Department of Energy & Climate Change

Review of data and methodologies used in the calculation of UK emissions from F-Gases

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Final Report to the Department of Energy and Climate Change

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Executive Summary

The existing UK inventory of fluorinated greenhouse gases (F-gases) includes emission estimates for HFCs, PFCs, and SF_6 from 1990 to 2011 from the refrigeration/air-conditioning (Ref/AC), foam blowing, aerosols, metered dose inhalers (MDI), firefighting, halocarbon production emissions, and magnesium sectors (see Appendix A). While HFC consumption and forecasting updates were made to the inventory in 2010, and further refinements to the Ref/AC sector were made in 2011, additional updates are needed to comply with the 2006 Guidelines released by the IPCC (hereinafter '2006 GLs'), for incorporation into the UK's 2015 submission of the inventory year 2013. This report assesses the existing UK inventory of F-gas emissions and identifies required updates and additions to comply with the 2006 GLs in both new and existing sectors.

Specifically, assessment of which F-gas sectors were in need of updating per the IPCC 2006 GLs was undertaken by Ricardo-AEA in autumn 2012 (with the exception of the Refrigeration/AC sector). Only emissions estimates for those sectors deemed in need of updating were provided to ICF for further assessment and revision. As ICF most recently updated the UK Refrigeration/AC model (in November 2011), ICF was responsible for assessing and ensuring compliance with the 2006 GLs for that sector. The existing inventory sectors flagged for updates, as well as the potential new sectors to add, are summarised in the table below.

Table 1: Required updates to comply with the 2006 IPCC GLs

Sector	Requirements for Compliance
Existing Sectors	
1. 2.F.3: Fire Protection	• Update activity data based on annual sales of F-gas in the fire protection sector • Disaggregate existing bank estimates into new and decommissioned systems • Confirm whether there is/was production of fire extinguishing agents in the UK and estimate any associated emissions if so
2. 2.F.3: Foam Blowing Agents (One Component Foams [OCF])	• Determine if there was HFC-based OCF manufacture in the UK pre-2009 and account for any associated emissions if so
3. 2.F.5: Solvents	• Update activity data based on annual sales of solvents • Update estimation methodology to account for longer time horizon of emission profile as well as destruction.
4. 2.E.1: Semiconductor Manufacture	• Update emission factors (utilisation and by-product) and destruction removal efficiency factors • Estimate disaggregated NF_3 emissions (remote clean and etch) • Include C_2F_6 and C_3F_8 by-product emissions based on 2006 GLs

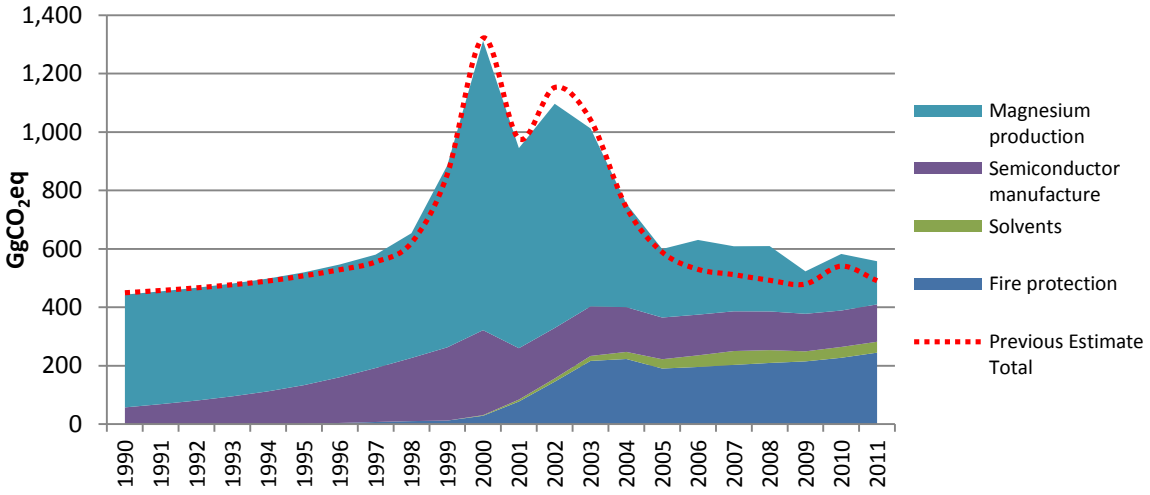
Sector	Requirements for Compliance
5. 2.C.4: Magnesium Production	• Update historical emissions from magnesium casting based on activity data or emission measurement data from operators • Update HFC-134a destruction rate and introduce destruction rate for SF_6
New Sectors	
1. 2.F.1: Refrigeration and Air Conditioning (Refrigerant Containers)	• Add manufacture and disposal emissions from refrigerant containers
2. 2.G.2.a: Military Applications	• Add emission estimates from Airborne Warning and Control System (AWACS) and other military applications, if information is available
3. 2.G.2.b: Accelerators	• Determine if emissions from particle accelerators are significant in the UK and estimate any associated emissions if so
4. 2.E.4: Heat Transfer Fluid (HTF)	• Identify any significant applications of PFCs and other F-gases used as HTFs in the UK and estimate any associated emissions if so
5. 2.E.2 TFT Flat Panel Display (FPD) & 2.E.3 Photovoltaics (PV)	• Determine if emissions from FPDs and PV manufacture is significant in the UK and estimate any associated emissions if so
6. 2.B.9.a: By-Product Emissions (Production of Other Fluorinated Chemicals)	• Identify if other significant by-product emissions occur in the UK and estimate any associated emissions if so
7. 2.G.2.c: Other (Sound-proof Windows**)**	• Determine if SF_6-containing windows were manufactured in the UK and estimate any associated emissions if so
8. 2.G.2.c Other (Cosmetic & Medical Applications)	• Determine if emissions of PFCs from cosmetic and medical applications are significant in the UK and estimate any associated emissions if so
9. 2.G.2.c: Other (Tracer Testing)	• Identify if other significant emissions occur from air tracers and leak detectors in the UK and estimate any associated emissions if so

As described in the table above, this study explores updates to five existing sectors—fire protection, one component foams, solvents, semiconductor manufacture, and magnesium production—as well as nine new sources—refrigerant containers, military applications (e.g., Airborne Warning and Control System [AWACS]), particle accelerators, sound-proof windows, heat transfer fluids, flat panel display & PV cell manufacture, cosmetic and medical applications, production of other fluorinated chemicals, and tracer testing. Of the existing sources reviewed, updates were made to all sectors except for the one component foams sector (as no updates were deemed necessary). Of the new sources reviewed, emissions estimates were added to the inventory for four sectors—refrigerant cylinders, AWACs, particle accelerators, and tracer testing. For all other new source sectors, emissions were not added to the inventory because they were either deemed to be

an insignificant source or because activity data were not sufficient to reasonably quantify emissions. Emissions were calculated for all actionable sectors based on GWPs from the IPCC Fourth Assessment Report (AR4).

The resulting emissions across these updated and new F-gas sectors are summarized in the figures below. The updated emissions for existing source sectors in 2011[1] collectively account for a 13% increase over the previous version of the inventory—or about 4% of total UK F-gas emissions, which themselves account for an estimated 3% of national GHG emissions. Figure 2 presents the annual percent difference between the old and updated emission estimates (for "existing" sources), showing an increase of over 10% almost every year after 2006. This large increase is mainly attributed to the higher calculated emissions in the fire protection, semiconductor manufacture, and magnesium production sectors. Specifically, the increase from the fire protection sector is because the estimates for years 2005 and beyond were based on actual data of F-gas placed on the market as opposed to using a project annual growth rate of 1% beyond 2005. The increase from the semiconductor manufacture is primarily due to the inclusion of by-products for C_2F_6 and CF_4, as well as inclusion of CF_4 by-products from more than one type of process gas compared to the previous methodology. The increase from the magnesium production sector is due to the reduction in the destruction efficiency of HFC-134a, assumed to be 80% in lieu of 90%.

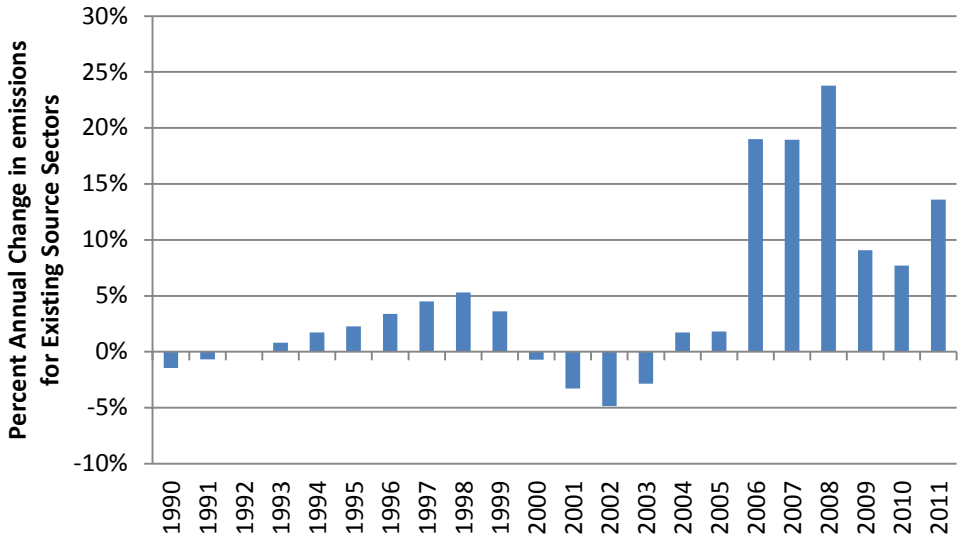
Figure 1: Updated Emissions from Existing Source Sectors*



*Emissions from the one component foams sector were also reviewed in this analysis, but no updates were deemed necessary.

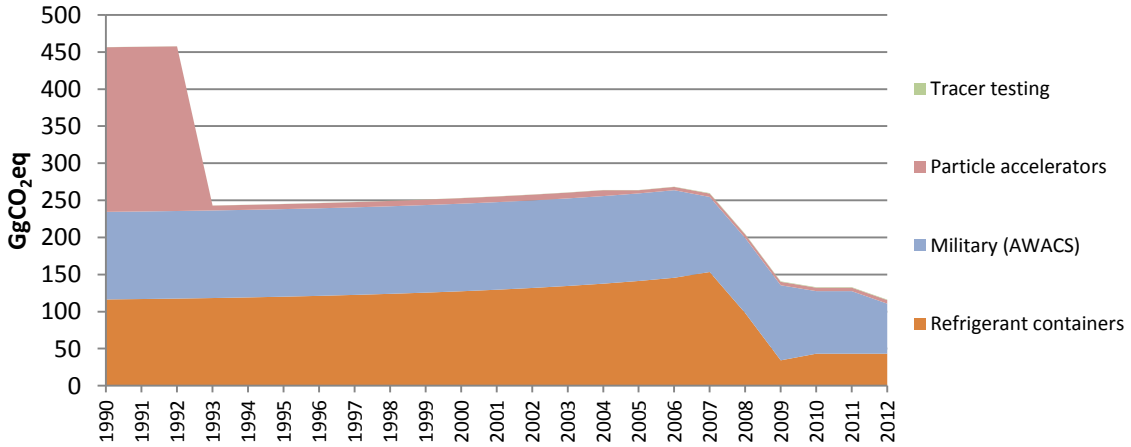
[1] 2011 is the most recent year for which disaggregated F-gas emissions data were made available to ICF.

Figure 2: Percent Annual Change for Existing Source Sectors



The new source sectors accounted for 133 $GgCO_2e$ in 2011, representing 19% of F-gas emissions from the source sectors explored in this report—or about 1% of total F-gas emissions. Emissions from these sources were estimated to decrease to 116 $GgCO_2eq$ in 2012, due to a decrease in emissions from AWACS.

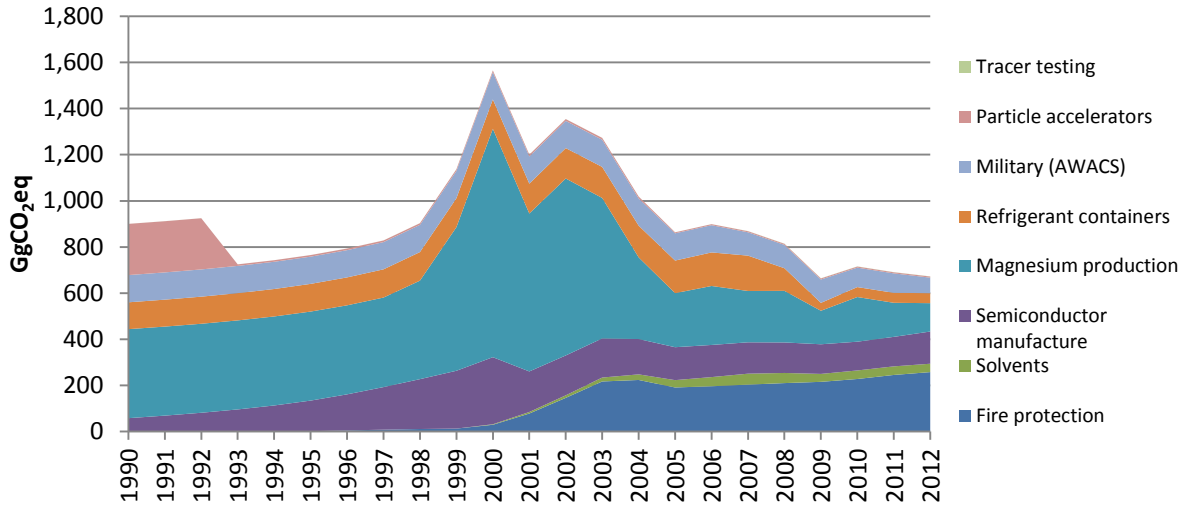
Figure 3: Emissions from Newly Added Source Sectors*



**Emissions were also explored for sound-proof windows, heat transfer fluids, flat panel display and PV cell manufacture, cosmetic and medical applications, and production of other fluorinated chemicals, but emissions from these sectors were not quantified in the inventory either because they were deemed insignificant or because insufficient data were available.*

The combined emission estimates from both existing and new F-gas sources are shown in the figure below.

Figure 4: Emissions from All Source Sectors (Updated and Newly Added)



While this study brings F-Gas estimates in line with IPCC 2006 Guidelines compliance, the following priority updates are suggested for the future to improve these emission estimates further.

Table 2: Suggested future updates to improve inventory estimates

Sector	Suggestion for improvement
2.E.4: Heat Transfer Fluid	More in-depth research is needed to gather activity data and emission factors for heat transfer fluids used in consumer electronics, cooling systems, and large ground-source heat pumps in the UK. MoD should also be contacted to estimate HTF emissions from military applications.
2.E.1: Semiconductor Manufacture	To improve upon the Tier 2a emission estimation methodology, consumption of gases (including NF_3) should be collected at the facility level, in lieu of the current method of projecting consumption based on assumed growth rates.
2.G.2.a: Military Applications	Emissions are high with the current Tier 1 estimation method using default emission factors; further effort should be placed on obtaining UK-specific loss rates from the UK Royal Air Force, which would reveal emission fluctuations based on periods of high or low military operations.
2.F.1: Refrigeration and Air Conditioning (Refrigerant Containers)	Additional research on the activity data for large (60 kg) cylinders, iso tanks, and small (340 g) cans of refrigerant should be undertaken. In addition, further research into the percent of disposable cylinders sold relative to reusable cylinders prior to the 2008 ban should also be conducted.

A number of other research activities can be conducted to improve the emission inventories of the F-gas sectors reviewed in this report, which are deemed lower priority based on their contribution to overall emissions. These activities include:

- *2.E.1: Semiconductor Manufacture:* explore further dialogue with National Microelectronics Institute (NMI) and other industry sources to identify/quantify emissions of CF_4 by-product associated with any use of F_2 and COF_2.
- *2.G.2.b: Accelerators:* collect user information on the charge of each SF_6-using accelerator and/or individual accelerator-level emission estimates for each accelerator.
- *2.G.2.c Other (Cosmetic & Medical Applications)*: confirm that PFC emissions from this source are insignificant by performing laboratory tests on the relevant cosmetics and/or medical application that use PFCs; contact the UK Cosmetic, Toiletry & Perfumery Association (CTPA) to determine the market size of cosmetic applications using PFCs, if any; conduct research to identify other UK companies producing and/or distributing relevant cosmetic products or performing medical applications relying on PFCs or other F-gases (e.g., freeze sprays and liquid bandages).

1 Introduction

The existing UK inventory of fluorinated greenhouse gases (F-gases) includes emission estimates for HFCs, PFCs, and SF_6 from 1990 to 2011 from the refrigeration/air-conditioning (Ref/AC), foam blowing, aerosols, metered dose inhalers (MDI), firefighting, halocarbon production emissions, and magnesium sectors. While HFC consumption and forecasting updates were made to the inventory in 2010, and further refinements to the Ref/AC sector were made in 2011, additional updates are needed to comply with the 2006 Guidelines released by the IPCC (hereinafter '2006 GLs'), for incorporation into the UK's 2015 submission of the inventory year 2013. This report assesses the existing UK inventory of F-gas emissions and identifies required updates and additions to comply with the 2006 GLs in both new and existing sectors.

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Table 3: Required updates to comply with the 2006 IPCC GLs

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As indicated by the table above, not all source categories identified in the 2006 GLs are necessarily relevant for the UK. ICF has investigated these potential sources and documented our investigations within this report.

This draft report is an output of the study “Review of data and methodologies used in the calculation of UK emissions from F-Gases” by ICF International for DECC, which

is being carried out under the UK Greenhouse Gas Inventory and Air Quality Pollutant Inventory Framework Agreement. The study's outputs are expected to feed into the parallel trial of new CRF reporting software in spring 2014.

Sections 2 and 3 of this report present the methodology and results for updating existing sectors already in the F-gas inventory and new sectors respectively. Section 4 of this report summarises the sector emission estimates identifies priority future updates. Section 5 looks at NF_3 emission forecasts.

2 Methodology and results for updated F-gas sources

This section includes the five sectors of F-gas emissions already in the existing UK F-gas inventory which have been assessed for compliance with the 2006 GLs: fire protection, one component foams, solvents, semiconductor manufacture, and magnesium production. For each of these sectors, this chapter describes the current inventory methodology applied; the updates required per the 2006 IPCC Guidelines; ICF's research approach undertaken; the resulting updated emissions; an uncertainty analysis of the revised methodology; recommended future inventory updates; and a list of references.

2.1 2.F.3: Fire Protection

Current Methodology
The current method for the fire protection sector estimates emissions using an IPCC Tier 2 method based on an estimate of the size of the HFC bank, together with annual leakage rates applied across the bank which includes losses during system maintenance and from the deployment of fire extinguishing equipment (AEA 2008). Bank estimates were obtained from March (1999) for years 1990-1996; for subsequent years, bank estimates were projected based on input from a UK trade organisation, the Fire Industry Council (FIC), and the European Association for Responsible Use of HFCs in Fire Fighting (ASSURE). Emissions are based on estimates of installed bank of HFC-227ea and an annual emission rate of approximately 5% until 2000, decreasing to 2.6% beginning in 2005. The 2.6% rate includes 1.5% for intentional discharge, 1% for servicing, and 0.1% for decommissioning. There are no emissions from HFCs assumed prior to 1995 (AEA 2012). In addition, no emission factor is applied for manufacture, as it was assumed that there is no production of F-gas fire protection agents in the UK.

Updates Required by 2006 IPCC Guidelines
The 2006 GLs state that, because F-gases in fire protection are emitted over a period longer than one year, countries must represent emissions from equipment charged during previous years. As such, the revised emission estimation equation (Equation 7.17) requires a modified approach to consider the time dependence of the emissions. Effectively, this requires disaggregating the annual bank estimates into 'new' versus 'existing' systems and then applying emission factors accordingly (i.e., applying a lifetime loss rate to banks from both new and existing systems, a servicing loss rate to the bank of existing systems, and a disposal loss rate to the bank of existing systems reaching disposal in any given year, based on an assumed average lifetime). Further, additional research was required to ensure that a manufacture loss rate should not be applied by confirming whether there is any production of F-gas fire protection agents in the UK. These updates apply the IPCC Tier 2 methodology, which is consistent with the current inventory and believed to be the most accurate method.

Additionally, the GWP used to calculate CO_2 equivalent emissions of HFCs must be updated based on the IPCC Fourth Assessment Report (AR4).

Research Approach
ICF reviewed available literature to confirm/update key assumptions—notably, EEA (2013)—and then refined and finalized the estimates based on consultation with ASSURE (European Association for Responsible Use of HFCs in Fire Fighting) and the UK Fire Industry Association (FIA). The sections below outline the updates implemented by key area.

Stock
Annual stock estimates from AEA (2012) for the years 1990 – 2005 were maintained, since they were based on historical data and input from industry experts. However, these annual stock figures were disaggregated into new versus existing systems by subtracting the current year's bank from the previous year's bank to estimate consumption in new systems, and then allocating the remainder of the bank to existing systems.

To determine the equipment stock in years beyond 2005, EEA (2013) estimates for net supply of F-gases in the fire protection sector from 2007-2012 (metric tonnes) in the EU, 85% of which is HFC-227ea, were scaled to the UK using a time-dependent GDP ratio. This annual net supply was assumed to equal annual consumption of fire protection agent in new systems. The bank estimate for 2006 was interpolated based on the existing 2005 estimate and the new 2007 estimate. The methodology and resulting stock estimates were reviewed and approved by ASSURE (2013) and FIA (2013). ASSURE confirmed that the estimates looked reasonable; FIA noted that the estimates looked reasonable for recent years, but that the 2000 estimates are slightly high; unfortunately, additional information to refine these historical estimates was not available. As this represents a minor overestimation of emissions, this was accepted.

Chemicals in Use
According to FIA (2013) and ASSURE (2013), HFC-227ea accounts for virtually 100% of F-gas consumption in this sector in the UK; consumption of other HFCs (e.g., HFC-23, HFC-125, and HFC-236fa) in the UK are statistically insignificant. Therefore, is it assumed that HFC-227ea accounts for 100% of F-gas consumption in this sector (over the full time period), which is consistent with assumptions previously applied by AEA.

Equipment Lifetime
According to FIA (2013) and ASSURE (2013), the average equipment lifetime of fire protection systems is 20 years.

Emission Factors
The emission factors used in the current inventory were reviewed by FIA (2013) and ASSURE (2013); they confirmed that no updates were required. A summary of the emission factors is provided in the table below. ASSURE emphasized that the high cost of specialty HFC fire protection systems creates a strong incentive for recovery and recycling, minimising leaks during servicing and decommissioning. Further,

ASSURE confirmed that there is no F-gas production in the UK in this sector, which is also supported by Defra (2008). Thus, no manufacturing loss factors are applied.

Table 4: Summary of Emission Factors for the Fire Protection Sector

Emission Factor	1990	2000	2005	2010	2012
Manufacturing Loss Rate[a]	0%	0%	0%	0%	0%
Lifetime Loss Rate[b]	1.5%	1.5%	1.5%	1.5%	1.5%
Servicing Loss Rate[b]	3.4%	3.4%	1.0%	1.0%	1.0%
Disposal Loss Rate[b]	0.1%	0.1%	0.1%	0.1%	0.1%

[a] ASSURE (2013) and Defra (2008).
[b] AEA (2013) and ASSURE (2013).

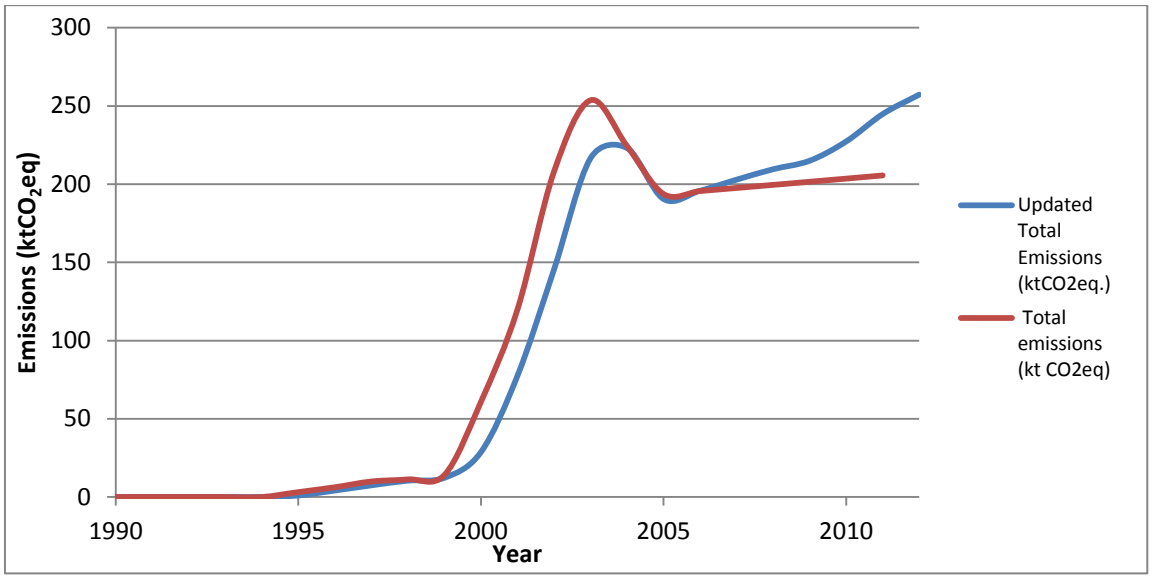
Lifetime emission factors were applied to the entire bank, while servicing emission factors—which decrease over time as more efficient servicing techniques are assumed to be implemented—were applied to the bank of existing systems (not to new or decommissioned systems). The disposal loss rate is applied to the bank of existing systems assumed to reach disposal; because the equipment lifetime is assumed to be 20 years, the disposal emissions will not be modelled until 2015—i.e., 20 years following the initial installation of F-gases in 1995.[2]

Results

The revised emission estimates for the fire protection sector are shown in the figure below in comparison to the old estimates in AEA (2012). As shown, the estimates are consistent in the early years, but the revised estimates are lower from 2000 to 2005, but higher in later years. The lower emissions in the earlier years result because disposal emissions are no longer being applied to the bank as of the first year of F-gas installation. More specifically, the previous method applied a decommissioning rate starting in 1995 whereas the updated inventory does not apply this emission factor until 2015 (the first year in which disposal of HFC-227ea systems is assumed to occur). In the later years, emissions are higher because consumption estimates are higher than those that were projected by AEA (2008, 2012).

[2] Both FIA (2013) and ASSURE (2013) confirmed that installation of F-gases in the UK fire protection sector began in 1995.

Figure 5: Comparison of Old vs. Updated F-gas Emission Estimates in the Fire Protection Sector



Uncertainty

The results of the uncertainty analyses for 1995 (base year) and 2011 are summarised in the table below. For 1995, HFC emissions were estimated to be between 0.87 and 1.06 gigagrams of carbon dioxide equivalent ($GgCO_2eq$) at the 95% confidence interval; this indicates a range of approximately +/-10% around the emission estimate of 0.97 $GgCO_2eq$. For 2011, HFC emissions were estimated to be between 220.64 and 267.68 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately +/-10% around the emission estimate of 244.06 $GgCO_2eq$. The most significant source of uncertainty in this sector is the UK bank size, which was scaled from EU estimates based on GDP. There is a high level of certainty in the 2011 estimates as the inputs and outputs were vetted by the key fire protection industry association in the UK.

Table 5: Quantitative Uncertainty Estimates for 1995 and 2011 HFC Emissions from Fire Protection

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		($GgCO_2eq$)	($GgCO_2eq$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HFCs	1995	0.97	0.87	1.06	-10%	10%
HFCs	2011	244.06	220.64	267.68	-10%	10%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.

Future Inventory Updates

Given the increasing use of low-GWP alternatives across the EU in response to the review of the EC F-Gas Regulation,[3] consumption of HFC-227ea in this sector is expected to decline. Therefore, to update the inventory, consumption in new systems should be estimated each year based on the annual EC F-gas data reported by companies on the production, import and export of F-gases in the EU. These reports, available for free online, provide quantities of F-gases placed on the market in the fire protection sector, which should be scaled to the UK based on GDP. The level of effort associated with this activity is low.

Future research should also be undertaken to improve the historical (pre-2007) emission estimates in this sector through further contact with FIA. Specifically, FIA suggested that the estimated consumption in 2000 was too large. ICF recommends contacting FIA in the future for this activity, which will require low effort.

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2.2 2.F.2: Foam Blowing Agents (One Component Foams [OCF])

Current Methodology

Emissions from the OCF sector are currently calculated using an IPCC Tier 2 method. UK estimates of emissions were derived from a European study (Harnisch

[3] According to ASSURE (2013), market penetration of FK-5-1-12 grew from 20% to 50% from 2007 to 2010.

and Schwarz 2003) and subsequently disaggregated by GDP to determine a top-down, UK-specific estimate. Harnisch and Schwarz (2003) estimated EU emissions from OCFs in 1996, 2000 and 2010, of which it was estimated that 5.52% of those totals correspond to UK emissions (AEA 2012). The current inventory assumes that HFC-134a and HFC-152a are the only HFCs consumed in this sector, representing 45% and 55% of the inventory respectively.

Updates Required by 2006 IPCC Guidelines

According to the 2006 GLs, to calculate a complete estimate of emissions from OCFs, emissions from manufacturing, in-use, decommissioning and chemical destruction should be included where data are available. However, HFCs used for open-cell foam blowing, which includes OCF, are released immediately. According to the 2006 GLs, emissions are calculated using the following equation:

$$Emissions_t = M_t$$

Where:

$Emissions_t$ = emissions from foam in year t, tonnes

M_t = total HFC used in manufacturing new foam in year t, tonnes

A disaggregated Tier 2a[4] method applies emission factors to specific sub-applications, in cases where consumption activity data are identified for each application. Where there is little use of OCF, a Tier 1a method could be followed where the equation above is applied at the broad application level (IPCC 2006).

In the UK, F-gas use in OCF was banned in July 2008. However, to comply with the 2006 GLs it is necessary to determine (1) if HFC-based manufacture of OCFs occurred in the UK prior to the 2008 HFC ban, and if so, (2) the total amount of HFC used to manufacture OCFs annually prior to the 2008 ban. Emissions from the consumption of imported HFC-based OCFs are already included in the inventory and do not need to be updated.

Research Approach

ICF conducted research to identify whether HFC-based OCF production occurred historically in the UK. Specifically, ICF contacted the Association of the European Adhesive & Sealant Industry (FEICA), which represents more than 90% of the European OCF manufacturing market, to determine if there was ever manufacture of HFC-based OCFs in the UK, or identify (and subsequently contact) any UK OCF manufacturers to obtain historical activity data.

Results

Emissions from this source were not updated in the inventory. Based on consultation with FEICA, it was confirmed that one OCF manufacturer in the UK—possibly called Bagstenden—did operate prior to 2009. While it is unknown exactly when the

[4] Tier 1a and Tier 2a refer to a methodology using an emission factor approach (as opposed to a mass balance approach, or Tier 1b or Tier 2b).

company closed, FEICA noted that this company was a small market player most active in the 1980s—i.e., prior to the start of the F-gas inventory timeframe- and less so in the 1990s. Activity data for the relevant timeframe was not possible to obtain because the manufacturer is no longer in operation.

Updated emissions calculations for this existing source in the inventory are not deemed necessary as emissions from the manufacture of OCF in the UK were concluded to be insignificant. This is because FEICA indicated that the market contribution of the one HFC-based OCF manufacturer in the UK was small and that it was most active prior to the inventory timeframe. Thus, past emissions from any HFC manufacture losses would not be significant.

Future Inventory Updates
No future inventory updates are needed to OCF manufacture emissions because there are no longer emissions from this source in the UK.

References

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2.3 2.F.5: Solvents

Current Methodology
The current method for the solvents sector estimates emissions using an IPCC Tier 1a method, which is an emission factor approach and is consistent with the IPCC 1996 guidelines. To estimate consumption, this approach assumes that 50% of solvent sales from the year (t-1) and 50% of sales from year (t) is equal to the consumption in year (t). This assumes that solvents are stored for an average of six months prior to use. Annual emissions were then estimated to be equal to the consumption of the solvent in the same year.

The current method used in the inventory relies on a 2003 EU study (Harnisch and Schwarz 2003) of HFC emissions from solvents in the EU and disaggregates total emissions down to the UK level. The UK consumption was estimated using the ratio of UK to EU consumption which is based on the UK to EU GDP ratio (AEA 2013). Harnisch and Schwarz (2003) provide consumption values from 2001 and 2002 as well as a projected consumption for 2010. Consumption was then interpolated for years 2003 – 2009 and extrapolated for 2000 and 2011. The inventory also currently assumes that HFC-43-10mee contributes to 100% of the solvent sector‘s consumption and there are no emissions of HFCs from the solvent sector prior to 2000 (AEA 2012).

Updates Required by 2006 IPCC Guidelines
Emissions from solvent applications are considered to be prompt emissions because 100% of the chemical is typically emitted within two years of initial use (IPCC 2006). To calculate HFC emissions from the solvent sector using a Tier 1a method, the

2006 IPCC Guidelines specify that activity data should be the quantity of solvent sold in a given year. Therefore, obtaining annual sales of solvents in the UK is required. Using sales data, emissions of HFCs from solvent use in year t are calculated using the following equation, as provided in the 2006 GLs:

$$Emissions_t = S_t \times EF + S_{t-1} \times (1 - EF) - D_{t-1}$$

Where:

$Emissions_t$ = emissions in year t, tonnes

S_t = quantity of solvents sold in year t, tonnes

S_{t-1} = quantity of solvents sold in year t–1, tonnes

EF = emission factor (= fraction of chemical emitted from solvents in the year of initial use), fraction

D_{t-1} = quantity of solvents destroyed in year t–1, tonnes

Research Approach

Because of the diverse industrial and commercial applications in which solvents are used, there is no UK or EU trade association for the solvents industry from which to solicit activity data. Therefore, ICF reviewed available literature to confirm/update key assumptions—notably, Harnish & Schwarz (2003), and EEA (2013).The sections below outline the updates implemented by key area.

Stock

Annual sales data of HFCs in the UK solvent sector were not available. Therefore, consumption of HFCs in this sector was estimated using the same estimates as in the previous inventory for 2001 and 2002 (i.e., based on Harnish & Schwarz 2003) in additional to historical F-gas supply data in the EU. Because the consumption estimates in Harnish & Schwarz (2003) in years beyond 2002 were projections, EEA (2013) data on intended F-gas supply data in the EU in the solvents sector was used to estimate HFC consumption from 2007-2012. To estimate the amount of HFCs placed on the market in the UK, the EU estimates from EEA (2013) were scaled down using a time-dependent UK to EU GDP ratio from EuroStat (2013). Using GDP as a scaling factor to estimate the UK F-gas supply in the solvent sector was deemed appropriate, given the wide variety of industrial and commercial industries that use solvents.

Chemicals in Use

Given the lack of data available on the extent of use of HFC-134a in the UK solvent sector, it is assumed that HFC-43-10mee accounts for 100% of UK F-gas consumption in this sector. This is consistent with assumptions previously applied by AEA (2012).

Product Lifetime

According to the 2006 IPCC GLs, the lifetime of all solvents is assumed to be two years. Therefore, any amount not emitted during the first year is assumed to be emitted in the second, final year (IPCC 2006).

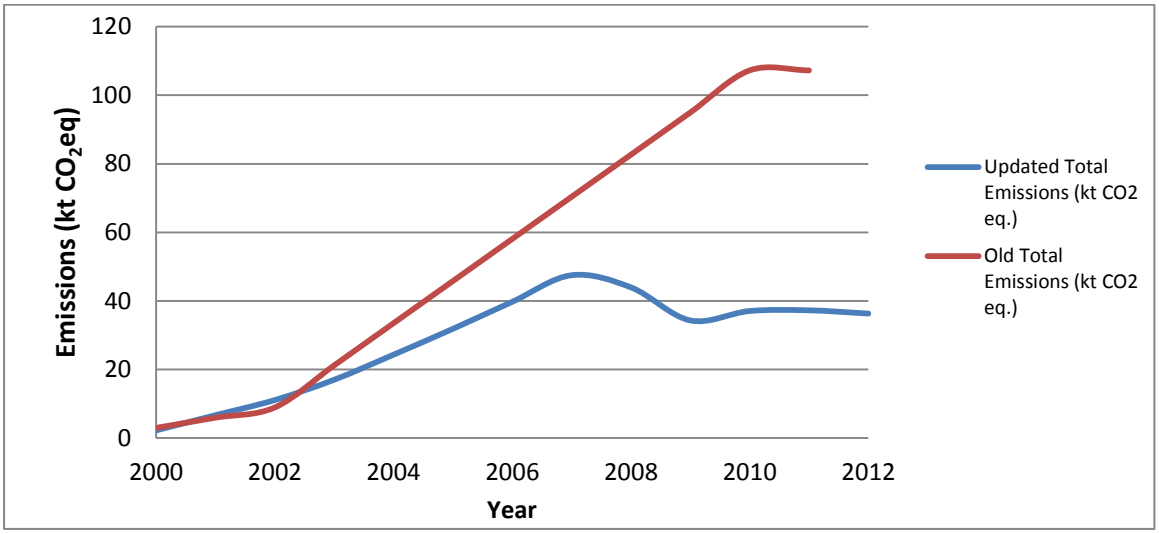
Emission Factors

A global report prepared by U.S. EPA (2013) assumes that approximately 90% of solvent that is consumed in a year is emitted, while 10% is destroyed. A lifetime emission factor is applied to the total amount of solvents placed on the market. Because the 2006 IPCC GLs provide that HFCs are emitted over a two-year period, an annual emission factor of 45% was applied in this analysis using the IPCC (2006) equation above. Recovery and recycling is not considered in emission estimates, per the 2006 IPCC GLs.

Results

The revised emission estimates for the solvent sector are shown in the figure below in comparison to the old estimates in AEA (2012). As shown, the revised estimates are much lower between years 2002 and 2012 and believed to be more accurate as they are based on actual F-gas supply data in the EU in the solvent sector (from EEA (2013), scaled to the UK based on GDP) rather than older projections developed by AEA based on Harnish & Schwarz (2003). Additionally, the previous estimates conservatively assumed that all solvent use would be replaced by HFCs as opposed to other alternatives due to a lack of information indicating the potential market share of those alternatives in the UK. Furthermore, the previous estimates assumed that 100% of the solvent was emitted in the same year as it entered the market; applying a two-year lifetime and a 50% annual emission factor delayed emissions and therefore decreased the previously calculated emissions.

Figure 6: Comparison of Old vs. Updated F-gas Emission Estimates in Solvent Sector



Uncertainty

The results of the uncertainty analysis for 2011 are summarised in the table below. As shown, HFC emissions were estimated to be between 21.85 and 41.44 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 41% below

and 11% above the emission estimate of 37.27 $GgCO_2eq$. The most significant sources of uncertainty for this source category are the amount of solvent destroyed and the emission factor, since the level of solvent destruction (i.e., emission abatement) in the UK is unknown, and was conservatively assumed to have a large range of uncertainty. Additionally, the lifetime emission factor, assumed to be 90% over two years, was also conservatively assumed to have a large range of uncertainty because those emissions are not necessarily uniform over two years and are directly impacted by the amount of solvent that is captured for destruction. The next most significant source of uncertainty is the level of HFC use in the UK. No emission estimates were developed for 1995, as there was no HFC solvent use in the UK prior to 2000; therefore no uncertainty analysis was conducted for the base year.

Table 6: Quantitative Uncertainty Estimates for 1995 and 2011 HFC Emissions from Solvents

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		($GgCO_2eq$)	($GgCO_2eq$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HFCs	2011	37.27	21.85	41.44	-41%	11%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.

Future Inventory Updates

To update the inventory each year, activity data should be obtained by DECC based on EU annual solvent sales (based on data reported by companies on the production, import and export of F-gases in the EU). It should be noted that, given the increasing use of low-GWP alternatives across the EU in response to the review of the EC F-Gas Regulation, consumption of HFC-43-10mee and other HFCs in this sector is expected to decline.

Future research may also be undertaken to improve upon the emission estimates in this sector by exploring the rate of solvent destruction in the UK (if any) and the extent of other F-gas solvent use apart from HFC-43-10mee (e.g. HFC-365mfc, HFC-134a, HFC-245fa). Given the diverse/widespread solvent uses in the UK, conducting this type of research will require a high level of effort.

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- AEA. 2012. UK Greenhouse Gas Inventory, 1990-2010. Annual Report for Submission under the Framework Convention on Climate Change. Prepared for Department of Energy and Climate Change. April 2012.
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2.4 2.E.1: Semiconductor Manufacture

Current Methodology

The current method used to estimate F-gas emissions from semiconductor manufacture corresponds to an IPCC Tier 1 method from the 2000 Good Practice Guidance (GPG). This method is based on the sales/purchases of gases, the fraction of gas remaining in containers after use (i.e., the heel), and the use rate of gases (AEA 2008). Emission estimates are based on consumption data (purchases) from 2001 for the gases CF_4, C_2F_6, C_3F_8, C_4F_8, CHF_3, SF_6 and NF_3 supplied by the UK Microelectronics Environmental Advisory Committee (UK MEAC) in conjunction with the UK Department of Trade and Industry (DECC 2013). Consumption data during the years before and after 2001 were estimated based on assumptions about the annual semiconductor industry growth rates, and the annual rate of change of f-gas usage per unit production, both data supplied by the MEAC (DECC 2013).

F-gas emissions were estimated using an equation provided by the World Semiconductor Council (WSC) that is a modified 2000 GPG Tier 1 equation. A sample equation derived from the existing methodology for CF_4 estimations is below:

Emissions for $PFC_i = PFC_i*(1-h)[(1-C_i)(1-A_i)*GWP_i + B_i*GWP_{CF4}*(1-A_{CF4})]$

h = fraction of gas_i remaining in container (heel)

PFC_i = purchases of gas_i = kgs_i

kgs_i = mass of gas_i purchased

GWP_i = 100 yr global warming potential of gas_i

C_i = average utilisation factor of gas_i (average for all etch and Chemical Vapour Deposition processes)

= 1-EF_i

EF_i = average emission factor of gas_i (average for all etch and CVD processes)

B_i = mass of CF_4 created per unit mass of PFC_i transformed

A_i = fraction of PFC_i destroyed by abatement = $a_{i,j}*V_a$

A_{CF4} = fraction of PFC_i converted to CF_4 and destroyed by abatement = $a_{CF4}*V_a$

$a_{i,j}$ = average destruction efficiency of abatement $tool_j$ for gas_i

a_{CF4} = average destruction efficiency of abatement $tool_j$ for CF_4

V_a = fraction of gas_i that is fed into the abatement tools

For all gases except NF_3, the fraction of gas that is fed into the abatement tools is assumed to be 0% until 2003, 10% in 2004, and an additional 5% per year thereafter (reaching 50% by 2012). For NF_3, the fraction is assumed to be 90% until 2003, 95% in 2004, and 100% in 2005 and onwards.

Updates Required by 2006 IPCC Guidelines

The 2006 GLs provide an updated method for estimating semiconductor manufacture emissions as compared to the 2000 GPG. Specifically, the 2006 GLs include updated methodologies for each tier, updates to emission factors, as well as inclusion of other sectors in the electronics manufacturing source category – flat panels display manufacturing, and photovoltaic manufacturing (see chapter 3). For the semiconductor manufacture sector, the 2006 GLs Tier 1 method estimates emissions based on the amount of substrate processed, in units of m^2. The Tier 1 method in the 2000 GPG most closely resembles the Tier 2a method of the 2006 GLs, which estimates emissions based on gas-specific consumption data, as well as the amount left in shipping containers after use, use rate of gas, fraction of gas used in processes with emission control technologies, and the fraction of gas destroyed by the emission control technology.

The 2006 GL Tier 2a method is represented by the following equation:

Emissions for E_i = $(1-h)*FC_i*(1-U_i)*(1-a_i*d_i)$

Where:

i = F-gas species

E_i = emissions of gas_i, kg

h = fraction of gas_i remaining in container (heel)

FC_i = consumption of gas_i, kg

U_i = use rate of gas_i

a_i = abatement rate of gas_i

d_i = fraction of gas_i destroyed by the abatement

The Tier 2a method also introduces by-product emissions of CF_4, C_2F_6, C_3F_8 and CHF_3. In the 2000 GPG, by-product emissions were limited to only CF_4. The Tier 2a equation used for by-product emissions is:

By-Product Emissions of gas j ($BPE_{j,i}$)= $(1-h)*B_{j,i}*FC_i*(1-a_i*d_j)$

$BPE_{j,i}$ = by-product emissions of gas *j* from the gas *i* used, kg

$B_{j,i}$ = emission factor, kg gas *j* created/kg gas *i* used

d_j = fraction of gas *j* by-product destroyed by the abatement

j = CF_4, C_2F6, CHF_3 and C_3F_8

The 2006 GLs also introduce updated emission factors, or use rates for gases. The destruction rates of abatement systems have been assumed to be the same in the 2006 GLs for all species except NF_3. The destruction rate of NF_3 has been updated to 0.95 from 0.90.

Research Approach

ICF attempted to update consumption data based on actual consumption as opposed to estimating consumption based on growth rates, which is currently done. However, it was not feasible given the scope, both time and budget, of the sector to collect individual gas collection data from each of the semiconductor manufacturers.

ICF identified several potential sources to use to update the activity data (i.e., consumption data)–notably, the National Microelectronics Institute (NMI) and European Semiconductor Industry Association (ESIA). ESIA collects industry F-gas emissions data at the European level and the data is not broken down by Member State; therefore UK-level emissions were not available via ESIA. ICF requested NMI to consult its members to ascertain availability of activity data, but no response was received in time for this report. Hence, the previous approach of estimating activity data based on assumed growth rates (which is compliant with the 2006 GLs) has not been updated.

The NF_3 consumption has been further sub-divided into NF_3 Remote Clean and all other NF_3 consumption (i.e., for in-situ chamber clean and etch processes). NF_3 remote clean refers to a cleaning method for chemical vapour deposition chambers in which the film cleaning-agents formed from NF_3 (F-atoms) are produced in a plasma upstream (remote) from the chamber being cleaned (IPCC 2006). In situ chamber cleans are chemical vapour deposition chamber cleaning processes, which may use NF_3 or other F-gases to generate F-atoms in the chambers whose walls are being cleaned. NF_3 may also be used to etch patterns (i.e., circuits) on semiconductors. The use of NF_3 remote clean is assumed to start in 2003 and growing increasingly over time. Because no data on the UK's use of NF_3 remote clean processes was made available from NMI, the US semiconductor market was

used as a proxy to estimate the use of NF_3 in remote clean processes relative to all other processes. Specifically, the share of NF_3 remote clean versus other uses was estimated based on industry-reported NF_3 usage data from US semiconductor manufacturers for the years 2009 and 2010 (US EPA 2011). This US data was readily available and is believed to be a good proxy for the UK given that semiconductor processes do not typically vary by world region. The ratio of NF_3 remote to other uses was interpolated for years between 2003 and 2009, assuming 0.0 (nil) in the year 2003. This was done as 2006 GLs provide emission factors for the NF_3 use in remote clean and NF_3 in-situ and etch use.

Additional Gases

In addition to the gases used in the current inventory, the 2006 GLs also identify other gases used in the semiconductor industry—namely, CH_2F_2, C_4F_6, C_5F_8, C_4F_8O, F_2 and COF_2. Although F_2 and COF_2 are not F-gases, their usage produces CF_4 as a by-product. Since no information was made available from NMI, the inclusion of these gases and their by-products in the inventory is flagged for future improvements.

Emission Factors and Other Default Factors

The emission factors used in the updated inventory were taken from 2006 GLs. A summary of the emission factors for the 2006 GL Tier 2a method is provided in the table below.

Table 7: Summary of 2006 GL Tier 2a Emission Factors for the Semiconductor Manufacture Sector

Process Gas (i)[a]	CF_4	C_2F_6	CHF_3	CH_2F_2	C_3F_8	c-C_4F_8	NF_3 Remote	NF_3	SF_6
Emission Factor (1-Ui)[b]	0.9	0.6	0.4	0.1	0.4	0.1	0.02	0.2	0.2
B_{CF4}	NA	0.2	0.07	0.08	0.1	0.1	0.02[c]	0.09	NA
B_{C2F6}	NA	NA	NA	NA	NA	0.1	NA	NA	NA
B_{C3F8}	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA = no data available based on information available during time of publication.
[a] B_x = $_X$ is a byproduct from the usage of another gas (in row headings).
[b] Ui = Utilization rate of gas i.
[c] Estimate reflects presence of low-k, carbide and multi-gas etch processes that may contain C-containing FC additive.

The default value used for the fraction of gas remaining in the shipping container (heel) is 0.10, which is unchanged from the IPCC 2000 GPG. The destruction efficiencies for emission control technologies are updated according to the 2006 GLs. The new default values are unchanged from the 2000 GPG for all gases other than NF_3, 0.90. For NF_3, the default was updated from 0.90 to a new value of 0.95.

Results

The updated emission estimates for the semiconductor manufacture sector are shown in 0. This figure also shows the previous estimates in AEA (2012). As shown, the updated estimates are slightly higher in all years. This is primarily due to the inclusion of by-products for C_2F_6 and CF_4, as well as inclusion of CF_4 by-products from more than one type of process gas compared to the previous methodology. It is also due to differences in the use rates (U_i) of various F-gases based on the 2006 GLs. Some fluctuations can also be attributed to updated GWPs based on the IPCC AR4.

The trend in F-gas emissions between years 2003 and 2012 is the result of two competing characteristic features used in the emission estimation methodology– (1) the growth in usage due to assumed growth rates, leading to an increase in emissions; and (2) an increase in abatement practices, leading to a decrease in emissions. After the introduction of abatement practices, the emissions are estimated to decrease despite growth in the industry. However, beginning in 2011, it is observed that the increase in abatement is not enough to keep up with the growth in the industry, resulting in a slight overall increase in emissions.

As seen in Figure 8, disaggregation of NF_3 consumption/emissions into NF_3 remote and NF_3 in-situ has led to a decrease in the NF_3 emission estimates because NF_3 remote clean has a higher utilisation rate, but the overall effect on the total emissions was insignificant as a result of this disaggregation. The disaggregation was done as the use of NF_3 in remote cleaning started in 2003 and its use has been increasing ever since. The effect of updated NF_3 emission factors on NF_3 emissions can be observed in the figure below, which shows higher emissions during the years 1990-2002 using the updated methodology compared to the previous version.

Figure 7: Comparison of Previous vs. Updated F-gas Emission Estimates in the Semiconductor Manufacture Sector

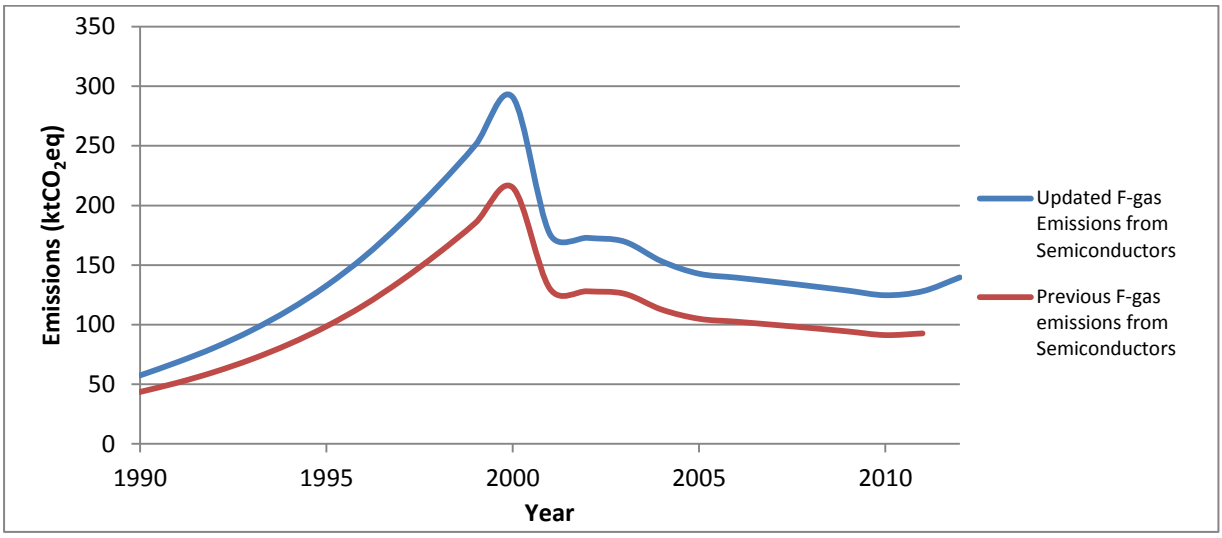
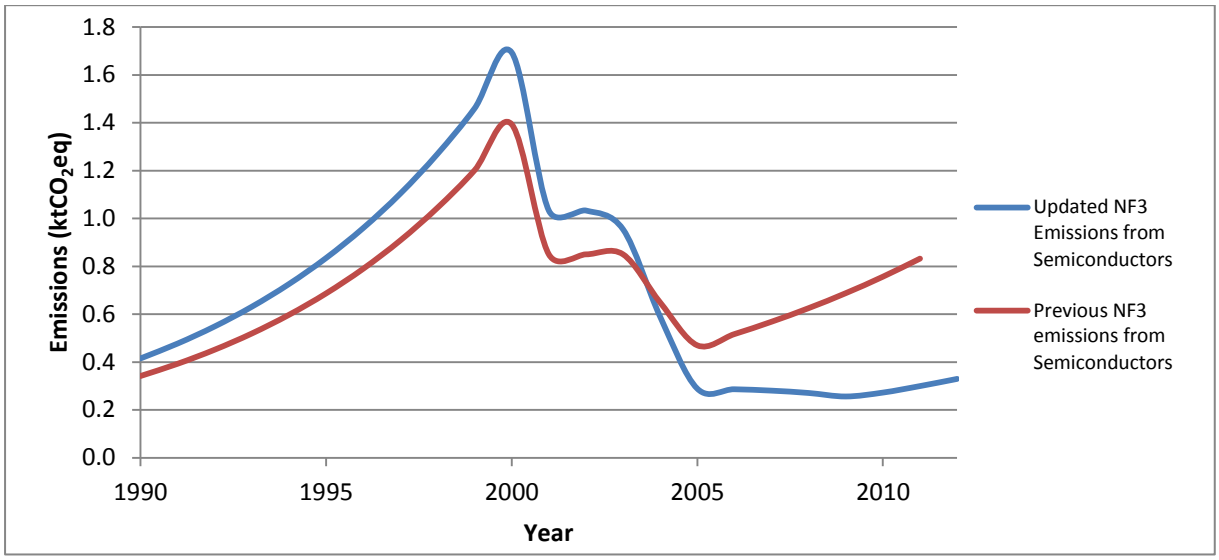


Figure 8: Comparison of Previous vs. Updated NF3 Emission Estimates in the Semiconductor Manufacture Sector



Uncertainty Assessment

The results of the uncertainty analyses for 1995 (base year) and 2011 are summarised in the table below. For 1995, total F-gas emissions were estimated to be between 80.92 and 187.23 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 39% below and 41% above the emission estimate of 132.68 $GgCO_2eq$ For 2011, total F-gas emissions were estimated to be between 80.08 and 183.81 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 37% below and 44% above the emission estimate of 128.03 $GgCO_2eq$ For both the 1995 and 2011 estimates, the key source of uncertainty in this sector is the amount of C_2F_6 consumed. For 2011, a secondary contributor to uncertainty is the fraction of C_2F_6 abated.

Table 8: Quantitative Uncertainty Estimates for 1995 and 2011 F-gas Emissions from Semiconductor Manufacture

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		($GgCO_2eq$)	($GgCO_2eq$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
SF_6, PFCs, HFCs, and NF_3	1995	132.68	80.92	187.23	-39%	41%
SF_6, PFCs, HFCs, and NF_3	2011	128.03	80.08	183.81	-37%	44%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.

Future Inventory Updates
To update future inventories, the preferred approach would be to obtain industry data from semiconductor manufacturers or the semiconductor association (NMI) on annual gas consumption and abatement (i.e., the fraction of gases fed to the abatement system). This is essential as the UK semiconductor industry has seen significant decline in production in the last few years with closure to many factories in "Silicon Glen". This was confirmed by a representative of NMI who stated that the UK semiconductor manufacturing sector declined in production by around 50% between 2005 and 2010 including closure of the three largest production sites (NMI 2014). To be conservative, ICF did not update the growth rates from the previous version of the inventory (i.e., the same methodology to estimate future growth rates was maintained). However, obtaining facility specific growth rates is suggested to update assumed growth rates; with approximately 25 production sites, this would require a medium to high level of effort. Alternatively, a lower level of effort can yield useful results by focusing on the three sites that represent over 50% of production.

Updated estimates of the share of NF_3 remote consumption out of total NF_3 consumption should also be updated based on industry information. However, if such industry data are not available, the industry growth rate of 10% may be applied to the previous years' activity data while maintaining the assumed 2012 share of NF_3 remote consumption and the mix of consumption by gas type constant.

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- AEA. 2012. UK Greenhouse Gas Inventory, 1990-2010. Annual Report for Submission under the Framework Convention on Climate Change. Prepared for Department of Energy and Climate Change. April 2012.
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2.5 2.C.4: Magnesium Production

Current Methodology
The current method for the magnesium sector estimates F-gas emissions using a 2006 GL Tier 2 method (DECC 2013). The methodology uses SF_6 emissions data reported by magnesium companies to the UK Pollution Inventory, and therefore are considered accurate. HFC-134a, an alternative to SF_6 in the magnesium industry, is assumed to have been used in the magnesium production sector starting in 2004. The current method assumes a shift in SF_6 usage towards HFC-134a based on an

assumption that only 90% as much HFC-134a is needed in comparison to SF_6, and that 90% of it is destroyed in the production process (DECC 2013, CSIRO 2005). After 2008, HFC-134a data is directly available from the UK Pollution Inventory.

Updates Required by 2006 IPCC Guidelines
The emission estimation methods for magnesium production in the 2006 GLs are updated from the 2000 GPG by introducing multiple tiered emission estimate methodologies along with new default emission factors. Since the current methodology utilises a 2006 GL Tier 2 method, no updates were required to ensure the SF_6 emission estimates are compliant with the 2006 GLs.

The IPCC 2006 GLs also require the estimation of emissions from other cover gases, mainly HFC-134a and FK 5-1-12. Inclusion of these cover gases require a Tier 3 approach which is the direct measurement approach, and/or reliable indirect measures of GHG emissions.

Research Approach
ICF attempted to update the activity data used – i.e. the amount of cover gas used – with more recent information for a Tier 2 method. For primary production, SF_6 usage was sought from the UK Pollution Inventory. However, the existing inventory activity data for primary producers was not modified as company-specific data from the Pollution Inventory was not provided to the study team in time for this report.[5] The slightly modified Tier 2 method introduces a 5% destruction rate for SF_6, based on expert opinion provided by SKM Enviros (2013). This methodology update is used for both primary and secondary production as well as magnesium casting (described below).

Because direct measurements of HFC-134a emissions were not available, an indirect method was used to estimate HFC-134a emissions. Based on SKM Enviros (2013), the HFC-134a destruction rate was assumed to be 80%. Similar to SF_6, past HFC-134a consumption data was sought from the UK Pollution Inventory but was not received in time for this update. The total SF_6 and HFC-134a consumption data for 2012 was obtained via market research conducted by SKM Enviros (2013). It was confirmed that the primary and secondary casters do not use FK 5-1-12 as a cover gas.

For the magnesium casters, market research was conducted by SKM Enviros (2013) to assess the SF_6 and other alternative cover gas emissions by obtaining 2012 cover gas consumption from operational casters. In addition, for one facility, historical SF_6 consumption data starting in 2006 was updated with revised data obtained directly from the facility by SKM Enviros.

Additional Gases
In addition to SF_6 and HFC-134a, the 2006 GLs also identify the use of FK 5-1-12 and SO_2 as cover gases in the magnesium industry. SKM Enviros (2013) confirmed that there was no use of FK 5-1-12 in the UK magnesium production sector through direct contact with the magnesium casters. 2006 GLs does not provide methods for

[5] Due to confidentiality issues, company-specific data could also not be provided by Ricardo-AEA.

estimating SO_2 emissions as SO_2 is outside the scope of reporting requirements of the 2006 GLs (IPCC 2006). Hence, information on consumption of SO_2 was not sought. Similarly, the carrier gases, mainly CO_2, are not estimated in this report as they are not F-gases.[6]

Emission Factors

SF_6 and HFC-134a emissions are estimated based on a modified Tier 2 method. A Tier 2 method does not have emission factors associated with it, but instead is based on the assumption that all gas used is emitted. The modified version of this method assumes that there is some destruction of the cover gases used. The IPCC Tier 2 emissions equation and its modification are shown below:

$$E_{SF6} = C_{SF6}$$

Where:

E_{SF6} = SF_6 emissions from magnesium casting

C_{SF6} = consumption of SF_6 in magnesium smelters and foundries

Modified IPCC Tier 2 equation:

$$E_i = d_i \cdot C_i$$

Where:

E_i = Emissions of gas i from magnesium casting

C_i = Consumption of gas i in magnesium smelters and foundries

d_i = Destruction efficiency of gas i, found below

Gas Type, i	Destruction efficiency, d
SF_6	5%
HFC-134a	80%

Results

The updated SF_6 emission estimates for the magnesium sector are shown in Figure 9 below. This Figure also presents the previous estimates in AEA (2012) for comparison. As shown, the estimates are consistently lower in all years prior to 2005 using the updated methodology. This is primarily due to the introduction of a destruction efficiency term in the modified Tier 2 estimation method. The increase in emissions starting around 2006 is a result of updating the inventory with direct consumption data from one of the casting facilities. The existing consumption data for years prior to 2006 were not modified as data for such years were not available. HFC-134a emission estimates are shown in Figure 10. Updated HFC-134a emissions are consistently higher in all the years using the updated methodology.

[6] Additional information on CO_2 use as carrier gas in the UK could be explored by contacting UK producers and casters. However, IPCC (2006) notes that "[t]he contribution of carbon dioxide carrier gas used in protective cover gas systems is normally a small fraction of the global warming potential. In general, these emissions may be disregarded."

This is primarily because of the reduction in the destruction efficiency, assumed to be 80% in lieu of 90%. Further, there is a disconnect in the current inventory which estimates the consumption of 102.9 t HFC-134a in 2011 (AEA 2008) compared to new data acquired through market research which estimates the consumption of 8.1 t HFC-134a (SKM Enviros 2013). Further insight into this deviation can be gained by reviewing company-specific HFC-134a consumption data from the UK Pollution Inventory and cross-checking it with existing data. However, such data were not made available to the study team in time for this analysis.[7]

Figure 9: Comparison of Old vs. Updated SF_6 Emission Estimates in the Magnesium Sector

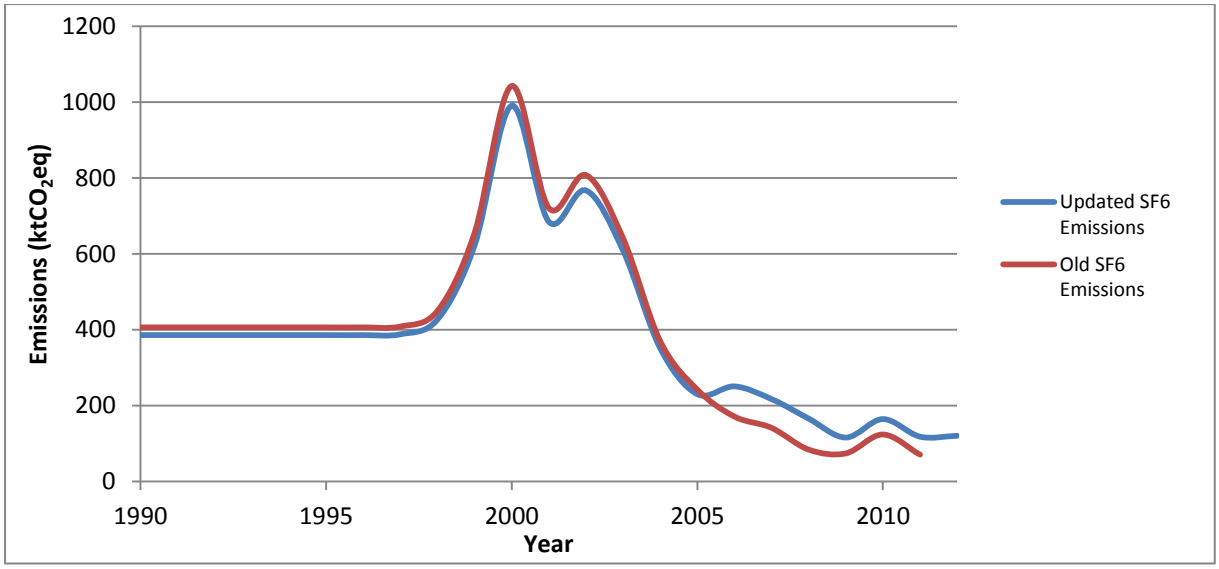
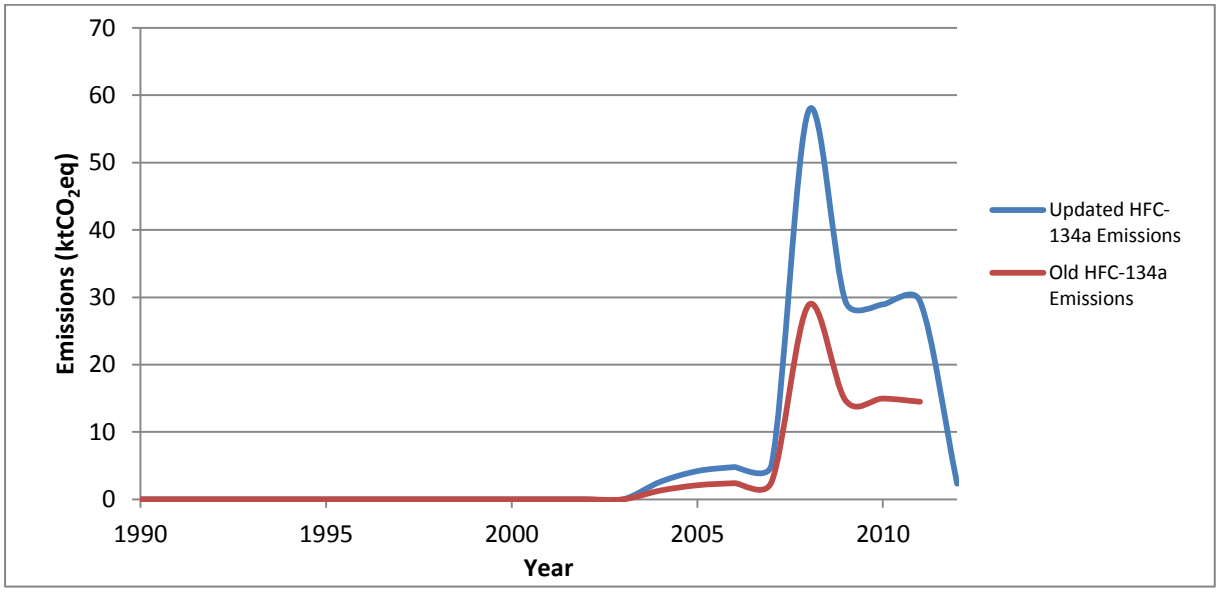


Figure 10: Comparison of Old vs. Updated HFC-134a Emission Estimates in the Magnesium Sector



[7] Due to confidentiality restrictions, company-specific data could also not be provided by Ricardo-AEA.

Uncertainty

The results of the uncertainty analyses for 1995 (base year) and 2011 are summarised in the table below. For 1995, total SF_6 emissions were estimated to be between 318.83 and 452.37 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately +/-17% around the emission estimate of 386.11 $GgCO_2eq$. For 2011, combined SF_6 and HFC-134a emissions were estimated to be between 134.67 and 160.72 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately +/-9% around the emission estimate of 147.74 $GgCO_2eq$. For the 1995 estimates, the key source of uncertainty in this sector is the amount of SF_6 used during secondary production. For the 2011 estimates, the most significant sources of uncertainty are the proportion of HFC-134a used that is emitted and the amount of SF_6 used by casters. There is greater confidence in the 2011 emission estimates compared to those from 1995 due to the higher confidence in the sources used to develop estimates of SF_6 use by secondary producers.

Table 9: Quantitative Uncertainty Estimates for 1995 and 2011 SF6 and HFC Emissions from Magnesium Production and Processing

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate [a]			
		($GgCO_2eq$)	($GgCO_2eq$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
SF_6	1995	386.11	318.83	452.37	-17%	17%
SF_6 and HFC-134a	2011	147.74	134.67	160.72	-9%	9%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval

Future Inventory Updates

Updating the inventory requires updating the amount of various cover gases used by the producers and casters, which must be obtained by consultation with key producers and casters. The key secondary producer identified is Magnesium Elektron; key casters currently operating that use SF_6 are Stone Foundries and Aeromet. This will require a medium level of effort that involves initial contact, correspondence and follow-up with the two casting companies and one secondary producer. Magnesium Elektron also submits emissions data to the UK Pollution Inventory, thus, such data should be obtained from the UKPI.

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3 Methodology and results for new F-gas sources

This section describes ten sectors of F-gas emissions investigated in this study that are not previously included in the existing UK F-gas inventory.

3.1 2.F.1: Refrigeration and Air Conditioning — Refrigerant Containers

Updates Required by 2006 IPCC Guidelines
Under the 2006 GLs, a new term in the IPCC Tier 2a method emissions equation for the Refrigeration and Air Conditioning sector is introduced to include emissions from the management of refrigerant containers used to service existing refrigeration/air-conditioning equipment, including refrigerant cylinders used by professional service technicians and small cans used by Do-It-Yourselfers (DIYers). No Tier 1 methodology is provided for this source.

Emissions from refrigerant containers occur when refrigerant is transferred from bulk containers (e.g., 40-tonne isotanks) to smaller capacity containers, typically ranging from approximately 300-500 grams (small cans) to 10-15 kg (cylinders). Emissions also occur at time of disposal if the refrigerant "heel" is not fully recovered. IPCC 2006 GLs require that emissions from each type of refrigerant container be calculated separately for refrigerant sold in small cans and in cylinders, including both disposables and reusables. The IPCC 2006 GLs default disposal emissions factors are 20% for small cans and 2% for disposable cylinders. Although the GLs do not specify a default emission rate for losses during the transfer of refrigerant into smaller containers, they do specify a default loss rate of 0.5 during the charging of refrigeration/air-conditioning equipment.

Research Approach
To add this new inventory source, emission estimates were developed according to the 2006 GL's bottom-up Tier 2a methodology, based on refrigerant container sales and distinct packaging and disposal emission factors for each type of refrigerant container.

ICF reviewed available literature to develop key assumptions on stock and emission factors—notably, Enviros (2008), Defra (2008), BRA (2010), and contacted the five largest refrigerant Fillers & Packers in the UK that reported sales data to BRA in order to confirm/refine the estimates (BOC, A-Gas, National Refrigerant, Harp International and IDS Refrigeration Ltd.). ICF received feedback from two of these fillers and packers—Harp International and BOC—as well as from BRA. The sections below outline the assumptions and methodology applied based on this process.

Stock
Annual stock estimates were developed using data on the sales of refrigerant into the UK market from BRA (2010) for the years 2006 – 2010. This sales data is

disaggregated by refrigerant type and channels of distribution in 2009 and 2010. According to BRA (2013), the Fillers and Packers rebottle the refrigerant from 1 tonne containers purchased from producers into smaller containers. Average cylinders in the UK are assumed to be 13.6 kg, while small cans are assumed to be 340 g (Harp International 2013, Enviros 2008). The average growth rate of individual refrigerant sales from 2006 – 2010 (BRA 2010) was used to determine the refrigerant sales in years prior to 2006. From 2011-2012, it was assumed that refrigerant sales remained constant at 2010 levels, due to the wide ranging trends across refrigerants in recent years, and the uncertain impact of pending revisions to the EC F-gas Regulations. Based on historical refrigerant sales into the mobile versus stationary sectors from BRA (2010), it is assumed that approximately 40% of HFC-134a is sold into the mobile sector, 90% of which is sold in cylinders for professional servicing of motor vehicle air-conditioners (MVACs), while the remaining 10% is sold into small cans for use by DIYers servicing their own MVACs. It should be underscored that the actual percent of service jobs performed by professionals versus DIYers in the UK, or the number of small cans sold onto the market, is highly uncertain. The remaining 60% of HFC -134a is sold into the stationary sector in 13.6 kg cylinders.

In July 2008, disposable refrigerant cylinders were banned from the UK market. Because historical data on the sale of disposable versus reusable cylinders prior to the 2008 ban are not available, ICF assumed that the UK refrigerant cylinder market included 50% disposables and 50% refillables from 1990 to 2007. To account for the transition due to the regulation from the use of disposables to the use of 100% refillables in 2009, it was assumed that the market consisted of 75% refillable containers and 25% disposables in 2008.

Chemicals in Use

According to BRA (2010), HFC-134a and HFC refrigerant blends R-404A, R-507A, R-407C, and R-410A are the dominant refrigerants sold in this sector. As BRA sales data for R-404A and R-507A are combined, it was assumed that R-404A represents 95% of sales and R-507A the remaining 5% (SKM Enviros 2014). BRA data also provides sales values for “Other HFC Blends”. “Other HFC Blends” represent only 1.4% of the market in 2006 which increases to 10.8% in 2010. Based on consultation with industry stakeholders, it was assumed that “Other HFC Blends” sales are evenly distributed amongst R-407F and R-407A. For the sake of HFC reporting, blends are shown based on their original constituents.

Emission Factors

A summary of the assumed emission factors is provided in the table below. The packaging loss rate of 0.1% is based on consultation with Harp International (2013) and SKM Enviros (2014). This rate is deemed conservative but appropriate for the UK industry as a whole, although certain facility-specific emissions are reportedly as low as 0.005%, based on mass balance measurements taken by Harp International (2013). The disposal loss rates for disposable cylinders and small cans are based on IPCC default values, which are further supported by Enviros (2008); the disposal loss rate for refillable cylinders is based on SKM Enviros (2014).

Table 10: Summary of Emission Factors for the Refrigerant Container Sector

Emission Factor	Disposable cylinders	Refillable cylinders	Small Cans
Packaging Loss Rate	0.1%	0.1%	0.1%
Disposal Loss Rate	2.0%	0.1%	20%

A major industrial gas supplier in the UK confirmed that all containers (cylinders and small cans) sold on the UK market are filled and packaged in the UK (BOC 2013). Due to a lack of readily available data on refrigerant container exports from the UK, no packaging emissions are assumed to occur from this potential source. Therefore, the packaging emission factors are applied to the total amount of refrigerant sold. Disposal emission factors were similarly applied annually to total refrigerant sales. As seen in the table above, these emission factors for cylinders are dependent upon the timing of the 2008 regulation. Harp International emphasized that strong economic incentives drive the recovery and recycling of refrigerants from cylinders, therefore leaks during recovery are generally minimised and these estimates are considered to be conservative (Harp International 2013).

It should be noted that the disposal emission factor for small cans may be overstated in recent years, as information indicates that there has been a UK industry take-back program in place for small cans since April 2010 to reduce refrigerant disposal losses and increase recycling; however, because the extent to which this take-back program has been implemented across the UK is unclear, emission factors have conservatively not been reduced.

Results

The emission estimates for the refrigerant container sector are presented in the figure below. As shown, the estimates demonstrate an increase in emissions over time until the regulation in July 2008 banned disposable refrigerant cylinders. This ban caused a steep decrease in emissions from this sector. Following this legislation, emissions increased slightly due to rising servicing demand in the refrigeration and air conditioning sector.

Figure 11: F-gas Emission Estimates in the Refrigerant Container Sector

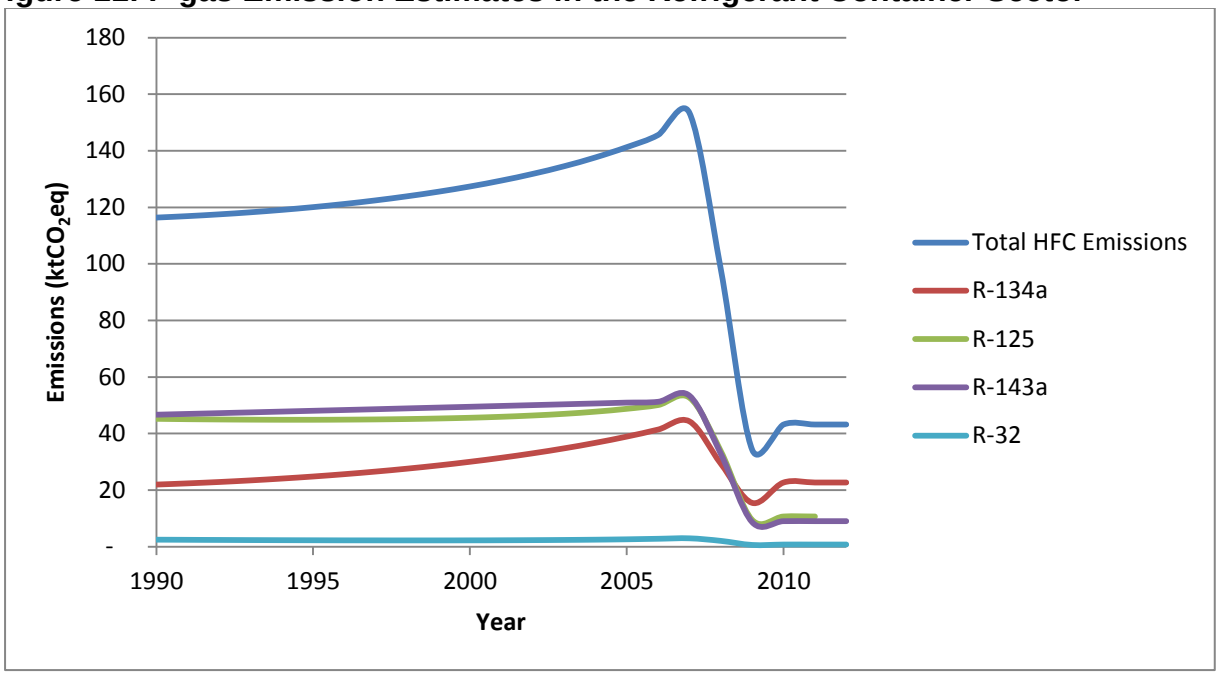
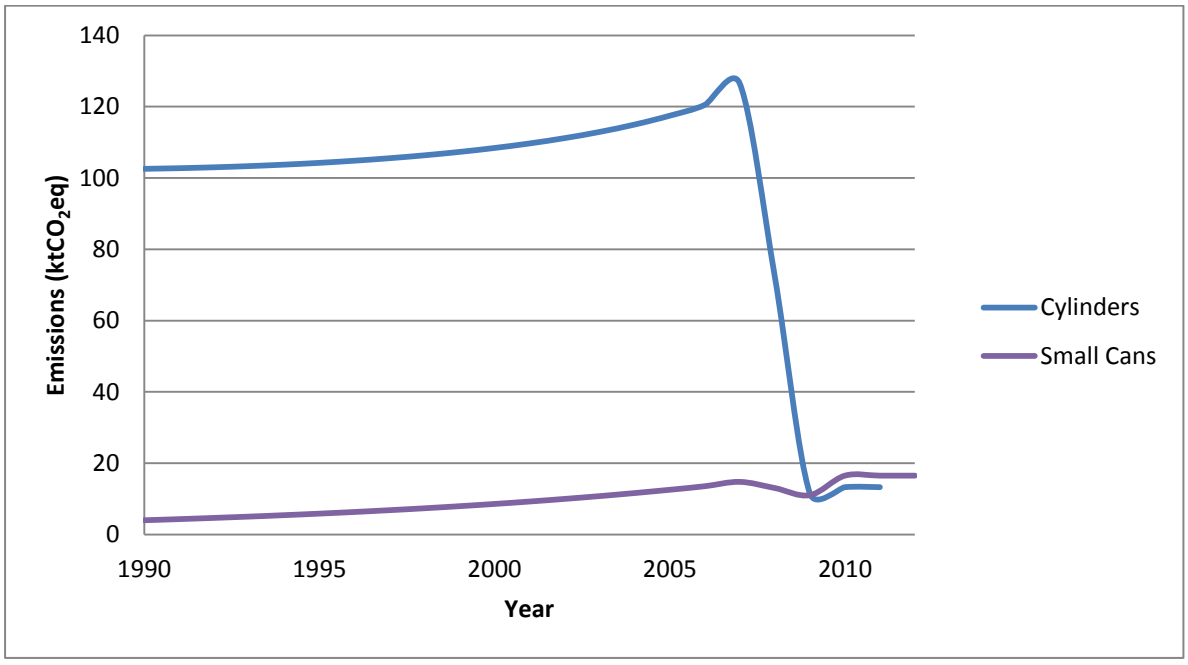


Figure 12: F-Gas Disposal Emission Estimates from Cylinders vs. Small Cans in the Refrigerant Container Sector



Uncertainty

The results of the uncertainty analyses for 1995 (base year) and 2011 are summarised in the table below. For 1995, HFC emissions were estimated to be between 61.53 and 182.41 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 49% below and 52% above the emission estimate of 120.08 $GgCO_2eq$. For 2011, HFC emissions were estimated to be between 20.05 and 56.37$GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 54% below and 30% above the emission estimate of 43.21

$GgCO_2eq$. For the 1995 estimates, the key sources of uncertainty in this sector are the quantity of refrigerant sold in refillable versus disposable cylinders (which impacts losses at disposal), as well as the back-casting of refrigerant use (sales) based on data from 2006-2010. For the 2011 estimates, the most significant source of uncertainty is the amount of refrigerant sold in cylinders versus small cans in the mobile sector; the lower bound of uncertainty is also driven by the emission factor at manufacture/packaging, as industry stakeholders indicated that release during packaging may be as low as 0.005% (compared to the 0.1% that is assumed).

Table 11: Quantitative Uncertainty Estimates for 1995 and 2011 HFC Emissions from Refrigerant Containers

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		($GgCO_2eq$)	($GgCO_2eq$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HFCs	1995	120.08	61.53	182.41	-49%	52%
HFCs	2011	43.21	20.05	56.37	-54%	30%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.

Future Inventory Updates

Given the increasing use of low-GWP alternatives across the EU in response to the review of the EC F-Gas Regulation as well as the MAC Directive, consumption of HFC-134a as well as other common HFC refrigerants is expected to decline. Therefore, it will be important to update the inventory, with actual refrigerant sales data which can be purchased from BRA for the price of £3,000. These reports provide five years of annual sales of refrigerant placed on the market in the UK, disaggregated by refrigerant type and channels of distribution. **ICF recommends that DECC purchase this data in 2015 to obtain sales data for 2011 through 2015.** The level of effort associated with this activity is low. Alternatively, trends in refrigerant consumption for the EU can be analysed as a proxy for refrigerant used in the UK servicing sector, based on the annual data reported by companies on the production, import and export of F-gases in the EU. However, because such reports track EU refrigerant consumption for both new and existing equipment, they are unlikely to serve as accurate proxies for refrigerant consumption trends in the service market alone.

In addition, further research should be conducted to improve the emission estimates from small cans by (1) confirming the number of small cans sold annually in the UK or the percentage of refrigerant sold into the mobile servicing sector in small cans versus cylinders, and (2) the extent to which a take-back program is being successfully implemented for small cans across the UK. This can be accomplished through a shelf survey and/or by contacting producers/distributors of small cans, which may require a high level of effort. Further research may also be conducted in the future to (1) confirm the prevalence of other HFC blends in the UK market, (2) modify assumed cylinder sales by refrigerant type to account for the use

of large (60 kg) cylinders, (3) incorporate emissions from 40-tonne isotanks, and/or (4) lower the assumed percentage of disposable cylinders relative to reusable cylinders prior to 2008.

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3.2 2.G.2.a: Military Applications

Introduction

The Boeing E-3 Sentry, a type of Airborne Warning and Control System (AWACS), provides air and sea surveillance, airborne command and control, weapons control and can also operate as an extensive communications platform (RAF 2013). SF_6 is known to be used as an insulating medium in the radar systems of AWACS to prevent electric flashovers in the hollow conductors of the antenna (IPCC 2006). The SF_6 is released from the system into the atmosphere to maintain the pressure difference between the system and the outside air when it ascends. In addition, SF_6 emissions can also occur due to system leakage, or losses during refill while planes descend.

Research Approach

In an attempt to accurately estimate emissions from this source, the MoD was contacted about its use of SF_6 for AWACS and other military applications. However, no information was provided by the MoD in time for this study. Instead, for AWACS,

a Tier 1 method from the 2006 GLs was used which relies on the use of a default emission factor and activity data (i.e., the number of planes in AWACS fleet). ICF conducted research to confirm if the IPCC-provided number of AWACS in the UK fleet, which was published in 2006, is the same in 2012 and how it has changed since 1990.

Activity Data

The Tier 1 method uses the total number of planes as the activity data. ICF's research of the UK Royal Air Force (RAF) website confirmed that the RAF carries the same number of AWACS (seven) in 2012 as reported in the 2006 GLs (RAF 2013). ICF further confirmed that RAF had seven AWACS since 1990. Indeed, AWACS are a part of the Number 8 squadron of the RAF and they were acquired in 1985 (8 Squadron 2012). However, of the seven AWACS present in UK Fleet, not all are designated as forward available fleets. During times of low activity, some AWACS are placed as depth fleet, i.e., not operational, and therefore do not contribute to emissions. In 2012, only four AWACs were classified as forward available fields (MOD 2012).

Emission Factors

The Tier 1 method uses a default emission factor of 740 kg SF_6 per plane per year.

Methodology

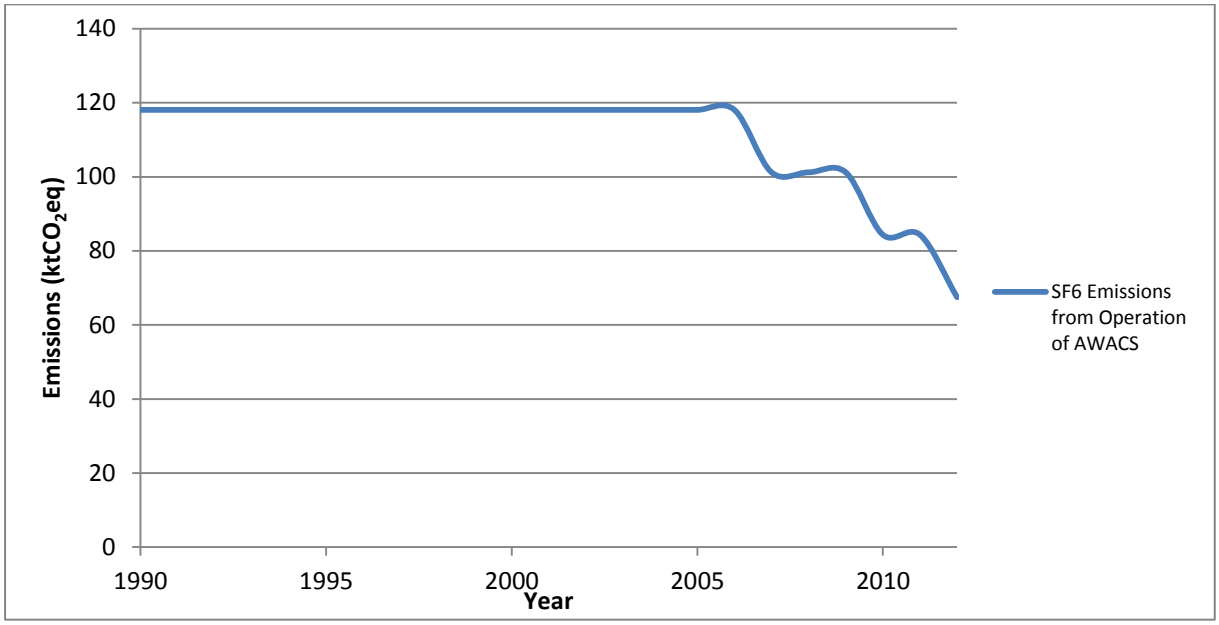
SF_6 emissions from the operation of UK AWACS are estimated based on a Tier 1 method. The Tier 1 emission equation is shown below:

$$User\ Emissions = 740\ kg\ \cdot Number\ of\ planes\ in\ AWACS\ fleet$$

Results

Estimated emissions for the military applications sector, more specifically for AWACs, are presented in the figure below. As shown, emissions are constant through 2005 but decrease through 2012 due to a reduced forward available fleet. It should be underscored that the Tier 1 method relies on a constant emission factor, but actual emissions will vary based on the number of sorties (missions), with emissions higher during periods of high military operations and lower during times of low military operations.

Figure 13: SF_6 emissions from the operation of AWACS



Uncertainty

The results of the uncertainty analyses for 1995 (base year) and 2011 are summarised in the table below. For 1995, SF_6 emissions were estimated to be between 102.04 and 134.12 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately +/-14% around the emission estimate of 118.10 $GgCO_2eq$. For 2011, SF_6 emissions were estimated to be between 72.85 and 95.82 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of also approximately +/-14% around the emission estimate of 84.36 $GgCO_2eq$. The key source of uncertainty in this sector is the emission factor, for which the uncertainty range was published in 2006 IPCC GLs.

Table 12: Quantitative Uncertainty Estimates for 1995 and 2011 SF6 Emissions from AWACS

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		($GgCO_2eq$)	($GgCO_2eq$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
SF_6	1995	118.10	102.04	134.12	-14%	14%
SF_6	2011	84.36	72.85	95.82	-14%	14%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.

Future Inventory Updates

To update the inventory each year, the number of AWACS in the UK's forward available fleet must be confirmed by consulting the website of the UK Royal Air

Force. This information can also be gathered from the Ministry of Defence Statistical Series 4 – Equipment Bulletin 4.01 – Formations, Vessels, & Aircraft. If possible, a shift from using a Tier 1 to a Tier 2 method is recommended. This would require obtaining data from the UK Royal Air Force on the SF_6 inventory, acquisitions of SF_6, disbursements of SF_6, and fleet charge.

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3.3 2.G.2.b: Accelerators

Introduction

SF_6 is used in particle accelerators as an insulating medium. High voltage equipment is usually contained and operated within a vessel filled with SF_6 at a pressure exceeding atmospheric pressure in order to prevent arcing and short circuits. SF_6 can be emitted from this use because of: leaks during maintenance (gas recovery and transfer), actuating pressure relief valves, and through slow leaks (IPCC 2006). Emissions from particle accelerators depend on various factors, the charge of the equipment being the most influential factor. Hence the IPCC identifies various types of accelerators to more accurately model emissions. The two broad categories include 1) research and university accelerators that holds higher charge and 2) medical and industry accelerators that hold lower charge than the former category. Industrial accelerators are further sub-divided into high voltage and low voltage accelerators. Medical accelerators, or linear particle accelerators, often called linacs, are used in radiotherapy applications.

The emissions from industrial particle accelerators are a result of leakage during operation and repair, Research and industrial high voltage systems usually need to be opened more frequently than industrial low voltage accelerators. Hence the emission factor of low voltage industrial accelerators is comparably lower. In the case of radiotherapy applications, industrially pre-set particle accelerators with hollow conductors filled with SF_6 are used. The emissions of SF_6 are planned releases of SF_6. Radiotherapy accelerators are typically opened two times a year when being serviced and the SF_6 contained is not captured but completely released. ([Schwartz, 2005).

Methodology

SF_6 emissions from research and university accelerators are estimated using an IPCC Tier 2 method – an accelerator-level emission-factor approach. This required information on the individual charge of the various research and university accelerators operating in the UK. This information is used in the following equation along with default emission factors (IPCC 2006):

$$Total\ Emissions = SF_6\ university\ and\ research\ particle\ accelerator\ Emission\ Factor \times \sum Individual\ Accelerator\ Charges$$

Where:

SF_6 university and research particle accelerator Emission Factor = 0.07 kg SF_6 per kg SF_6 charge, the average annual university and research particle accelerator emission rate as a fraction of the total charge.

Individual Accelerator Charges = SF_6 contained within each university and research accelerator.

The SF_6 emissions from medical and industrial accelerators are estimated using a Tier 1 method – country-level method. Given the scale of the number of medical and industrial particle accelerators, it was not feasible to collect individual charge information of each accelerator. The Tier 1 estimation method consists of the following equation, which relies on default emission factors (IPCC 2006):

$$Emissions = (Number\ of\ particle\ accelerators\ that\ use\ SF_6\ by\ process\ description\ in\ the\ country) \times (SF_6\ Charge\ Factor, kg) \times (SF_6\ applicable\ particle\ accelerator\ Emission\ Factor)$$

Where:

Number of particle accelerators by type in the country = The total number of particle accelerators by type (industrial high voltage, industrial low voltage and radiotherapy)

SF_6 charge factor = The average SF_6 charge in a particle accelerator by process description.

SF_6 particle accelerator Emission Factor = The average annual SF_6 particle accelerator emission rate as a fraction of the total charge by process description. These factors are presented below in Table 13.

Table 13: IPCC Default Tier 1 Particle Accelerator Emission Factors

Process Description	SF_6 Charge Factor, kg	Emission Factor, kg/kgSF_6 charge
Industrial Particle Accelerators – high voltage (0.3-23 MV)	1300	0.07
Industrial Particle Accelerators – low voltage (<0.3 MV)	115	0.013
Medical (Radiotherapy)	0.5	2.0

Research Approach

For the Particle Accelerators sector, ICF contacted the Science and Technology Facilities Council (STFC) and the Cockcroft Institute to gather activity data for the Tier 1 and Tier 2 methods.

STFC and the Cockcroft Institute were able to provide ICF with the charge information, years of operation and status of usage of SF_6 in the research and university particle accelerators in the UK. It is assumed that the charges of the accelerators are constant for all the years. For one facility whose charge was unavailable, a default charge in Tier 1 was assumed.

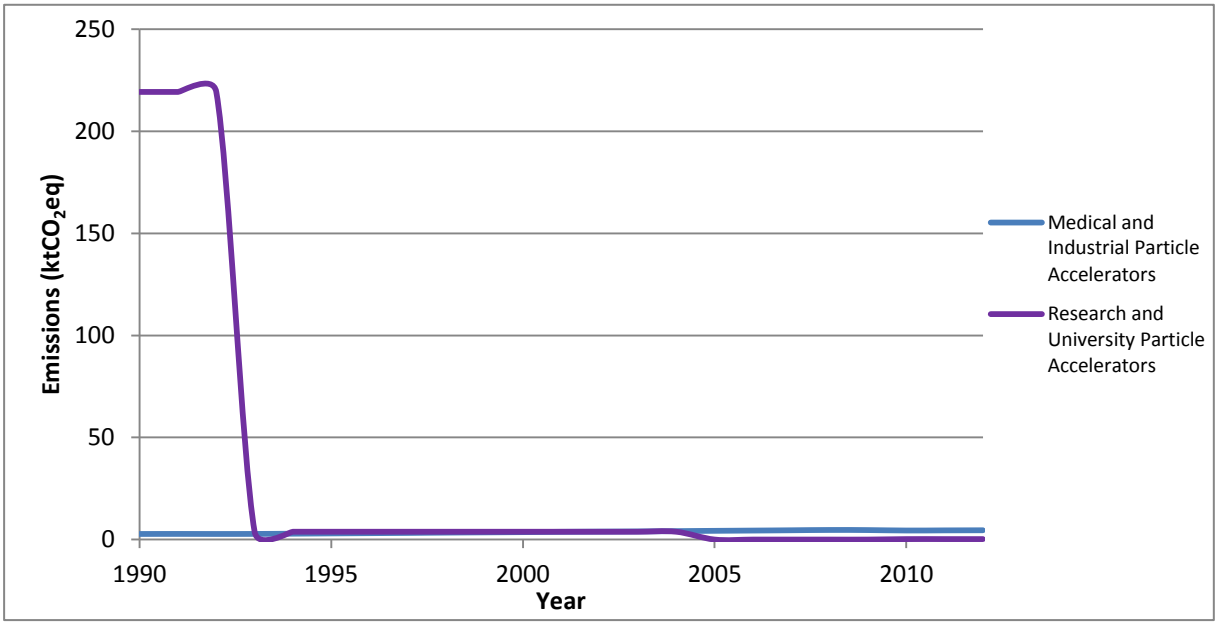
The Cockcroft Institute also provided a rough estimate of the number of low voltage industrial accelerators in the UK for 2012—approximately 100 (Cockcroft Institute 2013). The total number of medical accelerators for 2012 was estimated from a list of accelerators compiled by a member of STFC, estimated at 50 (STFC 2013). Due to the large number of medical and industrial accelerators, collecting accelerator-specific charge data was not feasible under this study. Therefore, a Tier 1 approach was used to estimate emissions. To confirm the number of accelerators, ICF also solicited information from the National Physical Laboratory and the Institute of Engineering and Technology, but without success. In the absence of specific information on the number or percent of medical particle accelerators that use SF_6, ICF conservatively assumed that 100% of UK medical particle accelerators use and emit SF_6. To estimate SF_6 emissions for years 1990-2011, ICF scaled the 2012 estimate based on historical UK GDP growth rates.

Results

The F-gas emission estimates for the particle accelerators sector are shown in the figure below. As shown, emissions of research and university particle accelerators are very high for the period 1990-1992. This is because of the operation of the Nuclear Structure Facility that held 135 tonnes of SF_6 charge. After its closure in 1992 (assumed to be at the end of 1992), the emissions of research and university particle accelerators and medical and industrial accelerators are at comparable scale. In 2004, the only operational particle accelerator ceased usage of SF_6 and, hence, the emissions are considered to be zero. Three other particle accelerators began operation in 2010, 2011, and 2012, respectively, leading to non-zero but small

SF_6 emissions due to their small charges. For the medical and industrial particle accelerators, the emissions rise as they were estimated based on GDP as proxy.

Figure 14: Estimated SF_6 Emissions from Particle Accelerators from 1990 to 2012



Uncertainty

The results of the uncertainty analyses for 1995 (base year) and 2011 are summarised in the table below. For 1995, total SF_6 emissions were estimated to be between 5.65 and 8.04 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 17% below and 18% above the emission estimate of 6.83 $GgCO_2eq$. For 2011, the SF_6 emissions were estimated to be between 4.00 and 5.44 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 15% below and 16% above the emission estimate of 4.71 $GgCO_2eq$. For both the 1995 and 2011 estimates, the key source of uncertainty in this sector is the total number of industrial and medical accelerators in operation. The uncertainty range is slightly higher in the base year as the total number of accelerators estimated was back-cast from 2011 estimates based on GDP.

Table 14: Quantitative Uncertainty Estimates for 1995 and 2011 SF6 emissions from AWACS

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		($GgCO_2eq$)	($GgCO_2eq$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
SF_6	1995	6.83	5.65	8.04	-17%	18%
SF_6	2011	4.71	4.00	5.44	-15%	16%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval

Future Inventory Updates

Updates to future inventories will involve updating activity data based on the number of operational research/university, medical, and industrial accelerators; this should be done by contacting the Cockcroft Institute and STFC. If this is not possible, updates may be done by scaling activity data based on proxy data, which could include GDP for medical/industrial accelerators, and research budgets for research/university accelerators.

To improve the inventory, further research can be conducted to use a Tier 3 approach for research and university particle accelerators and use a Tier 2 or Tier 3 approach for each medical and industrial accelerator. This would require collecting information on the charge of each SF_6-using accelerator (Tier 2) or performing individual accelerator-level emission estimates for each accelerator (Tier 3). A Tier 3 method would estimate emissions for each accelerator by tracking accelerator charge as well as the SF_6 consumption and disposal without the use of default emission factors. Such information would need to be collected by contacting each known accelerator, of which there are roughly 150.

References

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- AEA. 2013. UK Greenhouse Gas Inventory, 1990-2011 Annual Report for Submission under the Framework Convention on Climate Change. Prepared for Department of Energy and Climate Change. April 2013.
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3.4 2.E.4: Heat Transfer Fluid

PFCs are used as heat transfer fluids (HTFs) in commercial and consumer electronic applications. The various applications of PFC as HTFs use much smaller volumes of liquid PFCs than electronics manufacturing but are believed to be significant among

'niche' applications (IPCC 2006). Some examples of consumer applications include cooling kits for desktop computers and commercial applications include cooling supercomputers, telecommunication, and radar systems, as well as drive units on high-speed trains (IPCC 2006).

Methodology Identified

The specific PFCs used in consumer and commercial applications are similar to those identified in the electronics sector. To estimate emissions, the Tier 2 or Tier 3 method described in electrical equipment can be used to estimate emissions.

The Tier 2 method of electronics sector uses country-specific emission factor, along with the total nameplate capacity of the retiring equipment, fraction of retiring equipment whose PFCs are recovered, recovery efficiency, and fraction of recovered PFCs recycled, reused with no further treatment, or destroyed. Section 8.2.2 (Methodological Issues) of IPCC (2006) provides a detailed description of the methodology.

The Tier 3 method is a hybrid method that includes emissions by life cycle stage of equipment. This method is most detailed and estimates emissions from various stages such as manufacturing, installation, use, disposal and final use, and recycling and destruction. Section 8.2.2 (Methodological Issues) of IPCC (2006) provides a detailed description for estimating emissions from each stage of the life cycle.

Research Approach

Based on ICF's preliminary research, various applications of PFCs and other F-gases may be used as HTFs in the UK, including:

- Consumer electronics: cooling apparatus in personal PCs, workstations, gaming consoles, and server microprocessors, for both commercial and residential settings.
- Cooling systems that rely on convection to remove heat from an area, rather than relying on mechanical refrigeration, including recirculating coolers (i.e., systems with fluid pumps) and thermosiphons (systems relying on natural convection currents).
- Large ground-source geothermal heat pumps (organic rankine cycle [ORC] systems) and direct immersion cooling.

The amount of F-gases contained in these systems is wide-ranging. Consumer electronics typically have small charge sizes (e.g., on the order of 100 grams or less), whereas ground-source heat pumps range from hundreds to tens of thousands of kilograms of charge.

Based on ICF expert opinion, use of PFCs (e.g., C6F14) is likely to have been replaced by lower-GWP alternatives that are less costly, such as HFC-245fa, HFC-134a, HFC blends, or even new, low-GWP options such as HFO-1234ze or Solstice 1233zd(E).

However, given the broad and niche applications of these possible uses, the development of country-level emission factor for each of these uses in order to apply

IPCC's Tier 2 methodology was not feasible within the timeframe of this analysis. The Tier 3 mass-balance approach is also not feasible as the market research of the various uses was not possible given the time and budget constraints under this project. (As noted previously, a Tier 1 method is not possible given the type of activity data.) **For all of these reasons, ICF recommends that this sector be flagged for future research,** which should include identifying and contacting companies involved in each of the niche applications and gathering activity and/or emissions data. This would require a high level of effort.

References

- IPCC 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

3.5 2.E.2 TFT Flat Panel Display & 2.E.3 Photovoltaics

Methodology Identified

The 2006 GLs present multiple tiers of emission estimation methodologies from the flat panel display manufacturing and photovoltaic cell manufacturing sectors. The methodologies are the same as the tiers provided for the semiconductor industry, as the manufacturing processes of these sectors and semiconductor manufacturing are very similar. These sectors differ in only the default emission factors. The gases used in this sector are similar to semiconductor sector: CF_4, C_2F_6, C_3F_8, C_4F_8, CHF_3, SF_6, and NF_3. The tiers and their data requirements are:

- The Tier 1 method relies on the default emission factors along with the plant production capacity, in units of square meters (m^2) and the utilisation factor, in percentage. In the case of Photovoltaic cells a fraction of PV manufacture that uses fluorinated gases is also required as not all PV production processes requires the use of f-gases.

- The Tier 2a method relies on the consumption of various process gases. Default emission factor for each gas type is used to estimate emissions using this Tier. Please refer to section 22.4 where this methodology is described in detail.

- The Tier 2b method relies on process type-specific parameters which is the data on aggregate quantities of each gas fed into all etching and cleaning processes. This tier distinguishes between broad process types, but not between many possible individual processes. Industry-wide default values are provided in the 2006 GLs.

- The Tier 3 method relies on process-specific parameters using equations applicable to Tier 2b method. However, this method requires company- or plant-specific values as opposed to the default values provided in the 2006 GLs.

Research Approach
ICF identified either Tier 2a or Tier 1 to estimate the emissions from this sector. These options were identified as they were the methods with the highest likelihood of available data.

To obtain data for use in a Tier 2a method, ICF first identified that National Microelectronics Institute (NMI) represented flat panel display manufacturers in the UK (UK Government 2012). ICF sought activity data from NMI and was informed that NMI data is limited to semiconductor manufacturing and that UK does not have volume Flat Panel or PV manufacturing (NMI 2013). This information was corroborated by SKM Enviros (2012, unpublished), which indicated that UK NF_3 emissions are negligible.

ICF also contacted the British Photovoltaic Association to gather data from PV manufacturing in the UK. ICF was notified that there are no major PV manufacturers in the UK and statistics on F-gas use in the PV manufacturing in the UK are not available (BPA 2013).

After further evaluation of the information obtained on manufacturing practices in the UK, activity data for the Tier 1 method (capacity, in m^2) was not sought.[8] Applying Tier 1 EFs on non-volume manufacturers would result in erroneous estimates, since substrates that undergo processing do not necessarily result in final products; this is because non-volume manufacturers are R&D facilities that focus on only certain steps of the manufacturing process. Thus, on a per-manufacturing area capacity basis, R&D facilities will use more PFCs to process substrates compared to volume manufacturers.

Future Inventory Updates
Although not significant, emissions from this source could be added to future inventories by estimating emissions from small volume manufacturers of FPD and PV in the UK by directly contacting known facilities (e.g., FPD: Cambridge Display Technology, Sharp Laboratories; PV: G24i, Romag, Sharp UK, SunSolar Energy Limited).

References

- British Photovoltaic Association (BPA). 2013. Personal communications with Reza Shaybani. 4 November 2013.
- IPCC 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.
- National Microelectronics Institute (NMI). 2013. Personal Communications with Derek Boyd. 11 November 2013.

[8] This decision was made given the likely insignificant amount of emissions from this source and the limited remaining time available to collect additional industry data under this project

- UK Government. 2012. Flat panel display manufacturing: support and funding. Found at https://www.gov.uk/flat-panel-display-manufacturing. 11 September 2012.

3.6 2.B.9.a: By-Product Emissions (Production of Other Fluorinated Chemicals)

Updates Required by 2006 IPCC Guidelines

A large number of fluorine-containing greenhouse gases can be produced as by-products of fluorochemical manufacture and emitted into the atmosphere (IPCC 2006). While the current UK inventory includes estimates of fugitive and by-product emissions from halocarbon production,[9] the 2006 GLs cites examples of other chemical processes that lead to by-product emissions, including:

- Telomerisation Process used in the production of fluorochemicals fluids and polymers;
- Photooxidation of tetrafluoroethylene to make fluorochemical fluids;
- Direct Fluorination often used in SF6 production;
- Production of uranium hexafluoride (UF6), which can lead to by-product emissions of SF6;
- Halogen Exchange Processes to make low boiling PFCs like C2F6 and CF4, HFC 134a and 245fa; and
- NF3 manufacturing by direct fluorination.

Thus, inclusion of this sector into the UK's inventory may be needed to cover by-product emissions of fluorinated chemicals (other than those currently estimated, e.g., HFC-23 from HCFC-22 production).

Using a Tier 1 methodology, a default emission factor can be used to estimate production-related emissions of individual HFCs, PFCs, SF_6, and other fluorinated gases in the following equation per the 2006 GLs:

$$E_k = EF_{default,k} \times P_k$$

Where:

E_k = production-related emissions of fluorinated greenhouse gas *k*, kg
$EF_{default,k}$ = default emission factor, kg/kg
P_k = total production of fluorinated greenhouse gas *k*, kg

The Tier 2 methodology is based on process efficiencies and is less valuable for plants with expected lower inefficiency from these other by-product emissions. The Tier 3 methodology is the most accurate for estimating emissions from this source as it is the sum of specific emissions of each by-product determined using estimated

[9] This includes emissions from F2 Chemicals Limited (a manufacturer of PFCs) and Mexichem Fluor (a manufacturer of HFCs); it was confirmed by DECC/Ricardo-AEA that the methodology for estimating these emissions, based on data reported to the UK Pollution Inventory, is sound.

composition and flow rates of gas streams vented to the atmosphere. Therefore, specific activity data from manufacturers is required for the most accurate emissions calculations.

Research Approach

ICF conducted research to understand relevant production processes responsible for by-product emissions of fluorinated chemicals that may be carried out in the UK. ICF's approach was to contact producers of UF_6 to determine the extent to which processes that lead to by-product emissions of "other" fluorinated GHGs is occurring at manufacturing plants in the UK and if they significantly contribute to emissions (e.g., >1% of F-gas emissions).

Results

Emissions from this new potential source in the inventory were not estimated as they were deemed insignificant. The URENCO UK Limited site is the only UF_6 enrichment facility in the UK. UF_6 production facilities are located at Springfields near Preston and operated by Springfields Fuels Limited. URENCO UK Limited indicated that none of the production processes at their enrichment facility lead directly to the production of SF_6 or other F-gases. The enrichment plant processes UF_6 and this activity will lead to the discharge of fluorides through the gaseous vent system. In 2012, the discharge of fluorides[10] from the enrichment process amounted to only 3 kg (URENCO 2013). Furthermore, URENCO's Sustainability Report in 2009 indicates that they make no direct emissions of PFC or SF_6. Consultation with Springfields Fuels Limited indicated that they also do not have any SF_6 emissions from their facility (Springfields Fuels Limited 2013).

Based on consultation with industry stakeholders in this sector, emissions calculations for this new potential source in the inventory are not necessary as emissions from this sector were concluded to be insignificant.

Future Inventory Updates

Given that the list of chemical processes that lead to by-product emissions identified in the 2006 GLs is not extensive, it is possible that other UK sources of F-gas emissions may be identified in the future that could lead to emissions. Further research can be conducted if and/or when other production processes are identified in the UK, which would likely require a significant level of effort. Until that time, this source is not believed to be a priority for future inventory updates.

References

- European Environment Agency (EEA). 2013. Fluorinated greenhouse gases 2012: Data reported by companies on the production, import and export of fluorinated greenhouse gases in the European Union. Available at: http://www.eea.europa.eu/publications/fluorinated-greenhouse-gases-2012.
- IPCC 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel

[10] URENCO (2013) did not provide further details about the specific species of fluorides.

on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.
- Springfields Fuels Limited. 2013. Personal Communication with Andrew Parkinson of Springfields Fuels Limited on 28 November 2013.
- URENCO. 2013. Personal Communication with Michael Peers on 21 November 2013.

3.7 2.G.2.c: Other (Sound-proof Windows)

Methodology Identified
The 2006 GLs provides sets of equations to estimate SF_6 emissions from sound-proof windows during window assembly, use, and disposal. The IPCC provides only one methodological tier to estimate these SF_6 emissions; this tier is illustrated in the equations below:

Emissions from Assembly (IPCC equation 8.20)

$$Assembly\ Emissions\ in\ year\ t = 0.33 \times SF_6\ purchased\ to\ fill\ windows\ assembled\ in\ year\ t$$

Emissions from Use (IPCC equation 8.21)

$$Leakage\ Emissions\ in\ year\ t = 0.01 \times Capacity\ of\ Existing\ Windows\ in\ year\ t$$

Emissions from Disposal (IPCC equation 8.22)

$$Disposal\ Emissions\ in\ year\ t = Amount\ Left\ in\ Window\ at\ End\ of\ Lifetime\ in\ year\ t \times (1 - Recovery\ Factor)$$

The IPCC suggests the following assumptions: 1) the leakage rate of windows can be assumed to be 1% per year, which includes glass breakage; 2) the lifetime can be assumed to be 25 years for each window; and 3) the recovery factor in equation 8.22 can be assumed to be 0 if country-specific values are not available.

Research Approach
To obtain the data to estimate SF_6 from sound-proof windows, ICF contacted the UK Glass and Glazing Federation (GGF). The GGF notified ICF that SF_6 has not been used in windows in the UK as a sound proofing medium prior to the ban on its use in July 2007 (GGF 2013). GGF also notified ICF that for sound proofing, the UK either uses secondary glazing or primary glazing-like laminated glass, double glazing etc.; SF_6 is not used for these purposes. For insulating glass, other gases are used for cavity fill (GGF 2013). This is consistent with the finding from Defra (2012) that double glazing was produced in some EU countries using SF_6 as an insulating gas, but this practice has never been a popular option in the UK.

ICF was also notified by SKM Enviros that a 1999 research paper for Defra indicated that “[t]he proportion of barrier gas windows in the UK which use SF_6 is thought to be

negligible" (SKM Enviros 1999). Further research by SKM Enviros in 2007 also did not find emissions of SF_6 from windows (AEA 2004, ECOFYS 2002).

The UK situation described above is known to contrast with the situation in Germany based on personal communication with SKM Enviros, and supported by further research by ICF requested by DECC. ICF investigated the usage of SF_6 in sound-proofing windows in Germany and found sources citing that around half of total SF_6 emissions came from sound-proof windows in 2002 (ECO-WORLD. 2002). While this was the case in Germany, it was confirmed through GGF, coupled with the SKM view, that there was no use of SF_6 in sound-proof windows in the UK.

Future Inventory Updates
No inventory updates are required for this sector. It is believed that sufficient research has been conducted to confirm that sound-proof windows are not a significant source of emissions in the UK.

References

- AEA. 2004. "Emissions and Projections of HFCs, PFCs and SF6 for the UK and Constituent Countries". AEA Technology. 2004
- Department of Environment, Food and Rural Affairs (DEFRA). 2012. General Guidance: F Gas and Ozone Regulations Information Sheet GEN 3: Markets & Equipment. April 2012. Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/182572/fgas-gen3-markets-equipment.pdf
- ECOFYS. 2002. Costs and the impact on emissions of potential regulatory framework for reducing emissions of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. Draft report. September 2002.
- ECOWORLD. 2002. Gasfüllungen in Schallschutzfenstern und Autoreifen fördern Treibhauseffekt. http://www.eco-world.de/scripts/basics/econews/basics.prg?a_no=6747&main=drucken citing original source Umweltbundesamt für Mensch und Umwelt.
- Glass and Glazing Federation. 2013. Personal Communications with Russell Day, Technical Officer. 27 November 2013.
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- SKM Enviros. 1999. "UK Emissions of HFCs, PFCs, and SF6 and Potential Emission Reduction Options". March Consulting Group, 1999.

3.8 2.G.2.c Other (Cosmetic & Medical Applications)

Updates Required by 2006 IPCC Guidelines
According to the 2006 GLs, PFCs with relatively large molecular weights (e.g., $C_{10}F_{18}$) are used in certain cosmetic and medical applications. Cosmetic applications include anti-wrinkle creams and are estimated to consume fairly small amounts of PFCs. While the UNFCCC (2010) does not provide an exhaustive listing of known PFCs used in medical applications, it notes use of perfluorooctane (C_8F_{18}) for eye

surgeries, as well as perfluorodecalin ($C_{10}F_{18}$ or PFC-9-1-18) for storage of pancreatic tissue for transplants, eye surgery, lung therapy and diagnosis, use as a contrast agent in ultrasonic and MRI examinations, blood extension, wound healing, and treatment of diseases of the middle ear.

PFCs are assumed to be emitted into the atmosphere within one year of purchase for cosmetic applications; therefore, emissions should be calculated using an equation for prompt emissions, per the 2006 GLs:

$$Emissions_t = (0.5 \times Amount\ sold_t) + (0.5 \times Amount\ sold_{t-1})$$

For medical applications, the emission rates could be variable depending on the application.

Research Approach

ICF conducted research to understand the market size of cosmetic and medical applications using PFCs, determine a default emission factor for PFCs per various applications, and estimate the average quantity of PFCs used per product. The emission rates for medical applications are variable. Therefore, ICF's approach was to identify and contact UK manufacturers and suppliers of relevant cosmetic and medical applications to obtain activity data and further investigate the validity of an assumption for emission factors from this source. The only manufacturer/supplier readily identified through internet research was OriGen Biomedical, a manufacturer of Perflubronc®, a PFC solution for lung lavage. OriGen Biomedical is a U.S.-based manufacturer that distributes its products in the UK through Quest Biomedical.

Results

Emissions from this new potential source in the inventory were not estimated. Based on consultation with OriGen Biomedical, emissions of PFCs from lung lavage are insignificant and also cannot easily be quantified. The lung lavage procedure instills the PFC, which is in liquid form, into the lungs and then suctions the liquid out after a short period of time. OriGen Biomedical was unaware of studies investigating the evaporation rate of PFCs during this procedure. Additionally, the procedure only lasts a few minutes so there is not much time for a measurable amount of PFCs to be exhaled (OriGen Biomedical 2013).

Furthermore, Quest Biomedical indicated that they do not distribute PFC-containing products in the UK. They also could not identify any other UK manufacturers/suppliers of PFC-containing cosmetics or medical applications (Quest Biomedical 2013).

Based on this information, emission calculations for this new potential source in the inventory were not deemed necessary, as emissions from this sector are believed to be insignificant. Data availability is scarce and it is difficult to obtain data from stakeholders. Although the 2006 IPCC GLs provide a default emission factor for cosmetic applications, it was difficult to identify stakeholders to determine the market size of cosmetic applications using PFCs. Additionally, because OriGen Biomedical indicated that the use of PFCs in one particular medical application leads to insignificant emissions, it was not deemed worthwhile to devote significant resources to further researching this sector.

Future Inventory Updates
Additional research into this sector could be conducted to further confirm that PFC emissions from this source are insignificant by performing laboratory tests on the relevant cosmetics and/or medical application that use PFCs. Indeed, OriGen Biomedical suggested that, for a fee (which would need to be negotiated), their laboratory could attempt to study the evaporation rate of PFCs during lung lavage, although it is possible that the procedure is too short to conduct such analysis. Further, the
UK Cosmetic, Toiletry & Perfumery Association (CTPA) could also be contacted to estimate the market size of cosmetic applications using PFCs, if any. Additional research could also be conducted to identify other UK companies producing and/or distributing relevant cosmetic products or performing medical applications, which could require significant effort (given that the formulations of such products/applications are not typically disclosed to the public). This category can also be broadened to include medical aerosols, such as freeze sprays (e.g., wart removers, pain relievers) and liquid bandages. It is anticipated that this research would require a high level of effort.

References

- IPCC 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.
- OriGen Biomedical. 2013. Personal Communication with Shanna Seigel of OriGen Biomedical on 12 November 2013.
- Quest Biomedical. 2013. Personal Communication with Gary Cavanagh of Quest Biomedical on 14 November 2013.

3.9 2.G.2.c: Other (Tracer Testing)

Introduction
The use of SF_6 as a tracer gas to certify fume hoods is a practice established by ASHRAE in the test procedure ASHRAE-110, “Method of Testing Performance of Laboratory Fume Hoods” (ASHRAE 1995). SF_6 is emitted in the fume hood and the concentration of the gas is measured after some time has passed. This is to ensure that the gases created under the fumes, toxic or otherwise, are properly ventilated. The amount of gas used per test is dependent on the tester. All of the SF_6 used in tracer tests is lost in the atmosphere and so the emissions are treated as prompt emissions—i.e., each test results in direct emissions of SF_6 (IPCC 2006). SF_6 is also used for tracer testing of nuclear power plant control room emergency ventilation systems (CARB 2009).

Methodology
Due to data limitations, SF_6 emissions were estimated using a slightly modified Equation 8.23 of Volume 3 of the 2006 GLs. The SF_6 emission is calculated on a per-use basis as opposed to the amount purchased/sold as provided in the equation. This modified method relies on the number of tracer tests conducted annually as the activity data, which when multiplied by the emissions per test as the emission factor, gives the total SF_6 emissions from this sector. This method is represented in the following equation:

$$Total\ Emissions = Emissions\ per\ test \times Total\ Number\ of\ Tests$$

Additional emissions may also occur from bottling, leakage, and piping; however, such emissions cannot be estimated without activity data and are believed to be de minimis.

Research Approach

In order to apply the method above, ICF had to gather information on the number of tracer tests conducted annually (activity data) and the emissions per test (emission factor).

ICF first identified various companies that performed fume hood tracer testing. ICF contacted the three largest companies that perform tracer tests in the UK (Crowthorne, Dale Flow, and Invent-UK) and obtained the company-specific emissions per test and the total number of tests performed in 2012 (Crowthorne 2013, Dale Flow 2013, Invent-UK 2013). For the prior years, the total numbers of tests have been estimated by scaling the number of tests performed in 2012 to the UK's historical GDP growth rate. The amount of emissions per test for prior years was held constant unless a company specified that the volume had increased after a certain period. The value of the emissions per test differed among companies and ranged from 0.033 to 0.046 kg SF_6 per test.

ICF also verified when these companies came into existence. Other, smaller companies were identified but were not contacted as—according to qualitative information from Dale Flow (2013)—the bulk of the market is covered by the three major companies, and any additional research was not expected to result in significant changes to the emission estimates, which only account for a very small share of total F-gas emissions.

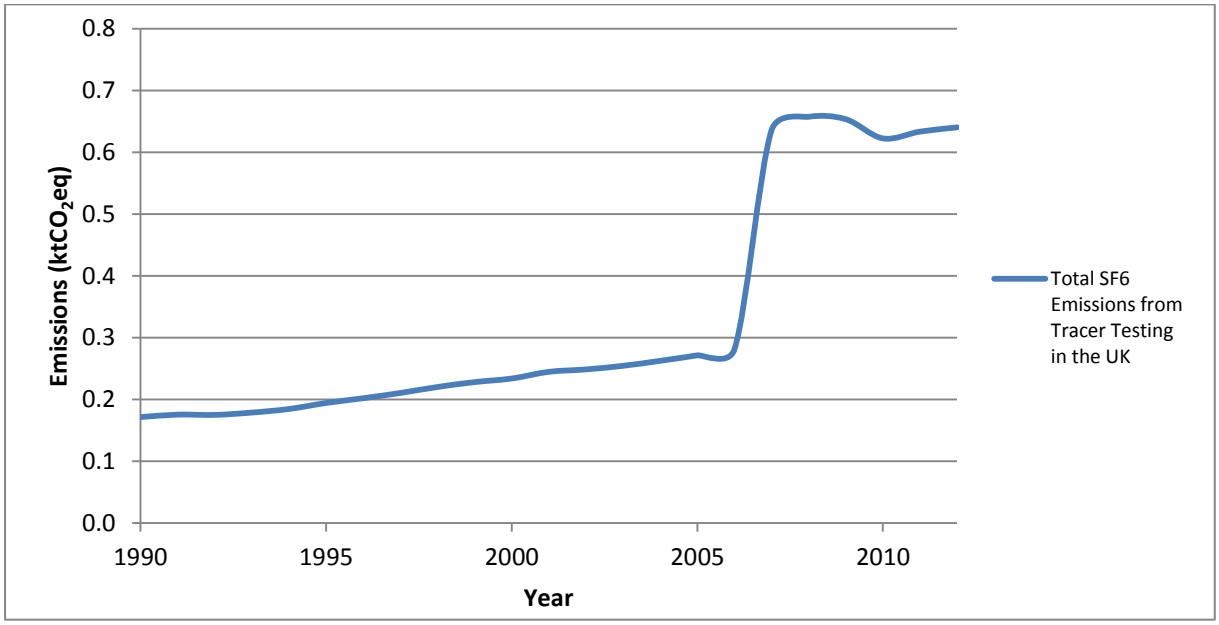
ICF also contacted Sellafield Ltd, a nuclear decommissioning company, which uses SF_6 to conduct tracer tests, and included their company specific emission factor and total number of emissions (Sellafield 2013).

Finally, ICF contacted the UK Nuclear Regulation Agency to confirm if there is any use of SF_6 in the tracer testing of nuclear power plant control room emergency ventilation systems in the UK. ICF was unable to obtain information because the inquiry did not fall within the remit of the Office of Nuclear Regulation/Health and Safety Executive. However, ICF experts believe that such use was replaced many years ago.

Results

SF_6 emission estimates from tracer testing are shown in the figure below. As shown, the estimates grow over time with a sharp increase in emissions in 2007 due to the establishment of a new facility that performs a significant amount of testing.

Figure 15: SF_6 Emissions from Tracer Testing



Uncertainty

The results of the uncertainty analyses for 1995 (base year) and 2011 are summarised in the table below. For 1995, total SF_6 emissions were estimated to be between 0.12 and 0.28 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 36% below and 44% above the emission estimate of 0.19 $GgCO_2eq$. For 2011, the SF_6 emissions were estimated to be between 0.60 and 0.73 $GgCO_2eq$ at the 95% confidence interval; this indicates a range of approximately 5% below and 15% above the emission estimate of 0.63 $GgCO_2eq$. For the 1995 estimates, the key sources of uncertainty in this sector are the total number of tests performed by the two major companies. The uncertainty in estimating the percent market share represented by the four companies that provided data on tracer testing activity introduces the next greatest impact on overall uncertainty. For the 2011 estimates, the latter represents the most significant source of uncertainty.

Table 15: Quantitative Uncertainty Estimates for 1995 and 2011 SF_6 Emissions from Tracers

Gas	Year	Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		($GgCO_2eq$)	($GgCO_2eq$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
SF_6	1995	0.19	0.12	0.28	-36%	44%
SF_6	2011	0.63	0.60	0.73	-5%	15%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.

Future Inventory Updates

To update future inventories, updated activity data (on the number of test performed) and emission factors should be solicited from Crowthorne, Dale Flow, Invent-UK, and Sellafield. If this is not possible, activity data can be scaled by using GDP as a proxy. Further research may also be conducted to confirm that no additional use of SF_6 takes place in the tracer testing of nuclear power plant control room emergency ventilation systems, although it is believed that such use was replaced many years ago (with argon or nitrogen).

References

- American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). 1995. Standard 110-1995 – Method of Testing Performance of Laboratory Fume Hoods.
- California Air Resource Board. 2009. The Adoption of a regulation to reduce sulphur hexafluoride emissions in non-semiconductor and non-utility applications.
- Crowthorne Hi-Tec Services Limited. 2013. Personal communications with Steve Robertson. November 15, 2013.
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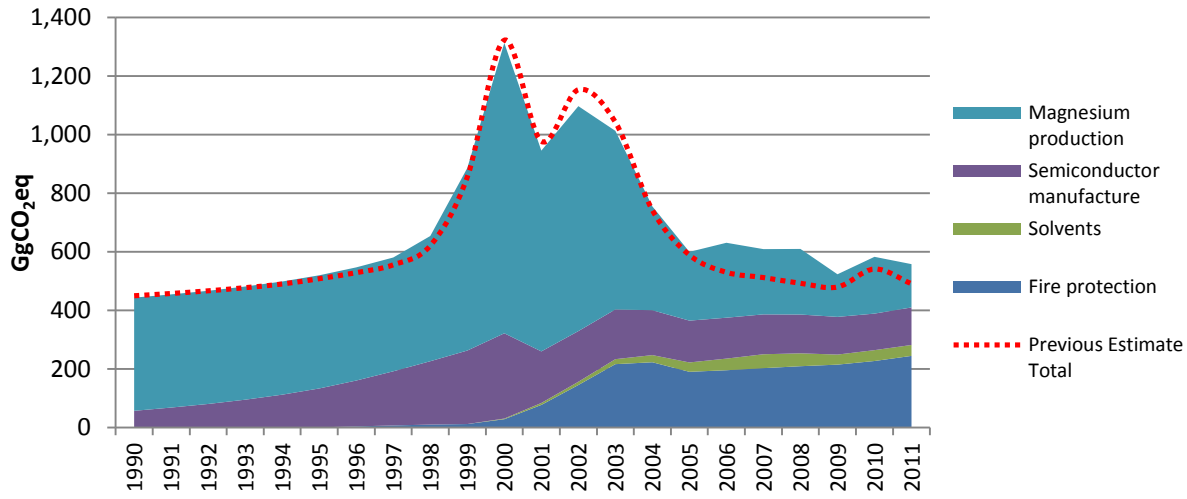
4 Overall results and prioritisation of sectors for future updates

This section presents the overall results in emissions across the F-gas sectors reviewed in this report, as well as the priority future updates.

4.1 Overall results

The resulting emissions across the updated and new F-gas sectors are summarized in the figure below. In 2011 the updated emissions for existing source sectors collectively account for a 13% increase over the previous version of the inventory.[11] Figure 17 presents the annual percent difference between the old and updated emission estimates (for "existing sources"), showing an increase of over 10% almost every year after 2006. This large increase is mainly attributed to the higher calculated emissions in the fire protection, semiconductor manufacture, and magnesium production sectors. Specifically, the increase from the fire protection sector is attributable to estimates for years 2005 and beyond being based on actual data of F-gas placed on the market as opposed to using a projected annual growth rate of 1% beyond 2005. The increase from the semiconductor manufacture is primarily due to the inclusion of by-products for C_2F_6 and CF_4, as well as inclusion of CF_4 by-products from more than one type of process gas compared to the previous methodology. The increase from the magnesium production sector is due to the reduction in the destruction efficiency, assumed to be 80% in lieu of 90%.

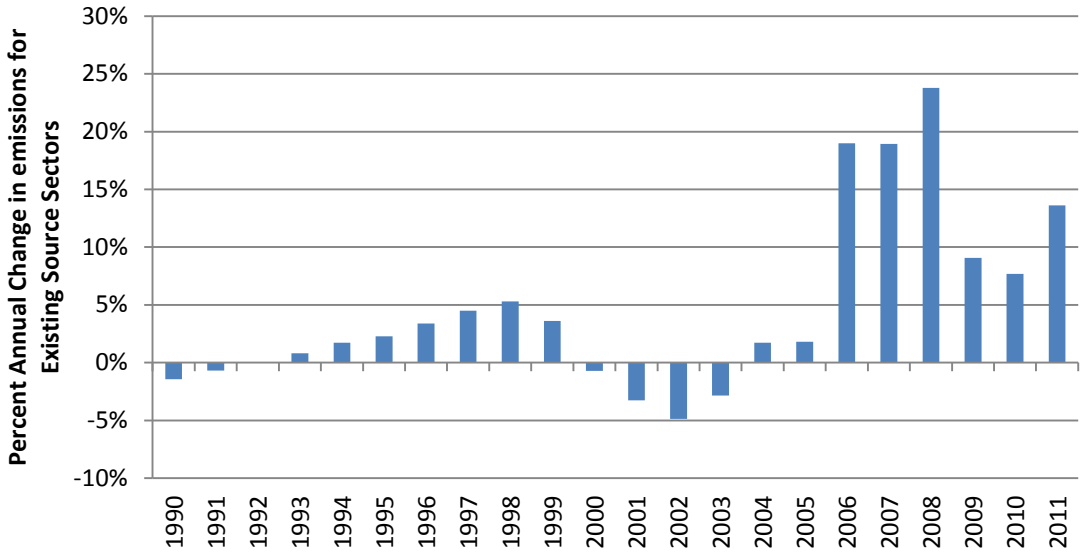
Figure 16: Updated Emissions from Existing Source Sectors*



*Emissions from the OCF sector were also reviewed in this analysis, but no updates were deemed necessary.

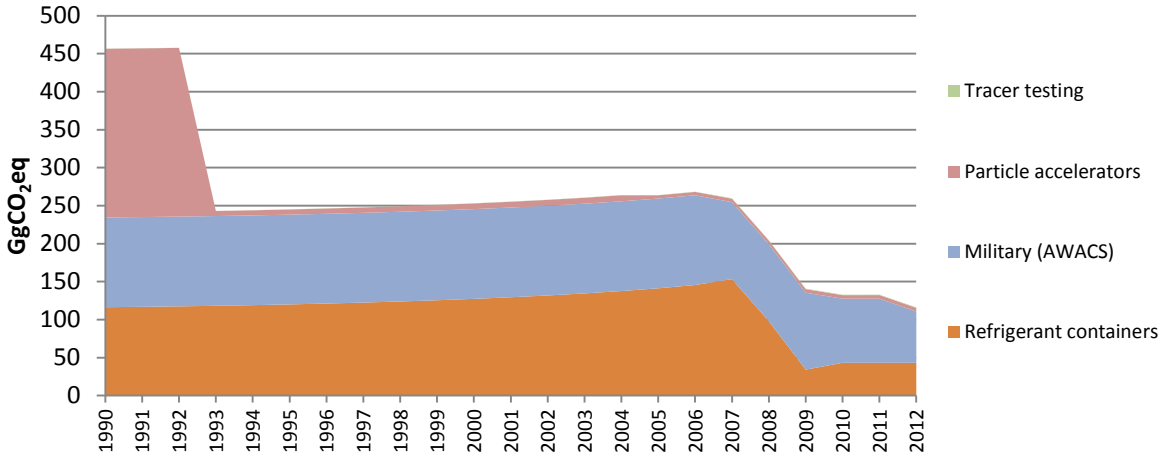
[11] For comparison purposes, 2011 is the most recent year for which disaggregated F-gas UK emissions data were made available to ICF.

Figure 17: Percent Annual Change for Existing Source Sectors



The new source sectors accounted for 133 $GgCO_2eq$ in 2011, representing 19% of F-gas emissions from the source sectors explored in this report—or about 1% of total F-gas emissions. Emissions from these sources were estimated to decrease to 116 $GgCO_2eq$ in 2012, due to a decrease in emissions from AWACS.

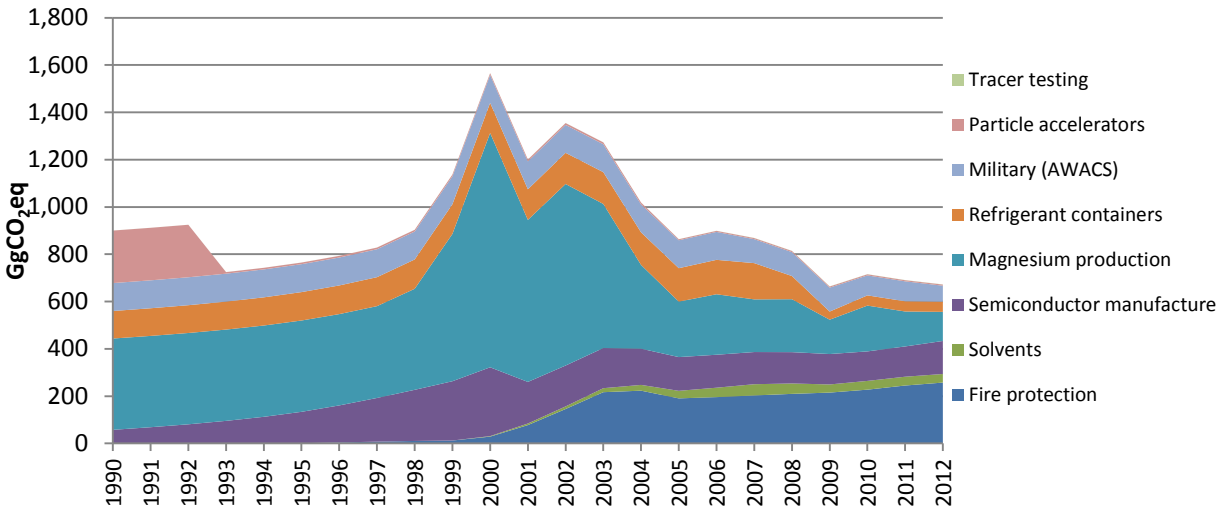
Figure 18: Emissions from Newly Added Source Sectors*



**Emissions were also explored for sound-proof windows, heat transfer fluids, flat panel display and PV cell manufacture, cosmetic and medical applications, and production of other fluorinated chemicals, but emissions from these sectors were not quantified in the inventory either because they were deemed insignificant or because insufficient data were available.*

The combined emission estimates for both existing and new F-gas sources are shown in Figure 19 below.

Figure 19: Emissions from All Source Sectors (Updated and Newly Added)



4.2 Overall results in context of all F-Gas emissions

To understand the significance of the updated and added F-gas sectors reviewed in this report, ICF compared the emissions of these sectors to total F-gas emissions in the broader UK inventory. In 2011, total F-gas emissions were estimated at 15,768 $ktCO_2eq$[12] (and additional 0.3 $ktCO_2eq$ of NF_3); relative to this amount, the updated and new sector emissions developed in this report account for 4% (690 $ktCO_2eq$). By gas type, these updated and new sectors account for 2.5% (365.9 $ktCO_2eq$) of the total HFC emissions, 30.6% (109.9 $ktCO_2eq$) of the total PFC emissions and 29.9% (213.9 $ktCO_2eq$) of the total SF_6 emissions. To put these emission estimates into perspective, the 2011 F-gas emissions represented 3% of total UK GHG emissions.

[12] This total includes emissions from sectors ICF did not update from 2011, as well as updated emission estimates from the sectors explored in this report.

Table 16: Comparison of total F-Gas emissions for 2011

Source	Emissions ($ktCO_2eq$)	Sector Status	% gas type	% all F-Gas
HFCs				
Refrigeration and Air Conditioning Equipment	11,220	Existing	76.4%	71.2%
MDI and Aerosols	2,721	Existing	18.5%	17.3%
Foams	312	Existing	2.1%	2.0%
Fire Protection	245	Updated	1.7%	1.5%
HFC and HCFC-22 Manufacture	72.6	Existing	0.5%	0.5%
Refrigerant Containers	43.2	New	0.3%	0.3%
Solvents	37.3	Updated	0.3%	0.2%
Magnesium Production and Processing	29.4	Updated	0.2%	0.2%
Electronics Manufacture	12.0	Updated	0.1%	0.1%
One Component Foams	0.0	Updated	0.0%	0.0%
Total HFCs	**14,692**			**92.7%**
PFCs				
Aluminium	162.4	Existing	45.2%	1.0%
Electronics Manufacture	109.9	Updated	30.6%	0.7%
PFC Manufacture	87.4	Existing	24.3%	0.6%
Trainers	0.0	Existing	0.0%	0.0%
Total PFCs	**359.7**			**2.3%**
SF_6				
Electrical Transmission and Distribution	502.6	Existing	70.1%	3.2%
Magnesium Production and Processing	118.3	Updated	16.5%	0.8%
Military AWACS	84.4	New	11.8%	0.5%
Trainers (included in ETD sector)	0.0	Existing	0.0%	0.0%
Electronics	5.9	Updated	0.8%	0.0%
Particle Accelerators	4.7	New	0.7%	0.0%
Tracer Testing	0.6	New	0.1%	0.0%
Total SF_6	**716.5**			**4.5%**
Total F-Gas	**15,768**			**100%**

4.3 Prioritisation of sectors for future updates

The table below highlights the sectors ICF recommends as prioritising for future updates. Prioritisation was given to sectors that are likely to contribute to the most significant sources of emissions.

Table 17: High priority F-gas inventory updates

Sector	Notes
2.E.4: Heat Transfer Fluid	More in-depth research is needed to gather activity data and emission factors for heat transfer fluids used in consumer electronics, cooling systems, and large ground-source heat pumps in the UK. MoD should also be contacted to estimate HTF emissions from military applications.
2.E.1: Semiconductor Manufacture	To improve upon the Tier 2a emission estimation methodology, consumption of gases (including NF_3) should be collected at the facility level, in lieu of the current method of projecting consumption based on assumed growth rates.
2.G.2.a: Military Applications (AWACS)	Emissions are high with the current Tier 1 estimation method using default emission factors; further effort should be placed on obtaining UK-specific loss rates from the UK Royal Air Force, which would reveal emission fluctuations based on periods of high or low military operations.
2.F.1: Refrigeration and Air Conditioning (Refrigerant containers)	Additional research on the activity data for large (60 kg) cylinders, iso tanks, and small (340 g) cans of refrigerant should be undertaken. In addition, further research into the percent of disposable cylinders sold relative to reusable cylinders prior to the 2008 ban should also be conducted. .

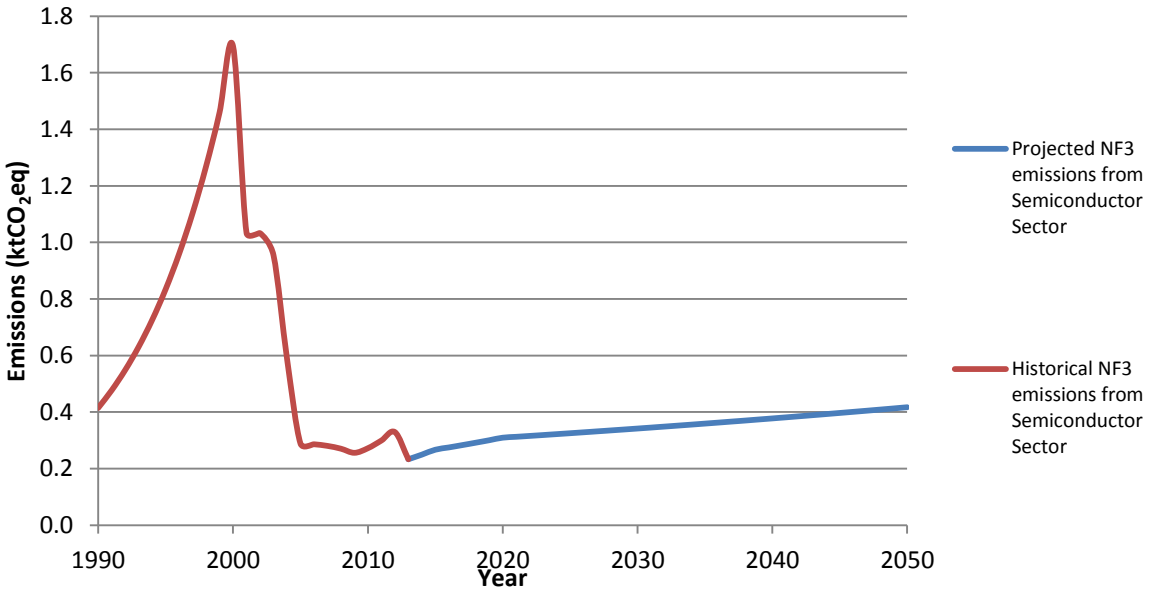
5 Projections of NF_3

The only source sector with emissions of NF_3 estimated is semiconductors. To project the NF_3 consumption in the semiconductor sector, ICF applied the following assumptions:

- The annual growth rate of the semiconductor industry in 2013-2015 is 7% (PWC 2012);
- Beyond 2015, annual growth rate slows, reaching 3% per year through 2020, and 1% per year beyond that (to 2050) (US EPA 2012).[13]
- The annual NF3 usage in the semiconductor industry per unit area remains constant.
- The fraction of NF3 used in remote applications versus other uses remains constant at 2012 levels (i.e., 61% for remote and 39% for other uses).

Based on these assumptions and the methodology presented in Section 22.4, the NF3 emissions were projected, as shown below.

Figure 20: Projection of NF3 from the electronics sector



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[13] This global report prepared by US EPA was used due to a lack of readily available UK-specific data.

- PWC. 2012. Faster, greener, smarter – reaching beyond the horizon in the world of semiconductors. Available online at: http://www.pwc.com/en_GX/gx/technology/publications/assets/pwc-faster-greener-smarter.pdf. January 2012.

Appendix A: Glossary of Gases

Common Name	Chemical Formula	Sector of Use (Relevant to this Report)	Lifetime (yrs)	GWP		Composition											
				TAR	AR4	PFC-14	PFC-116	PFC-218	PFC-318	SF_6	NF_3	HFC-43-10mee	HFC-227ea	HFC-134a	HFC-125	HFC-143a	HFC-32
PFC-14	CF_4	Semiconductor Manufacture	50,000	5,700	7,390	100%		-	-	-	-	-	-	-	-	-	-
PFC-116	C_2F_6	Semiconductor Manufacture	10,000	11,900	12,200	-	100%	-	-	-	-	-	-	-	-	-	-
PFC-218	C_3F_8	Semiconductor Manufacture	2,600	8,600	8,830	-	-	100%	-	-	-	-	-	-	-	-	-
PFC-318	C_4F_8	Semiconductor Manufacture	3,200	10,000	10,300	-	-	-	100%	-	-	-	-	-	-	-	-
Sulphur hexafluoride	SF_6	Semiconductor Manufacture; Magnesium Production; Military Applications; Accelerators; Tracer Testing;	3,200	22,200	22,800	-	-	-	-	100%	-	-	-	-	-	-	-
Nitrogen trifluoride	NF_3	Semiconductor Manufacture	740	10,800	17,200	-	-	-	-	-	100%	-	-	-	-	-	-
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	Solvents	15.9	1,500	1,640	-	-	-	-	-	-	100%	-		-	-	-
HFC-227ea	CF_3CHFCF_3	Fire Protection	34.2	3,500	3,220	-	-	-	-	-	-	-	100%	-	-	-	-
HFC-134a	CH_2FCF_3	Magnesium Production; Refrigerant Containers	14	1,300	1,430	-	-	-	-	-	-	-	-	100%	-	-	-
HFC-125/ R-125	CHF_2CF_3	Refrigerant Containers	29	3,400	3,500	-	-	-	-	-	-	-	-	-	100%	-	-
HFC-143a/ R-143a	CH_3CF_3	Refrigerant Containers	52	4,300	4,470	-	-	-	-	-	-	-	-	-	-	100%	-

Common Name	Chemical Formula	Sector of Use (Relevant to this Report)	Lifetime (yrs)	GWP		Composition											
				TAR	AR4	PFC-14	PFC-116	PFC-218	PFC-318	SF_6	NF_3	HFC-43-10mee	HFC-227ea	HFC-134a	HFC-125	HFC-143a	HFC-32
HFC-32/ R-32	CH_2F_2	Refrigerant Containers	4.9	550	675	-	-	-	-	-	-	-	-	-	-	-	100%
R-404A	-	Refrigerant Containers	-	-	-	-	-	-	-	-	-	-	-	4%	44%	52%	-
R-507	-	Refrigerant Containers	-	-	-	-	-	-	-	-	-	-	-	-	50%	50%	-
R-407C	-	Refrigerant Containers	-	-	-	-	-	-	-	-	-	-	-	52%	-	-	-
R-410A	-	Refrigerant Containers	-	-	-	-	-	-	-	-	-	-	-	-	50%	-	50%
R-407F	-	Refrigerant Containers	-	-	-	-	-	-	-	-	-	-	-	40%	30%	-	30%
R-407A	-	Refrigerant Containers	-	-	-	-	-	-	-	-	-	-	-	40%	40%	-	20%

Appendix B: Additional Information for CRF Reporter

Updated F-gas Sources

2.F.3: Fire Protection

In this sector, activity data for the amount filled into new manufactured products can be found in the annual amount of consumption in new systems while the average annual stock can be found in the annual UK bank size. The amount remaining at decommissioning in a certain year is equal to the amount of product added to the market 20 years prior. Emissions from stocks are equal to lifetime plus servicing emissions while emissions from disposal can be found in disposal emissions. Emissions from manufacturing were not estimated because there is no F-gas production in the UK in this sector. Emissions from recovery were not estimated because they are not applicable.

2.F.2: Foam Blowing Agents (One Component Foams [OCF])

In this sector, activity data for the amount filled into new manufactured products and in operating systems as well as emissions from manufacturing, stocks and recovery are not applicable because no UK production is assumed.

2.F.5: Solvents

In this sector, activity data for the amount filled into new manufactured products is assumed to equal the annual amount of solvent placed on the market. The average annual stock can be calculated using the lifetime, annual emission factor, and associated annual destruction. Emissions from manufacturing or recovery were not estimated because they are not considered in the 2006 GLs.[14]

2.E.1: Semiconductor Production

In this sector, there is no recovery of process gases. Hence, all the estimated emissions are released into the atmosphere.[15] Activity data on consumption per substance[16] are not applicable as emissions are estimated using a different tiered methodology where activity data is total gas consumed.

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[14] The 2006 GLs state “Equation 7.5 [Emission estimation method for solvent uses] assumes total release of solvent within two years regardless of the emission factor applied in year t. Additionally, there is no consideration of recovery and recycling, which may be a factor in some situations. However, it would be assumed that recovery and recycling would, in general, be reflected in reduced sales of virgin materials.” The 2006 GLs do not consider emissions during the manufacturing of the solvents (apart from any releases that occur during fluorochemical production, which are covered under section 3.10 of the GLs).

[15] ICF accounted for abatement in estimating emissions; however, this is distinct from gas recovery. During abatement, a gas is essentially destroyed from the exhaust stream before it enters the atmosphere. Any gases remaining (i.e., that the abatement system did not destroy) is emitted to the atmosphere. Gas recovery has not been commonly adopted in semiconductor manufacturing. In other words, gases are not recovered from an exhaust stream and recycled for process use or sale.

[16] Consumption of gases per substance may refer to (a) number of devices manufactured, (b) total manufactured substrate area, or (c) total manufactured layers area (TMLA) of final products. These distinctions are necessary as PFC usage varies among equipment types – whether they are discrete drives, memory devices, or logic devices. For example, simple one layered, discrete devices like transistors consume less PFCs, while complex multi-layered, integrated circuits consume more PFCs during the manufacture phase. Estimating ‘consumption per substance’ would only be possible after defining what ‘substance’ is – total number of devices, total substrate area, or TMLA.

2.C.4: Magnesium Production

In this sector, recovery emissions are not estimated as all SF_6 used is assumed to be emitted. Activity data on amount of magnesium casted is available from the UK Pollution Inventory (unless commercially confidential), although such data are not directly used by the methodology applied.[17]

New F-gas Sources

2.F.1: Refrigeration and Air Conditioning (Refrigerant Containers)

In this sector, the amount filled into new manufactured products is equal to the amount sold in cylinders and small cans. The activity data for average annual stocks and products remaining at decommissioning are not applicable for this sector (as such data would apply to the equipment in which the refrigerant is used to service, not the containers themselves). Emissions from manufacturing and disposal are listed as packaging and disposal emissions, respectively, from cylinders and small cans. Emissions from stocks and recovery are not applicable for this sector (as such emissions are relevant for the equipment for which the refrigerant containers are used to service, not the containers themselves).

2.G.2.a: Military Applications

In this sector, activity data on amounts of gases filled into new manufactured products, in operating systems, and remaining in products at decommissioning are not applicable as emissions are estimated using a different tiered methodology where activity data is the total number of AWACS in the fleet. Recovery emissions also do not occur in this sector as the SF_6 is released into the atmosphere during flight.

2.G.2.b: Accelerators

In this sector, activity data on amounts of gases filled into new manufactured products, in operating systems, and remaining in products at decommissioning are not applicable as emissions are estimated using a different tiered methodology where activity data is individual charges on research particle accelerators and the total number of accelerators for low voltage industrial and medical particle accelerators. Recovery emissions also do not occur in this sector as emissions are assumed to be fugitive emissions.

2.E.4: Heat Transfer Fluid

Due to data limitations, emissions in this sector are not estimated. Therefore, activity data on consumption per substance and recovery emissions are not applicable.

2.E.2 TFT Flat Panel Display

Due to data limitations, emissions in these sectors are not estimated. Therefore, activity data on consumption per substance and recovery emissions are not applicable.

[17] Rather, the methodology uses SF_6 emissions data reported by magnesium companies to the UK Pollution Inventory.

2.G.2.c: Other (Tracer Testing)

In this sector, activity data on amounts of gases filled into new manufactured products, in operating systems, and remaining in products at decommissioning are not applicable as emissions are estimated using a different tiered methodology where activity data is total number of tests performed by various individual companies. The recovery emissions are also not applicable as they are not occurring (given that all gases used are released in the environment for this sector).

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