasticity of the alloy could not be achieved by means of other cleaning agents such as chlorine or argon, which had been tested already.

In this study, it was not possible to verify this point of view. External sector experts were not able to give an opinion without detailed information on the alloys and the production technology. We hence accept the position of the operator that SF₆ presently cannot be replaced in the production of this special alloy for technical reasons.

Conclusion

On the basis of the findings above, containment and recovery are not technically feasible measures and therefore the policy option of mandatory or voluntary containment and recovery, identified at the beginning of this chapter, is abandoned. The third technical solution, substitution of SF₆ by alternative cover gas, is likewise technically infeasible in three of the five screened sectors, for the time being. However, in magnesium die casting and in recycling of magnesium die casting alloys, SF₆ replacement is a possible technical solution to effectively reduce SF₆ emissions.

Conversion from SF₆ to alternative gases can be implemented presently in two ways. Chapter 1 has shown that in Europe two cover gases are available which are already used to replace SF₆, such as SO₂ and HFC-134a.

Conversion to the third alternative cover gas, Novec-612, is not possible right now as it is commercially not available in Europe. Therefore, this study cannot draw on practical experience of foundries based in the EU. Even in Japan and the USA, where the fluid is sold, industrial experience is still poor because the first conversions were completed in 2008 in both countries. In the upcoming revision of the F-Gas Regulation, Novec-612 and any other new cover gases cannot be taken into account as technical choices.

Before we further screen and refine the remaining policy options identified (chapters 7 and 8), we analyse the available experience with cover gas substitution in magnesium die casting (chapter 5) and the costs which potentially arise to the die casting foundries < 850 kg/a SF₆ consumption, which are not subject to the F-Gas Regulation so far (chapter 6).

Chapter Five

Experience with cover gas conversion in magnesium die casting

As the chapter 4 has shown, at the present time the examination of the conditions for a change-over from SF₆ to alternative cover gas systems is technically feasible only in die casting and recycling of common die casting alloys. This chapter 5 discusses present experience with cover gas conversion from SF₆ to HFC-134a or SO₂. In recycling, SF₆ replacement dates back more than twenty years. As a consequence, this chapter relates to cover gas conversion in die casting foundries.

1. To date no conversion in foundries < 850 kg SF₆ /a

In the past ten years, no EU die casting foundry with annual SF₆ consumption < 850 kg has completely converted to HFC-134a or SO₂. This is why there are no respective field reports available on that issue.

In the past five years, since 2004, in one Polish die casting foundry of the relevant order of magnitude SO₂ was introduced. However, this was not a matter of conversion but it was a start-up. In 2008, a small Swedish foundry converted one of their two hot chamber machines to SO₂; yet beforehand they had not used SF₆ but flux-salt (MgCl₂).

In several foundries with SF₆ consumption < 850 kg/a, HFC-134a has already been tested, although without much insistence in some cases. In the 2009 Öko-Recherche survey and at the UBA workshop 2007 [UBA 2008] tests were reported by the German foundries GE-3, GE-4, GE-6 and GE-8 as well as by an Italian foundry.

Most extensive tests were carried out at TRW. They were not stopped until the same technical problems with the melting pot emerged (corrosion of equipment, ignition of molten metal) as in the Pierburg foundry (see chapter 1), which supposedly could be solved only by means of relatively expensive converters (in order to save the protective film on the melt surface). As a result of the exemption from SF₆ prohibition (F-Gas Regulation 2006) for foundries below the 850 kg/a threshold, the TRW tests were ceased for the time being because the conversion was considered too expensive. At the expert discussion in Berlin 2007 [UBA 2008] the other German foundries with some experimental experience also pointed out that the legal exemption from the impending SF₆ ban was the main reason for stopping the conversion tests.

Consequently, the successful conversions to HFC-134a or SO₂ in foundries with prior SF₆ consumption > 850 kg/a (subject to 2006 F-Gas Regulation) are the sources of experience that can be consulted for conversions in die casting foundries with SF₆ consumption < 850 kg/a (types 1-3). This is not necessarily a disadvantage because the technical problems arising at large consumers of SF₆ hardly differ from those at medium and small sized SF₆ users. Here the conversion to HFC-134a could be even easier due to the fact that furnaces with smaller bath surface and lower melting temperature (hot chamber) are much more frequently in operation than in larger magnesium foundries (see table 9).

Table 9: Former and present SF₆ users in Mg die casting by hot and cold chamber machines		
	Hot Chamber	Cold Chamber
8 former users of SF ₆ > 850 kg/a	1	64
19 users of SF ₆ < 850 kg/a	27	27
<i>Type 1 (small)</i>	5	2
<i>Type 2 (middle)</i>	20	7
<i>Type 3 (big)</i>	2	18

Source: Öko-Recherche survey 2009.

2. Technical conversion in die casting foundries with SF₆ > 850 kg/a

On the basis of available experience with recent SF₆ replacement, we show technical alteration measures of the cover gas delivery system, which are considered necessary for conversion from SF₆ to HFC-134a or SO₂. These measures are considered relevant also for the 19 die casters who use SF₆ in quantities < 850 kg/a.

2.1 Basic features of cover gas systems in die casting foundries

The cover gas system in a die casting foundry consists of the following main components, irrespective of the type of active protective agent in use.

1. Gas mixing unit with mass-flow-controller (MFC) for exact dosage of active gas and carrier gas.
2. Piping from gas mixer to the furnaces.
3. In case of central gas supply to several furnaces: gas distribution devices (with flow meter, valves, display) at the junctions of the common supply line.
4. Gas discharge into the atmosphere over the melt in the crucible.

The following lessons can be drawn from past experiences in conversion to HFC-134a or SO₂.

2.2 Conversion from SF₆ to HFC-134a (AM-cover)

HFC-134a is a "drop-in" cover gas, which means that it is possible to continue using the existing gas delivery system without major technical expenditure. Only a few adjustments must be made at the gas mixing station including MFC to set up the optimum gas flow rate and gas concentration. In case of centralised gas supply systems, also the downstream distribution boxes at the junctions of the piping need recalibration. Due to the difference in pressure and density of the gases, some modifications of the parameters are usually sufficient to make sure that the required quantity of cover gas flows to the furnaces. It is necessary to set up a gas concentration which allows safe operation, according to the performance of the furnaces, the magnesium alloy in use, the temperature of the melt, etc. Occasionally, the software of the MFC parameters of the gas mixer has to be adjusted as otherwise the displayed gas concentration differs too much from the effective concentration.

These adjustments of the gas delivery system can be carried out by a service technician within five days.

Normally, the furnaces require only some minor technical adjustments. However, in exceptional cases, major alterations are necessary when the new protective film provides insufficient melt protection due to higher susceptibility to interference, or when sufficient protection can only be achieved by very high cover gas concentrations which enhance the risk of corrosion.

Minor usual measures are new seals against the inflow of air into the crucible, and the preparation of the crucible lid for well-directed and more even gas flow to the bath surface – e.g. by fixing of several tubes instead of only two tubes for the gas inflow.

If the listed measures at gas mixers and furnaces are not sufficient to ensure safe operation, as it is sometimes the case at very high melt temperatures in cold chamber furnaces, it can be necessary to stabilise the bath surface additionally by means of the converter technology (as reported in task 1, part 1 from the German Pierburg foundry). The installation of a converter is costly, particularly when all furnaces need this device.

2.3 Conversion from SF₆ to SO₂

The conversion from SF₆ to SO₂ scarcely requires alterations of the furnace since SO₂ provides virtually the same protection as SF₆. However, extensive technical restructuring of the gas delivery system is absolutely necessary because of the toxicity and corrosiveness of SO₂.

- Mixing station

The existing MFC in the mixing unit cannot be used for SO₂. It must either be exchanged completely or retrofitted with high effort. Due to the corrosiveness of the gas, the MFC must feature high-quality performance (SO₂ proof) comprising highly resistant seals and stainless metal. The gas mixing unit must be specified as gas safety cabinet with SO₂ detector, exhaust shaft/ventilator, and tight doors in order to provide sufficient protection from the toxic SO₂.

- Piping

The use of SO₂ as a cover gas requires conduit pipes made of stainless steel to prevent corrosion in case of humidity influx. The length of the pipe works between mixing station and furnaces amounts to 20 - 200 metres. Material and laying of the pipes including the mounting to walls and ceiling are costly.

- Gas distribution box (central gas supply)

In case of central gas supply to several furnaces, the gas distribution boxes (with flow meter, valves, display) at the junctions of the common supply line have to be exchanged by SO₂ proof devices.

A service technician must stay at least one week (five days) in the foundry to install and calibrate the gas mixing station and distribution devices. In addition he trains the operating personnel in SO₂ handling.

- Furnace

Normally, technical measures are not necessary. However, the personnel should be equipped with protective clothing (e.g. ventilated hard hats with face shield) for activities at the furnace such as periodic cleaning with the crucible lid being open. SO₂ containing air which permanently emerges out of the furnace flows off through the existing exhaust shaft over the furnace. In this way the maximum allowed concentration of SO₂ in workplaces is normally not exceeded.

Chapter Six

Costs of conversion to HFC-134a and SO₂ in magnesium die casting

The impact assessment of several policy options to reduce SF₆ emissions in chapter 8 relies on cost data in considerable parts. As stated in chapter 4, sector-specific estimates of the costs of SF₆ replacement are only sensible in magnesium die casting so far but not in sand casting, recycling of special alloys, and secondary aluminium production. In recycling of die casting alloys, the impact assessment can be based on available cost estimates of the plant operator which are not repeated here.

In this chapter, we estimate the potential costs of SF₆ replacement in the EU magnesium die casting foundries consuming less than 850 kg/a SF₆. From chapter 4 it emerged that to date and in foreseeable future, the only available alternative cover gases in die casting are SO₂ and HFC-134a. Therefore we consider the conversion to these two gas systems.

The cost estimates include a cost comparison between SO₂ and HFC-134a cover gas systems. The analysis is carried out for all individual foundries in four steps: (1) absolute investment cost of the conversion, (2) annualised capital cost of the conversion, (3) additional or saved annual operating cost, (4) total annual cost of SF₆ replacement.

Preliminary remark on SF₆ as secondary cover gas and fire extinguishing agent

It was shown in chapter 3 of this report that nineteen die casting plants exist in the EU who apply SF₆ as cover gas in quantities of < 850 kg/a. Prior to the cost estimates of their potential SF₆ replacement, a preliminary remark on the number of foundries subject to further analysis is necessary.

The big die casting foundry UK1 has been applying SO₂ as the primary cover gas for many years but still consumes 350 kg/a SF₆. The latter is used two to three times per day when the crucible is opened for removing dross from the bath surface. Short term application of SF₆ instead of SO₂ is supposed to both stabilise the protective film on the melt against the inflowing air, and protect the cleaning worker from toxic gas he would be exposed to otherwise. Both problems are solved by temporary application of SF₆.

This case of incomplete SF₆ substitution raises a fundamental question: Does SF₆ replacement imply full phase-out, or can a certain quantity of SF₆ continued to be used for secondary activities in the magnesium foundry?

As far as we know and learned in the survey, the other EU die casters using SO₂ apply one and the same cover gas for both normal operation and cleaning. Therefore, we suggest that conversion from SF₆ to SO₂ or HFC-134a should cover the full application of cover gas, not just the quantity for normal operation.

It is important for the progress of this study to keep in mind that the potential replacement of the remaining SF₆ in foundry UK1 is quite different from the SF₆ replacement in the other eighteen plants: SF₆ phase-out in UK1 does not require costly technical conversion measures as in the other foundries. Only the method of operation needs to be changed, which would not impose additional costs. As a consequence, our analysis of the costs of technical conversion in the EU die casting plants consuming < 850 kg/a SF₆ excludes the foundry UK1 (350 kg/a) and discusses only eighteen foundries.

SF₆ used on cleaning will be subject to SF₆ replacement as well. However, this does not exclude that small quantities of gas may be held available in the foundries for acute fire fighting. SF₆ is considered the most effective extinguishing agent in case the metal starts burning. The survey revealed that storage of one or two bottles of SF₆ as back-up stock is common practice, even in foundries that apply SO₂ or HFC-134a. It was agreed at the Brussels stakeholder meeting that the replacement of SF₆ refers to its use as cover gas, not as fire extinguishing agent. The foundries, however, should be encouraged to apply another fluid for fire fighting as soon as an effective alternative is available.

1. Investment cost of the conversion

The one-time costs of the conversion depend first of all on the chosen cover gas. The extent of technical modifications is normally higher if SO₂ is introduced (see chapter 5). Other factors affecting the costs are the number of existing furnaces, the distance between gas mixer and furnaces, and the amount of existing SF₆ equipment which can continue to be used for the new gas system.

Our assessments of the plant specific invest costs are based on the information obtained from the survey and from additional follow-up interviews. We estimate the investment costs for each die casting foundry twice, once for the introduction of SO₂, and once for the introduction of HFC-134a. In so doing we can identify the cover gas system that can be introduced more cost effective than the other under the specific conditions of the foundry.

The individual technical measures of a conversion to either SO₂ or HFC-134a, and the pieces of equipment that must be exchanged or reinstalled for the conversion are listed in the previous chapter. In table 10 all these measures, technical equipment and their costs are presented. The majority of cost data were collected from German companies for dedicated foundry equipment.

In order to calculate the investment costs for conversion to either of the two cover gas systems, the prices indicated in table 10 are applied to the specific conditions (number of furnaces, length of piping, etc.) of each of the 18 die casting foundries as provided by the Öko-Recherche survey.

Table 10: Invest cost positions for conversion from SF₆ to SO₂ or HFC-134a		
Investment in €	HFC-134a	SO₂
Euro per week conversion service	5,000	5,000
Sealing of furnace	500	
Adjustment of crucible lid	1,000	
Converter	43,000	
Single gas mixer complete		25,000
Central gas mixer complete		31,000
Single gas mixer w/o MFC		15,000
Central gas mixer w/o MFC		20,000
Distribution box in the piping		3,000
Stainless steel piping €/m		60.00
Lifetime in years	10	10
Discount rate	5%	5%
Annuity factor (10y, 5%)	0.1295	0.1295

The investment costs of the conversions in 18 foundries total 770,000 € (SO₂) vs. 470,000 € (HFC-134a). The cost for conversions to SO₂ amount to the 1.6 fold of the cost for conversions to HFC-134a. This result is not surprising considering the fact that conversion to HFC-134a normally requires only some minor adjustments of existing equipment while SO₂ can only be used after installation of new and costly equipment (gas mixer, piping system, distribution boxes).

Diagram 4 reveals some exemptions from this "rule of thumb" among the 18 foundries.

The investment cost per foundry is estimated on average 43,000 (SO₂) and 9,000 (HFC-134a) euros. In two cases, however, the conversion cost to HFC-134a are much higher, and amount to the four to five fold of the cost to an SO₂ cover gas system. This is because after long tests with HFC-134a, the concerned plants (RO1 and GE8) came to the conclusion that they need a converter for each furnace (43,000 € per piece). In our

survey, the two foundries explicitly specified this anticipated cost. Both plants do not intend to introduce SO₂ for reasons of occupational safety.

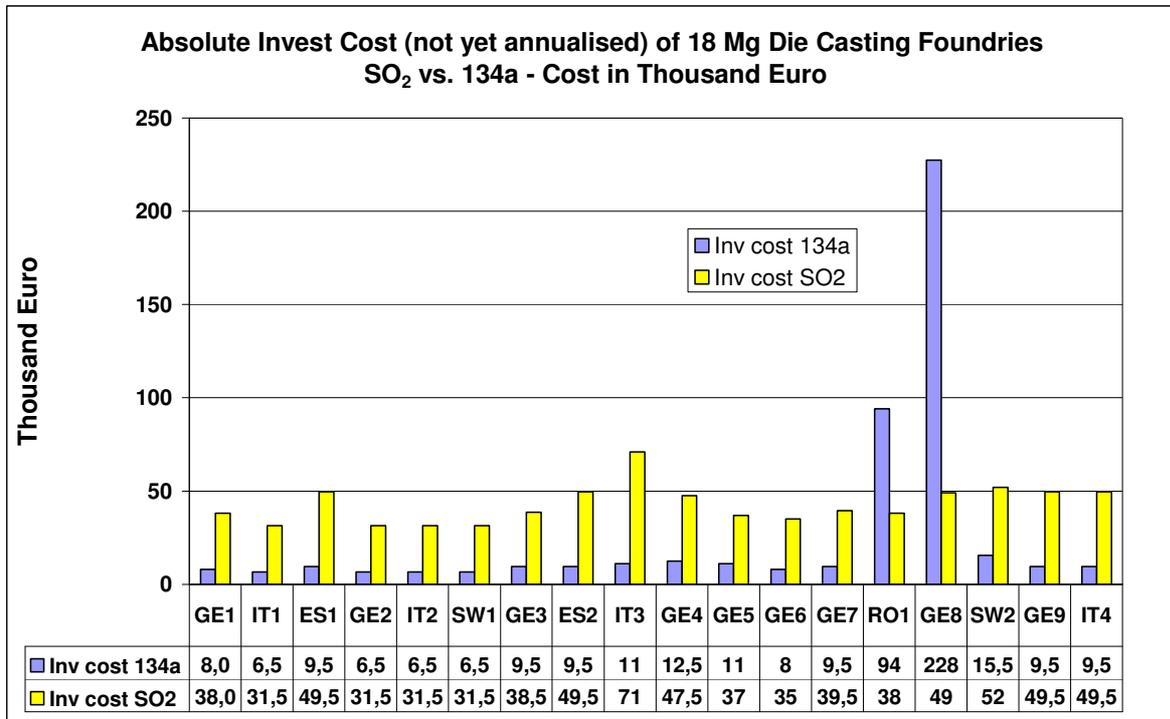


Diagram 4. In 16 of the 18 foundries the conversion to SO₂ amounts to the 4 - 5 fold of the SF₆ substitution by HFC-134a. However, in two cases (RO1 und GE8) the opposite is true. Here, operation with HFC-134a requires additional furnace equipment (converters) which is expensive. As a consequence, in these two foundries the HFC system costs four to five times more than conversion to SO₂ would cost.

2. Annualised capital costs of investments

The assessment of the annual conversion costs requires annualisation of the capital costs of the investment.

The annualised capital costs are calculated by multiplying the total investment and the annuity factor, where d = the discount rate ($100\% = 1$) and n is the depreciation period of the measure in years:

$$\text{Annuity Factor} = \frac{d}{(1 - (1 + d)^{-n})}$$

Investment costs are annualised for a depreciation period of 10 years and a discount rate of 5 % p.a. in order to resemble common industrial procedures on investment decisions (see table 10).

By multiplication of the resulting annuity factor (0.1295) and the twice calculated invest cost for SO₂/for HFC-134a the annual capital cost of the conversions can be calculated for each of the 18 foundries. These costs are given in table 11.

On an annual basis, the results are the same as in terms of absolute investment costs shown in Diagram 4. The annual capital costs of HFC-134a cover gas systems are four to five times lower than equivalent SO₂ systems (16 of 18 cases) as long as the conversions proceed without problems. If a conversion to HFC-134a does not succeed, supplementary technical measures might be necessary (like the installation of converters) that significantly inflate the costs. Foundry RO1 and GE8 anticipate annual capital costs of 12 and 29 thousand Euro, respectively, thus by far exceeding the costs of equivalent SO₂ systems.

Table 11. Annualised investment costs of conversion to SO₂ or 134a, in the 18 die casting foundries with SF₆ consumption < 850 kg/a, in thousand Euro			
Foundry	Type	Conversion to SO ₂	Conversion to 134a
IT1	1	4.08	0.84
ES1	1	6.41	1.23
GE2	1	4.08	0.84
IT2	1	4.08	0.84
SW1	1	4.08	0.84
GE3	2	4.99	1.23
ES2	2	6.41	1.23
IT3	2	9.19	1.42
GE4	2	6.15	1.62
GE5	2	4.79	1.42
GE6	2	4.53	1.04
GE7	2	5.12	1.23
RO1	3	4.92	12.17
GE8	3	6.35	29.46
SW2	3	6.73	2.01
GE9	2	6.41	1.23
IT4	3	6.41	1.23
GE1	-	4.92	1.04

3. Annual operating costs (difference to prior SF₆ system)

Operational costs under consideration are only the running expenses for the active cover gas. The carrier gas is not affected by the exchange of the gas system; maintenance and control of the new gas system can be set equal to the expenditure for the former SF₆ system. The relevant individual cost items for the analysis are presented

in table 12. Information on the prices of gases per kg was given by German gas traders in March 2009; the indicated prices are average.

Table 12: Cost data on the cover gases SF₆, SO₂ and HFC-134a (AM-cover)		
Operation in €	HFC-134a	SO₂
Gas € per 1 kg (SF ₆ = 20)	10	2.50
134a License fee > 500 t/a Mg outp € /t	10	
134a License fee < 500 t/a Mg outp €	5,000	
Gas concentration vol % [Cvol]	0.2	1.6
Density kg/m ³ (SF ₆ = 6,07) [d]	5.3	2.73
Gas concentration mass % (Cvol x d)	1.06	4.37
Mass SO ₂ vs. 134a	1	~ 4

Source: Several German gas distributors, March 2009.

In our estimates of the SF₆ replacement costs, the absolute amount of the annual gas cost is not relevant but only the differences in annual costs of SO₂ or HFC-134a from the formerly used SF₆.

The following gas prices per kg (see table 12) were used: 20 € for SF₆, 10 € for HFC-134a and 2.50 € for SO₂. Usually, the concentration of HFC-134a in the carrier gas can remain at the same level as before when SF₆ was used, e.g. 0.2%, so that the total demand for cover gas does not change. Under equal conditions, the annual gas cost would decrease by 50%. SO₂ must be applied in higher concentration than SF₆ or HFC-134a; 1.6 percent by volume is a common value which is the eightfold of 0.2%. However, the required mass of SO₂ (in kg) is only four times higher because of the density of SO₂ compared to SF₆/HFC-134a (2.73 vs. 6.07/5.3). Given a price of 2.50 € per kg SO₂, the annual expenditure at the same melt protection effect is almost the same for SO₂ as for HFC-134a, and ranges at 50% of the annual costs of SF₆.

In case of HFC-134a as a cover gas, an important cost related aspect that needs to be taken into account is that the use of HFC-134a is patented (AM-cover®), and every user has to pay a license fee to the holder. The annual fee is 10 € per t magnesium cast pieces, from 500 t magnesium onwards. Yet, every user irrespective his output of magnesium parts must pay a minimum of 5,000 € per year. A foundry with an annual output of 50 t magnesium parts pays the same base fee (5,000 €/a) as a foundry with magnesium output of 450 t/a. It must be noted that the payment of the license fee does not include the cost of the HFC-134a gas itself. The user must buy the gas at its market price in addition to the base fee of 5,000 €. Consequently, the annual costs of HFC-134a consist of both the license fee and the cost of the purchased quantity of cover gas.

As a consequence of this pricing, the annual expenditure for HFC-134a (assuming 10 €/kg) is higher than that for SF₆ (assuming 20 €/kg) as long as the magnesium output is

lower than 500 t/a. There are only five EU foundries (SF₆ consumption > 850 kg/a) who produce more than 500 t/a cast parts (all type-3, one type-2). The majority of foundries would have to spend more money on HFC-134a than on SF₆ before the conversion.

For all 18 foundries, the additional annual costs for HFC-134a cover gas totals 69,000 Euro. In contrast, in case of SO₂ the savings of the 18 foundries total 56,000 Euro.

In Diagram 5, the differences in annual costs for cover gases are shown for all of the 18 foundries, in each case for both SO₂ and HFC-134a, and in comparison with SF₆. Savings (SO₂) are negative values; additional costs (HFC-134a) are positive figures.

The negative bars in the diagram clearly indicate that the application of SO₂ cover gas results in substantial savings of annual operating cost. The more cover gas is used, the higher the savings relative to SF₆.

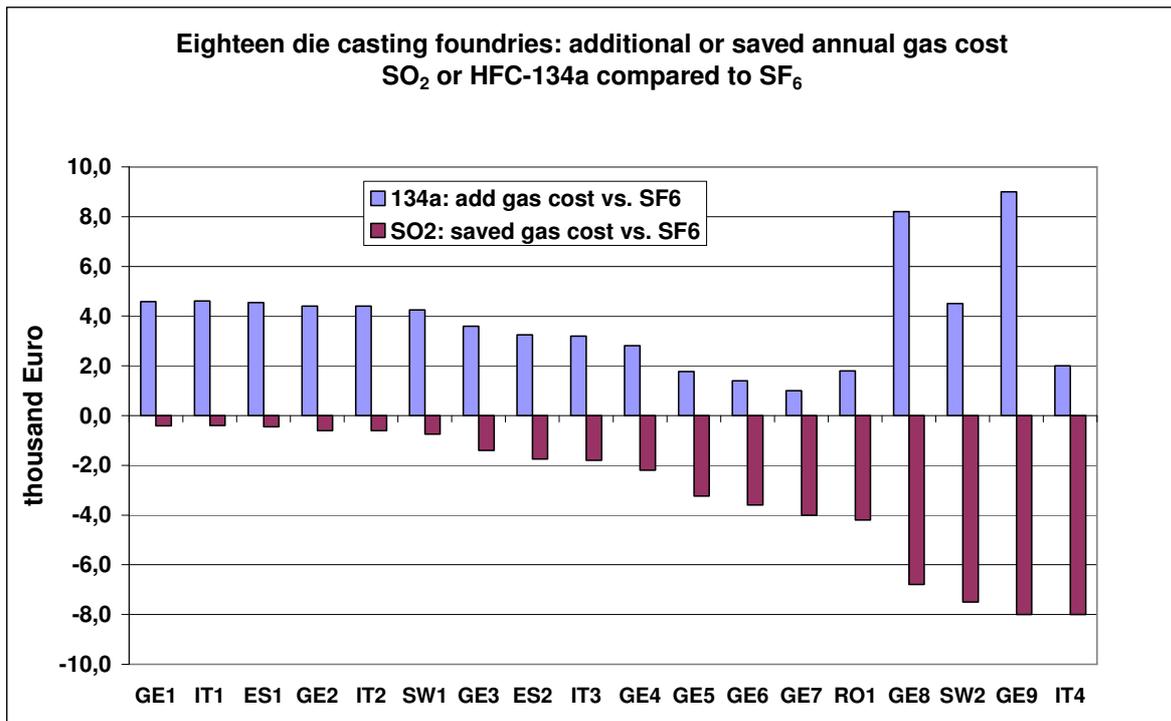


Diagram 5: Additional or saved annual gas costs in the 18 die casting foundries vs. SF₆. The differences in annual costs for cover gases are shown in each case for both SO₂ and HFC-134a, and in comparison with SF₆. Savings (SO₂) are negative values; additional costs (HFC-134a) are positive figures.

As compared to SO₂, the higher market price of HFC-134a (without license fee) is balanced by lower quantity; the annual costs for HFC-134a (without fee) and SO₂ are equal (in this study). As a consequence, the savings caused by the use of SO₂ as shown

in the diagram, and the savings caused by the use of HFC-134a would range at the same level if there were no license fees.

It is only due to the license fees that the operation costs of HFC-134a are considerably higher than those of SO₂.

4. The total annual costs of SF₆ replacement by SO₂ and HFC-134a

The assessment of both annualised investment costs and annual operation costs allows estimations of the total costs of SF₆ replacement per year for both SO₂ and HFC-134a. In table 13, these annual costs are listed for each individual foundry. In 15 of 18 cases, the annual costs arising from the SF₆ replacement are higher for HFC-134a; in four cases the use of SO₂ is even economically beneficial because it saves money compared to the SF₆ system (negative values). In three cases the introduction of SO₂ is more expensive than HFC-134a, on an annual basis. See table 13.

Table 13: Total ann. cost of conversion from SF₆ to SO₂ or HFC-134a by individual die casting foundries, in €		
Foundry	1. HFC-134a	2. SO ₂
GE1	5,626	4,511
IT1	5,442	3,679
ES1	5,780	5,960
GE2	5,242	3,479
IT2	5,242	3,479
SW1	5,092	3,329
GE3	4,830	3,586
ES2	4,480	4,660
IT3	4,625	7,395
GE4	4,419	3,951
GE5	3,195	1,562
GE6	2,436	933
GE7	2,230	1,115
RO1	13,973	721
GE8	37,662	-454
SW2	6,507	-766
GE9	10,230	-1,590
IT4	3,230	-1,590
Total	130,242	43,964

Table 13 shows that the individual foundries exhibit large differences in the comparison of costs for HFC-134a and SO₂ cover gas systems.

Under present circumstances, the conversion of all 18 foundries to SO₂ cover gas systems causes total annual costs of 43,964 Euro. This is only one third of the annual

total costs arising from conversion to HFC-134a. From this it follows that on an annual basis the SO₂ system is less costly than the HFC-134a system.

Diagram 6 illustrates graphically the cost estimations for the 18 foundries taken together, from left to right in the order

1. Annualised invest costs.
2. Annual gas costs without license fee.
3. Annual expenditure for license fee.
4. Total annual costs of SF₆ replacement.

The diagram 6 clearly indicates that the elevated costs of the conversion to HFC-134a are a consequence of the license fee in its present form. Without license fees, the operation with HFC-134a is significantly less expensive than the use of SO₂.

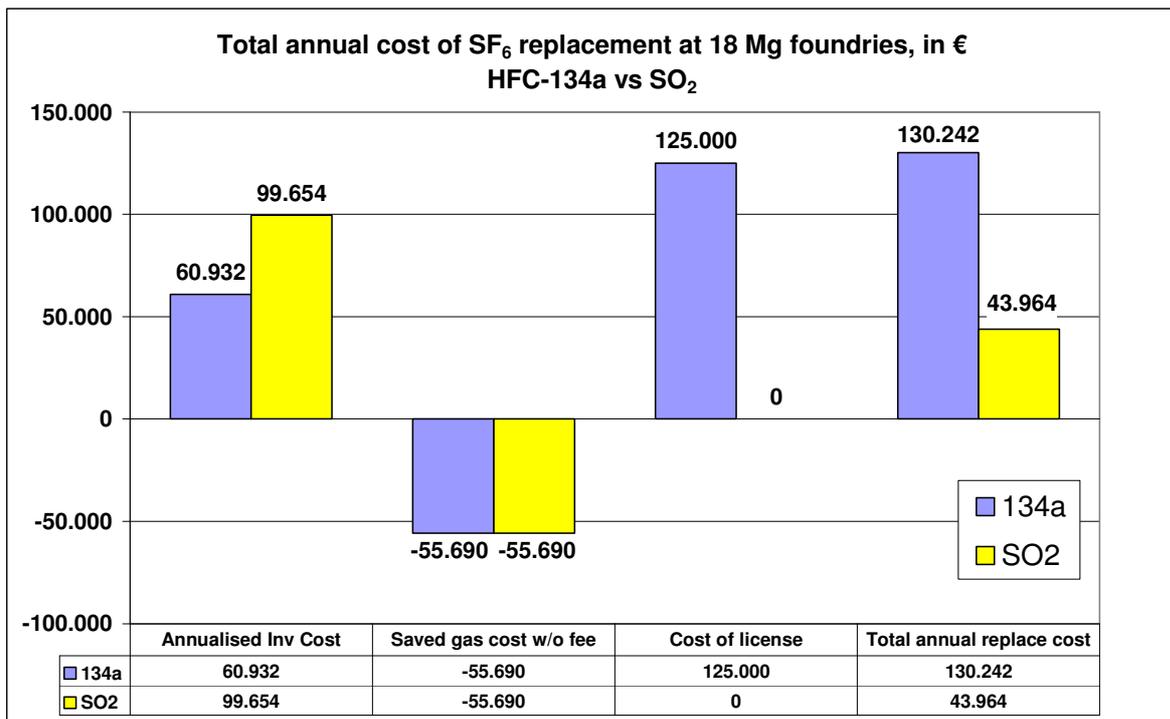


Diagram 6: On an annual basis the SO₂ system is less costly than the HFC-134a system. The conversion of all 18 foundries causes total annual costs of 43,964 Euro (SO₂) or 130,242 Euro (HFC-134a). The higher costs of the conversion to HFC-134a are a result of the license fee in its present form. Without license fee, the HFC-134a system is less expensive than the SO₂ system.

5. Cost burden from cover gas conversion

The additional annual costs arise to the individual die casting foundries as a result of cover gas conversion to either HFC-134a or SO₂. Whether or not these costs are feasible to the operators of the die casting foundries depends on the economic power of the individual companies. In the final section of this chapter we estimate the share of the annual conversion cost in the turnover of the involved foundries.

The financial power of a company is often measured by its annual sales. The business volumes of the companies operating the eighteen foundries significantly differ. There are global players, who turn over much more than one billion Euro per year. The foundries of type 3 are classified into this category. The other foundries belong either to small enterprises operating only one small foundry for NF metals (type 1) or to medium-sized enterprises which run large casting plants (type 2) for NF metals. It must be noted that in the foundries of small and medium enterprises (SME) casting of aluminium (or zinc) contributes considerably more to the turnover than magnesium casting.

In order to establish the share of the annual conversion costs in the annual turnover we draw on magnesium production as the only turnover benchmark. Figures on the magnesium-related earnings are not published. Therefore we estimate them indirectly based on the annual production of magnesium cast parts. The production data were collected in the course of our survey.

The sales price of one kilogram magnesium parts presently amounts to approx. 20 Euro when produced in medium series²¹. By rating the magnesium production with 20 Euro per kg, we estimated the magnesium specific sales (or magnesium specific internal value creation) of the eighteen magnesium foundries. Relating the individual additional annual costs of the cover gas conversions to these sales data, we obtain the share (%) of these costs in magnesium specific turnover, which is considered to be an expression of the cost burden to these foundries.

Table 14 presents the annual cost burden of SF₆ replacement for the three types of die casting foundries as share (%) in the respective average magnesium specific turnover. The latter is calculated by multiplying the output of magnesium parts in kg and the assumed sales price of 20 € per kg.

²¹ The internal price in case of integrated type 3 foundries with extremely large series is lower than 20 Euro, but higher than 10 Euro.

Table 14: Average cost burden from SF₆ replacement to different cover gas systems in the three types of die casting foundries, cost in €/year			
	Type1	Type2	Type3
Av sales of Mg foundry €	980,000	7,012,500	21,500,000
Av ann. costs of conversion to SO ₂	3,986	2,702	-522
Share (%) costs in sales	0.4%	0.04%	0.00%
Av ann. costs of conversion to HFC-134a	5,359	4,556	15,343
Share (%) costs in sales	0.5%	0.06%	0.07%

Sources: Öko-Recherche survey (sales), Table 13 (costs).

The share of additional annual costs (vs. SF₆) in the magnesium specific turnover (roughly estimated) does not exceed 0.5% in any case. In the 13 foundries of type 2 and 3, the cost burden averages even less than 0.07% (HFC-134a system). The five magnesium foundries of type 1, which are operated by small enterprises, are subject to higher burdens which, however, never account for more than 0.5% (HFC-134a system).

It should be noted that the magnesium foundries represent only a small part of the companies' sales (as the larger proportion is contributed by aluminium parts). By relation of the annual costs of the cover gas conversion to the total turnover of the companies, the cost shares will decrease further.

Chapter Seven

Screening of policy options to reduce SF₆ emissions from NF metal industry

At the beginning of chapter 4, we identified possible policy options to reduce SF₆ emissions from NF metal industry. After screening for technical feasibility of the technical measures upon which those options relied, we ruled out “containment and recovery” from further analysis. Only options qualified for substitution of SF₆ by conversion to SO₂ or HFC-134a were left, for the sectors of magnesium die casting and recycling of die casting alloys. In chapter 5 and 6, technical experience with cover gas replacement was discussed for die casting and the costs of the conversions were assessed. On the basis of the findings in chapters 4-6, preliminary policy options identified are further screened and refined into policy options which are suitable to reduce emissions in a technically and economically feasible way.

1. No further action

This option represents the baseline scenario and describes the trend of SF₆ emissions until 2020 without any further action. As assessed in the previous chapters, this option is the only possible option for certain applications of SF₆ for which replacement is technically not feasible at this stage. As discussed in the previous chapters of this study, measures to reduce emissions are technically not feasible for the time being in:

- magnesium sand casting,
- recycling of special magnesium alloys, and
- the production of a special aluminium alloy.

By 2020, technical measures to reduce emissions in these sub-sectors of the non-ferrous metal industry might be available. However, a discussion of other options for the particular subsectors is not meaningful at present.

2. Full removal of exemption from SF₆ ban in magnesium die casting

The successful substitution of SF₆ by SO₂ or HFC-134a in large die casting foundries (annual consumption of SF₆ > 850 kg/a) has shown that the replacement of SF₆ is technically feasible in die casting in general. As outlined in chapter 6, the conversion to SO₂ or HFC-134a (Novec-612 as a potential alternative is commercially not yet available in Europe) does not overly charge the remaining 19 magnesium foundries. This will be assessed in the impact assessment.

The removal of the exemption of the ban of the use of SF₆, i.e. the full ban of the use of SF₆ in magnesium die casting is an obvious policy option to consider in depth in the impact assessment. The assessment will be based on two technical choices for conversion: SO₂ or HFC-134a.

3. Revision of the 850 kg/a threshold in magnesium die casting

The cost analysis in chapter 6 has revealed that the five small magnesium die casting foundries are facing relatively higher cost burdens caused by the conversion to SO₂ or HFC-134a than the medium-sized and large foundries. The respective five small foundries use less than 100 kg SF₆ per year, the larger foundries use a lot more than that.

The special situation of users of small quantities of SF₆ is taken into account in a policy measure which revises the threshold for the use of SF₆ from 850 kg to 100 kg. According to this option the use of SF₆ will remain allowed in foundries that use less than 100 kg/a.

4. Voluntary agreement to reduce SF₆ emissions from die casting

In contrast to the policy measures discussed earlier, a voluntary agreement (VA) is a non-regulatory policy option. An agreement between the 19 die casting foundries with the European Commission could commit them to replace SF₆ fully or above the threshold of 100 kg/a.

In that case, a legal measure would no longer be necessary.

Under certain organizational prerequisites, a VA might constitute an efficient instrument to reduce emissions. Among others, it is necessary that a functional body assures the compliance of the committed emission reductions. Yet, this organizational framework does not exist in EU magnesium industry.

1. At European level, an umbrella association of the foundry industry (CAEF) exists but focuses clearly on economically important sectors of the ferrous metal industry and aluminium. Magnesium casting is only covered marginally.

2. At national level in some Member States, associations of magnesium foundries are organized. However, only some foundries of the respective country are members.

3. The association for magnesium die casting foundries in Germany (nine of the nineteen foundries < 850 kg/a are based in this country) holds the opinion that the same regulatory measures should enter into force for foundries < 850 kg/a as it is in force for

foundries > 850 kg/a. A voluntary agreement is not considered a useful tool to reduce emissions from magnesium industry.

The organizational preconditions for a VA to reduce SF₆ emissions from magnesium die casting are not given in Europe. Therefore, this non-regulatory instrument will not be treated any further in the impact analysis.

5. Joint Implementation in magnesium die casting

The Joint Implementation (JI) mechanism allows an investor (project developer) in an industrialized country (i.e. Annex B Party to the Kyoto Protocol) to carry out climate change projects in another industrialized country and earn carbon credits. The certificates generated from JI projects are called emission reduction units (ERU). They are issued from 2008 onwards and may be used in the EU Emissions Trading Scheme. ERUs can be sold to operators of industrial installations or combustion facilities that must participate in the EU Emissions Trading Scheme (ETS). The price of one ERU (1 t CO₂ eq.) is of the order of €10, which is somewhat lower than the price of common EU emission allowances.

So far, projects for reductions of SF₆ emissions from magnesium industry have been implemented only under the CDM (Clean Development Mechanism) outside of Europe (China, Israel), and only in primary magnesium production. JI projects for reductions of SF₆ emissions have not been implemented in the EU secondary magnesium industry. Nevertheless, they are possible and can be cost-effective for investors in the magnesium industry if the revenue from ERUs exceeds the costs for cover gas conversion.

Full replacement of SF₆ could be reached if project developers from other industrialised countries, which are Annex B parties to the Kyoto Protocol, invest in the conversion of the nineteen die casting foundries. This condition is difficult but not unlikely to be met over the next years.

6. Extension of SF₆ use prohibition to recycling of magnesium die casting alloys

For many years, six out of the seven recycling plants for magnesium die casting alloys in the EU have been using SO₂ as a cover gas. Therefore, the conversion of the remaining recycling plant to SO₂ is considered possible.

Banning the use of SF₆ in recycling of magnesium die casting alloys is a regulatory policy option to be treated further in the impact analysis.

It must be noted that in recycling the establishment of a threshold value (minimum SF₆ consumption in kg/a) is not a reasonable measure as it is in die casting. The only plant consumes 3,000 kg/a. Only full SF₆ prohibition is a meaningful policy option.

7. Voluntary agreement in recycling of die casting alloys

In recycling, a voluntary agreement to replace SF₆ does not need be ruled out for organisational reasons. There is only one recycling company in the EU; they can directly commit themselves, with no representing body being necessary to assure compliance with the objective. The agreement can much easier be established and implemented than in die casting. Therefore, it will be included in more in-depth analysis of its impacts.

8. Joint Implementation in magnesium recycling of die casting alloys

We consider JI projects possible options to replace SF₆ in die casting foundries. There is no reason to exclude recycling from this mechanism.

Conclusion

The screening of possible policy options to reduce SF₆ emissions from the NF metal industry, results in seven policy options for more in-depth impact analysis.

Table 15: Policy options to replace SF ₆ emission in NF metal industry							
Application	All	Die Casting SF ₆ < 850 kg/a			Recycling		
	Opt 1	Opt 2	Opt 3	Opt 4	Opt 5	Opt 6	Opt 7
Option	No Action	Full Prohibition	Revision to 100kg	Joint Implementation	Full Prohibition	VA	Joint Implem.

Option 1: No policy action for magnesium and aluminium industry

Option 2: Full SF₆ prohibition in magnesium die casting

Option 3: Revision of the 850 kg/a threshold in Mg die casting (reduction to 100 kg/a)

Option 4: Joint implementation mechanism for magnesium die casting

Option 5: Full prohibition of SF₆ in recycling of magnesium die casting alloys

Option 6: Voluntary agreement to replace SF₆ in recycling

Option 7: Joint implementation mechanism for magnesium recycling.

Chapter Eight

Impact Assessment of Policy Options to reduce SF₆ emissions

This chapter analyses the impacts of the seven relevant policy options to reduce SF₆ emissions from the NF metal industry in the EU-27 as derived in the previous chapter. The assessment includes environmental, social and economic dimensions which are considered extensively for each option.

At first, we discuss the no-action option. This is the only one that refers to all sectors of the NF metal industry. Afterwards, we analyse three options for die casting (options 2-4), and, finally, three options for recycling of die casting alloys (options 5-7).

Table 16: Options and technical solutions in the impact assessment										
Application	All	Die Casting SF ₆ < 850 kg/a						Recycling		
	Opt 1	Opt 2		Opt 3		Opt 4		Opt 5	Opt 6	Opt 7
Option	No Action	Full Prohibition		Revision to 100kg		Joint Implementation		Full Prohibition	VA	Joint Implem.
Technical solution	-	SO ₂	134a	SO ₂	134a	SO ₂	134a	SO ₂	SO ₂	SO ₂

As shown in table 16, different "technical choices" or "technical solutions" are distinguished in options 2-7. These indicate alternative cover gases, SO₂ or HFC-134a, available for conversion of the plants that are affected by an "option". It should be highlighted that the technical choices are not binding but probable solutions for the implementation of a specific replacement option. Operators have the choice to apply either SO₂ or HFC-134a, and are not forced to convert to one particular cover gas²². This implies that – in die casting – not a single technology is likely to be implemented universally and a "mix" of conversions to HFC-134a and SO₂ is much more likely to be established. As a consequence, in the impact assessment, the two technical solutions indicate the real range of environmental, social and economic impacts that a particular option will show when implemented.

In recycling of die casting alloys, where only one plant is using SF₆, only the technical choice SO₂ will be analysed. The operator claimed SO₂ to be the only possible alternative to SF₆ in his plant and this is considered in the impact assessment.

²² The comparison between HFC-134a and SO₂ may guide decisions in a political approach which does not allow high-GWP fluids like HFC-134a, but requires conversion to low or no GWP cover gases.

Option 1: No policy change

If no action is taken, the total SF₆ emissions from the NF metal sector will continue increasing until 2020 to 600 kt CO₂ eq. The present (2008) SF₆ consumption of 21,920 kg/a of the EU magnesium industry is assumed to grow by 12% to approx. 24,700 kg/a (563 kt CO₂ eq.). The annual rate is assumed 1%. SF₆ emissions from the aluminium industry are expected to grow at the same rate from 1,500 kg/a to 1,690 kg/a by 2020 (38 kt CO₂ eq.).

Our survey on the magnesium casting plants in Europe (die casting, sand casting, recycling) did not reveal any indications of a falling usage trend for SF₆ independent from political pressure. On the contrary, several German die casters below the 850 kg/a threshold ceased tests with the alternative cover gas HFC-134a when they were informed about their exemption from the SF₆ prohibition.

Without further policy measures it is very likely that specific SF₆ consumption will remain at the same level, more precisely that the SF₆ consumption increases with the growth rate of the magnesium production and the production of the relevant aluminium alloy.

The annual growth rate of magnesium casting amounted to approx. 2% over the last ten years in spite of higher forecasts and expectations by manufacturers and their associations. Considering the present economic crisis which affects the magnesium industry particularly because of its high dependency on the automotive sector, an average annual growth rate of 1% until 2020 seems to be realistic. The special aluminium alloy for which SF₆ is used as a cleaning agent is produced exclusively for the automotive industry and thus not likely to grow as fast as in the past.

Table 17: SF₆ emissions from EU NF metal industry 2008 (kg) and 2020 (kg and kt CO₂ eq) Option 1: No further action undertaken			
	2008	2020	2020
	kilograms	kilograms	kt CO ₂ eq
Mg die casting	5,919	6,670	152
Recycling of Mg die casting alloys	3,000	3,381	77
Mg sand casting	10,000	11,269	257
Recycling of special Mg alloys	3,000	3,381	77
Production of aluminium alloy	1,500	1,691	38
Total	23,419	26,392	600

Option 2: Full prohibition of SF₆ in die casting

This regulatory measure affects all operators of magnesium die casting foundries which presently use SF₆. As a result of a full prohibition of the use of SF₆, the die casters will change to SO₂ or HFC-134a, both of which are technically available alternatives.

Therefore, we consider two technical solutions of SF₆ replacement:

- a) die casting: substitution of SF₆ by SO₂,
- b) die casting: substitution of SF₆ by HFC-134a.

a) Die casting with SO₂

Environmental impacts

The introduction of SO₂ instantly eliminates all projected 2020 SF₆ emissions of 6,670 kg (152 kt CO₂ eq).

As mentioned in chapter 1, SO₂ fed to the furnaces and machines hardly decomposes and is completely released to the atmosphere as part of the mix of waste gas. Instead of SF₆ emissions, about 26 t of SO₂ will be emitted in 2020. These emissions, however, are environmentally not irrelevant as SO₂ is an air pollutant that contributes to acidification of aqueous and soil ecosystems.

Most EU Member States strictly limit the concentration of SO₂ in the waste gas from industrial facilities. The limits, however, are relevant from a minimum mass flow of the substance (kg/h). For example, the German Technical Instructions on Air Quality Control (TA Luft) determines the minimum (minor) mass flow of SO₂ at 20 kg/h. It is therefore important to know that none of the 19 die casting foundries reaches a 20 kg/h mass flow, with 750 g/h being the calculated maximum value (SO₂ consumption of 3,200 kg/a).

Direct economic and social impacts on the foundries

All die casting companies are facing the cost for new equipment on the one hand and savings from the lower price of the new cover gas on the other hand. According to the cost analysis in chapter 6, the net cost of the conversion from SF₆ to SO₂ in all 19 foundries amounts to € 43,964 on an annual basis.

As shown in chapter 6, these costs are relatively low. The burden for medium-sized and large foundries ranges between 0.0% and 0.04% of the turnover from magnesium casting parts. Even for small foundries, the burden is no higher than 0.4% of their annual magnesium-specific sales. We thus conclude that no increased job risk arises from the conversion to SO₂.

It should, however, be noted that the toxicity of SO₂ adds risks to occupational health in case of accidents, e.g. sudden leakages of the gas piping system, when discharging SO₂ temporarily exceeds the workplace exposure limit in the workshop. It also adds risks on a regular basis. During the daily cleaning process of the melt, when the crucible is open, the SO₂ concentration to which the cleaning worker is exposed exceeds the exposure limit for a short time. The exposure limit at the workplace is very low in all EU Member States, e.g. in Germany it is 1.3 mg/m³. As a safety measure, it is recommended that the cleaning workers wear protective masks.

In contrast to the job risk, the risk for occupational health could not be assessed quantitatively.

Indirect economic and social impacts

Positive and negative impacts are expected for actors affected indirectly such as manufacturers of equipment and gas distributors.

Equipment manufacturers can expect gains of ca. € 99,654 on an annual basis from the conversion to SO₂. However, no additional jobs will be generated. According to a recent study for the Commission²³, we presume that a new position will be created if the turnover of equipment suppliers increased by € 200,000/ year. Furthermore, the foundries will purchase from several equipment suppliers which reduces the gains of each company.

The distributors of cover gases will face a net decrease in sales of ca. € 55,690 as the revenues from the sale of SO₂ is about half the revenues from the sales of SF₆. Jobs at these companies are not at risk as several gas distributors in each Member State will get confronted with minor decline.

²³ BiPRO, Study on the potential application of Art 3 and 4 of Regulation (EC) n° 842/2006, final report December 2008.

b) Die casting with HFC-134a

Environmental impacts

The application of HFC-134a significantly reduces the global warming emissions from the cover gas. However, it does not eliminate the full 2020 emissions of 152 kt CO₂ eq., as the GWP value of HFC-134a is not zero but 1,430 (6.27% of the GWP of SF₆ = 22,800). For simplification, we disregard the actual decomposition of HFC-134a over the hot melt and apply the unmitigated GWP²⁴. The HFC-caused global warming emissions caused by the cover gas HFC-134a amount to 9.5 kt CO₂ eq. in 2020. This equals an emission reduction of 142.5 kt CO₂ eq.

HFC-134a is not acid itself. However, on application it is broken into highly acid HF. In chapter 1, the HF-formation was estimated to range at about 30-40% of the initial quantity of HFC-134a. Applying this ratio, we estimated that the consumption of 6,670 kg of HFC-134a results in waste gas emissions of approx. 2,200 kg.²⁵ In relevant EU legislation (e.g. Directive 2000/76/EC) and national legislation of the Member States, the mass concentration limits for this waste gas are usually 50 times lower than for SO₂ as HF is an extremely potent acid. Thus the acidification effect from the use of HFC-134a should not be considered less severe than that from the use of SO₂.

In the German Technical Instructions on Air Quality Control the minor mass flow is only 0.15 kg/h (SO₂: 20 kg/h). It is therefore important to know that none of the 19 die casting foundries reaches the limit of 0.15 kg/h HF mass flow. This refers to the calculated maximum sample value of 0.05 kg/h (HFC-134a consumption of 800 kg/a).

Direct economic and social impacts on the foundries

All die casting companies are facing costs for new equipment on the one hand and savings from the lower price of the new cover gas on the other hand. Yet, the gains from the relatively low price of HFC-134a are exceeded by the fee which operators have to pay to the license holder. According to the cost analysis in chapter 6, the annual net costs for conversion of all 19 foundries from SF₆ to HFC-134a amount to €130,242 (including license fee of €125,000).

Despite those high fees, the net costs of a conversion to HFC-134a are relatively low. The charge for medium-sized and large foundries ranges between 0.06% and 0.07% of

²⁴ We consider the decomposition of HFC-134a in the sensitivity analysis in Annex 1.

²⁵ It is contradictory, definitely, to use the initial characteristics of HFC-134a for the calculation of the GWP and the characteristics of decomposition products of HFC-134a for the acidity effect. It is to underline that the full GWP is used due to a lack of a scientifically approved default value. In contrast to the calculation of the GWP, the acidity effect is assessed qualitatively. The decomposition of HFC-134a is taken into account in the sensitivity analysis.

the turnover from Mg casting parts. In one case, the extreme burden of 0.13% is caused by additional investment costs (converter) of the respective foundry. The annual charge for small foundries is 0.5% on average.

We conclude that no increased job risk arises from the conversion to HFC-134a.

Unlike SO₂, HFC-134a is not toxic before decomposition. Therefore, accidental leakages of the gas piping system rarely increase risks for occupational health. During the daily cleaning process of the melt, however, the lid of the crucible is open which could cause a risk to the cleaning workers' health. The concentration of the by-product HF, generated during decomposition of HFC-134a, rises to up to 40 times the limit of the concentration tolerated (e.g. Germany: 0.83 mg/m³ /1 ppmv). As a safety measure, it is recommended that the workers wear protective masks.

In contrast to the job risk, the risk for occupational health cannot be estimated quantitatively.

Indirect economic and social impacts

Positive and negative impacts are expected for indirectly affected actors like manufacturers of equipment, gas distributors, and the license holder.

Equipment manufacturers benefit from conversion to HFC-134a not as much as from conversion to SO₂. The annual gains amount to ca. €60,932, which will not lead to the creation of a new place of employment as a minimum difference in turnover of €200,000/year would be required.

The distributors of gas will face the same net decrease in sales of ca. € 55,690 as for the conversion to SO₂. The revenues from the sale of HFC-134a amount to only half the revenues from the sales of SF₆. Jobs at these companies are not at risk as several gas distributors in each Member State will get confronted with minor decline.

The company which provides the license for the HFC-134a system AMT-cover®, benefits most from the conversion to HFC-134a. They gain a fee of €125,000 per year. A company representative outlined that the earnings from the license fee are not sufficient to create a full place of employment, at best a half job.

Option 3: Revision of 850 kg/a threshold to 100 kg/a in Mg die casting

In the following, we analyse the impacts of a revision of the 850 kg/a threshold in magnesium die casting. In the EU-27, six die casting foundries use less than 100 kg SF₆ per year. In option 3, these are assumed to continue applying SF₆. The number of foundries affected by a use-prohibition of SF₆ is reduced to 13, compared to a full prohibition as discussed in option 2.

a) Die Casting with SO₂

Environmental impacts

The introduction of SO₂ in 13 medium and large foundries eliminates projected 2020 SF₆ emissions of 143.8 kt CO₂ eq. The remaining six small foundries continue emitting 8.2 kt.

25.2 t SO₂ (compared to 26.2 t under option 2) are released to the atmosphere contributing to acidification of ecosystems. Legal emission limits for SO₂ must be maintained by operators only if the SO₂ mass flow in the waste gas exceeds a minimum value. The threshold is not reached by one of the 13 foundries.

Direct economic and social impacts on foundries

The annualized net costs arising to the 13 die casting foundries from conversion to SO₂ total €19,525, compared to €43,964 arising to all 19 plants. The financial burden for the 13 operators is very low, ranging from 0.0% to 0.04% of the revenue from Mg casting parts, and does not create job impacts.

The toxicity of SO₂ adds risks to occupational health in case of accidents (e.g. leakage of the piping) and on a regular basis during the daily cleaning process when the concentration of SO₂ exceeds temporarily the exposure limit at the cleaner's workplace. As a safety measure, the cleaning workers should wear masks.

Indirect economic and social impacts

The equipment manufacturers of SO₂ gas delivery systems gain ca. € 72,005. This amount is not sufficient for the creation of a new place of employment as the necessary difference in turnover is assumed to range around €200,000/year, and the total equipment sales are split into several companies.

The gas distributors will face a net decrease in sales of ca. € 52,480 as the revenues from SO₂ is about half the revenues from SF₆. Jobs are not at risk as several gas distributors in each Member State will be confronted with minor decline.

b) Die casting with HFC-134a

Environmental impacts

The application of HFC-134a reduces the 2020 cover gas emissions of the 13 affected foundries from 143.8 to 9 kt CO₂ eq. – not to zero because new HFC-134a emissions of 9 kt CO₂ eq. arise. In addition, the six small foundries continue emitting 8.2 kt CO₂ eq.

On use, HFC-134a breaks down into highly acid HF of ca. 2,100 kg. Strict emission limits must be observed by operators if the HF mass flow in the waste gas exceeds a minimum value. The threshold is not reached by any of the 13 foundries.

Direct economic and social impacts on foundries

The annualized net costs arising to the 13 die casting foundries from conversion to HFC-134a total €97,818 (compared to €130,242 arising to all 19 plants). The financial burden for medium and large foundries ranges between 0.06% and 0.07% of the turnover from Mg casting parts. In one case, a higher charge of 0.13% is caused by additional investment costs (converter) of the respective foundry. We conclude that no increased job risk arises from the conversion to HFC-134a.

The new cover gas is not toxic itself. Accidental leakages of the piping system do rarely increase risks for occupational health. During the daily cleaning process, however, the concentration of the by-product HF temporarily exceeds the exposure limit at the cleaner's workplace. For safety, the worker must wear a protective mask.

Indirect economic and social impacts

Equipment manufacturers gain annually ca. € 55,298, which would not lead to the creation of a new job as a minimum difference in turnover of € 200,000/year would be required.

The distributors of gas will face the same net decrease in sales of ca. € 52,420 as for the conversion to SO₂. Jobs at these companies are not at risk as several gas distributors in each Member State will be faced with minor decline.

The company which provides the license for the use of HFC-134a (AM-cover®), gains a fee of €95,000 per year (minus €30,000 that the six smaller foundries would pay under option 2). A company representative outlined that the earnings from the license fee are not sufficient to create a full place of employment, at best a half job.

Option 4: Joint implementation in magnesium die casting

All 19 foundries could be covered by option 4. Within the joint implementation mechanism, a project developer can undertake the conversion of the cover gas system of a foundry at own costs in order to earn ERUs. In this way, the conversion will not result in additional investment costs for the magnesium die casting foundry. Although operating costs will still arise, in many cases net additional costs will turn into savings.

Apart from the investment, the project developer has to pay the costs for an expertise (annualized €6,500), annual monitoring (annualized €5,000), and administration (annualized €300). The total costs including investment costs amount to ca. €15,000 (HFC-134a) - €17,000 (SO₂) (annualised).

Based on a realistic price of €10 per 1 tonne CO₂ eq., the project developer has to cut down emissions of at least 1,500 – 1,700 t CO₂ eq. in the long term in order to work profitably. This refers to the use of 65 – 75 kg of SF₆ per year.

Therefore, the conversion of the six small die casting foundries using 40 – 75 kg of SF₆ per year is not profitable for the project developer. In contrast, the substitution of SF₆ in the 13 relatively large foundries which use more than 140 kg of SF₆ per year is highly profitable. Therefore, we consider it quite likely that these foundries get converted under the joint implementation mechanism, while the six small foundries will not.

Taking these considerations into account, the environmental impacts of Option 4 do not differ from these of Option 3, while different economic and social impacts exist.

a) Die Casting with SO₂

Environmental impacts

The conversion to SO₂ of 13 medium-sized and large foundries eliminates projected SF₆ emissions of 143.8 kt CO₂ eq. in 2020. SF₆ Emissions of 8.2 kt CO₂ will still be released by six small foundries.

After the conversion, 25.2 t/y of SO₂ will emit to the atmosphere and contribute to the acidification of ecosystems. Foundry operators must respect certain emission limits if the SO₂ mass flow in the waste gas exceeds a minimum threshold. None of the 13 medium-sized and large foundries would reach this threshold.

Direct economic and social impacts on the foundries

The net costs, which have to be paid by the 13 die casting foundries, do no longer include the costs for the conversion but the annual costs for the cover gas only. The

price of SO₂ quantity ranges at only 50% of the price of SF₆. All of the 13 foundries will achieve savings of €52,480 per year compared to the use of SF₆. The foundries are hence not facing financial burdens, and places of employment are not at risk.

Due to the toxicity of SO₂, certain risks to occupational health do exist, both in case of accidents and on a regular basis. During the cleaning process, the concentration of SO₂ exceeds the exposure limit at the cleaner's workplace temporarily. As a safety measure, it is recommended that the cleaning workers wear protective masks.

Indirect economic and social impacts

Positive and negative indirect impacts are expected for project developers, manufacturers of equipment, and gas distributors.

The project developers pay the full costs of the conversion. These amount to about €222,000, and include the annualised investment costs for the conversion of 13 foundries (€72,005), and the project costs (ca. €150,000 per year).

The project developers can improve their return from the conversion if they manage to sell the ERUs issued and transferred by the host country. If the price of sale would be €10/t CO₂ eq. and the conversion reduces emissions of 127.6²⁶ kt CO₂ eq., revenues of €1.276, 000 per year might be possible. The profit would range around €1 million. It remains unknown if the project developers will subsequently create jobs. This decision certainly depends on their field of business. A project developer might come from a totally different sector.

Compared to the potential profit of the project developers, the revenues of the equipment manufacturers are quite modest. From the installation of the new SO₂ gas delivery systems, they earn ca. annualized €72,005. This amount is not sufficient for the creation of a new place of employment as the necessary difference in turnover is assumed to range around €200,000/year. Furthermore, is it unlikely that only one company on the market will profit from the conversion of all foundries.

The gas distributors will face a net decrease in sales of ca. €52,480 as the revenues from SO₂ amount to about half of the revenues from SF₆. Jobs are not at risk as several gas distributors in each Member State will be confronted with minor decline.

²⁶ We do not refer to the emissions of 143.8 kt CO₂ eq. projected in 2020 but assume that conversion is completed by then. The number of ERUs issued is not based on projected emissions but on verified and quantified emission reductions.

b) Die casting with HFC-134a

Environmental impacts

The conversion to HFC-134a reduces the cover gas emissions of the 13 medium-sized and large foundries from 143.8 kt CO₂ eq. to 9 kt CO₂ eq. in 2020. Emissions are not reduced completely as emissions of HFC-134a occur in return. The six small foundries release HFC-134a emissions of 8.2 kt CO₂ eq.

During application, HFC-134a decomposes into highly acidic HF and other substances. About 2,100 kg of HF are generated in this way. The foundry operators must respect strict emission limits if the HF mass flow in the waste gas exceeds a minimum value. None of the 13 medium-sized and large foundries will reach this threshold.

Direct economic and social impacts on the foundries

As the project developers bear the investment cost for the conversion to HFC-134a, the net costs, which have to be paid by the 13 die casting foundries, are limited to the cover gas only (costs for gas and license fee).

The price of HFC-134a ranges at only 50% of the price of SF₆. Consequently, all of the 13 foundries will achieve savings of €52,480 per year compared to the use of SF₆. The expenses for the license amount to €95,000 per year. Therefore, the annualised net costs amount to €42,520, compared to €97,818 in option 3. Accordingly, the financial burden for the 13 foundries is lower than in option 3. Jobs are not at risk.

The new cover gas is not toxic itself. During the daily cleaning process, however, the concentration of the by-product HF temporarily exceeds the exposure limit at the cleaner's workplace. As a safety measure, it is recommended that the cleaning workers wear protective masks.

Indirect economic and social impacts

Positive and negative indirect impacts are expected for project developers, equipment manufacturers, gas distributors and license holder.

The project developers pay the full costs of the conversion. These amount to about €205,000, and include the annualised investment costs for the conversion of 13 foundries (€55,208), and the project costs (ca. €150,000 per year).

The project developers can improve their return from the conversion if they manage to sell the ERUs issued and transferred by the host country. If the price of sale would be

€10/t CO₂ eq. and the conversion reduces emissions of 119.6²⁷ kt CO₂, revenues of €1.196, 000 per year might be possible. The profit would range around almost €1 million, just slightly less than in the case of conversion to SO₂. It remains unknown if the project developers will subsequently create jobs. This decision certainly depends on their field of business. A project developer might come from a totally different sector.

From the installation of the new gas delivery systems, equipment manufacturers earn ca. annualized €55,298. This amount is not sufficient for the creation of a new place of employment as the necessary difference in turnover is assumed to range around €200,000/year. Furthermore, is it unlikely that only one company on the market will profit from the conversion of all foundries.

The gas distributors will face the same net decrease in sales of ca. €52,480 as for conversion to SO₂ since the revenues from the new gas amount to about half of the revenues from SF₆. Jobs are not at risk as several gas distributors in each Member State will be confronted with some decline.

The company which provides the license for the use of HFC-134a (AM-cover®) receives a fee of €95,000 per year. A company representative outlined out that the revenues from the license fee are not sufficient to create a full place of employment.

²⁷ We do not refer to the emissions of 134.8 kt CO₂ eq. projected in 2020 but assume that conversion is completed by then. The number of ERUs issued is not based on projected emissions but on verified and quantified emission reductions.

Option 5: Prohibition of SF₆ use in recycling of die casting alloys

In recycling of die casting alloys, only conversion to SO₂ is considered. .

Recycling with SO₂

Environmental impacts

The introduction of SO₂ to the last EU recycling plant for die casting alloys using SF₆ instantly cuts all global warming emissions from the cover gas used in this facility. It completely eliminates SF₆ emissions of 77 kt CO₂ eq. projected for 2020.

Instead of SF₆ emissions of 3.4 t about 13.5 t emissions of SO₂ will occur in 2020 and contribute to the acidification of ecosystems. The Member State where the plant is located controls the mass concentration of SO₂ in the waste gas from industrial facilities by emission limits. The calculated SO₂ mass flow from the recycling plant amounts to 2.6 kg/h, which is well below the threshold for minor mass flow.

Direct economic and social impacts on the recycling plant

The operator of the recycling plant is facing investment costs of €12,950 (annualised), however, the lower price of the new cover gas leads to net savings of about €17,000 per year. Furthermore, after the year of the investment to be made, no additional charge arises. However, the savings are not sufficient to create a new place of employment.

The toxicity of SO₂ adds risks to occupational health in case of accidents (e.g. sudden leakage of the gas piping systems) and on a regular basis during the daily cleaning process when the concentration of SO₂ exceeds temporarily the exposure limit at the workplace. As a safety measure, it is recommended that the workers wear protective masks.

Indirect economic and social impacts

Positive and negative impacts are expected for the indirectly affected manufacturer of equipment and gas distributor.

The equipment manufacturer of the gas delivery system benefits from conversion to SO₂ and gains annual revenues of about €12,950. Yet, this amount is not sufficient for the creation of a new place of employment as the necessary difference in turnover is assumed to range around €200,000/year.

The gas distributor, whom we estimate to be the same one who delivered SF₆ previously, is facing a significant net decline in sales of ca. €30,000 as the revenues from SO₂ are just about half as much as from SF₆. Relative to the high turnover per jobholder in trading companies, this decline in sales does not necessarily increase the job-risk.

Option 6: Voluntary agreement in recycling of die casting alloys

In recycling of die casting alloys, only conversion to SO₂ is considered. In the following, we analyse the impacts of the conversion to SO₂ as the consequence of a successful implementation of a voluntary agreement to replace SF₆.

Recycling with SO₂

Environmental impacts

The application of SO₂ to the last EU recycling plant for die casting alloys using SF₆ cuts all global warming emissions from the cover gas used in this facility. It completely eliminates SF₆ emissions of 77 kt CO₂ eq. projected for 2020.

Instead of SF₆ emissions of 3.4 t about 13.5 t emissions of SO₂ will occur in 2020 and contribute to the acidification of ecosystems. The Member State where the plant is located controls the mass concentration of SO₂ in the waste gas from industrial facilities by emission limits. The calculated SO₂ mass flow from the recycling plant amounts to 2.6 kg/h, which is well below the threshold for minor mass flow.

Direct economic and social impacts on the recycling plant

The operator of the recycling plant is facing investment costs of €12,950 (annualised), however, the lower price of the new cover gas leads to net savings of about €17,000 per year. After the year of the investment to be made, no additional charge arises. The savings are not sufficient to create a new place of employment.

The toxicity of SO₂ adds risks to occupational health in case of accidents (e.g. sudden leakage of the gas piping systems) and on a regular basis during the daily cleaning process when the concentration of SO₂ exceeds temporarily the exposure limit at the workplace. As a safety measure, it is recommended that the workers wear protective clothing.

Indirect economic and social impacts

Positive and negative impacts are expected for the indirectly affected manufacturer of equipment and gas distributor.

The equipment manufacturer of the gas delivery system benefits from conversion to SO₂ and gains annual revenues of about €12,950. Yet, this amount is not sufficient for the creation of a new place of employment as the necessary difference in turnover is assumed to range around €200,000/year.

The gas distributor, whom we estimate to be the same one who delivered SF₆ previously, is facing a significant net decline in sales of ca. €30,000 as the revenues from SO₂ are just about half as much as from SF₆. Relative to the high turnover per jobholder in trading companies, this decline in sales does not necessarily increase the job-risk.

Option 7: Joint Implementation in recycling of die casting alloys

In recycling of die casting alloys, only conversion to SO₂ is considered. In the following, we analyse the impacts of the conversion to SO₂ as the consequence of a successful joint implementation project to replace SF₆.

Recycling with SO₂

Environmental impacts

The only EU recycling plant for die casting alloys which presently uses SF₆ could cut their global warming emissions resulting from the use of SF₆ as cover gas through conversion to SO₂. These emissions are projected to amount to 77 kt CO₂ eq. in 2020.

Instead of SF₆ emissions of 3.4 t, about 13.5 t of SO₂ emissions are projected to occur in 2020 and will contribute to acidification of ecosystems. The Member State, where the plant is located, controls the mass concentration of SO₂ in the waste gas from industrial facilities through emission limits. The calculated SO₂ mass flow from the recycling plant amounts to 2.6 kg/h, which is well below the threshold for minor mass flow.

Direct economic and social impacts on the plant

The project developer would pay the full costs of the conversion which amount to about €12,950 (annualised). Consequently, the plant operator's savings resulting from the relatively low price of SO₂ increase from €17,000 per year (option 5) to €30,000. This amount is not sufficient for the creation of a new place of employment as the amount required is assumed to range around €80,000/year. Yet, the savings from deliberate use of SO₂ are significant.

Due to the toxicity of SO₂, certain risks to occupational health do exist, both in case of accidents (e.g. leakage of the gas piping) and on a regular basis. During the daily cleaning process, the concentration of SO₂ exceeds the exposure limit at the cleaner's workplace temporarily. As a safety measure, it is recommended that the cleaning workers wear protective masks.

Indirect economic and social impacts

Positive and negative indirect impacts are expected for project developer, manufacturer of equipment, and gas distributor.

The project developer pays the full costs of the conversion. These amount to about €28,000, and include the annualised investment costs for the conversion of the recycling plant (€12,950), and the project costs (ca. €15,000 per year).

The project developer can improve his return from the conversion if he manages to sell the ERUs issued and transferred by the host country. If the price of sale would be €10/t CO₂ eq. and the conversion reduces emissions of 68.4²⁸ kt CO₂ eq., revenues of €684,000 per year might be possible. The profit would range around €650,000. It remains unknown if the project developer will subsequently create jobs. This decision certainly depends on his field of business. A project developer might come from a totally different sector.

From the installation of the new gas delivery system, the equipment manufacturer earns ca. annualized €12,950. This amount is not sufficient for the creation of a new place of employment as the necessary difference in turnover is assumed to range around €200,000/year.

We estimate the gas distributor to be the same company who delivered SF₆ previously. This company will face a net decrease in sales of ca. €30,000 as the revenues from SO₂ are just about half as much as from SF₆. Relative to the high turnover per jobholder in trading companies, this decline in sales does not necessarily increase the job-risk.

²⁸ We do not refer to the emissions of 77 kt CO₂ eq. projected in 2020 but assume that conversion is completed by then. The number of ERUs issued is not based on projected emissions but on verified and quantified emission reductions.

Summary of Impact Assessment

The analysis of the impacts of six policy options according to several criteria (multi-criteria analysis) conducted in previous parts of this chapter is summarized as follows.

Table 18: Comparison of policy options for die casting and recycling of magnesium All indications are given per year											
Applications		All	Die Casting SF ₆ < 850 kg/a						Recycling		
		Opt 1	Opt 2		Opt 3		Opt 4		Opt 5	Opt 6	Opt 7
Option		No Action	Full SF ₆ Prohibition		Revision to 100 kg		Joint Implementation		Full Ban	VA	Joint Impl.
Technical solution			SO ₂	134a	SO ₂	134a	SO ₂	134a	SO ₂	SO ₂	SO ₂
1. SF ₆ emission reduction	kt CO ₂	-	152	143	144	135	144	135	77	77	77
2. SO ₂ emiss	tons	-	26	-	25	-	25	-	13	13	13
3. HF emiss	tons	-	-	2.2	-	2.1	-	2.1	-	-	-
4. Occ. health risk		-	••	•	••	•	••	•	••	••	••
5. Equipment cost	k€	-	99.6	60.9	72.0	55.3	[72.0]*	[55.3]*	13	13	[13]*
6. Saved gas cost	k€	-	-55.7	-55.7	-52.5	-52.5	-52.5	-52.5	-30	-30	-30
7. License fee	k€	-	-	125.0		95.0		95.0	-	-	-
8. Net cost/saving	k€	-	43.9	130.2	19.5	97.8	- 52.5	42.5	- 17	- 17	- 30

[]* paid by project developer •• risks exists • risks are lower than with SO₂

Table 18 summarizes policy options for the die casting sector (options 2, 3 and 4) and the recycling sector (options 5, 6 and 7) and indicates the main impacts expected.

1. Emission reduction potential

Apart from “no action” (option 1), all options (option 2 – 7) have the potential to reduce SF₆ emissions if implemented successfully. The reduction potential ranges from 135 to 152 kt CO₂ eq. per year in die casting, and estimated at 77 kt CO₂ eq. per year in recycling of die casting alloys. The emission reduction potential is generally higher in conversions from SF₆ to SO₂ compared to HFC-134a. This relates to the fact that SO₂ does not have a global warming potential.

Option 2 “full prohibition” shows a higher potential for emission reductions in the die casting sector (143-152 kt CO₂ eq) than the other options which only cut emissions of some foundries. In case of the three options related to the recycling sector (options 5-7),

the potential extent of emission reductions is equal since there is only one plant affected, which has excluded the introduction of HFC-134a.

2./3. SO₂ emissions and HF emissions

In all technical choices “SO₂“, we assume that all cover gas is emitted to the atmosphere in the stream of waste gas. As SO₂ contributes to the acidification of ecosystems, emissions are controlled strictly by national law. During the application of HFC-134a, the acidic gas HF is generated. Emissions of this gas are controlled strictly, too.

Although the quantity of HF emissions is relatively low, their environmental impact is severe. The limits for the concentration of HF in waste gas are usually 50 times lower than for SO₂. Hence the acidification effect from the use of HFC-134a should not be considered less severe than that from the use of SO₂.

4. Risk to occupational health

The toxicity of both SO₂ and HF increase the risk for occupational health at the workplace. In particular during the cleaning of the melt, the concentration limits of these gases are exceeded for a short time.

In the case of conversion to SO₂, it has to be noted that an additional risk occurs. Accidental leakage of the delivery system can lead to high concentrations of SO₂ in the workplace. In case of HFC-134a, leakage would not cause major risks to occupational health because the formation of HF has not taken place in the piping system yet.

5./6./7. Equipment, gas, and license fee

The expenses for equipment (and hence the revenues of the equipment manufacturers) are generally higher for conversion to SO₂ than for conversion to HFC-134a. In contrast, the costs for the cover gas (and hence the revenues of the gas distributors) are about the same in case of conversion to SO₂ and conversion to HFC-134a and range around 50% of the costs for SF₆. The most important cost factor, however, is the license fee which has to be paid in case of conversion to HFC-134a. Therefore, additional annual net costs are higher in case of conversion to HFC-134a than for conversion to SO₂.

8. Net costs and net savings

In general, the cost burden resulting from conversion of the cover gas is relatively low, and in some options the conversion even causes net savings (options 5 -7, as well as option 4 “SO₂”). In none of the cases, net costs or net savings will threaten existing places of employment but neither will create new jobs. Hence the conversion can be considered economically neutral in all options.

Chapter Nine

Ranking and recommendation of policy options

In this final section, we rank the available seven policy options including their technical solutions and give recommendations. The ranking is based on the evaluation criteria: coherence, efficiency and effectiveness.

1. Coherence

None of the seven policy options conflicts with the general objective of the EU policy on fluorinated greenhouse gases, or implies notable economic and social trade-offs. Therefore, they meet the evaluation criterion coherence.

One could argue that the potential replacement of SF₆ with HFC-134a would lead to a growth in the use of high GWP HFCs which conflicts with the overall proposal of the EU in the international climate negotiations for controlling and gradually reducing production and consumption of HFCs. In the authors' view, the high climate benefit resulting from replacing SF₆ justifies some conversion to HFCs which in some cases is considered the only feasible replacement solution. In this regard, it should be highlighted that these applications do not result to total emissions due to the partial decomposition of HFC-134a over the hot metal melt.

However, it must be noted that all options for SF₆ replacement, excluding the no-action option, cause emissions of acidic waste gas (SO₂, HF) through the use of alternative cover gases. As these emissions range below the threshold for legal waste gas concentration limits, they are considered acceptable considering the high environmental benefit of the replacement SF₆ for climate protection.

2. Efficiency (cost effectiveness).

Table 19 gives an overview of the seven options including their technical solutions, and the abatement costs per t CO₂ eq. (€/t CO₂ eq.). Abatement costs express the ratio of the net costs (net savings) in thousand € (k€) to be paid by the foundry operators concerned, and the respective potential for emission reductions (kt CO₂ eq.).

In general, conversion to SO₂ causes significantly lower costs than conversion to HFC-134a. In all options for the die casting sector, conversion to SO₂ is hence more cost effective than conversion to HFC-134a.

Table 19: Abatement costs of options for SF₆ emission reduction in magnesium industry (die casting and recycling of die casting alloys)											
		Opt 1	Opt 2		Opt 3		Opt 4		Opt 5	Opt 6	Opt 7
Option		No Action	Full SF ₆ Prohibition		Revision to 100 kg		Joint Implementation		Full Ban	VA	Joint Impl.
Technical solution			SO₂	134a	SO₂	134a	SO₂	134a	SO₂	SO₂	SO₂
SF₆ emission reduction	kt CO ₂	0	152	143	144	135	144	135	77	77	77
Net cost/saving	k€	0	43.9	130.2	19.5	97.8	- 52.5	42.5	- 17	- 17	- 30
Abatement cost	€/tCO ₂	0	0.29	0.91	0.14	0.72	- 0.36	0.31	- 0.22	- 0.22	- 0.39

In die casting, option 4 (joint implementation) shows the best cost performance. This is due to the principle of the JI mechanism saying that the project developer pays the investment costs. Therefore, the direct costs for the foundries affected are relatively low.

The principle is also applied in the recycling sector. Option 7 (joint implementation) causes abatement costs that are a bit lower than the abatement costs resulting from the regulatory approach of option 5 and the non-regulatory option "voluntary agreement".

Concerning options 2 and 3, which are both based on a regulatory approach, it has to be noted that the abatement costs in option 2 (full ban) are somewhat higher than in option 3 (revision of the threshold to 100 kg/a). Option 2 includes also the small foundries which cause minor amounts of emission only, but the costs for their conversion are almost as high as for medium-sized and large foundries.

Although the abatement costs for the seven options are relatively different, it must be pointed out that the absolute abatement costs are very low in each case. They vary between a minimum of -0.39 €/t CO₂ eq. and a maximum of only 0.91 €/t CO₂ eq.

Compared to significantly higher costs for feasible measures in other sectors, these amounts have to be considered as extraordinary low costs. Therefore, all options are found to be efficient.

3. Effectiveness

Effectiveness becomes the key criterion for ranking of options and their technical solutions because efficiency does not vary significantly due to the low absolute level of the abatement costs for these cases.

Here, "effectiveness" refers to the reliability of one particular option to reduce emissions.

Under this criterion, the options relying on the joint implementation mechanism (options 4 and 7) and on voluntary agreement (option 6) score low. JI projects are implemented on voluntary basis and depend on cost effectiveness. Therefore, it remains uncertain whether JI projects to replace SF₆ will be implemented in most or all foundries. The success of a voluntary agreement for recycling is likewise uncertain. It depends on the willingness and the decision of the plant operator. .

In comparison to these options, the regulatory approach of option 2 and option 3 (die casting) and option 5 (recycling) are more effective to completely or mostly reduce SF₆ emission.

In option 3 for the die casting sector, the quantities of SF₆ emissions reduced are smaller than in option 2.

Hence option 2 is the most effective option for the die casting sector while option 5 is most effective for the recycling sector.

Conclusion and recommendation

In total, option 2 is considered the most favorable option for the die casting sector as it is highly effective in reducing SF₆ emissions. For the recycling sector, option 5 is considered to be the option of choice.

Table 20: Evaluation and recommendation of the policy options to reduce SF₆ emissions from the NF metal industry in the EU-27				
	Coherence	Cost effectiveness	Effectiveness	Recommendation
Option 1 No action	Yes	Yes	No	Yes - in sand casting, recycling of special alloys, and in Al sector
Option 2 Full use prohibition in Mg die casting	Yes	Yes	Yes	Yes
Option 3 Revision of threshold for ban in die casting	Yes	Yes	Yes (< option 2)	No
Option 4 Joint implementation for die casting	Yes	Yes	No	No
Option 5 Full use prohibition in recycling of common alloys	Yes	Yes	Yes	Yes
Option 6 Voluntary agreement in recycling	Yes	Yes	No	No
Option 7 Joint implementation for recycling of common alloys	Yes	Yes	No	No

Option 1 (no-action) should be restricted to sectors in which alternatives to the use of SF₆ are not available yet. These sectors include magnesium sand casting, recycling of special magnesium alloys, and the production of one particular aluminium alloy.

The concluding table 21 summarizes the environmental, social and economical impacts of the recommended policy options 2 and 5.

Table 21: Recommendation of the policy options to reduce SF₆ emissions from the NF metal industry in the EU-27				
Application	Magnesium die casting		Recycling of common alloys	Sand casting, recycling of special alloys, and in aluminium sector
Recommended option	Option 2- Full use prohibition		Option 5 – Full use prohibition	Option 1 - no further action
Technical choice	SO₂	134a	SO₂	
SF ₆ emission reduction (kt CO ₂)	152	143	77	
SO ₂ emiss (tons)	26	-	13	
HF emiss (tons)	-	2.2	-	
Occ. health risk	low	very low	low	
Net cost/saving (k€)	43.9	130.2	- 17.0	
Abatement cost (€/tCO ₂)	0.29	0.91	- 0.22	

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Annex I Sensitivity analysis

1. Reduced GWP through conversion to HFC-134a

Unlike SO₂, HFC-134a is a fluorinated greenhouse gas and is characterized by a global warming potential of 1,430 (GWP 1,430). Due to this potential, the conversion from SF₆ to HFC-134a does not result in 100% emission reduction but is limited to approx. 94%.

During the melting process in the foundry, HFC-134a is used to protect the melt from oxidation through the formation of a protective MgF₂ film. Over the hot magnesium melt, HFC-134a is largely decomposed, and HF is created as a by product.

The 2006 IPCC-Guidelines do not present GWP default values for HFC-134a after use. This is due to the fact that the conditions of application of HFC-134a differ widely by temperature, concentration, carrier gas mixture, etc.

As mentioned in chapter 1, Bartos [2007] observed destruction rates of HFC-134a over the melt. Under the specific conditions of a US die casting foundry, he found a decomposition rate of 71%-77% which translates into an effective global warming potential of ~ 400 for HFC-134a after use. We decided to use this value to estimate the effect of the use of HFC-134a on emission reductions with a more realistic GWP than 1,430 (GWP of HFC-134a before use).

Table 22: Emission reduction effect of HFC-134a with GWP 1,430 and GWP 400					
HFC-134a		GWP 1,430		GWP 400	
	SF ₆ emissions kt CO ₂ eq.	Reduction kt CO ₂ eq.	Reduction rate (%)	Reduction kt CO ₂ eq.	Reduction rate (%)
Option 2	152.1	142.5	93.7	149.4	98.2
Option 3/4	143.8	134.8		141.4	

Taking into account the reduced GWP of HFC-134a after use, the effect on emission reductions rises from 93.7 to 98.2%, both in option 2 (from 142.5 to 149.4 kt CO₂ eq.) and in options 3 and 4 (134.8 to 141.4 kt CO₂ eq.). Under these conditions, the conversion to HFC-134a has almost the same effect on emission reductions as SO₂ although they are never equally effective.

If calculations are based on the reduced GWP of HFC-134a after use (GWP 400), the abatement costs for the sub-option HFC-134a decrease slightly from €0.91 to €0.87 (option 2), and from €0.73 to €0.69 (option 3 and 4). However, the abatement costs do not differ widely.

2. Reduction of the license fee for HFC-134a

Another disadvantage of conversion to HFC-134a is the relatively high annual expenses for this cover gas compared to SO₂. While the costs for the gas itself are about the same, the license fee for the use of HFC-134a is added. This fee increases the annual gas costs by €125,000 (option 2) or €95,000 (option 3 and 4). As a consequence, the annualised total costs and the specific abatement costs (€/t CO₂ eq.) are considerably higher for conversion to HFC-134a than for conversion to SO₂.

As known in the magnesium industry, the license holder has granted significant discounts of the license fee to magnesium die casting foundries which converted from SF₆ to HFC-134a in recent years under the 2006 F-Gas Regulation.

We hence assume discounts of the annual license fee to be granted to the small foundries (annual SF₆ consumption < 850 kg) as well in order to examine the influence of such discounts on cost-effectiveness in case of full conversion to HFC-134a. The threshold below which conversion to HFC-134a becomes more cost-effective than conversion to SO₂ is of particular interest.

Several scenarios on fees related to conversion to HFC-134a are described in the following.

"Basic fee" means the fixed minimum sum of €5,000 which has to be paid by the foundry if the annual metal output is below 500 t.

"Output fee" refers to the amount of €10/a per tonne metal production which has to be paid by the foundry if the annual metal output exceeds 500 t.

1. Basic fee of €5,000 and output fee of €10/t Mg

Currently, the license fee amounts to €5,000 per year and the output fee is €10/t Mg. Under these conditions, the annualized total costs for conversion to HFC-134a are considerably higher than for conversion to SO₂. The difference in annualized total costs ranges between €86,278 (option 2) and €78,294 (options 3 and 4).

2. No basic fee, output fee of €10/t Mg

It is assumed that the basic annual fee of €5,000 is skipped, but the output fee remains at €10/t Mg (for all foundries including those who produce less than 500 t/a). Without the basic annual fee to be paid by each foundry, the costs for the license would decrease by €51,300 (€23.950). The annualized total costs for conversion to HFC-134a decrease by the same amount, but are still considerably higher than for conversion to SO₂, by €51,525 (option 1) or €29,736 (option 3 and 4).

3. No basic fee, output-fee of €6.45/t Mg

It is assumed that the basic annual fee of €5,000 is skipped, and the output fee is reduced to €6.45/t Mg.

In option 2, the annualized total costs for conversion to HFC-134a of all 19 foundries would be at the same level as for conversion to SO₂ in that case, and would amount to €43,964. The amount of €6.45/t Mg has been identified as the threshold below which conversion to HFC-134a becomes more cost-effective than conversion to SO₂.

4. No basic fee, output-fee of €2.80/t Mg

It is assumed that the basic annual fee of €5,000 is skipped, and the output fee is reduced to €2.80/t Mg.

In options 3 and 4, the annualized total costs for conversion to HFC-134a of the 13 foundries (instead of 19 in options 3 and 4) would be at the same level as for conversion to SO₂ under these conditions, and would amount to €19.525.

5. No fees

It is assumed that the license holder abandons his right to charge fees.

Under these conditions, the annualized total costs for conversion to HFC-134a would be no higher than €5,242 in option 2, and €2,818 in options 3 and 4. In that case, conversion to HFC-134a would be significantly more cost-effective than conversion to SO₂.

**Table 23: Influence of the license fee for HFC-134a on total annualized costs of SF₆ replacement by HFC-134a compared to replacement by SO₂
Specific abatement costs for conversion to HFC-134a in options 2, 3 and 4**

	Annual. conversion costs in € HFC-134a difference to SO ₂		Abatement costs HFC- 134a €/t CO ₂ eq.	
	Option 2	Options 3+4	Option 2	Option 3+4
1. Basic fee €5,000, output fee €10	+ 86,278	+ 78,294	0.87	0.69
2. No basic fee, output-fee €10	+ 21,278	+ 43,294	0.44	0.44
3. No basic fee, output-fee €6.45	0.00	+ 21,994	0.29	0.29
4. No basic fee, output-fee €2.80	- 21,922	0.00	0.15	0.14
5. No fee	- 38,702-	- 16,706	0.04	0.02

The outlined scenarios on fees related to the conversion to HFC-134a also influence the level of abatement costs and, hence, improve the cost-effectiveness of conversion to HFC-134a.

Assuming that the HFC-134a after use features an effective GWP of 400 and that fees for the use of HFC-134a are skipped, the abatement costs would decrease from 0.87 €/t CO₂ eq. to 0.04 €/t CO₂ eq. in option 2. In options 3 and 4, the abatement costs would decrease from 0.69 €/t CO₂ eq. to 0.02 €/t CO₂ eq.

If this calculation would be based on the input global warming potential of HFC-134a of 1,430, the abatement costs would range at almost the same level.

The conversion to HFC-134a would be more cost effective for all 19 foundries (option 2) than conversion to SO₂ if the license fee charged was less than €6.45 per t magnesium production.

In options 3 and 4 (revision of SF₆ threshold to 100kg/a), conversion to HFC-134a would be more cost effective than conversion to SO₂ if the license fee was below €2.80 per t magnesium production.

3. Increase in the price of HFC-134a

If the production and consumption of HFCs were controlled in the near future, an increase in the price of HFC-134a could be the consequence. There are some more regulatory instruments that might be discussed such as taxes on HFCs, etc. possibly resulting in higher expenses of foundry operators for the HFC gas, disregarding the license fee. We try to answer two questions:

Firstly, how higher gas costs would affect the cost effectiveness of SF₆ substitution in terms of abatement costs vs. SF₆.

Secondly, could higher prices for HFC-134a reduce the propensity of foundry operators to convert from SF₆ to HFC-134a, and instead increase the propensity to the SO₂ solution?

We analyse the impacts of three price steps: 1. current level (€10/kg), 2. doubling (€20/kg), and 3. triplication (€30/kg).

In the two central columns, table 24 shows for the total annualised costs of SF₆ replacement the difference between HFC-134a and SO₂ solution in option 2 (all foundries) and in options 3+4 (13 major foundries). If the HFC price per kg increases from €10 to €30, the difference in total annual conversion costs rises from €86,278 to €197,658 (all foundries) and from €78,294 to €187,254 (13 foundries), or by 230%.

In the columns on the right the abatement cost per tonne CO₂ eq. is indicated, rising from €0.87 to €1.62 (all) and from €0.69 to €1.44 (13 foundries).

Table 24: Influence of the increase in the price of HFC-134a on total annualized costs of SF₆ replacement by HFC-134a compared to replacement by SO₂ and on specific abatement costs for conversion to HFC-134a in options 2, 3 and 4				
	Annual. conversion costs in € HFC-134a difference to SO ₂		Abatement costs HFC- 134a/SF ₆ €/t CO ₂ eq.	
	Option 2	Options 3+4	Option 2	Option 3+4
€10 per kilogram	+ 86,278	+ 78,294	0.87	0.69
€20 per kilogram	+ 141,968	+ 133,592	1.24	1.06
€30 per kilogram	197,658	+ 183,254	1.62	1.44

The data on the additional conversion cost resulting from increasing HFC-134a prices are more informative if the total amounts are averaged for individual foundries, and classified by the three foundry types. The additional costs per foundry types are shown in Diagram 7 and table 25.

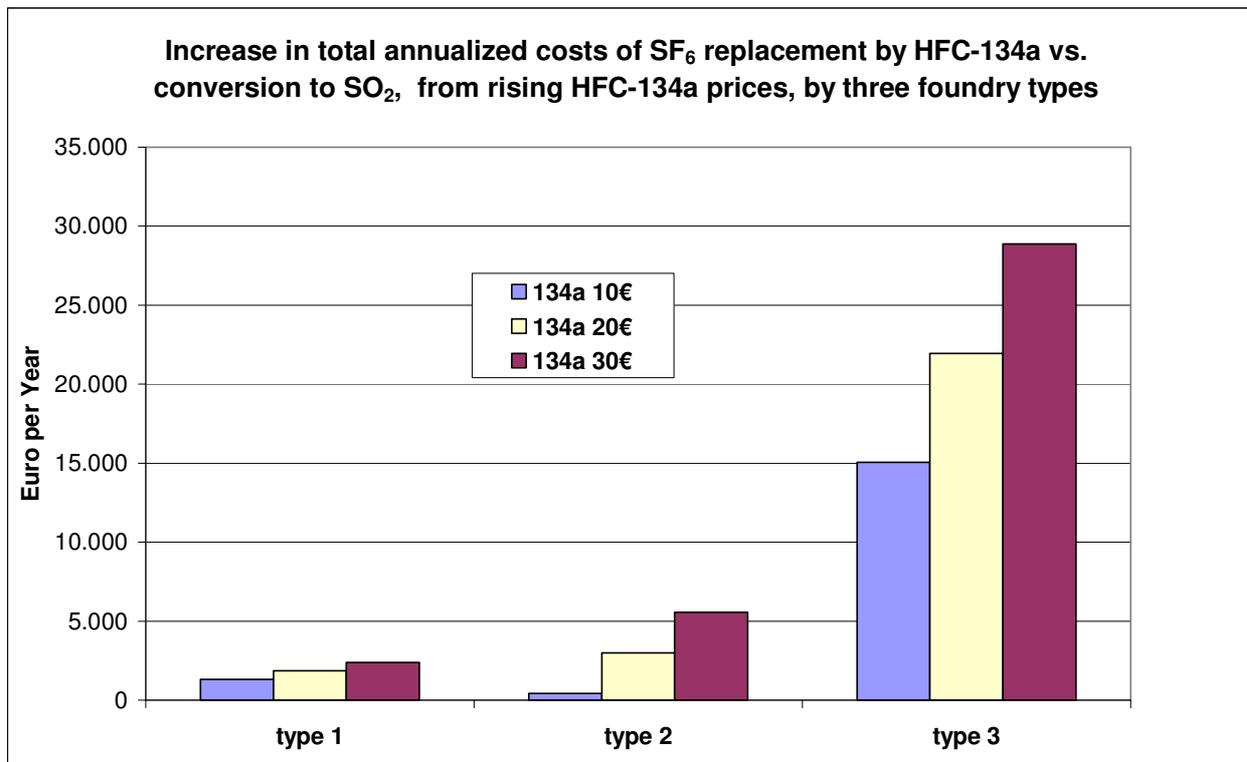


Diagram 7. In absolute amounts, the increase in total annualized costs of SF₆ replacement by HFC-134a compared to conversion to SO₂, in consequence of rising HFC-134a prices, is low for type 1 and type 2 foundries, and very high for the major foundries of type 3.

Table 25: Increase in total annualized costs of SF₆ replacement by HFC-134a compared to replacement by SO₂, resulting from rising HFC-134a prices by individual foundries, differentiated by three foundry types (€ per year)			
	Type 1 (Small)	Type 2 (Medium)	Type 3 (Large)
€10 per kilogram	1,331	430	15,056
€20 per kilogram	1,866	2,999	21,956
€30 per kilogram	2,401	5,567	28,856

Diagram 7 and table 25 and show that rising HFC-134a prices lead to relevant absolute increase in cost difference between the HFC-134a solution and the SO₂ solution in type 3 foundries only. It cannot be excluded that the steep rise by almost €14,000 per year, resulting from triplication of the present price, lowers the propensity of the operators to choose the HFC solution.

Annex II Surveyed Magnesium Casting Companies

Die Casting

Austria	Georg Fischer GmbH & Co KG
Austria	TCG Unitech AG Kirchdorf
France	Autoliv Isodelta
France	Société Aveyronnaise de Metallurgie SAM
Germany	Honsel GmbH & Co. KG
Germany	KS-Pierburg GmbH
Germany	Takata-Petri
Germany	Volkswagen
Germany	Schweizer & Weichand
Germany	Audi AG
Germany	Dietz-Metall GmbH & Co. KG
Germany	Druck- und Spritzgusswerk Hettich
Germany	Druckguss Heidenau GmbH
Germany	Dynacast Deutschland GmbH & Co.KG
Germany	HDO-Druckguss- und Oberflächentechnik GmbH
Germany	Laukötter Dessau GmbH
Germany	TRW Automotive GmbH
Germany	AMZ Weissenseer Präzisionsguss GmbH
Germany	Laukötter Gusstechnik GmbH
Germany	Albert Handtmann GmbH
Germany	Andreas Stihl AG & Co. KG
Germany	Auer Guss GmbH
Germany	BMW
Germany	C&C Bark Metall Druckguss und Formbau GmbH
Germany	Daimler
Germany	KSM Castings
Germany	Magnetech GmbH
Germany	TMG Zitzmann GmbH
Italy	MPI - Meridian Products of Italy Spa
Italy	Walmec S.p.A
Italy	Fima Spa
Italy	Rifimpres SNC
Italy	Alpipress Srl
Italy	Baggioli Pressofusione Europe Srl
Italy	Key Safety Systems, Inc.
Neth.	Brabant Alucast Products
Poland	Euromag
Poland	FAM Technika Odlewnicza Sp z o.o
Poland	Finnveden Metal Structures SP zoo
Poland	Magnesia S.A. (NTP Spolka zoo)
Poland	Polmag Sp.z o.o.
Poland	Alpha
Romania	TRW Automotive Safety Systems SRL
Romania	Takata Petri Romania
Slovenia	TCG Unitech LTH-ol d o o
Spain	Zatorcal SL
Spain	Dalphi Metal Espana SA
Spain	Grupo Antolin Magnesio
Spain	Magnesio y Metal, S.L.
Sweden	Gjuteribolaget SA

Sweden	STG Svensk Tryckgjutning AB
Sweden	Finnveden Mtal Structures
Sweden	Husqvarna AB
Sweden	ADC Gruppen
UK	Meridian Technologies Inc.

Sand Casting

Germany	Metallgießerei Wilhelm Funke GmbH&CoKG
Germany	Eifelwerk H. Stein GmbH & Co. KG
Germany	Metallguss Steinrücken
Germany	Metallgießerei Stauss
Denmark	A/S Temponik
UK	Stone Foundries
UK	UK Racing Castings
UK	Aeromet International PLC
France	Fonderie Messier
Italy	Marvic
Sweden	Näfverqvarns Bruk
	Avio

Recycling

Germany	Magontec
Hungary	Salgo-Metall Kft
Czech Republic	Magnesium Elektron
Austria	Ecka Granules
France	Thermo-Magnesium France
Germany	Aleris Recycling GmbH
UK	Magnesium Elektron

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Dr. Christian Kettler provided important information on HFC-134a (AM-coverTM).

Linda Ederberg was a great help in conducting the survey on the EU magnesium industry.

Annex IV Questionnaire for the Die Caster Survey

Questionnaire* on the feasibility of options to reduce emissions of SF₆ from the EU magnesium industry

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* This questionnaire was developed by Oeko-Recherche GmbH to facilitate collection of up-to-date data in the context of a study for the European Commission to assess the feasibility of options to reduce emissions of SF₆ from the EU non-ferrous metal industry and to analyse their potential impacts (07.0307/2008/511418/SER/C4). It is not an official document from the European Commission.

Introduction

Under the Kyoto Protocol, the European Commission has committed itself to reducing its greenhouse gas emissions by 8% compared to the base year 1990 during the period 2008-2012. In this context the European Community adopted Regulation (EC) 842/2006 on certain fluorinated greenhouse gases (the F-Gas Regulation). This Regulation entered into force on 4th of July 2007 and, inter alia, prohibits the use of SF₆ in magnesium die-casting as of 1 January 2008, except where the quantity involved is below 850kg per year (Art 8(1)).

Art 10(2) of the Regulation requires the European Commission to assess whether the substitution of SF₆ in gravity casting (e.g. sand casting) is technically feasible and cost-effective, and to review the 850kg-threshold exemption in die-casting in the light of available alternatives. In this context the Commission has launched a study to assess options for reducing SF₆ emissions from the non-ferrous metal industry.

This questionnaire aims at collecting up-to-date data on the use of cover gases in all European magnesium casting and recycling plants and on the plant-specific possibilities and lessons-learned to replace SF₆ by alternatives, including the costs of the conversion.

Confidentiality

All data will be treated confidentially and will only be used within the context of the study. No company-specific information shall be disclosed; all company data shall be aggregated into summary reports before being made available to the public.

Company

Name of the company operating the foundry			
Country of the plant			
Contact person			
Telephone			
Fax			
E-mail			
Number of employees of the company that operates the foundry*	< 50	50 – 250	> 250

* Please tick the box in question

A) Basic data on the foundry

1	Number of hot chamber machines in 2009	<input type="text"/>	
2	Number of cold chamber machines in 2009	<input type="text"/>	
3	Maximum melt temperature in the casting furnace	No. of machines	
	< 650 °C		
	650 – 690 °C		
	> 690 °C		
4	Type of cover gas supply		
	Central		
	Single units for each furnace		
5	Cover gas (active component) in use (2008/2009)		
	SF ₆		→ Continue Question 6
	SO ₂		→ Continue Question 12
	R-134a		→ Continue Question 12
	Other*		→ Continue Question 12
	* please specify		

B) Questions to SF₆ users

6	Quantity of SF ₆ consumed in your plant in 2008?	<input type="text"/>	kg
	<i>Only quantity of SF₆ in the mixture (not total weight of gas mixture)</i>		
7	Have you ever estimated the total costs for substitution of SF ₆ ?		
	No		
	Yes		
	Estimated cost for substitution to R-134a		€
	Estimated cost for substitution to SO ₂		€
	Estimated cost for substitution to other gas		€
8	Have you ever technically tested alternative cover gases to SF ₆ in your foundry?		
	No		→ End of interview, please send questionnaire back
	Yes		
	Testing of R-134a		
	Testing of SO ₂		
	Testing of other gas*		
	* please specify		
9	What is the current stage of the tests?		
	Still ongoing		
	Stopped		

10 Why have the tests been stopped?
 Economically no feasible solution
 Technical problems

If possible, please detail lack of economic feasibility or the technical problems in the box below. For instance: corrosion of equipment, ignition of the molten metal, sludge, new gas system too expensive, or suchlike.

11 In case of potential conversion from SF₆, which cover gas would you prefer?
 R-134a
 SO₂
 Other* * please specify

→ End of interview, please send questionnaire back

C) Questions to users of alternative cover gas

12 Have you replaced SF₆ by an alternative cover gas in the past five years?
 No, introduction of SO₂ dates back longer → End of interview, please send questionnaire back
 No, introduction of R-134a dates back longer → End of interview, please send questionnaire back
 Yes, conversion was completed within the past five years Pls enter year of completion

13 How much SF₆ have you substituted? Please enter the quantity of SF₆ in the year before the conversion, in kg

14 Duration of the conversion (number of months)

If possible, please list below important experiences and lessons learned of the conversion to the alternative cover gas. If possible, indicate also invest costs of the conversion, and the operational costs of the new system (percentage compared to operational costs before the conversion).

→ End of interview, please return the questionnaire

In case of any questions please contact

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Please return the questionnaire by 16th February 2009 to

ws@oekorecherche.de

Thank you for your cooperation