CENTRE FOR CHEMICAL REGULATION AND FOOD SAFETY
The Lenz, Hornbeam Business Park,
Harrogate. HG2 8RE UK
T (+44) 1423 853200 F (+44) 1423 810431
info@uk.exponent.com

CENTRE FOR CHEMICAL REGULATION AND FOOD SAFETY
1 Pride Point Drive, Pride Park,
Derby DE24 8BX UK
T (+44) 1332 868000
info@uk.exponent.com

Application of Fluorinated Gases (F-Gases) in the European Economic Area

Prepared by:

Mike Holland and Steve Hollins

Exponent International Ltd.

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Application of Fluorinated Gases (F-Gases) in the European Economic Area

Report for Project on PFAS-based Fluorinated Gases (F-gases) Used as Refrigerants or in other Applications

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Authors: Mike Holland and Steve Hollins
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1. Summary

This report provides summary information from a study investigating the use of fluorinated gases (F-gases) on the European market and the potential for their substitution with alternatives.

A wide range of applications use F-gases, including refrigeration, air conditioning, foam blowing, and several more niche areas such as fire suppression, solvents, and magnesium casting. The study has considered potential alternatives for each use.

The study provides data to inform the Competent Authorities of Denmark, Germany, Netherlands, Norway and Sweden as they assess different applications of PFAS for the 'universal restriction' on the use of PFAS in the EU. This study is one of several undertaken on different sectors that use PFAS according to the definition adopted by the Competent Authorities.

2. Introduction

- **What are per- and polyfluoroalkyl substances (PFAS) and fluorinated gases (F-gases)?**

The definition of PFAS used for this work is the same as used in a call for evidence during 2020 and covers any substance containing at least one -CF2- or -CF3 group within in its chemical structure. This definition covers most F-gases which are a family of man-made gases used in a range of industrial applications. The number of PFAS in use today totals several thousand.

- **What are they used for?**

A range of applications use F-gases, including refrigeration, air conditioning and heat pumps where they provide the 'working fluid' moving heat from one place to another; foam blowing agents used to manufacture insulation foams, fire-fighting foams and fire suppressants; propellant gases in medical devices and other aerosol devices; and various industrial applications.

Use of PFAS more generally includes non-stick coatings for cookware, ski waxes, waterproofing of textiles, production of electronic devices and semiconductors, chrome plating, cosmetics, lubricants and the energy industry. These applications are being investigated for the restriction but are outside the scope of the work reported here.

- **Why is there concern about them?**

Earlier concerns about F-gases focused on their potential for depleting the ozone layer and contributing to climate change. Legislation, including the Kyoto and Montreal Protocols and associated implementing measures in Europe, addresses these issues. Since the early 2000s some specific PFAS have been identified as toxic, including PFOS (perfluorooctane sulfonic acid) and PFOA (perfluorooctanoic acid). There is concern that additional PFAS may be hazardous to humans and the environment. The persistence of some PFAS, and the persistence of their degradation products such as TFA (trifluoroacetic acid), has the potential to lead to accumulation of PFAS in the environment, compounding concerns over possible toxicity. Whilst the Montreal and Kyoto Protocols have gone some way to reducing dependence on F-gases based on their effects on the ozone layer and climate change, they have not addressed the concerns relating to persistence and accumulation given continued development and application of F-gases such as HFOs.

- **What is the REACH Regulation?**

REACH stands for Registration, Evaluation, Authorisation and Restriction of Chemicals. It is a major part of the European Union's legislation to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry. REACH also promotes alternative methods for the hazard assessment of substances to reduce the number of tests on animals. Authorisation and restriction of chemicals under REACH limit the use of potentially harmful substances. Restriction prevents the use of specified substances from one or more of their uses. Authorisation bans the use of substances except where a company has successfully applied for permission for continued use on the grounds that risks are adequately controlled, or when the benefits of continued use exceed the costs.

- **Why may certain F-gases become regulated as PFAS under REACH?**

As indicated above, concern arises because of the persistence of some F-gases and PFAS and their degradation products. Other legislation directed at ozone depletion or their contribution to global warming does not address persistence explicitly. The work reported here deals with F-gases only, but wider uses of PFAS, as listed above, are also under investigation. In theory, the restriction that is finally adopted could cover all PFAS in all applications. However, this is, in part, dependent on the availability of satisfactory alternatives for each application. Such alternatives are available in some cases, but not all, including some 'essential uses' such as health care and fire control.

3. Overview of the use of F-Gases and Emissions

As noted above, sectors that use F-gases included in the broad definition of PFAS cover refrigeration, heating and air conditioning, foam blowing, propellants, solvents, fire suppressants and cover gases[1] used in magnesium smelting.

Many of these applications used gases (or liquids) other than F-gases at the outset of their commercialisation. For example, early refrigerants included ammonia, chloromethane and sulphur dioxide. Although functioning well, each of these substances were associated with recognised limitations. For example, exposure to high concentrations of ammonia, e.g., in the event of a leak, can cause adverse health effects such as immediate burning of the eyes, nose, throat and respiratory tract. Industry identified CFCs as (what was then considered to be) a harmless substitute for use in these applications in the 1930s, leading to widespread use by the 1950s of freons, such as CFC-11, CFC-12 and CFC-13. However, CFCs were identified as the causal agent in damage to the stratospheric ozone layer that protects the earth from the harmful effects of ultraviolet radiation from the sun during the 1970s, which led to their being banned under the 1987 Montreal Protocol. Subsequent amendments increased the scope of the protocol, for example leading to the banning of HCFCs that replaced CFCs because of lower (but not negligible) ozone depletion potential. These measures have contributed to the phase-out of CFC use around the world, as well as the phase-out of HCFC use to be achieved by 2030. In Europe HCFCs have been phased out already, in accordance with the EU regulation on ozone depleting substances.

Industry developed hydrofluorocarbons (HFCs) as direct replacements for CFCs and HCFCs. HFCs did not damage the ozone layer. Refrigeration examples include HFC-134a and blends of HFCs such as R-407C. However, many HFCs have a high global warming potential (GWP) contributing to the greenhouse effect. HFC use was addressed by the 1997 Kyoto Protocol, an international treaty that extended the 1992 United Nations Framework Convention on Climate Change (UNFCCC) to reduce greenhouse gas emissions. However, some HFCs are still in use today in Europe, for certain applications and where the GWP is below a specified level[2] as defined in the EU F-gas regulation. This regulation has contributed considerably to the reduction in use and impact of HFCs on the climate.

[1] Cover gases protect the molten surface of magnesium from oxygen in the atmosphere during casting operations.
[2] Generally, 150 times the GWP of carbon dioxide.

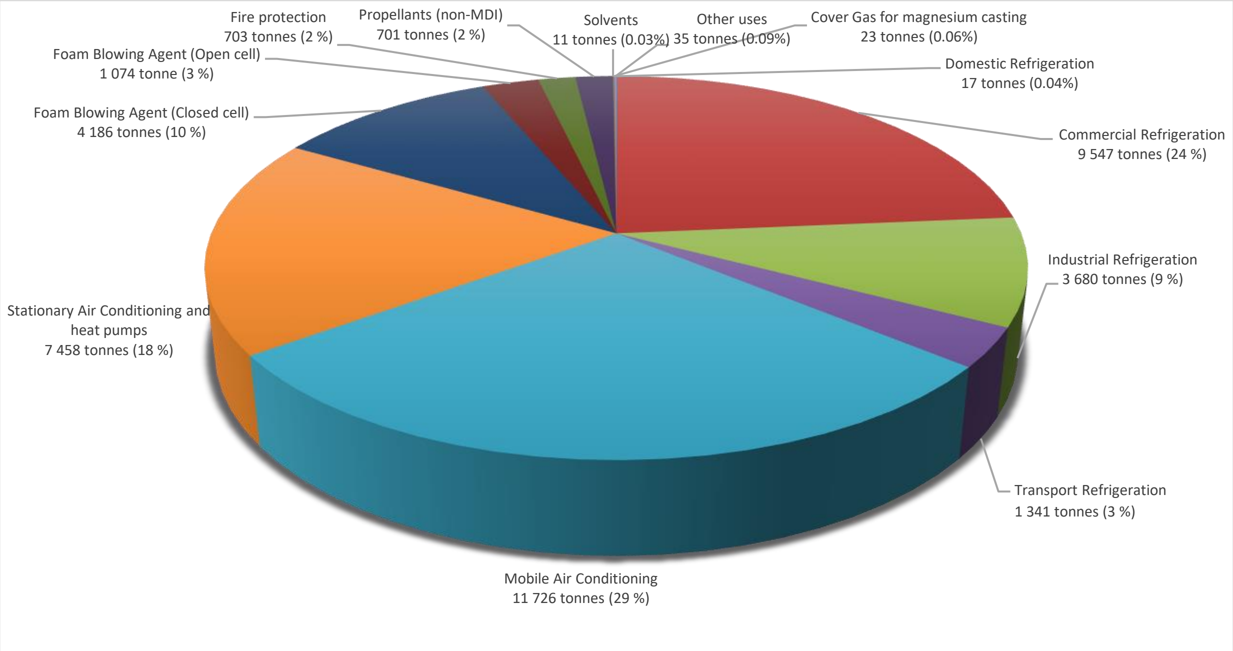
Hydrofluoroolefins (HFOs) are the latest generation of drop-in fluorinated refrigerants. HFOs do not impact the ozone layer and have low GWP. However, some of these substances degrade in the environment to persistent substances such as trifluoroacetic acid (TFA), which has been linked with high mobility in the environment and possible adverse environmental effects due to their persistence in the environment, although other reports contradict these findings.

Table 1 provides information on the quantities of F-gases in use and released each year according to analysis made for this study. The most important emission sources are (in order) mobile air conditioning, commercial refrigeration and stationary air conditioning and heat pumps. The latter sector is likely to grow significantly in the coming years because of climate change, with more air conditioning being used to address higher temperatures and heat pumps being introduced to avoid fossil fuel use for space and water heating.

Table 1 Annual Usage, Stocks and Emissions of F-Gases in the EU27+Norway+UK

Application	**New use**	**Amount in stocks**	**Total emission**	**% of total emission**
	t/y	**t**	**t/y**	
Domestic Refrigeration	122	4,496	17	0.04%
Commercial Refrigeration	7,915	90,992	9,547	24%
Industrial Refrigeration	2,360	34,358	3,680	9%
Transport Refrigeration	1,010	9,915	1,341	3%
Mobile Air Conditioning	5,221	115,763	11,726	29%
Stationary Air Conditioning and heat pumps	7,465	148,791	7,458	18%
Foam Blowing Agent (Closed cell)	4,940	57,635	4,186	10%
Foam Blowing Agent (Open cell)	271	9,848	1,074	3%
Fire protection	863	20,201	703	2%
Propellants (non-MDI)	504	907	701	2%
Solvents	No data	0	>11	0.03%
Cover Gas for magnesium casting	No data	No data	>23	0.06%
Other	No data	267	35	0.09%

Figure 1 Total F-gas Emissions by Sector 2018. Source (EU, 2020a).



4. Market Segments: Description, Trends and Alternatives

4.1 Refrigeration, Air Conditioning and Heat Pumps

We are familiar with refrigerants in our refrigerators, freezers, and air conditioning units at home and in our cars. An emerging market concerns the use of heat pumps for space and water heating, and in some consumer products such as ‘tumble dryers’ for clothes. Refrigeration and heat pumps are also widely used commercially and in industry, for example, supermarket refrigerators and freezers, drinks chillers in bars and restaurants, manufacturing and transporting chilled and frozen goods, and in specialised applications such as for cooling large data centres, for servers, electronics and for industrial heating.

To function as refrigerators or heat pumps, refrigerant substances or mixtures act as working fluids to maintain low temperatures in an enclosed environment. The most common refrigeration and air conditioning cycle used in these settings is the vapour-compression cycle, in which the circulating refrigerant absorbs and removes heat from the space to be cooled and expels the heat elsewhere. Heat pumps work on the same principle, but in reverse.

Figure 2 Outdoor condensing units: ‘Condensing Units’ by Mike On Maui is licensed with CC BY 2.0. To view a copy of this license, visit https://creativecommons.org/licenses/by/2.0/

4.1.1 Trends in Refrigeration, Air Conditioning and Heat Pumps

There are still many hydrochlorofluorocarbon (HCFC) /CFC chillers used globally, although these refrigerants have been phased out in new chillers. They have been replaced by equipment using HFCs and HFOs, or alternatives, mainly hydrocarbons, CO_2 and NH_3, depending on the sector concerned.

The F-gases that have replaced CFCs and HCFCs include HFC-32, HFC-125, HFC-134a and HFC-245fa and more recently HFOs such as HFO-1234yf and HFO-1234ze(E).

Historically, HCFC-22 was used as the main refrigerant in air conditioning units, but this has now been replaced by HFC blends which may include HFC-32, HFC-125 or HFC-134a. The EU F-Gas Regulation 517/2014 has banned the placing on the market of HFCs with GWP of 150 or more (covering all of those just listed) in movable room air conditioning equipment from 1 January 2020.

Due to its low GWP and increasing pressure from EU regulations, HFO-1234yf is the main refrigerant now used in mobile air conditioning of new cars in Europe. Before this, HFC-134a was the refrigerant of choice due to its non-ozone-depletion-potential (ODP) properties and low cost; this agent remains widely used both in Europe and other parts of the world. It is expected that HFO-1234yf will become adopted globally as regulations move towards low GWP options. Trains use HFC-134a and blends of HFC-32, HFC-125 and HFC-134a for air conditioning, and a move away from these agents in the short to medium term looks unlikely.

Hydrocarbon alternatives are available for smaller air conditioning units, as flammability is a lesser issue. Carbon dioxide is available for use in commercial systems but is less efficient at high ambient temperatures. The possibility of using HFO blends is being tested in air conditioning applications, but the cost of these refrigerants is higher.

HCFC-22 has been used historically for water and space heating pumps, though the refrigerants used for new equipment are now HFC-32, HFC-125, HFC-134a, hydrocarbons and carbon dioxide. There is a gradual market movement towards lower GWP HFO options such as HFO-1336mzz(E) and HFO-1224yd(Z), as well as propane (in smaller systems with small charges), carbon dioxide (in water heaters) and ammonia (large district heating and space heating, especially in Northern Europe).

4.1.2 The Use of Alternatives in Refrigeration, Air Conditioning and for Heat Pumps

There is a range of alternatives to the use of persistent and expensive F-gases, but again each has its limitations or drawbacks:

- Hydrocarbons pose a risk of flammability when used in larger quantities (larger ‘charge sizes’).
- Ammonia is toxic.
- Carbon dioxide is hazardous, operates at higher pressures and is less efficient at high ambient temperatures.

These issues largely explain current market shares. All domestic refrigerators considered in our analysis (including large ‘larder refrigerators’) used hydrocarbons, a market where charge size can be limited to mitigate the flammability risk. Industrial refrigeration mainly uses ammonia though there is still a significant presence of F-gas used in that market: for this market there is separation of equipment from the public and risks can be adequately controlled. Refrigeration on commercial premises is provided using a range of refrigerants, hydrocarbons for smaller units and F-gases or CO_2 for larger units. For the industrial market particularly, there appear to be specific niches where alternatives are unable to provide the conditions required for some processes.

The same issues affect use in air conditioning and heat pumps, though with some variations reflecting specific characteristics of the market and the equipment used. Compared to the widespread adoption of hydrocarbons in domestic refrigeration, the domestic air conditioning market is far more dependent on F-gases. For this sector the ‘split’ nature of many units (part inside and part outside a building) creates a greater risk of damage to cooling circuits and hence release of gas. However, these problems are being overcome.

The motor industry has ruled out the use of hydrocarbons in mobile air conditioning on safety grounds. The main alternative considered is carbon dioxide, but associated systems need to be engineered to a higher quality to cope with the greater gas pressures involved. The industry considers these costs to be too high, though analysis in this study found that they are within indicative benchmarks of proportionality for justifying adoption.

4.2 Foam-Blowing Agents

Foams are widely used in household, commercial and industrial settings often to provide thermal insulation, for example to retain heat within a building or boiler, to keep heat out of refrigerated areas, or to prevent pipes from freezing and cracking in cold weather conditions. Foam is also used to fill gaps in buildings to prevent excessive air movement and can be used as a protective and cushioning cover, such as for seat covers or vehicle steering wheels. Key factors in selection of foam blowing agents relate to the cost of substances, flammability and efficiency of insulation. Additional factors apply in some applications for specific foams, for example relating to compression and flexural strength and resistance to water.

Figure 3. Prefabricated XPS foundation insulation being installed at a building site (left) and direct application of insulating foams (right). Both images used royalty-free from CC BY 2.0, from akhouseproject; and dunktanktechnician.

Foam-blowing agents are present in the mixtures created for foam production, ensuring that foam expands after release and prior to solidifying. Foams may be open-cell or closed-cell depending on application. For open-cell foams, emissions of blowing agents occur during manufacture and use or shortly after. Most emissions from closed-cell foams occur during the service-life of the foams or at disposal of the product into which the foam has been added.

4.2.1 Trends in Foam-Blowing Agents

In a similar pattern to that of refrigerants, the substances and mixtures used as foam-blowing agents have evolved through the use of CFCs, to hydrochlorofluorocarbons (HCFCs) to HFCs and then recently to HFOs. Historically CFC-11 and CFC-12 were used as foam-blowing agents. These then transitioned to HCFC-141b, HFC-152a, HCFC-142b/22 blends or directly to hydrocarbons such as n-pentane and cyclopentane.

Currently HFC-245fa, HFC-227ea, HFC-365mfc/227ea and HFC-134a are used as foam-blowing agents. HFO replacements include HFO-1233zd(E), HFO-1336mzz(Z) and HFO-1234ze(E). Non-PFAS alternatives currently used include methyl formate, cyclopentane, iso-pentane, n-pentane and carbon dioxide (water) blowing agents.

Since 2008, HFCs or HFC containing preparations with a global warming potential of more than 150 have been banned from one-component foams in the EU under the F-gas regulation. In 2015, HFCs with GWP greater than 150 were banned for foam use in domestic appliances and from extruded polystyrene (XPS) from 2020. By 2023, HFCs with GWP greater than 150 will cease being used in all foam manufacturing in the EU. This will cover all of the HFCs listed above except HFC-152a.

4.2.2 The Use of Alternatives for Foam Blowing

here is a range of alternatives to the use of persistent and expensive F-gases, but again each has its limitations or drawbacks:

- Hydrocarbons, methyl formate and methylal pose a risk of flammability. Building codes may prevent their use in some applications and some SME producers may not be licensed to hold significant quantities of highly flammable gas. Inferior insulation performance to F-gases.
- Carbon dioxide has an inferior insulation performance to F-gases.

There is also a wide range of ‘not-in-kind alternatives’ available on the foam market. For insulation these include fiberglass, mineral wool, cellulose, cotton, sheep’s wool, straw, hemp, and cementitious foam. Their performance as insulators is not as good as foams blown using F-gases. The questions around insulation performance lead to interaction between a possible restriction on foam blowing agents with climate policies.

4.3 Solvents – Trends and Alternatives

The main applications of F-gases used as solvents are metal cleaning to remove oil and grease, electronics cleaning for the removal of flux and precision cleaning to remove particulates or dust. Solvents are also used as carrier fluids to deposit fluorolubricants, silicones, coatings, adhesives and other materials in smooth coatings. There is also some evidence for the use of F-gases as solvents when processing 3D printed parts for smoothing the surface of printed objects.

Key factors in selection of solvents relate to the cost of substances, non-flammability, thermal and chemical stability, dielectric properties (poor electrical conductance meaning that they can be used safely in contact with electronics), compatibility with dissolved materials, low surface tension and viscosity, high liquid density, and low toxicity. Although there are many alternatives for this use, PFAS-substances, such as HFCs, HFEs and HFOs, are still required for some applications, especially precision cleaning.

4.3.1 Trends in Solvent Use

CFC-11, CFC-113 and 1,1,1-trichloroethane (TCA) were historically used as solvents in precision and electronics cleaning, but these solvents have now been phased out except in some aerospace applications. Replacements included HCFC-141b and HCFC-225ca/cb, which have now themselves also been phased out except in some aerospace and military applications, where use is still required to service existing equipment. Most ozone-depleting solvents were replaced with hydrocarbons or not-in-kind technologies such as no clean flux and aqueous cleaning systems.

For precision cleaning, electronics cleaning and metal cleaning, PFAS substances are still currently in use. That includes HFC-43-10mee, HFC-365mfc, HFC-245fa, HFE-569mccc, HFE-449mccc, HFE-64-13s1, HFE-347mcc, HFO-1336mzz (Z) and HFO-1233zd(E). Some metal cleaning has switched to using aqueous and semi-aqueous alternatives and to n-propyl bromide (nPB). nPB is now being phased out and HFE (hydrofluoroether) alternatives are being used.

4.3.2 Alternative Solvents

The following solvents are identified as potential alternatives for metal cleaning: isopropyl alcohol (IPA), n-propyl bromide (nPB), dichloromethane (DCM, methylene chloride), trans-1,2-dichloroethylene, trichloroethylene (TCE), perchloroethylene (PER), volatile methyl siloxanes, hydrocarbons (hexane, heptane, benzene) and acetone. Many of these alternatives have health concerns and regulatory restrictions. Other alternatives such as IPA are considered highly flammable and therefore not suitable for some uses.

In addition to the alternatives listed, other processes may be used which do not use, or reduce the use of, solvents. These include semi-aqueous or aqueous cleaning, manual cleaning methods such as using aerosols, brush, trigger spray, liquid immersion, spot cleaning, wipes, ultrasonic cleaning and plasma cleaning.

The same substances and processes are also considered as potential alternatives for precision and electronics cleaning, with the addition of supercritical carbon dioxide, which is not suitable for large-scale use. No-clean fluxes are another option for electronics cleaning, for which no solvent is required. For carrier fluids the same substances may be acceptable; however, choice of carrier fluid is highly dependent on the intended application.

Available information suggests that F-gases are generally more expensive than alternative solvents: this means that there is already a driver in the marketplace for switching to alternatives when they can provide satisfactory performance. The quantities of F-gas used as solvents are believed to be small (noting the lack of data in Table 1, reflecting limited use). These factors suggest that remaining uses may be in very specific niches of the market where the combined benefits of F-gas solvents may justify their continued use.

4.4 Propellants

Propellants are used to expel the contents of an aerosol from a canister through a nozzle, in products such as deodorants and hair sprays. Technical propellants are used for industrial uses for items such as lubricant sprays, dusters, cleaners, safety horns, degreasers, and paints.

Liquified compressed gases are widely used, as they maintain a relatively constant pressure as the contents are dispensed, maintaining consistent droplet size and spray rate which may be required for technical aerosols. In contrast, compressed gases, such as carbon dioxide, cannot produce a consistent particle size and spray rate, thereby limiting their applicability, with performance falling as the contents of a can are used up and pressure within the can falls. Where a non-flammable propellant is required as an alternative to hydrocarbons, HFOs may be used, alone or as a propellant blend.

Figure 4 "Fresh Spray Deodorant" by twitchery is used royalty-free from Creative Commons (CC) "Holy Spray Can!" by Ms. Phoenix is licensed with CC BY 2.0.

4.4.1 Trends in Propellants

Historically CFC-12 was used as a propellant in aerosols. When CFCs were phased out, CFC-12 was replaced with HCFC-22, which was then replaced with HFCs including HFC-134a, HFC-152a and other alternatives.

The EU F-Gas Regulation 517/2014 banned the use of HFCs with GWP of 150 or more, in technical aerosols from 1 January 2018, except when required to meet national safety standards or when used for medical applications. The use of HFCs with GWP of more than 150 had been banned since 2009 in entertainment and decorative products for sale to the public such as signal horns.

Today, the aerosol industry has primarily shifted to flammable liquefied propellants (hydrocarbons and dimethyl ether), but still uses HFCs, specifically non-flammable liquefied propellant HFC-134a and HFC-152a, for a small range of products (FEA, 2020). Use of HFC-134a is controlled through the F-Gas Regulation given its GWP is greater than 150, but this does not apply to HFC-152a. Propellants that do not meet the requirements of the Regulation may still be used in the EU when required to meet national safety standards, such as for products with flammability or inhalation safety concerns.

Two HFO propellants that are classified as non-flammable are HFO-1234ze(E) and HFO-1336mzz(Z). Since the ban on HFC use in novelty aerosols, that market transitioned to HFO-1234ze(E) (SKM Enviros, 2013). Not-in-kind alternatives are commonly used for consumer products in place of aerosols, such as trigger sprays, roll-on products, squeeze bottles and powder alternatives.

4.4.2 Alternatives as Propellants

The following are considered as potential alternative substances or methods for the replacement of PFAS propellants: compressed gas (carbon dioxide, nitrous oxide), not-in-kind alternatives (trigger sprays, finger pumps, squeeze bottles, roll-on liquid), hydrocarbons (propane, butane, isobutane), and dimethyl ether. The alternatives listed may not produce the same quality of spray and some are flammable and therefore not acceptable for some specific uses. Again, it is noted that F-gases are an expensive option for propellants and so there already exists pressure in the market for substitution to other substances.

4.5 Cover Gases

A cover gas (or shielding gas) is used to prevent rapid oxidation of molten magnesium during die-casting and sand-casting. The cover gas is applied to the molten magnesium surface where it forms a protective film, preventing oxidation.

4.5.1 Trends in Cover Gases

Historically only salt fluxes and powdered sulphur were used for surface protection in magnesium casting. Sulphur dioxide was the first cover gas used in magnesium foundries; however, since it is toxic and corrosive, it was replaced with sulphur hexafluoride (SF_6). SF_6 was banned for this use in the EU from 2018 due to its very high GWP. Currently sulfur dioxide (SO_2), SO_2 mixtures and HFC-134a and possibly HFC-125 are used as cover gases.

4.5.2 Alternatives Used as Cover Gases

The PFAS substances used as cover gases have largely been developed as replacements for SF_6, which has been banned in the EU due to its high GWP. SF_6 replaced sulphur dioxide, which can still be used but is both toxic and corrosive, with implications for human health and equipment costs. Salt fluxes and powdered sulphur were used historically, but these caused contamination of the product, and so were replaced. The main alternative available on the market is SO_2, and conversion of plants currently using HFCs as cover gases to SO_2 would be feasible for the die casting market.

Little information was identified for the sand-casting sector. The information that was obtained suggested that PFAS are not being used in that part of the market.

4.6 Fire Suppressants[3]

In certain specialised situations, such as electronic fires affecting data centres, or museums containing sensitive cultural heritage, fast acting and ‘clean’ (i.e. non-residue forming) fire suppressants are required in order not to damage the items in the area in which they are used.

4.6.1 Trends in Fire Suppressants

Halons, HCFCs and HFCs have been commonly used for applications involving ordinary combustibles, flammable liquids, flammable gases, and electrical equipment. Criteria considered when determining the most appropriate fire suppressant for any application include a variety of factors such as local climate (temperature and pressure), occupation of the area to be protected, the type of asset to be protected, the type of combustible material present and the availability of a water supply. The relevant Technical Committee to the Montreal Protocol notes significant problems in identifying alternatives that provide the same functionality as F-gas fire suppressants.

A trend in several other sectors above is to move from HFCs to HFOs. However, this does not apply to the fire suppressant market, as HFOs are flammable.

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[3] Aqueous Film-Forming Foams (AFFFs) commonly used in some industrial situations and at airports are being considered under a separate restriction.

4.6.2 Alternatives Used as Fire Suppressants

Several options are available on the market, including the use of inert gases (nitrogen and argon), CO_2, water mist technologies, inert gas generators, fine solid particle technology, dry chemical agents, water and aqueous salt solutions. However, these have several limitations:

- Several are not 'clean'
- They tend to take longer to extinguish fires than F-gas equivalents
- Some are hazardous to health and cannot be used where there is a risk of human exposure.

The problem of substituting away from F-gases in this sector is highlighted by continued use of substances that are not permitted for use in other sectors on account of their climate and other burdens.

5. Conclusions

In the absence of a restriction, there will be continued use of F-gases for the foreseeable future. In many sectors this will be through continuation of the switch from HFCs to lower-GWP HFOs to meet the requirements of the F-Gas regulation. However, in some sectors, most notably fire suppressants, this process is taking a much longer time.

The high price of F-gases provides a natural incentive for switching to alternatives. However, this leaves several areas where F-gases are still the preferred option from a performance perspective. In some cases, including some areas associated with significant emissions, our analysis indicates that there is good potential for substituting to non-F-gas alternatives.

The main sectors for emissions are mobile air conditioning, commercial refrigeration, stationary air conditioning and heating, foam blowing and industrial refrigeration, which together account for 93% of emissions during the manufacture of products and their use.

Several barriers exist to the adoption of alternatives. Some are toxic and hence will not be adopted where there is a risk of human exposure. Some (e.g., hydrocarbons) are flammable. Use of these alternatives is constrained by legislation including national and local building codes. There is evidence that these are in some cases too restrictive, with modern standards of engineering and quality assurance mitigating risks. As a result, some of the constraints on alternatives could be relaxed to a degree at least.

The appropriate course of action may vary across the sector. Rather than a blanket restriction it may be appropriate to consider specific conditions for regulation of some sectors individually.

The Competent Authorities in the five countries working on the PFAS restriction (Denmark, Germany, Netherlands, Norway, Sweden) will consider the information presented in the reports produced under this and other contracts in the development of a restriction that will be submitted to the European Chemicals Agency for evaluation by its Risk Assessment and Socio-Economic Assessment Committees.

6. Key references

REACH Regulation: Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).

EU legislation to control F-gases: https://ec.europa.eu/clima/policies/f-gas/legislation_en.

ODS Regulation: Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on substances that deplete the ozone layer. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009R1005.

Montreal Protocol Technical and Economic Assessment Panel: https://ozone.unep.org/science/assessment/teap.

7. List of PFAS substances mentioned in this report

Designation	PFAS substance	Chemical Formula (if available)
CFC-11	Trichlorofluoromethane	CCl3F
CFC-113	1,1,2-Trichloro-1,2,2-trifluoroethane	Cl2FC-CClF2
CFC-12	Dichloro(difluoro)methane	CCl2F2
CFC-13	Chloro(trifluoro)methane	CClF3
HCFC-141b	1,1-Dichloro-1-fluoroethane	C2H3Cl2F
HCFC-142b	1-Chloro-1,1-difluoroethane	CH3CClF2
HCFC-22	Chloro(difluoro)methane	CHClF2
HCFC-225ca	3,3-Dichloro-1,1,1,2,2-pentafluoropropane	CHCl2CF2CF3
HCFC-225cb	3,3-Dichloro-1,1,1,2,2-pentafluoropropane	CHClFCF2CClF2
HFC-125	Pentafluoroethane	CHF2CF3
HFC-134a	1,1,1,2-tetrafluoroethane	CH2FCF3
HFC-152a	1,1-difluoroethane	CH3CHF2
HFC-227ea	1,1,1,2,3,3,3-heptafluoropropane	CF3CHFCF3
HFC-245fa	1,1,1,3,3-pentafluoropropane	CHF2CH2CF3
HFC-32	Difluoromethane	CH2F2
HFC-365mfc	1,1,1,3,3-pentafluorobutane	CF3CH2CF2CH3
HFC-43-10mee	1,1,1,2,2,3,4,5,5,5- decafluoropentane	CF3CHFCHFCF2CF3
HFE-347mcc	Methyl perfluoropropyl ether	CF3CF2CF2OCH3
HFE-449mccc	Methyl Perfluorobutyl Ether	C5H3F9O
HFE-569mccc	(Perfluorobutoxy)ethane	C6H5F9O
HFE-64-13s1	Pentane, 1,1,1,2,2,3,4,5,5,5-decafluoro-3-methoxy-4-	C6F13OCH3
HFO-1224yd(Z)	(Z)-1-Chloro2, 3, 3, 3,-Tetrafluoropropene	(Z)-CF3CF=CHCl
HFO-1233zd(E)	trans-1-chloro-3,3,3-trifluoro-1-propene	CF3CH=CHCl
HFO-1234yf	2,3,3,3-Tetrafluoropropene	CF3CF=CH2
HFO-1234ze(E)	Trans-1,3,3,3-tetrafluoroprop-1-ene	trans — CHF = CHCF3
HFO-1336mzz(E)		(Z)-CF3CH=CHCF3

R-407C	Mixture of Difluoromethane, Pentafluoroethane and 1,1,1,2-Tetrafluoroethane	CH2F2 and C2HF5 and CF3CH2F