# Flexible and Rigid Foams Technical Options Committee

## 2022 Assessment Report

UN environment programme | ozone secretariat

Montreal Protocol on Substances that Deplete the Ozone Layer

**Montreal Protocol on Substances that Deplete the Ozone Layer**

**United Nations Environment Programme (UNEP)**
**Report of the Flexible and Rigid Foams Technical Options Committee**

**2022 Assessment Report**


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## DISCLAIMER



## Acknowledgements

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# Foreword

## The 2022 FTOC Assessment Report

The 2022 FTOC Assessment Report consists of one volume:

***Volume 1:*** *TEAP 2022 Assessment Report*

This is Volume 1
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# UNEP
# 2022 Report of the Flexible and Rigid Foams Technical Options Committee

## 2022 Assessment

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# 1.0 Introduction

This is volume 1 of 1 of the 2022 Flexible and Rigid Foams Technical Options Committee (FTOC) Assessment Report. This report contains updates on technical advancements in alternatives to hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), especially in high ambient temperature countries and with particular focus on energy efficiency and safety. It also details progress in sector transitions, and the status of banks and stocks and options to avoid emissions to the atmosphere. The report finally documents challenges parties are facing.

This report also includes the FTOC membership and appointment terms as of 31st December 2022 and the matrix of needed expertise for the TOC.

The FTOC co-chairs would like to express their sincere gratitude for the voluntary service and contributions of members of the FTOC. FTOC's tasks have continued to be particularly challenging in view of the COVID-19 pandemic which imposed restrictions to global travel, and changes to scheduled meetings and typical modes of working. To meet these challenges in delivering its reports on time to parties and ensuring the safety of its members, FTOC has held virtual meetings throughout the period of preparation,

**Decisions by Parties to the Montreal Protocol Relevant to the FTOC Assessment Report**

**Decision XXXI/2 Related to the 2022 TEAP Assessment Report(s) Paragraph 6**
**"That, in its 2022 report, the [TEAP] should include an assessment and evaluation of the following topics:**

Technical progress in the production and consumption sectors in the transition to technically and economically feasible and sustainable alternatives and practices that minimize or eliminate the use of controlled substances in all sectors;

The status of banks and stocks of controlled substances and the options available for managing them to avoid emissions to the atmosphere;

Challenges facing all parties to the Montreal Protocol in implementing Montreal Protocol obligations and maintaining the phase-outs already achieved, especially those on substitutes and substitution technologies, including challenges for parties related to feedstock uses and by production to prevent emissions, and potential technically and economically feasible options to face those challenges;

The impact of the phase-out of controlled ozone-depleting substances and the phase down of HFCs on sustainable development;

Technical advancements in developing alternatives to HFCs suitable for usage in countries with high ambient temperatures, particularly regarding energy efficiency and safety."

At their Twenty-eighth Meeting in 2016, the parties took Decision XXVIII/2, "Decision related to the amendment to phasedown hydrofluorocarbons", which included a request to the Technology and Economic Assessment Panel (TEAP) under paragraph 4 "to conduct periodic reviews of alternatives, using the criteria set out in paragraph 1 (a) of decision XXVI/9, in 2022 and every five years thereafter, and to provide technological and economic assessments of the latest available and emerging alternatives to hydrofluorocarbons."

**Decision XXVI/9, "Response to the report by the Technology and Economic Assessment Panel on alternatives to ozone-depleting substances",** and specifically the above referenced paragraph 1(a) criteria is as follows:

1. To request the TEAP, if necessary, in consultation with external experts, to prepare a report identifying the full range of alternatives, including not-in-kind technologies, and identifying

applications where alternatives fulfilling the criteria identified in paragraph 1(a) of the present decision are not available, and to make that report available for consideration by the OEWG at its 36th meeting and an updated report to be submitted to the 27th MOP that would:

a) Update information on alternatives to ODS in various sectors and subsectors and differentiating between parties operating under paragraph 1 of Article 5 and parties not so operating, considering energy efficiency, regional differences, and high ambient temperature conditions in particular, and assessing whether they are:

   I. Commercially available;
   II. Technically proven;
   III. Environmentally sound;
   IV. Economically viable and cost effective;
   V. Safe to use in areas with high urban densities considering flammability and toxicity issues, including, where possible, risk characterization;
   VI. Easy to service and maintain;

   and describe the potential limitations of their use and their implications for the different sectors, in terms of, but not limited to, servicing and maintenance requirements, and international design and safety standards;.

## 1.1 Executive Summary from the Flexible and Rigid Foams Technical Options Committee (FTOC)

Significant progress has been made by parties to phase-out the use of hydrochlorofluorocarbons (HCFCs) in foams. There are Foam Blowing Agents (FBAs), that are not controlled substances, in use commercially today for nearly every foam sector. However, there are some technical and economic challenges remaining for A5 parties and especially for Small and Medium Enterprises (SMEs) and the safety requirements related to field applied foams.

There is no single ‘drop-in’ FBA replacement for currently used HCFCs or hydrofluorocarbons (HFCs). There are different technical, economic, safety, and environmental performance properties for each low global warming potential (GWP), zero ozone depletion potential (ODP) alternative and different needs for each market subsector. There is a proliferation of blends across the whole of the foam sector which is an indication of the reality that there is no single best solution. Often a key factor is the size of the manufacturing plant since the economies of scale have a considerable bearing on the relative importance of capital and operational costs. Overall cost also is a major factor in the consideration of the major emerging technologies.

The transition away from ODS foam blowing agents in some regions and market segments (e.g., spray foam and extruded polystyrene) may be delayed because of cost, especially where local codes require higher thermal performance[1]. It should be noted that the price of HFC blowing agents has risen substantively during the pandemic and is nearly as high as hydrofluoroolefin (HFO) and hydrochlorofluoroolefin (HCFO) prices were prior to the pandemic in some A5 parties.

Low-GWP FBA shortages continue in both A5 and non-A5 parties but now to a lesser degree than previously reported. Supply issues are understood to have started in 2020 as a result of logistics issues, raw material shortages, manufacturing issues, severe weather, and increasing

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[1] Although the cost of hydrochlorofluorocarbons (HCFCs) was approximately 20-30% of the cost of high-GWP HFCs, HCFC price is increasing as they are phased out globally. The low price of some high-GWP HFCs, particularly HFC-365mfc which is banned in some non-A5 parties, is leading to an increase in market share, which is slowing the conversion to low-GWP blowing agents

demand for low-GWP FBAs. Undisclosed manufacturing issues from at least one HFO/HCFO supplier led to *force majeure* declarations, according to several foam manufacturers. There have also been reported shortages of hydrocarbons of sufficient purity for foam use, such as cyclopentane.

As a result, there has been a significant increase in the use of hydrofluorocarbons HFC-365mfc/HFC-227ea or HFC-365mfc/HFC-245fa blends in some A5 parties and a reversion to HFC-365mfc blends and HFC-245fa in some non-A5 parties. It is worth noting that the availability of high-GWP HFCs, particularly HFC-365mfc/HFC-227ea (which is banned in many non-A5 parties), is slowing the transition to low GWP FBAs. However, one foam manufacturer has informed the FTOC that they have received notice that at least one HFC FBA manufacturing facility will close in 2024.

There have been recent announcements that additional production capacity for HFOs/HCFOs has come on-line. This has eased the supply constraints to some degree; although, there are still reports of continued use of allocation procedures to parse out supply to customers due to inability to fulfil all supply requests. An additional update on planned supply relative to forecasted demand will be provided in 2023 TEAP Reports as additional information becomes available.

Finally, there continues to be a trend away from the use of fluorocarbon (FC) FBAs with every transition. As the phaseout of HCFCs and the phasedown of HFCs progress, there will be limited availability and increasing prices of FBAs which will drive the selection of alternative foam blowing agents. It has been estimated that less than 20% of the FBA volume will be comprised of FCs after the transition to low GWP FBAs globally. This is in part due to direct conversions to other FBAs and in part as a result of the use of blends with lower concentrations of FCs.

## 1.2 Overview of Foam Market

### *1.2.1 Global Foams Market*

Raw material shortages and limited access to production sites during quarantine periods reduced manufacturing supplies and demand during the early years of the global pandemic, including raw materials for foam manufacture and foams for the end-uses that incorporate them, such as refrigeration equipment. These markets have also been impacted by severe weather. According to *Fortune Business Insights*, the foam market contracted by 1.7% in 2020,[2] However, some economists note that there are continued supply disruptions and labour-market pressures which, coupled with interest rate increases, may contribute to continued slow recovery or even local or global recessions[3].

According to *The Future of Polymer Foams*, the annual production of polymer foam was estimated to be 29,357 thousand tonnes in 2021 and is projected to grow to 37,254 thousand tonnes in 2026 with a growth rate of 4.9% over this period, with a significant portion of this growth projected to occur in Asia. The polyurethane foams market was estimated to have the largest market share of polymer foams with approximately 51% of the market share with extruded polystyrene foams at 37% of the market in 2020.[4]

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[2] Fortune Business Insights Polyurethane Market Size, Share & COVID-19 Impact Analysis, By Product Type (Rigid Foam, Flexible Foam, Molded Foam, Elastomers, Adhesives & Sealants, Coatings, and Others), By Application (Furniture, Construction, Electronics, Automotive & Transportation, Packaging, Footwear, and Others), and Regional Forecast, 2021-2028 https://www.fortunebusinessinsights.com/amp/industry-reports/polyurethane-pu-market-101801

[3] The World Bank: Risk of Global Recession in 2023 Rises Amid Simultaneous Rate Hikes https://www.worldbank.org/en/news/press-release/2022/09/15/risk-of-global-recession-in-2023-rises-amid-simultaneous-rate-hikes

[4] DeMuse, Mark The Future of Polymer Foams Smithers and Smithers, as viewed 9/4/22

According to *Mordor Intelligence*, the extruded polystyrene (XPS) market is projected to grow by over 4% per year from 2022 to 2027, after a significant slowdown in building construction during the pandemic. As construction resumes, increased demand for insulation materials to reduce building heating and cooling load is expected to lead to the growth of insulation markets for XPS, polyurethane (PU) and other insulation in the coming years. Polymer insulation growth is expected to increase at the fastest pace in the residential market due to population growth (new homes) and increased focused on better insulation in existing homes. Growth in the Asia-Pacific region is expected to dominate the market.[5]

### *1.2.2 Major Issues Influencing the Global Foams Market*

There is likely to be some recovery in all markets negatively impacted by the pandemic, in the near-term, including construction projects halted due to lack of funds, quarantine mandates, and resulting labour shortages.

Global population growth drives demand for polymeric foams used in the main end-use industries, including building & construction, cold chain, furniture & bedding, packaging, and transportation industries (e.g., automotive industries (cars, buses, motorcycles), trains, ships etc.). Polyurethane, polyisocyanurates, polystyrene and phenolic foams contribute to the energy efficiency of heating and cooling systems in buildings, while flexible polyurethane foams provide acoustic insulation, energy absorption for packaging and comfort in applications such as mattresses and furniture. Increasing focus on reducing heating and cooling load in buildings and appliances to meet the climate challenge will increase demand for polymeric foams as thermal insulation.

The main factors influencing thermal insulation requirements are legislative, regulatory, and building standard mandates to reduce heating and cooling loads in both commercial and residential buildings. The European Union (EU) and North America are currently the leading proponents of building codes to improve energy efficiency in the construction industry, while the global appliance industry continues to develop new more energy-efficient models.

Investment in decarbonization and infrastructure will drive increased use of insulation including several end-uses for foamed products produced from polymeric MDI.  For example, in China, the "Dual Carbon" vision (peaking carbon in 2030 and neutrality in 2060)– has further pushed for energy conservation. China's investment programme includes a range of opportunities for rigid foams and light-weight polyurethane composites in the cold chain, district cooling and heating, high speed rail, new electric vehicles (NEVs), and the construction of temperature-controlled data server centres. Many innovations are on-going to make thermal insulation products that meet the stringent fire standards in residential and commercial buildings.

According to *Global Newswire*, the global cold chain market is expected to grow from a value of approximately $245 billion in 2021 to $800 billion in 2030, with[6] a growth rate of over 14%.  There is increasing demand from the retail sector to mitigate food waste and degradation. Asia Pacific is expected to grow at the fastest rate due to the presence of major food and healthcare providers. For example, China's cold chain industry has been growing at a remarkable 19% since 2014.

Extruded Polystyrene (XPS) is typically used for its low-moisture permeability and high-compression strength in applications including refrigerated transport, perimeter insulation and cold stores.

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[5] It should be noted that it has been estimated by F-TOC members that XPS foam manufacturing capacities in North America and Europe are currently close to capacity to meet current market demand.
[6] Global Newswire , Cold Chain Logistics Market Size to Worth Around USD 801.26 Bn by 2030, as viewed September 4, 2022

Polyurethane, polyisocyanurate[7], and phenolic rigid foam are not used as widely as other thermal insulation materials (i.e., mineral wool or fibreglass) in building insulation due to relatively high cost. However, the low thermal conductivity of all three types of foam at wide operating temperatures dominates the insulation demand from the cold chain and district cooling and heating systems, including internal building services usage.

In Europe, the volume of XPS foam insulation is generally increasing at a rate corresponding to gross domestic product (GDP) growth with variation in individual countries. There is increased demand for thick (>200mm) XPS panels to meet specific construction requirements[8].

In North America, the insulation market continues to recover from the pandemic. However, the use of XPS appears to be growing at a lower rate especially where other products (e.g., EPS for construction below ground) may be replacing XPS as building insulation requirements change and builders seek the most cost-effective insulation.

[7] For simplicity, any reference to rigid polyurethane foam in this report is understood to include foams referred to as polyisocyanurate foams. These foams have similar chemistries and use similar starting materials. Most foams sold a polyisocyanurate are usually mixture of polyurethane and polyisocyanurate polymers.

[8] Thicker XPS is used decoratively and for roofs where they can be cut around protruding features. Thicker foams also do not allow for moisture intrusion between layers which reduces thermal performance and provide more weight for ballast to prevent wind uplift and may have implications for building structure.
Multiple layer XPS foam manufacturing techniques usually require the use of bonding chemicals which may increase thermal conductivity or water transfer. Additionally, those chemicals are likely to make the recycling process of XPS either much more complicated or impossible which is economically undesirable. There are very few manufacturers that can produce this as a monolithic board, leading to the use of multiple layers, which has some disadvantages, or the need by producers to invest in new thermal bonding technology.

# 2.0 Technical Progress in the Transition to Technically and Economically Feasible and Sustainable Alternatives and Practices that Minimize or Eliminate the Use of Controlled Substance

## 2.1 Introduction

There is no single foam blowing agent replacement for currently used HCFCs or HFCs. There are different technical, economic, safety, and environmental performance properties for each low global warming potential (GWP), zero ozone depletion potential (ODP) alternative and different needs for each market subsector. There is a proliferation of blends across the whole of the foam sector which is an indication of the reality that there is no single best solution. Often a key factor is the size of the manufacturing plant since the economies of scale have a considerable bearing on the relative importance of capital and operational costs. Cost is also a major factor in the consideration of the major emerging technologies.

Some important properties are shown in the tables below that highlight the differences between generations of foam blowing agents (FBAs) and the historic high boiling point (BP) option, CFC-11, and low boiling point option, CFC-12. Note that higher BP FBAs are often referred to as "liquid" FBAs while lower BP FBAs are referred to as "gaseous" FBAs. Lower BPs mean that higher pressure equipment and storage are needed and there are more emissive losses during the foaming process.

From a cost perspective, the price of the newer FBAs is higher and more loading is needed because of higher molecular weights, which increases the cost of foam systems. This is because blowing agents are purchased based on weight, but they are used based on volume which is inversely proportional to molecular weight.

Water is added as a supplementary FBA to reduce costs. Water reacts with isocyanate during the foaming reaction creating carbon dioxide. Blends are used to optimize cost and physical properties of most low GWP, zero ODP for both gaseous and liquid FBAs. Cost is also impacted by capital investment needed to use flammable alternatives (See flash points in the tables below.).

Another important consideration is FBA solubility and diffusion in polyols and its impact on long-term thermal performance and some safety requirements. For example, some FBAs will be emitted sooner after the foam is manufactured. This is true for extruded polystyrene (XPS) foams, which are generally produced with gaseous FBAs, and are often carefully stored in warehouses to ensure that some high emitting, and sometimes flammable,[9] FBAs are emitted and to ensure that dimensional stability is maintained prior to shipment.

Finally, thermal resistance (lambda value) of FBAs is an important consideration especially for insulating foams. However, it should be noted that foams may perform differently, depending on foam formulations and FBA blends. Interestingly, some blends of FBAs seem to behave as azeotropes, much like refrigerant blends with low glide[10], and provide better performance than either component on its own.

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[9] Low solubility blowing agents are not necessarily high emitters, 134a for instance. Also, not all flammable blowing agents are high emitters in XPS (isobutane, for example), but some as DME and ethanol are.

[10] Some blends of FBAs seem to behave as azeotropes, much like refrigerant blends with boiling point reductions, a feature that provides better performance than either component on its own in low temperature insulation applications.

**Table 2.1 Foam blowing agents (FBAs) with lower boiling points**

| FBAs with lower boiling points<br>Gaseous FBAs | CFC-12 | HFC-134a | HFC-152a | HFO-1234z(E) |
|---|---|---|---|---|
| **Mol weight** | 120.9 | 102 | 66.1 | 114 |
| **Boiling point (°C)** | -29.7 | -27 | -25 | -19 |
| **Lambda gas -10°C (mW/m.K)** | 8.23 | 12.5 | 14.8 @ 25C | 13 |
| **Flash point (°C)** | None | None | 50 | None |
| **Polyol Solubility** | | Low | | Low |
| **ODP** | 1 | 0 | 0 | 0 |
| **GWP (AR 6)** | 11200 | 1530 | 164 | 1.37 |
| **GWP (AR 5)** | 10200 | 1300 | 138 | <1 |
| **GWP (AR 4)** | 10900 | 1430 | 124 | Not Listed |

**Table 2.2 Foam blowing agents (FBAs) with higher boiling points**

| FBAs with higher boiling points "Liquid" FBAs | CFC-11 | HCFC-141b | HFC-245fa | HFC-365mfc | HFC-365mfc HFC-227ea 93/7 | Cyclo-pentane | Normal pentane | Iso-pentane |
|---|---|---|---|---|---|---|---|---|
| **Mol weight** | 137 | 117 | 134 | 148 | 150 | 70 | 72 | 72 |
| **Boiling point (°C)** | 24 | 33 | 15 | 40 | 30 | 49 | 36 | 28 |
| **Lambda gas -10°C (mW/m.K)** | 7.4 | 9 | 11 | 11 | 11 | 11.5 | 13.5 | 12.5 |
| **Flash point (°C)** | None | None | None | -24 | None | -40 | -49 | -51 |
| **Polyol Solubility** | High | Very High | High | High | High | Moderate | Low | Low |
| **ODP** | 1 | 0.11 | 0 | 0 | 0 | 0 | 0 | 0 |
| **GWP (AR 6)** | 5560 | 860 | 962 | 924 | 1102 | Not listed | Not listed | Not listed |
| **GWP (AR 5)** | 4660 | 782 | 858 | 804 | 982 | Not listed | Not listed | Not listed |
| **GWP (AR 4)** | 4750 | 725 | 1030 | 794 | 964 | Not listed | Not listed | Not listed |

**Table 2.3 Foam blowing agents (FBAs) with higher boiling points and lower global warming potential (GWP)**

| FBAs with higher boiling points "Liquid" FBAs | Methyl Formate | HFC-1225ye | HCFO-1233zd(E) | HCFO-1224yd | HFO-1336mzz(E) | HFO-1336mzz(Z) |
|---|---|---|---|---|---|---|
| **Mol weight** | 60 | | 130 | 148.5 | 164 | 164 |
| **Boiling point (°C)** | 31.5 | | 19 | 19 | 7.5 | 33.4 |
| **Lambda gas -10°C (mW/m.K)** | 10.7 | | 10.2 @20C | | 11.5 @25C | 10.7 @25C |
| **Flash point (°C)** | 5 to 23 vol% | | None | None | None | None |
| **Polyol Solubility** | | | High | | High | High |
| **ODP** | 0 | | 0.00034 | 00023 | 0 | 0 |
| **GWP (AR 6)** | Not listed | 0.118 – 0.344 | 3.88 | Not Listed | 17.9 | 2.08 |
| **GWP (AR 5)** | Not listed | <1 | 1 | Not Listed | Not listed | 2 |
| **GWP (AR 4)** | Not listed | Not listed | Not listed | Not Listed | Not listed | Not listed |

Hydrocarbon (HC), methylal, methyl formate, 1,2 dichloroethylene, and methylene chloride are reportedly being used in blowing agent blends to reduce costs in some parties. FTOC is seeking additional details on the safety measures being taken to address exposure and safety risks.

For example, some spray foam (SPF) formulators use 1,2 dichloroethylene, predominately the trans isomer, as an additive for ostensibly improving solubility of HFC and now HFO blowing agents as a means of extending their value. With a boiling range of 48 – 60 C for both isomers, it can support blowing and may be used further as HFO and HFC supplies are tight[11]. As the transition proceeds and there are continued challenges in supply and costs, foam manufacturers and chemical producers are introducing new options and potential challenge

**Supply and economic challenges**

The transition away from ODS foam blowing agents in some regions and market segments (e.g., spray foam and extruded polystyrene) may be delayed because of cost, especially where local codes require higher thermal performance[12]. It should be noted that the price of HFC blowing agents has risen substantively during the pandemic and is nearly as high as hydrofluoroolefin (HFO) and hydrochlorofluoroolefin (HCFO) prices were prior to the pandemic in some A5 parties.

[11] Toxicity of 1,2 dichloroethylene is currently being reviewed by at least one party. Field studies related to Indoor Air Quality in SPF installations often shows some concentration of 1,2-dichloroethane up to months or years after installation due to its higher boiling point and high solubility in foam matrixes.

[12] Although the cost of hydrochlorofluorocarbons (HCFCs) was approximately 20-30% of the cost of high-GWP HFCs, HCFC price is increasing as they are phased out globally. The low price of some high-GWP HFCs, particularly HFC-365mfc which is banned in some non-A5 parties, is leading to an increase in market share, which is slowing the conversion to low-GWP blowing agents

Low-GWP FBA shortages continue in both A5 and non-A5 parties but now to a lesser degree than previously reported. Supply issues may have started in 2020 due to logistics issues, raw material shortages, manufacturing issues, severe weather, and increasing demand for low-GWP FBAs. Undisclosed manufacturing issues from at least one HFO/HCFO supplier led to *force majeure* declarations, according to several foam manufacturers. There have also been reported shortages of hydrocarbons of sufficient purity for foam use, such as cyclopentane.

As a result, there has been a significant increase in the use of hydrofluorocarbons HFC-365mfc/HFC-227ea or HFC-365mfc/HFC-245fa blends in some A5 parties and a reversion to HFC-365mfc blends and HFC-245fa in some non-A5 parties. It is worth noting that the availability of high-GWP HFCs, particularly HFC-365mfc/HFC-227ea (which is banned in many non-A5 parties), is slowing the transition to low GWP FBAs. However, one foam manufacturer has informed FTOC that they have received notice that at least one HFC FBA manufacturing facility will close in 2024.

There have been recent announcements that additional production capacity of HFOs/HCFOs. This has eased the supply constraints to some degree; although, there are still reports of continued use of allocation to parse out supply to customers due to inability to fulfil all supply requests. An additional update on planned supply relative to forecasted demand will be provided as additional information becomes available in 2023 TEAP Reports.

Finally, there continues to be a trend away from the use of fluorocarbon (FC) FBAs with every transition. As the phaseout of HCFCs and the phasedown of HFCs progress, there will be limited availability and increasing prices of FBAs which will drive the selection of alternative foam blowing agents. It has been estimated that less than 20% of the FBA volume will be comprised of FCs after the transition to low GWP FBAs globally. This is in part due to direct conversions to other FBAs and in part due to blends with lower concentrations of FCs.

## 2.2 Evolution of Foam Blowing Agents

There are several important criteria considered when foam manufacturers select a new suitable foam blowing agent (FBA), and not all FBA characteristics are equally important in the manufacturing of each type of foam. Since no one single low GWP, zero ODP FBA embodies all the criteria, foam manufacturers must prioritize these traits and select the most suitable option for their application. Various perspectives on key characteristics in the manufacture of certain types of foam has led to a proliferation of the number of FBAs with more variation in the development of FBAs as noted in the Executive Summary.

One key challenge has been the increasing cost of fluorocarbons (FCs) with each generation, which has created some preference in minimizing the use of FCs in foam systems and seeking lower cost alternatives to use alone or in blends with FCs. Despite best efforts by chemical manufacturers to find alternatives that closely emulate the performance of the previous generation, newer FCs generally bring specific challenges that do not necessarily meet the needs of the entire industry.

The demand for FCs for foam is significantly smaller than the demand for FCs in refrigerants. The investment priority may be more focused on the larger FC refrigerant markets with an effort in some companies to use refrigerants as FC FBAs for foams rather than to develop and commercialize FC FBAs specifically for foam use alone.

Cost and robust fitness of FCs for foams have led to the growth in the use of other FBAs, such as hydrocarbons, water, and methyl formate. The next figure illustrates how the foam market has changed over the lifetime of the Montreal Protocol. Note that the height of the bars in the histogram are normalized. It should not be interpreted that the total market size is the same for each decade.

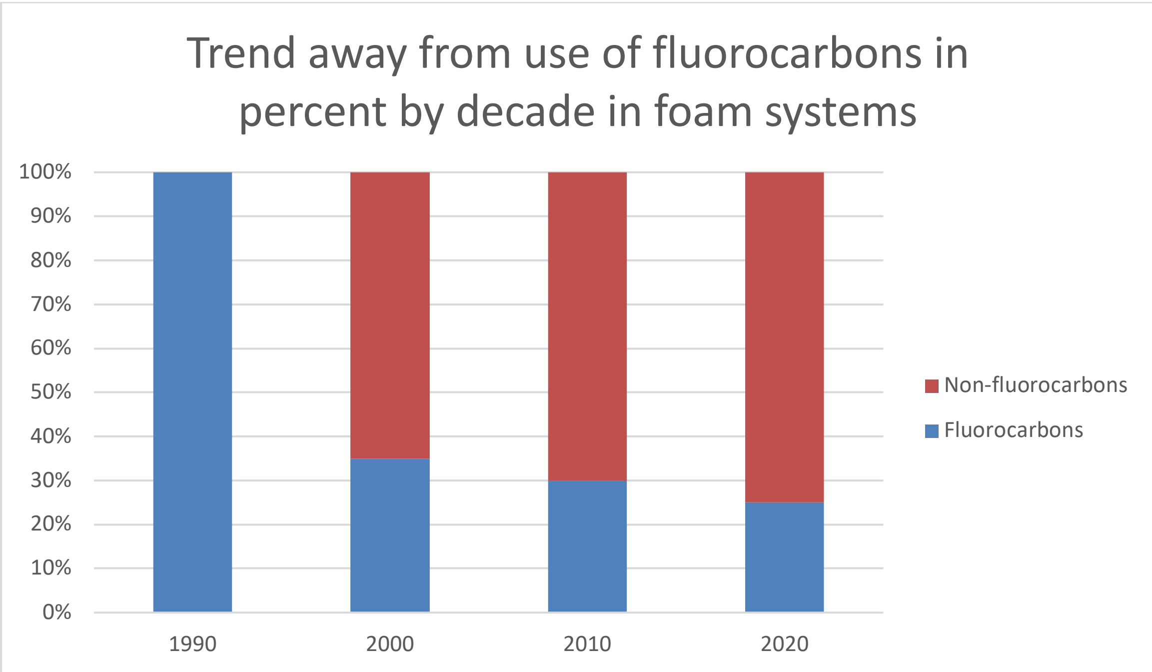
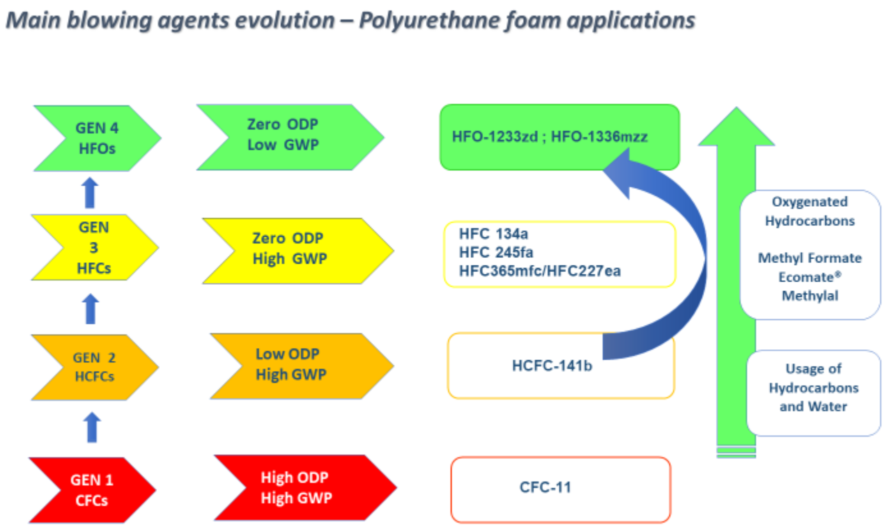



**Figure 2.1: Estimated trend of fluorocarbon use as foam blowing agents**

## 2.3 Polyurethane Foams and A History of Fluorocarbon Usage in Foams

Until the CFC-11 phase-out in 1996 in non-Article 5 parties and in 2010 in Article 5 parties, it was the primary blowing agent used in polyurethane flexible and rigid foams. Until the mid-1960s, CFC-11 was used primarily in open-celled flexible polyurethane foams (e.g., bedding and other uses), after which its use in closed-cell polyurethane foams (e.g., insulating foams in appliances and construction) started to increase. Its peak usage in foams was reported to be in the late 1980s.

**Figure 2.2 Evolution of blowing agents for polyurethane foam applications**



CFC-11 was not known to be used in extruded polystyrene foams (XPS) which were foamed with CFC-12. PU foam formulations generally contained between 3% CFC-11 in flexible slab foams to 12% in rigid PU foams. It has been estimated that 86% to 100%[13] of the blowing agent is emitted during the foaming process for flexible foams and 4% (e.g., appliance foams) to 25% (e.g., spray foam) is emitted in the manufacture of rigid foams. Earlier literature describes emissions rates of 98% (flexible foams) and up to 30% (closed cell foams) during installation[14]. The lower emissions rate may reflect more sophisticated technologies and application techniques.

**Polyurethane Foam chemistry**
Polyurethane foams are manufactured through an exothermic reaction of di-isocyanate and polyol by forming cells from gas bubbles in the polymer mixture by use of a "foam blowing agent" which is either a gas chemically formed through reaction with the isocyanate or a physical blowing agent which volatilizes during foam formation. Polyurethane foams can be classified into three major categories: rigid, flexible, and integral skin/expanded elastomers. Product applications include insulating materials for buildings and appliances, cushioning products for furnishings and automobiles, packaging for protection of high-value products, automobile instrument panels and steering wheels and shoe soles.

Historically, CFC-11 was low cost and widely used in most polyurethane foam applications. The boiling point is room temperature making handling easy and providing for wide processing windows (e.g., temperature and other conditions). CFC-11 has good compatibility with equipment materials of construction and raw materials used in foam formulations making them generally stable for long periods of time (i.e., long shelf-life). CFC-11 foams had good dimensional stability, compressive strength, and insulation capability.

Due to its physical properties and good insulating properties, CFC-11 blown rigid foams could be used with lower densities offering low thermal conductivity for hot and cold applications. It was used in tanks, pipes, and construction in panels, roofing, and spray foam in industrial, commercial and residential buildings. It was also used in the cold chain (commercial and domestic refrigeration and transportation).

**Transition away from fluorocarbon foam blowing agents in closed-cell or rigid foams**

The 2006 FTOC Assessment Report[15] included a detailed summary of blowing agent usage by foam type globally and regionally which has been updated in subsequent assessment reports. The 2006 report is referenced because it is the earliest and most detailed report available to extrapolate to the fluorocarbon (FC) usage in closed-cell foams. The report estimated that, in 2006, 360,000 tonnes of blowing agent was consumed globally and noted that there had been a stabilization and even slight drop in blowing agent consumption due to more efficient processes with lower losses than previous years. According to the 2006 report, approximately 55% of the blowing agents at that time were used for closed-cell polyurethane foams[16].

The majority of the blowing agent in use for closed-cell foam was CFC-11 in non-Article 5 parties prior to its ban before 1990. A small amount of CFC-12 was used as a propellant for foams requiring enhanced distribution across longer distances (e.g., spraying foam for refrigerated trailers or containers). CFC-11 was low-cost and easy to use and did not require high-cost additives or equipment (e.g., surfactants and catalysts, high pressure storage equipment). According to reporting

[13] Ashford *et al.*, 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*, Chapter 7, Emissions of Fluorinated Substitutes for Ozone Depleting Substances https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_7_Ch7_ODS_Substitutes.pdf; Industry expertise.
[14] TEAP Task Force Report on Unexpected Emissions of CFC-11
[15] https://ozone.unep.org/sites/default/files/2019-05/ftoc_assessment_report06.pdf
[16] Peak CFC-11 usage identified for closed-cell foams occurred in the late 1980s according to AFEAS and production and consumption data reported to the OS.

through AFEAS and to the Ozone Secretariat, the Task Force estimates that usage of CFC-11 in closed-cell foams peaked in the 1980s just under 200,000 tonnes.

In non-Article 5 parties, during the 1970s, when energy efficiency became a priority, insulation for homes and commercial building increased significantly. In the 1980s, polyurethane foam replaced other types of insulation in refrigerators in non-Article 5 parties. Polyurethane foam was primarily used in appliances (e.g., household refrigerators and freezers) in Article 5 parties through 2010. After a series of tragic fires occurred, use of polymer foams in construction slowed, until flammability concerns were addressed through building code modifications and fire testing of foams.

In non-Article 5 parties, nearly two-thirds of the conversion from CFCs was to non-fluorocarbon technology such as water (carbon dioxide) and hydrocarbons in appliances and boardstock. By 2010, it has been estimated that less than one hundred thousand tons of fluorocarbon blowing agent (including HCFCs, HFCs and HFOs) was used for closed-cell foams globally. Usage of fluorocarbons has continued to decrease as appliance and boardstock have largely been converted to other alternatives during conversions to comply with ODS and GWP regulations.

**Supply Chains for Foam Manufacturers**

Thermoset polyurethane foams are largely used as board stock or applied as a spray foam in construction, for industrial uses (e.g., pipe insulation), and in refrigeration (e.g., refrigerators, commercial refrigeration display cases, transportation, coolers, etc.). Foams can be manufactured and sold in finished form, manufactured, and cut, or applied in the field.

**Supply Chain for Large Foam Manufacturers**

The figures below depict the production processes for board and spray foam for large and medium manufacturing processes. Larger enterprises purchase raw materials directly (polyols, blowing agents, isocyanate, etc.) and blend them to produce foams as shown below. Blowing agent is delivered in drums or in tanks or cylinders. Unless the foam manufacturer provides very specific blending instructions, it would be unlikely that the manufacturer would be unaware of the type of blowing agent in use when manufacturing foam.

**Figure 2.3 Supply chain for some large and medium foam manufacturing**

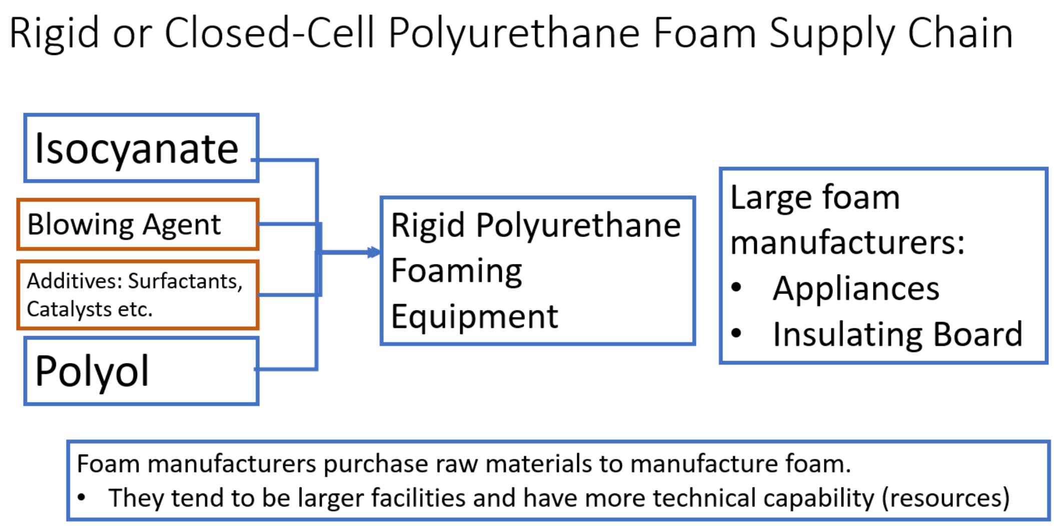


**Figure 2.4 Board production process**

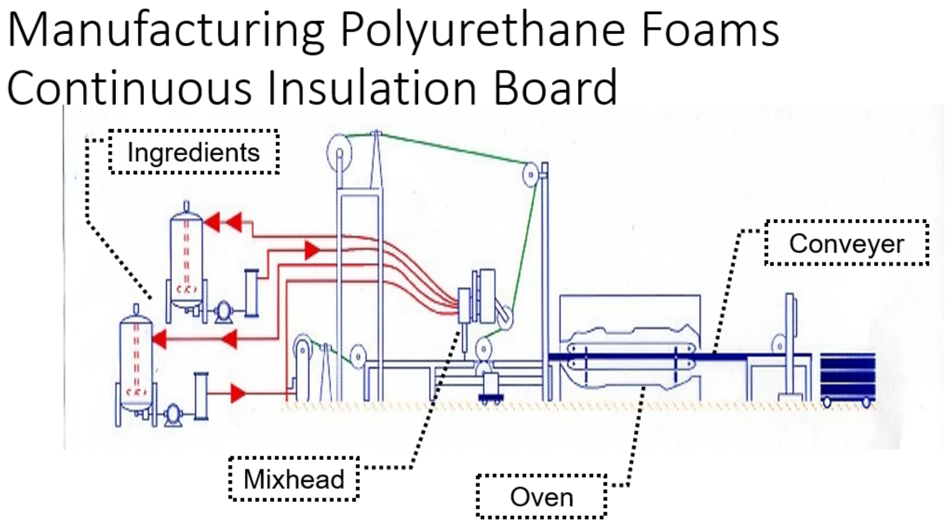



**Figure 2.5 Spray foam and foam molds blending process**

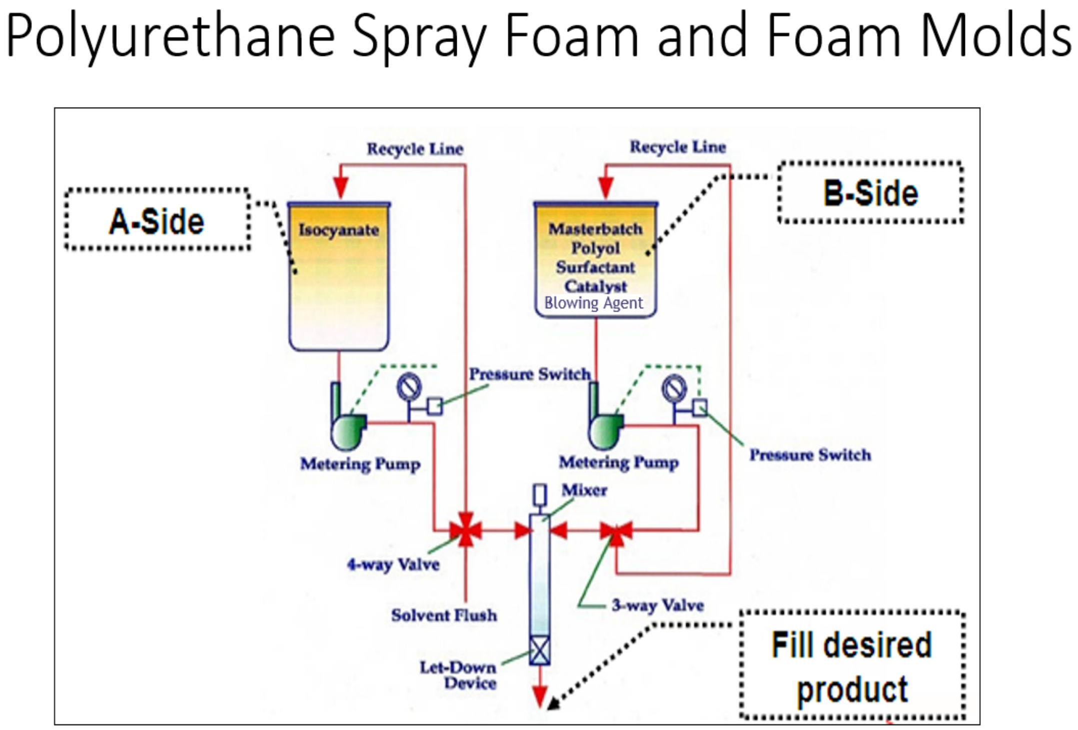


**Figure 2.6 Foam products generally produced by large and medium manufacturing processes[17]**

Polyurethane Closed-Cell or Rigid Foams: Refrigeration, construction, manufacturing

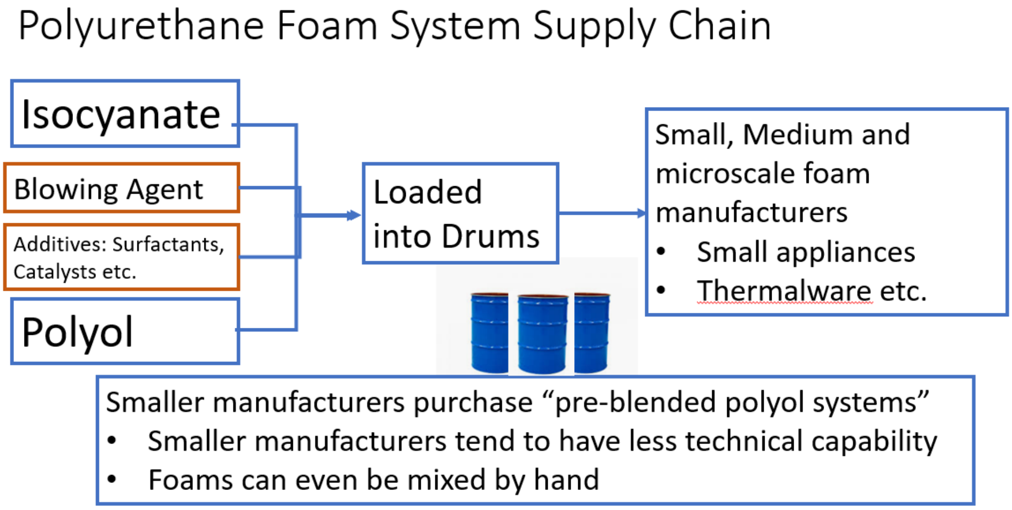
## Supply Chain for Smaller Foam Manufacturers

Small, micro (and even some medium) enterprises generally purchase isocyanate and polyol blends in drums or other containers. These are commonly referred to as "foam systems". The polyol blend consists of polyol, blowing agent, and additives (e.g., catalysts and surfactants). Provided the components in the polyol system are blended in appropriate ratios and the user is provided with proper instructions to blend isocyanate in the right ratio with the polyol system, the foam manufacturer could be unaware of the blowing agent used in the blend. Although some enterprises may have blending and spray equipment similar to that used by larger companies, other equipment can be much more simplistic, even blending ingredients manually.

There is a growing trend for SMEs consuming 1000 tonnes or more to self-formulate blends for their own systems especially in Asia.

[17] Note that in many countries the "B" side describes the isocyanate while the "A" side describes the polyol blend.

**Figure 2.7 Supply chain and production processes for small and medium manufacturing processes**




**Pre-blended polyol systems**

Several parties import pre-blended polyol containing blowing agent for local foam production. According to data provided directly to the Technical and Economic Assessment Panel (TEAP) Task Force on Unexpected Emissions of CFC-11 the MLFS, 33 out of 68 parties reporting HCFC-141 consumption also reported import of pre-blended polyol systems. The summary does not state from which country these were shipped. In individual discussions with some parties, it was noted that foam system houses ship polyol systems to other countries in close proximity, especially to countries with very small foam production. There is likely additional pre-blended polyol shipped to other countries. that has not been reported by these 68. As much as 7500 tonnes of HCFC-141b was reported as being shipped in pre-blended polyol to other countries in 2009. None of the parties reporting production of HCFC-141b to the Ozone Secretariat reported to the MLFS that they had received pre-blended polyols. It should be noted that emissions from pre-blended polyols are similar to, or higher than, emissions from foam components that are not pre-blended, as emissions from drums are not always well-controlled, especially from drums that are not cooled in high ambient temperature countries.[18]

**Factors Impacting Blowing Agent Choice**

Significant progress has been made by parties to phase-out the use of hydrochlorofluorocarbons (HCFCs) in foams. There are Foam Blowing Agents (FBAs) in use commercially today for nearly every foam sector that are not controlled substances. However, there are some technical and economic challenges remaining for A5 parties and especially for Small and Medium Enterprises (SMEs) and the safety requirements related to field applied foams

It has been estimated that 80-84% of HCFC-141b in A5 parties will be replaced with non-fluorocarbon alternatives including water or carbon dioxide-blown foams. Evolving HCFC and HFC phase-out plans will have a large impact on the choices of non-ODP options. Some FC use is likely to continue for the foreseeable future: Spray foams and SMEs, for safety reasons), and for insulation where there are stringent thermal performance requirements. There are also uses of FCs where structural or fire safety properties are of concern.

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[18] Blowing agent emissions from loading drums can be as high as 20% in high ambient temperatures as measured by one foam system house and reported to FTOC.

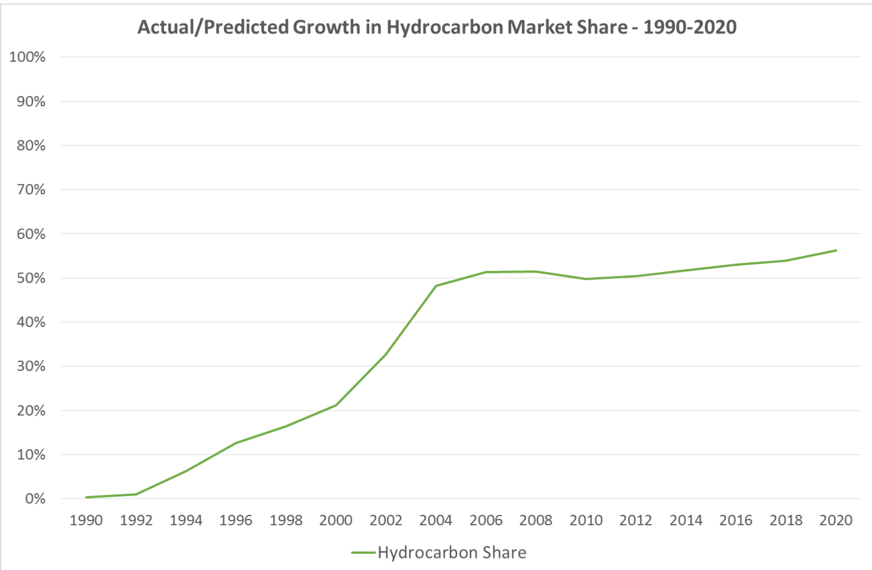
## 2.4 Regulations and costs impacting blowing agent selection

The major blowing agent transitions being driven by regulation at present are those in Article 5 parties resulting from the enactment of Decision XIX/6 and being funded under a series of national HCFC Phase-out Management Plans (HPMPs). Since Decision XIX/6 required a "worst first" approach, the phase-out of HCFC-141b was targeted first. CFC-11 had largely converted to HCFC-141b for rigid insulating polyurethane foams and to methylene chloride [dichloromethane (DCM)][19] or water in flexible foams in both Article 5 and non-Article 5 parties. The conversion from HCFC-141b to hydrocarbon FBAs has been largely successful within larger and some medium enterprises where the critical mass of the operation is sufficient to justify the investment. In several instances, individual enterprises have been willing to co-fund the investment where the funding thresholds available under the Multilateral Fund have been insufficient, despite the economies of scale.

The many SMEs have posed a challenge for non-Article 5 parties and continue to do so in Article 5 parties. The lack of economies of scale does not allow for the adoption of hydrocarbons, while the adoption of high GWP alternatives such as HFCs will result in high levels of emission within processes which are either less well engineered or are unavoidably emissive because they are used in-situ (e.g., PU Spray Foams). Although there is increasing pressure now to switch to low-GWP technologies, approximately one third of HCFC consumption was initially converted to HFCs in non-Article 5 jurisdictions.

As a result of the trade-offs in properties and costs of various alternatives in the different sectors, the HCFC-141b conversion has resulted in more diverse transitions than the CFC-11 conversion. An estimated 2/3 of rigid PU foams manufacturing has converted to hydrocarbons, water (carbon dioxide), and methyl formate. A small portion of the market has converted to high GWP HFCs (e.g., HFC-245fa and HFC-365mfc blended with HFC-227ea. For example, in SMEs due to cost of alternatives and in spray foam due to safety concerns related to flammable alternatives. In general, HCFCs are less than half of the cost of high GWP HFC. and HFO/HCFO blown foams remain more expensive than HFC foams due to the total cost of the blowing agent together with the required additives.

**Figure 2.8 Evolution of Hydrocarbon market share for Foam Blowing Agents**



Under HCFC Phase-out Management Plans (HPMPs), projects that transition from HCFC-141b FBAs for polyurethane foams to low GWP alternatives have been funded and many have been completed or are in progress. However, unfunded companies (e.g., companies that were established after September 2007, multi-national companies, and companies in unfunded parties) operating in Article 5 parties may convert from HCFCs to high GWP HFCs to meet HCFC phase-out deadlines rather than converting directly to low GWP alternatives.

Most parties used a command-and-control regulatory structure banning the consumption HCFC-141b altogether in specific uses. This has been coupled with the requirement to reduce production by steps. As designed, the production phase-out creates a mismatch between supply and demand in the market which increases the price of HCFC-141b. This is meant to create an impetus for industry to self-select a lower cost alternative that has a smaller environmental footprint.

At times, rising prices have also created a "black" market for illegal trade. There have been imports of illegal substances labeled as other products; while in other cases, no effort has been made to mask the sale of the banned chemical. When discovered, these cases have largely been addressed within the party where the illegal trade has taken place or in customs at borders. However, foams add another level of complexity in detecting illegal trade as pre-blended polyol systems containing the foam blowing agent are shipped from parties that produce polyols to parties that do not produce them. If the blowing agent is not documented, collecting, and analysing a sample requires more steps than collecting a refrigerant sample.

Some parties have taken measures to reduce import of ODS-containing polyol blends establishing regulations to phase out HCFC-141b in polyurethane foam through a quota system, with a permit for the import of bulk HCFC-141b. Additional regulations in development in these parties include a restriction on the import of HCFCs and polyols containing HCFC-141b after conversion projects are completed and a prohibition of the expansion of existing HCFC-based manufacturing capacities or building new facilities. In some Article 5 parties, HCFC-141b in spray foam is still allowed because of technical, safety and cost concerns about replacement products. This mismatch of supply and demand may be influencing blowing agent selection.

Some parties require labelling of pre-blended polyols and insulation boards containing HFCs as of January 1, 2015, and "included in descriptions used for advertising" of finished goods. In addition, there is an annual reporting obligation on manufacturers of pre-blended polyol containing HFCs (covering imports and exports).

**Spray Foam Additives**

Several spray foam (SPF) formulators use 1,2 dichloroethylene, predominately the trans isomer, as an additive for ostensibly improving solubility of HFC and now HFO blowing agents as a means of extending their value. With a boiling range of 48 – 60 C for both isomers, it can support blowing and may be used further as HFO and HFC supplies are tight. As the transition proceeds and there are continued challenges in supply and costs, foam manufacturers and chemical producers are introducing new options and potential challenges.

Hydrocarbons (HC), methylal, methyl formate, 1,2 dichloroethylene (DCE), and methylene chloride are all reportedly being used in blowing agent blends to reduce costs in some parties. FTOC is seeking additional details on the safety measures being taken to address exposure and safety risks.

While HCFC phase-out and HFC avoidance are being pursued in tandem, the more challenging areas such as spray foam safety, blend requirements and SMEs are yet to be fully tackled. Much still depends on the future availability and cost of low-GWP blowing agents. Whether or not this has resulted in usage of previously banned blowing agents on a large-scale basis has not been confirmed.

**Flexible Foams**

Low density, flexible, water-blown foams were introduced as an alternative of CFC-11 systems, but urea linkages formed because of the reaction between isocyanate and water created "hardness" quality issues. In the mid-1990's, supercritical carbon dioxide ($CO_2$) blown system was developed, which could achieve low density and low hardness. Although the supercritical $CO_2$ process requires additional investment to safely use high pressure $CO_2$, the cost may be absorbed for large scale flexible slab stock foam manufacturers, where this technology is widely adopted in non-Article 5 and Article-5 parties.

For flexible foams, several Article 5 and non-Article 5 parties substituted CFC-11 with dichloromethane (DCM), commonly known as methylene chloride. DCM is non-reactive and vaporizes during the foam blowing process, providing additional gas to expand the foam and reduce the density of flexible foams. DCM-blown flexible foams are often used in upholstered products such as furniture, cars and trucks and some appliances.

Some countries have placed limitations on the use of DCM due to health concerns. In Europe, DCM is subject to the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation which prohibits its use in paint strippers in concentrations exceeding 0.1%.[20] Several European countries have restrictions on the use of DCM. For example, the Danish Environmental Protection Agency lists DCM as a substance that is harmful for human health and should be avoided when substitutable[21] and Sweden prohibits the use of DCM, except for use in scientific research.[22] In the United States (US), the EPA's National Emission Standards for Hazardous Air Pollutants (NESHAP) for area sources limits, and in some cases prohibits, the use of dichloromethane in foam fabrication.[23] In China, the Ministry of Environmental Protection included DCM in the Prioritized List of Substances to be Subject to Control under the Water Pollution Control Action Plan released in 2015.[24]

However, even though several countries identify DCM as a potentially hazardous substance, there is sparsity of strict regulations of DCM in flexible foam products. In addition, the TEAP Task Force on Unexpected Emissions of CFC-11 questioned the economic incentive to broadly replace DCM, given its very low cost, with CFC-11 in open-cell flexible foams. Also, there are several low-cost alternatives to DCM including methyl formate, water and HFCs and HFOs as well as other alternatives that have been used for many years in non-Article 5 parties. It seems unlikely that restrictions on the use of DCM in a small number of countries due to toxicity concerns may have provided an incentive for foam manufacturers to revert to CFC-11 in certain flexible foam products.

## 2.5 Foam blowing agent transition in A5 parties

A growing number of foam producers are required to transition to zero ODP, and in some cases low GWP, foam blowing agents due to local regulations. In some parties, use of HCFCs is now limited to applications where HCs are nearly universally considered to be unsuitable, such as PU spray foam. Many parties are limiting the import of CFC-11 and HCFC-141b pre-blended polyols to prevent manufacture of foam using controlled ODS.

**China**

[20] European Parliament and Council Regulation (EC) No. 1907/2006, 18 December 2006
[21] Effects List 2009, Danish Ministry of Environment, Environmental Protection Agency Document No.4, 2010
[22] Prohibition in Certain Cases in Connection with the Handling, Import and Export of Chemical Products Ordinance (1998:944), 5–7§§.
[23] 40 CFR Part 63, Docket No. EPA-HQ-QAR-2006-0897
[24] Chemical Inspection and Regulation Service (CIRS), China MEP Published List of Priority Chemicals, 5 January 2018, http://www.cirs-reach.com/news-and-articles/China-MEP-Published-List-of-Priority-Chemicals.html

According to *Chemlink*[25], China to plans to end the use of HCFCs from Jan 2023 in pipe insulation and solar water heaters, which are likely to convert to water (carbon dioxide), hydrocarbons, and HFO FBAs. HCFCs will be banned from Jan 2025 for all PU applications except spray foam3000t HCFC141b will be allowed in spray foam until Dec 2025, the final year of HCFC141b phaseout.

There has been significant growth in PU foam production in China, and this is expected to continue for the foreseeable future as the government drives decarbonization.  Continued growth can be expected in thermal insulation of buildings to reduce energy consumption and in light weight composites like window lintels if relevant building standards are introduced or revised.

The prevalent alternatives to HCFC FBAs include hydrocarbons, $CO_2$ (water), and to a lesser extent HFCs and HFO/HCFOs. HFCs and HFO/HCFOs are used when higher thermal insulation performance is required. There is an increase in the use of foam blowing agent blends, also known as "co-blowing agents," to balance performance and cost. One Chinese company has introduced various chemical (in contrast to the typically used physical) blowing agents. However, their use is currently limited to co-blowing with physical foam blowing agents like hydrocarbons, HFCs, and HFO/HCFOs. Another company in China has developed co-blowing technologies using butane / isobutane (R-600 / R-600a) with pentane & HFCs, achieving more than 7% injection weight reduction in appliances.

**Latin America**

The large foam manufacturing economies in Latin America have already phased out HCFC-141b.  Some parties are also considering labelling requirements stating "containing HCFC-141b" on drums and containers of formulated polyols comprising HCFC-141b and its blends. These measures could improve control on HCFC-141b commercialised in the region.  During the last decade, major enterprises, mainly in the domestic/commercial refrigeration and continuous panel sectors have been successfully converted to HCs. HCFC Phaseout Management Plan (HPMP) projects continue to focus on implementation at SMEs, examining a wide range of non-HC pure and blended blowing agents (e.g., low volumes of HFOs, CO2 (water), methyl formate, methylal (dimethoxymethane), and blends).

The use of hydrocarbons pre-blended in foams continues to be of concern, as their use requires safety measures and plant modifications for blending facilities and for SMEs. In some A5 parties, there has been an increase in the use of methylal, methylene chloride[26] and hydrocarbons, specifically pentanes, in combination with HFCs to reduce cost. There are some limits to availability and allowance of use because of safety (flammability) and health (human exposure) concerns.

**Southeast Asia**

In southeast Asia, several parties have ratified or are considering ratification of the Kigali amendment. These parties manage the import of regulated HFCs import and use reporting to meet the obligations of the Kigali Amendment.

Singapore plans an 80% phase down in the consumption of HFCs. Since January 1, 2019, HFCs imported into Singapore have been subjected to licensing controls.

At the end 2018, Malaysia banned the export HCFC-141b contained in preblended polyols and banned import and use of HCFC-141b contained in preblended polyols from 1 Jan 2022. Pre-blended polyols may include blends of HC and HFO as co-blowing agents.

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[25] China proposes to ban HCFCs in polyurethane foam and disposable medical devices. https://chemical.chemlinked.com/news/chemical-news/china-proposes-to-ban-hcfcs-in-polyurethane-foam-and-disposable-medical-devices#:~:text=China%20Proposes%20to%20Ban%20HCFCs%20in%20Polyurethane%20Foam%20and%20Disposable%20Medical%20Devices,-Dec%2021%2C%202022&text=The%20use%20of%20HCFCs%20in,banned%20from%20July%201%2C%202023 .

[26] Methylene chloride is a controlled substance in some parties due to its use in processing cocaine.

In Vietnam, the government supports beneficiary enterprises in the foam sector to establish blending houses, foam production conversion to hydrocarbon, methyl formate, HFO/HCFO, or other low GWP alternatives.

Hydrofluorocarbons Phase out Management plan (HPMP) in some countries converts the use of HCFC-141b in PU foam manufacturing causing an increased use of HFCs in some applications where HFOs are difficult to replace HCFC-141b due to limited formulations adjustment knowledge and HFOs high cost compared to HFCs. (Thailand will prohibit using HCFC-141b in foam application and ban imported HCFC-141b preblended polyol on 1 January 2024.)

| Indian Foam Sub-sector | Interim Technology Selection | Long Term Technology |
|---|---|---|
| Flexible Molded PU Foam | Water-based | Water-based |
| Integral Skin PU Foam | HCFC-142b HFCs | Hydrocarbons, Water, Methyl Formate and Methylal |
| Rigid PU Foam | HCFC-141b HFCs | Hydrocarbons, Water, Methyl Formate, Methylal |
| Phenolic Foams | HFCs | Hydrocarbons, Methyl Formate, Methylal |
| Thermoplastic Foams | HFCs | Hydrocarbons, Methyl Formate, Methylal |

**Table 2.4 Foam Transition Technology Examples from India**

**India**

In India, approximately 70% of companies are using non-ODS, low-GWP technologies. The remainder are using HFCs. No companies are using HCFCs. India completed its transition away from HCFC-141b through an ambitious program supporting even small manufacturers with technical research into key attributes of foam products, funded through the HCFC Program Management Plan (HPMP)[27]. The goals of the program were to reduce cooling loads of buildings while replacing HCFCs with a focus on using alternate technologies.

The program encouraged best practices training and enhancing skills to use low GWP alternatives and building capacity at technical institutions. Technical institutions assisted with testing and data analysis to optimize formulations for various applications. A wide variety of challenges were raised by participants including foam shrinkage after a few weeks, poor adhesion, non-uniform cell morphology, lack of dimensional stability, phase separation, reactivity drift issues, poor surface structure, slow rising of foams, and core density. The technical support team assisted with lab-, pilot-, and commercial-scale testing and support. Numerous foam types were optimized including integral skin, thermal-ware, discontinuous panels, general insulation, commercial refrigeration, and spray foam. Most issues were resolved within the test program, or an alternate FBA was selected that better met the needs of the manufacturer.

**Figure 2.9 Cup-foam samples demonstrating physical properties of foam formation**

[27] Implementation of Hydrochlorofluorocarbons (HCFC) Phase-out Management Plan (HPMP) Stage II The HCFC Phase out Management Plan (HPMP) Stage-II project for India has been approved by the Executive Committee (Ex-Com) of the Multilateral Fund (MLF) during its 77th meeting with associated requirements published in the Gazette of India *inter alia* prohibiting the issuance of import license for HCFC-141b from January 1, 2020.

Nearly all of the ten largest economies in the **Latin American r**egion have transitioned away from HCFC usage in foams. Mexico was the first country in Latin America to phase out HCFC-141b in 2016 with the technical conversion in foam sectors and systems houses complete and the initial phases of the phase down of HFCs under Kigali Amendment initiated. It is worth noting that in some parties, there have been continued challenges to gaining sufficient access to HFOs/HCFOs which has driven some companies to use HFCs in some applications.

The Latin American domestic appliance industry is consolidated with strong presence of global manufacturers who have generally converted to hydrocarbons with few lines using HFCs and HC/HFCs or HC/HCFOs blends to maintain high energy efficiency levels. Mexican companies manufacture the largest number of domestic appliances followed by Brazil, Argentina, Colombia, Chile, Peru, and Ecuador. Considerable volume of Mexican production is exported to North America and Europe and other countries with strict efficiency standards and labelling requirements. Brazil has recently increased its energy efficiency standard by 30%.

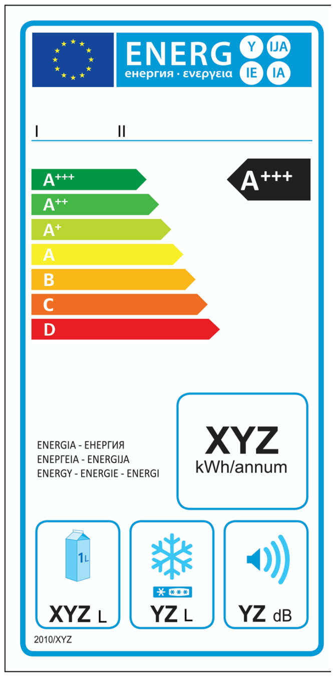


**Figure 2.10 Sample energy label for appliance**

Commercial refrigeration manufacturing uses large volumes of polyurethane foam. Most HC FBAs are used in nearly all commercial refrigeration in Latin America. Although, some medium-size companies use HFO/HCFOs.

HFC-365mfc/227ea 93% / 7% ratio by weight is widely used in Latin America due to the high prices of HFO/HCFOs, High water content in the formulations and blends with oxygenated FBAs, such as methylal and methyl formate, are blended in with HFCs to reduce cost of PU systems. Water- blown systems where energy efficiency is not critical is used by a few companies

There are few manufactures of continuous panels in Latin America and larger enterprises have fully converted to hydrocarbons. Hydrocarbons are also used for low density PU foams for roofs and flexible face minimum thickness, aluminium faced laminates. The low-density PU foam laminate market has increased in the region for usage in air conditioner ducts for commercial and industrial areas. When there are stringent energy efficiency or flammability requirements, blends of HC with HFCs or HFOs / HCFOs are used.

HFCs and methylal or methyl formate blends are used in discontinuous panels. Most manufacturing facilities use fully formulated polyols. Blends are used to reduce costs. Due to lack of availability and high prices, HFOs/HCFOs have very limited use. High water content used in formulations with HCFOs has had only limited market acceptance. Independent systems houses find it challenging to formulate stable blends with sufficient adhesion for these systems.

There are continuing shortages of FBAs in Latin America with very limited availability of HFOs/HCFOs. HFC-365mfc/HFC-227ea is the main HFC used as blowing agent in Latin America, especially by SMEs. Formulation is simplified because of the higher boiling point and stable blends. Although, there was a significant price increase during the pandemic making HFOs/HCFOs more competitive when available. System houses are using higher levels of water and blends with methyl formate, methylal, and even dichloromethane (DCM) to create cost competitive systems with limited flammability (>60 C Flash Point). It is worth noting that different blend combinations are gaining share in all market segments

Refrigerated transport, trucks, and trailers, in Latin America are generally manufactured using pour-in-place PU injection and laminated boardstock assembling. There are no longer refrigerated maritime containers and reefers manufacturers in Latin America. The overwhelming majority of plants use fully formulated polyols with HFCs or blends with oxygenated FBAs. Again, use of HFOs/HCFCs is limited due to high price and lack of availability. Temperature displays and or graphs to record temperature are adopted in the region to guarantee that cold transportation follows requirements per type of product. Strict rules are applied to transport vaccines, where special compartment must keep very low temperature with minimum variation, for 48 hours, in case of cooling equipment failure.

HFCs and the remaining volume of HCFC-141b are used to manufacture spray foam Latin America as these FBAs are non-flammable and safe to use in field-applied foams and allow foams to meet energy efficiency requirements. HFOs/HCFOs may be used if required due to a specific requirement. Methyl formate or methylal have been used to reduce costs; however, flash point may be a concern in field-applied spray foams. Water blown systems are used in the region in small volumes.

Spray foam is primarily produced in Argentina and Mexico. In Brazil spray foam is used for tank volume insulation and to insulate roofs in old industrial and commercial building and poultry farms. However, new roofs with low density polyurethane (PU) / polyisocyanurate (PIR) and expanded polystyrene (EPS) are becoming the preferred solution to replace old roofs.

Most Latin American parties have energy efficiency standards and labelling requirements, with Mexico having the most stringent requirements, especially for products exported internationally, such as domestic appliances. In other countries in Latin America, especially South America labelling systems are harmonized with the European system. For example, Brazil implemented a new efficiency standard with 30% of improvement in July 2022 with another increase of 25% targeted for 2025 with a goal that by 2030, the Brazilian standard will be close to European standards.

Pure or blended methyl formate is used in Latin America with limited adoption as there are technical challenges in some formulations with concerns about blend stability limitations and challenges in achieving long term dimensional stability. Compatibility of manufacturing equipment and finished product should be considered to eliminate instances of chemical attack compared to other FBAs. This can be as simple as using more compatible materials of construction. Non-flammable formulated polyol blend can be achieved (>60 C of flash point). However, higher concentrations are classified as flammable for purposes of transportation (GHS) and handling/processing. Nonetheless, methyl formate is low cost and available, so SMEs are re-evaluating its use in blends with HFCs or HCFOs.

Use of methylal as an unblended FBA is limited in Latin America. Formulated polyols are normally flammable and require high investments for safe processing. Methylal in very low concentration in blends with HFCs can provide formulated polyol with low flammability and lower cost. This approach is gaining share in Latin America and the same approach has been considered for HFOs/HCFOs. Blends of methylal with methylene chloride have been evaluated to mitigate flammability. However, the use of these blends is rather limited.

There is limited availability of HFOs / HCFOs in Latin America with a relatively high price. However, they produce excellent foams. There is limited adoption in Latin America except in large and medium enterprises. A lack of available supply has led to higher adoption rated of HFCs in Latin America, primarily HFC-365mfc/ HFC-227ea)

There is some use of water-blown foams in Latin America where energy efficiency is not critical in thermal-ware, milk tanks, niches in commercial appliances, sliding shutters, filling of cavities, water heaters and spray foam. There continue to be challenges related to poor adhesion. In general, independent system houses are challenged with providing product that consistently meets performance requirements for this technology.

## 2.6 Foam blowing agent transition in non-A5 parties

In the EU, high-GWP fluorinated gases are being phased down under F-Gas Regulations. In 2015 in the EU, all HFCs with GWP greater than 150 were banned for foam manufacturing for use in domestic appliances. By January 2023, all HFCs with GWP greater than 150 will cease being used in all foam manufacturing. Foams and polyol-blends containing HFC must be labelled, and the presence of any HFC must be mentioned in the technical documentation and marketing brochures. The F-Gas Regulation operates on the supply-side through a quota system, which means that supply of HFC blowing agents to the foam sector is being constrained well before the phase-out dates and sees a major shift from HFC systems towards HFO. Product standards are being reviewed to incorporate the new blowing agents to support CE marking and the Declaration of Performance required when placing construction products on the EU market.

The regulation of HFOs and HCFOs are different between parties. In some EU countries, unsaturated HCFCs and HFCs (or HFOs/HCFOs) are defined as volatile organic compounds (VOC), albeit with low Photochemical Ozone Creation Potential (POCP) values and require environmental permits for use. Other EU countries exempt them from VOC regulations based on their Maximum Incremental Reactivity (MIR) or POCP in comparison to ethane. Denmark, which previously regulated HFOs/HCFOs by the same laws as high GWP HFCs, has lifted the restriction when the GWP value is below 5 through a dedicated ordinance. In Switzerland, under the Swiss ODS Ordinance, HCFO-1233zd(E) which has an ODP of 0.00034 is considered an ODS. However, the law provides a mechanism for obtaining exemption based on the low-GWP value and its energy efficiency.

Some European governments are consulting on the development of regulations related to per- and poly-fluoroalkyl substances (PFAS), the definition of which may or may not include Montreal Protocol controlled substances and their substitutes. This is creating uncertainty for industry regarding long-term availability of some alternatives. Some companies and other stakeholders have reported that they are delaying decisions regarding selection of alternatives with concerns about how some or all those fluorinated alternatives might be limited as a result of future regulations.

In Japan, "The Act on Rational Use and Proper Management of Fluorocarbon", was amended effective April 1, 2020, to require companies to submit a voluntary action plan for the HFC phase down /phase out. In 2020, the average GWP of blowing agents used by the residential spray foam industry was limited to less than 100, with a target HFC consumption of less than 620 metric tonnes (MT) in 2020 and 450MT by 2024. The average GWP of the system houses that met the goal by 2020 was 17.3 with the remainder achieving the goal by September 2021. There were challenges with the cold chain transition and the total HFC consumption was more than the action plan due to a lack of available supply of HFOs/HCFOs.

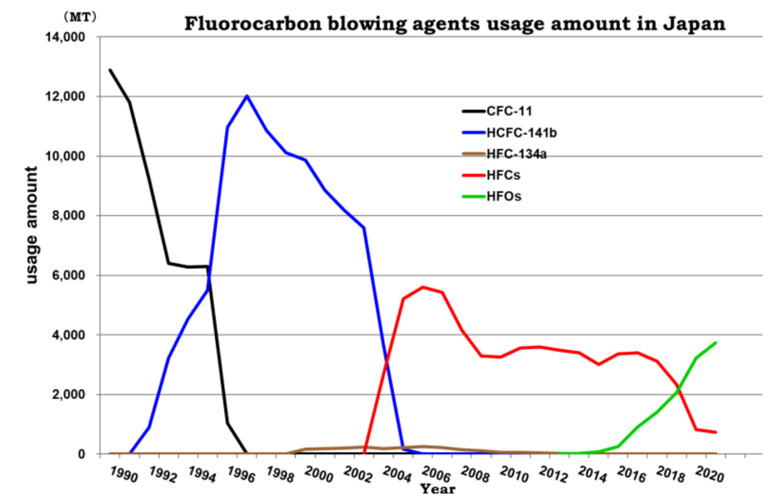


**Figure 2.11 Fluorocarbon blowing agent usage in Japan**

Please see the figure describing fluorocarbon FBA usage in Japan, courtesy of the Japanese industry association. Of significance is the continued transition away from FC FBAs in Japan and other parties during each transition.

Figure 2.12 Multi-door refrigerator

In Japan, domestic appliance manufacturers adopted hydrocarbons FBAs and refrigerants in the mid-1990's, with "non-fron[28]" certification. The thermal conductivity of hydrocarbon-blown foam is higher than that of CFC-11 or HCFC-141b foams, but the blends were optimized and used in combination with vacuum panels. Excellent thermal performance of rigid PUR foams is combined with multi-door designs to minimize the release of cold air when doors are opened to minimize electricity consumption of the appliance.

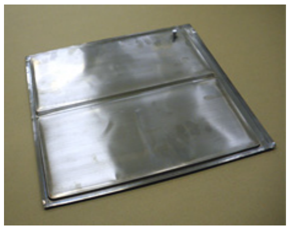

Figure 2.13 Vacuum panel used in domestic appliance

## 2.7 Indications and implications of recent CFC-11 marketing for foams use

In 2018, The Foams Technical Options Committee (FTOC) was made aware of the marketing of CFC-11 for use in foams. FTOC was provided with a copy of an offer for sale for CFC-11 for $2200/tonne through distribution, saw offers on the internet websites, and learned more through industry discussions.

CFC-11 conversion to HCFC-141b required significant adjustments to the formulation because of HCFC-141b solvent properties. However, replacing HCFC-141b by CFC-11 in an HCFC-141b formulation would require minimal adjustment. More adjustments would be required for use of CFC-11 in hydrocarbon or HFC formulations.

Many of the additives used for foams produced with CFC-11 are also used for foams produced with other foam blowing agents. (e.g., surfactants and catalysts). For example, gelling/blowing catalysts and surfactants that were used for CFC-11 foams and are still used today.

Under certain circumstances, CFC-11 can decompose to form chloride and fluoride ions creating hydrochloric and hydrofluoric acid, which reacts with amine catalysts reducing their activity in the foam. Amine catalysts are commonly used in polyol blends and facilitate the reaction of the polyol with diisocyanate to form the urethane polymer foam matrix. Therefore, CFC-11 was supplied with a stabilizer (e.g., alloocennine, alphamethylstyrene). Alloocennine stabilizer was not used for HCFC-141b, HFCs or hydrocarbons. However, at least one company added alphamethylstyrene to HCFC-141b.

**Flammability and patents related to CFC-11**

The concern about foam flammability has increased since 2010, following a series of major building fires which occurred during the construction of some high-rise buildings. Some parties have very stringent standards related to the design of construction foam including foam fire and smoke test demonstrations. However, this has not been true for all jurisdictions. Other parties have responded to the fires in different ways. For example, China halted the use of polyurethane and extruded polystyrene (XPS) foams for some time while new codes were developed (European fire codes were adopted and made more stringent in China in their national fire code for buildings GB50016 on May

[28] High Pressure Gas Safety Act exemption https://www.cas.go.jp/jp/seisaku/hourei/data/HPGSA.pdf

1, 2015). These changes significantly altered the landscape of thermal insulation in the construction sector. This has greatly reduced the use of rigid polyurethane foam as a thermal insulation material for buildings.

Neat CFC-11 is non-flammable (ASTM E681); however, foam flammability is controlled by several factors beyond the flammability of the blowing agent. CFC-11 blown polyurethane foams still required flame retardants (e.g., tris (2-choloroisopropyl) phosphate or TCPP) to maintain low flammability.

In addition to marketing CFC-11 for use in foams, some patent applications[29] describing the use of CFC-11 in various uses have recently been published. Many of the examples below describe the use of CFC-11 in concrete foams and XPS foams in spite of the fact that the boiling point of CFC-11 is higher than would normally be considered technically appropriate to produce XPS foams. FTOC is not aware of the commercialization of the products described in the patents.
Patents could be developed for several reasons.

- Patents incorporating a product may be a result of trying to find new ways to market and use available or excess supply.
- Companies or governments may reward patent-owners for writing new patents even if they are never used.
- Patent authors could be trying to solve technical issues such as foam flammability.

A small sample of the patents is included below.

- Preparation method of environment-friendly fireproof and heat-insulating material for building external wall - China (CN) 108070166 A 20180525[30],
- Preparation method of fire-resistant board CN 107814543 A 20180320[31]
- Sandwich panel using quasi-incombustible resin composition and method for manufacturing the same Korea - (KR) 1823003 B1 20180131[32]
- Heat-insulating fireproof material for external wall CN 107383761 A 20171124[33]

There are new patents describing a method to make fire retardant, high-strength materials for exterior walls using CFC-11. Historically, CFC-11 has never been demonstrated as having capability as a fire suppression agent and it is not likely to reduce flammability when used in or sprayed on foams. However, there may be foam manufacturers and others in the construction industry that believe that CFC-11 might reduce flammability in foams.

There is a gap between the projected emissions from foams in banks (including landfills) based on emission rates found in the literature and the emissions derived from measured changes in atmospheric concentrations, even in regions where CFC-11 has not likely been used in decades (<1.5% versus 3-4%). It is possible that further processing of foams before disposal through shredding and crushing of foams accounts for at least some of that difference.

One example of shredding and reuse of foams is its use in lightweight bricks in the construction industry in Hebei province in China. One company recently reported in a seminar the reuse of 2.86 million cubic meters of foam from 2011 through 2018. This might result in the release of up to an average of 850 tonnes[34] of a blowing agent per year for seven years. These volumes are not sufficient

[29] A quick patent search yielded 13 patents in 2017 related to the use of CFC-11 in foams. There have been many more filed in recent years.
[30] https://patents.google.com/patent/CN108070166A/en?oq=108070166
[31] https://patents.google.com/patent/CN107814543A/en?oq=+107814543+
[32] No additional information found
[33] https://patents.google.com/patent/CN107383761A/en?oq=107383761
[34] Assumptions: 100% of the blowing agent is CFC-11 and 50% of the blowing agent is released from 32kg/m3 density foam containing 13% CFC-11 by weight in the polyol side of the blend.

to explain the unexpected emissions of CFC-11 and the foams may not all be blown with CFC-11. FTOC continues to examine the gap between literature data related to release rates as well as re-use and disposal of foams containing CFC-11.

## 2.8 FTOC interpretation of criteria listed in Decision XXVI/9 paragraph 1(a)

The criteria outlined in Decision XXVI/9 paragraph 1 (a) can be subject to interpretation depending on the context of their use. The FTOC interprets the criteria as:

**"Commercially available"**
Foam blowing agents are generally researched, developed, and tested in the laboratory first in very small quantities (less than a tonne). Small quantities (less than 10 tonnes per annum) may then be manufactured in a pilot plant sufficient only to further prove fitness for purpose, optimize manufacturing processes, market development, and for toxicity, safety, and other testing. Once potential market adoption is proven, required testing is passed, and production facilities are designed, larger scale commercial facilities may be built to serve the foam, and in many cases, refrigerant market. Full-scale chemical plants tend to be costly to build, which leads to a limited number of chemical plants with product shipped around the world, using a generally efficient, well-proven supply chain.

FTOC considers FBAs to be commercially available once commercial facilities are operational supplying a minimum of about 2,000 tonnes per year of product. However, it should be noted that the FBA FC market is much greater, and this quantity would be insufficient to supply all the demand globally. However, the product has met critical testing and certification criteria, government approvals and is generally accepted in some significant parts of the market. Finally, the alternative is in use in significant volumes in commercial foam systems. The product must be available for sale with some certainty of future supply and allowed to be used in multiple regions or parties.

However, this does not necessarily mean that the foam blowing agent or foam systems are accessible in all countries (for example A5s versus non-A5s). In this context "accessible" follows the concept explained in section 6.1.2 of this report but in the context of FBAs. It is also important to note that there can be insufficient capacity of "commercially available" alternatives to meet global demand and that there may be interruptions to global supply chains of "commercially available" alternatives. FTOC discusses capacity, alignment of supply and demand, and supply chain interruptions in more detail in its 2022 Assessment Report.

**"Technically proven"**

FTOC considers an FBA to be "technically proven" when the foam blowing agent is accepted by regulators and industry because the FBA and the foam systems containing the FBA meet all necessary performance, safety, and environmental requirements for the intended application. Safety and efficacy properties for each foam type must be met including, but not limited to, compatibility testing with metals and elastomers for reactivity and corrosiveness, density, fire testing of foams, initial and long-term thermal performance, structural integrity, compressive strength and other mechanical properties, foam cell size, stability of foam systems, loss of blowing agent over time and others to demonstrate that the alternative FBA provides acceptable results. High ambient temperature testing is also required especially for stability of foam systems.

It should be noted that some of this testing is mandated in certain jurisdictions by building codes or regulators, while other testing is voluntary or may be required by foam end-users. For example, fire and smoke testing are required in some building codes with conformity needed to International Organization of Standardization (ISO) and American National Standards Institute (ANSI) recognized Underwriters Laboratories (UL™) standards. In some regions, testing to meet criteria set by insurers is also required, for example Factory Mutual (FM Global®) test standards primarily in North America and Europe but becoming more common globally. In addition, testing is done with a variety of additives, such as catalysts and surfactants to further optimize performance.

FTOC concludes that alternatives are technically proven once there is some commercial uptake of the alternative, rather than wading through candidates as they go through the testing and qualification process, for two reasons: (a) requirements are different for different foam types, and (b) different companies may optimize performance based on different characteristics.  Alternatives that are still testing the many parameters successfully but are not yet used commercially are considered by FTOC to “show technical promise”.

**“Environmentally sound”**

New chemicals must be approved by regulators in several countries including, but not limited to, China, Japan, The Republic of Korea, Australia, Switzerland, Europe, and the U.S through new chemical registries such as the European Chemicals Agency (ECHA) registration process, the U.S. Environmental Protection Agency (EPA) Toxic Substances Control Act, and Inventory of Existing Chemical Substances in China (IECSC). Chemical approvals for specific uses, along with the U.S. EPA Significant New Alternatives Policy (SNAP) program create a clearinghouse of approved alternatives that foam manufacturers, and some parties rely on to ensure that alternatives are, at least comparatively similar to existing FBAs overall in safe use and improved environmental impact relative to incumbent FBAs.

FTOC considers that alternatives must have minimal environmental impact (e.g., short atmospheric lifetime) compared to ODS or HFC FBAs. They have zero or very low ozone depleting potential (use could be subject to individual party determination), have very low global warming potential and are not foreseen to be subject to future production phasedowns.

**“Economically viable and cost effective”**
FBA price sensitivity is different for various foam segments and even for different manufacturers and end-users. It should be noted that the price of the alternative is not the only consideration impacting cost to foam manufacturers and end-users. Capital investment to use flammable alternatives, the cost of new additives to address stability performance, foam density, and thermal performance all impact economic viability and cost effectiveness.

FTOC concludes that alternatives are economically viable and cost effective once there is some commercial uptake of the alternative because of the variability of the optimization process for different foam types and different end-users that must balance performance with cost. No assessment has been made for alternatives that are not yet commercial, because there is likely significant information to be learned regarding FBA price, cost of foams and foam systems and in addition to performance in foams.

**“Safe to use in areas with high urban densities considering flammability and toxicity issues, including, where possible, risk characterization”**
HFO/HCFO foam blowing agents have similar toxicity exposure limits and routes to currently used HFCs and other FCs, with key exposure concerns for workers being frostbite and oxygen deprivation in the case of large releases in enclosed spaces. A significant body of work has been completed by the Center for Polyurethane Industry (CPI) to assess safe re-entry times after spray foam is applied in buildings and homes for other workers and families. To date, there has been no difference shown between residual off-gassing of HFO/HCFO foam blowing agents compared to the incumbents. It should be noted that personal protective equipment should be worn to prevent exposure from all chemicals in foam systems, including non-FBA chemicals.

Flammability of hydrocarbons and oxygenated alternatives is mitigated to reduce the risk of reaching flammable mixtures and to remove potential for introduction of ignition sources[35]. References have been added below to provide some examples of the methodologies used to mitigate flammability. Please note that local safety requirements may vary. Mitigation is costly. The use of flammable alternatives may not be cost effective for small and medium enterprises because of this significant capital investment requirement. There are also shipping and transportation requirements regarding flammable foam blowing agents.

It should be noted that some testing has been done to examine whether the addition of flammable foam blowing agents to foam systems might reduce flammability sufficiently to avoid mitigation requirements. However, to date, no blends have been found to sufficiently reduce concentrations such that flammable transportation regulations could be eliminated.
Handling and transportation of flammable fluids and blends, including the addition to foam systems, must comply with international shipping requirements, such as those in the Global Harmonized System (GHS). Safety Data Sheets (SDSs) must include flash points and safety information. Local building codes, fire safety requirements, and laws may limit the use of flammable FBAs and even systems containing flammable FBAs. The flash point of blends may not be a sufficient indication of risk while applying spray foam (or other foam manufacturing processes) where there may be localized concentrations greater than the lower explosivity limit (LEL). FTOC is not aware of any testing confirming that LEL concentrations are not reached while spraying foam systems containing flammable FBAs.

Finally, foam blowing agents can be categorized as “volatile organic compounds” (VOCs) further requiring mitigation to reduce smog-forming off-gassing and releases into communities, forming ground-level ozone or smog. HFOs / HCFOs and other chemicals are often compared an index chemical, such as ethane, using a parameter such as Maximum Incremental Reactivity[36] (MIR) or Photochemical Ozone Creation Potential (POCP) to determine whether chemicals will be considered VOCs or how severe a VOC the chemical is, perhaps requiring mitigation. HFOs/HCFOs known to have been evaluated have been determined to be lower than this index and have been exempted from mitigation requirements in some jurisdictions[37]. It should be noted that use of FCs in VOC abatement systems would require significant upgrades to raise temperatures to avoid production of dioxins and other chemicals. FCs by-products are also corrosive to standard carbon-steel equipment.

FTOC notes that safety precautions must be taken in all foam manufacturing. Many of the chemicals used to manufacture foams are hazardous and require the use of personal protective equipment and mitigation to reduce exposure and flammability during blending, foaming and even off-gassing of finished foams. FTOC also notes that several of the replacements of HFCs have been in use for some time and the hazards associated with them are well understood. The one exception is HFOs/HCFOs which have similar safety and toxicity properties to HFCs, as noted above.

Due to the general hazards related to foam manufacturing, the precautions that must be taken regardless of the FBA used, the current use of many alternatives, and the similarities between HFCs and HFOs/HCFOs, FTOC has highlighted specific precautions needed for alternatives when used in densely populated areas. FTOC has concluded that HC foam manufacture in densely populated areas could be challenging to mitigate but finished products containing HC are likely safe to be used.

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[35] Hydrocarbon solvents handling and safety: ESIG Flammability Guide and resource videos Facility storage and handling modifications required by some building codes. Flammable liquid tank storage requirements

[36] Maximum Incremental Reactivity (MIR) is one measure of photochemical reactivity, which estimates the weight of ozone produced from a weight of a chemical (e.g., lbs ozone per lb of chemical) under worst case conditions.

[37] An example of a jurisdiction determining exemption to requirements for HFO/HCFO foam blowing agent based on MIR.

**"Easy to service and maintain"**.
Foam blowing agents are used to manufacture foams, as a finished product or part. As such, they are not serviced like refrigeration systems. In carrying out the assessment below, FTOC notes that the HFC alternatives are already in use today and that mitigation may be needed, except for specific uses highlighted below, most alternatives are suitable provided they deliver the necessary technical benefits to the end-product. FTOC also notes that some characteristics discussed in this report are specific to the foam blowing agent, including ccommercial availability; environmental soundness, or economically viable and cost effective, and safeness for use in areas with high urban densities considering flammability and toxicity issues, including, where possible, risk characterization and has documented its evaluation in the table below. However, whether FBAs are technically proven are associated with the end-use. There are also some specific challenges to safety for certain situations noted by foam type where concerns have been identified by FTOC.

The following table describes the requested attributes that are specific to foam blowing agents of the most used alternatives to HFCs. This excludes a discussion of technical suitability which is more specific to the type of foam being manufactured. Please note that additional details regarding selection for commercialization by sector are included later in the report. Again, FTOC has assumed that only solutions that are economically feasible and cost effective have been selected for use by foam manufacturers. This table refers to the manufacture of foam and not the safe use of finished products in areas of high urban density.

**Considerations Related to Hydrocarbons**
Hydrocarbons are frequently used in several foam types as non-ozone depleting substances (ODS) with low global warming potential (GWP) and are not controlled by the Montreal Protocol. It should be noted that hydrocarbons are considered volatile organic compounds (VOCs) which produce smog at ground level and may require investment for abatement in some populated communities. Hydrocarbons integrated into foam systems also provide good energy efficiency performance. Hydrocarbons can be blended with fluorocarbons to further enhance thermal efficiency. However, even blended foam blowing agents containing hydrocarbons still create flammable mixtures and require that safety precautions, as do hydrocarbons in foam systems. In addition, FCs in VOC abatement systems would require significant upgrades to raise temperatures to avoid production of dioxins and other chemicals. FCs by-products are also corrosive to standard carbon-steel equipment and require equipment made with alloys specialized to avoid corrosion issues.

Necessary safety precautions include explosion proofing of facilities and use of non-sparking tools. Capital costs have been reported to range between \$250,000 USD to \$1,000,000 USD per operating facility. Hydrocarbons have lower operating costs, but the significant capital investment has made them less attractive for smaller enterprises.

**Table 2.5 Attributes specific to foam blowing agent of most used alternative FBAs to HFCs.**

| Foam Blowing Agent | Commercially Available | Environmentally Sound | Safe for use in high urban densities | Cost |
|---|---|---|---|---|
| HFOs/HCFOs | Yes | Low GWP, very low or no ODP, generally exempted from VOC requirements | HFC handling precautions | Higher operating cost than HFCs |
| Hydrocarbons | Yes | Low GWP, no ODP, VOC mitigation may be needed | May be limitations due to flammability / explosivity properties | Lower operating cost, but capital investment for safety needed |
| Methyl formate | Yes | Low GWP, no ODP, Generally exempted from VOC mitigation requirements | May be limitations due to flammability properties and local requirements. Methyl formate in a foam system can be provided to foam manufacturers which may reduce limitations of use. | Lower operating cost, but capital investment for safety needed |
| Methylal | Yes | Low GWP, no ODP, VOC mitigation - unknown | May be limitations due to flammability properties | Lower operating cost, but capital investment for safety needed |
| CO2 (Water) | Yes | Yes | Yes | Low cost |

As a reminder, FTOC has assumed that only HFC alternatives that are economically feasible and cost effective *and* technically proven have been selected for widespread commercialization.

### 2.9 Refrigeration foam insulation

**Figure 2.14 Stacked appliances are another example of the need for foams to provide reliable structure**

Refrigeration foam insulation systems must have specific thermal and structural properties. A key factor is the selection of the FBA is the size of the manufacturing plant since the capital requirements for handling flammable foam blowing agents and the economies of scale have a considerable bearing on the relative affordability of capital and operational costs. Operating cost also is a major factor in the consideration of HFO/HCFO technologies. Most medium and large manufacturers of transport, commercial and domestic refrigeration equipment that have converted away from HCFC-141b and HFCs (HFC-245fa and HFC-365/227) are now using hydrocarbon foam blowing agents with some continued use of fluorocarbons (HFO/HCFOs) alone or in blends with hydrocarbons. As the cost of metals has increased, foams have become a part of the structure of appliances (and cars). The foam must be strong enough to support weight during shipping under heavy load and vibration and still maintain its integrity so that it provides a barrier to warm air. Dimensional stability and compressive and flexural strength are foam properties that allow companies to use less metal in their finished goods.

Foam and appliance manufacturers must provide the same performance in the finished product, as they select new FBAs. In addition, necessary foam performance is dictated by local market conditions and unique manufacturing conditions. For example, historically, the importance of energy consumption in the US and Japanese markets led manufacturers to use formulations with higher levels of FBAs to achieve lower conductivities than were required in European markets.

As noted in previous reports, the major emerging technologies in the appliance sector are based mostly around liquid HFO/HCFOs. These are all similar in their properties and all seem to suggest a stepwise improvement in thermal performance over other low-GWP alternatives. HFO-1233zd(E) and HFO-1336mzz(Z) are in use commercially, limited by supply chain issues and available capacities. However, their high comparative cost to non-fluorinated alternatives has led to some market preference to use lower operating cost options or blending with hydrocarbons.

**Emissions during Manufacture of Appliances**

Liquid chemicals are injected between the outer shell and the interior liner of an appliance cabinet where they react, flow, and expand to form rigid polyurethane foam throughout the cavity. Substantial fixtures are provided to support the walls which are under pressure from the foam.

Historically, it was thought that less than 5% of the FBA was emitted during the manufacturing process of appliances, which is thought to be one of the least emissive manufacturing applications until research measuring emissions was published showing a relationship between partial pressures of foam blowing agents and measured emissions rates. The minimum emissions rate was over 9% for HFC-245fa and over 35% for HFC-134a.

1 Aprahamian, Steve et al Quantification of HFC Blowing Agent Emissions of Typical Appliance Insulating Foam

However, even blended foam blowing agents containing HCs still create flammable mixtures and require safety precautions, as do hydrocarbons in foam systems. Necessary safety precautions include explosion proofing of facilities and use of non-sparking tools. Capital costs have been reported to range between $250,000 USD to $1,000,000 USD per operating facility. Hydrocarbons have lower operating costs, but the significant capital investment has made them less attractive for smaller enterprises.

However, other considerations must be considered, including costs, and balanced by manufacturers, who may use other design features to promote efficiency. To achieve a good balance of thermal insulation performance and cost, various co-blowing technologies are adopted. Many manufacturers use HFCs, HFO/HCFOs to co-blow with pentane. At least one company in China uses R600/R600a to co-blow with pentane & HFCs – achieving more than 7% injection weight reduction in appliances.

There is more prevalence of continued fluorocarbon use in commercial systems especially in parties with ever more stringent energy efficiency requirements. However, conversion away from HFCs used in commercial refrigeration equipment in non-A5 parties has been somewhat stalled due to the lack of supply of HFO/HCFO foam blowing agents.


**Figure 2.15 Refrigerated truck**

Polymer foam encased vacuum-insulated panels in appliances and aerogels in industrial pipe insulation offer ultra-high insulation performance and are used in specialized applications in refrigeration and construction. However, there use continues to be limited due to cost and installation and maintenance challenges.

***Small and Medium Enterprises***

It should be noted that small and medium enterprises (SMEs) may still be facing challenges related to the adoption of HFOs/HCFOs, due to their operating cost, and hydrocarbons, due to necessary capital investment for safety. This continues to be an unresolved challenge to smaller companies, regardless of their location.

### 2.19.1 **Domestic refrigeration**

As noted in previous reports, the major emerging technologies in the appliance sector are based mostly around liquid HFO/HCFOs. These are all similar in their properties and all seem to suggest a stepwise improvement in thermal performance over other low-GWP alternatives. HFO-1233zd (E) and HFO-1336mzz(Z) are successfully in use, limited by supply chain issues and available capacities. However, their high comparative cost to non-fluorinated alternatives has led to some market preference to use lower operating cost options or blending with hydrocarbons.

**Figure 2.16 Domestic refrigerator**

However, other factors must be considered, including costs, and balanced by manufacturers, who may use other design features to promote energy efficiency, which is often mandated by regulation. To achieve a good balance of thermal insulation performance and cost, various co-blowing technologies are adopted. Many manufacturers use HFCs or HFO/HCFOs to co-blow with pentane. At least one company in China uses HC-600/HC-600a to co-blow with pentane & HFCs – achieving more than 7% injection weight reduction in appliances. It should be noted that hydrocarbons are widely used in domestic refrigeration products with vacuum panels, which increase operating costs, to provide better energy efficiency.

In Japan, domestic appliance manufacturers adopted hydrocarbons FBAs and refrigerants in the mid-1990's, with "non-fron" certification. The thermal conductivity of hydrocarbon-blown foam is higher than that of CFC-11 or HCFC-141b foams, but the blends were optimized and used in combination with vacuum panels. Excellent thermal performance of rigid PUR foams is combined with multi-door designs to minimize the release of cold air when doors are opened to minimize electricity consumption of the appliance.

**Commercial refrigeration**

There is more prevalence of continued fluorocarbon use in commercial refrigeration systems especially in parties with ever more stringent energy efficiency requirements. However, conversion away from HFCs used in commercial refrigeration equipment in non-A5 parties has been somewhat stalled due to the lack of supply of HFO/HCFO foam blowing agents. As noted in previous reports, the major emerging technologies in the appliance sector are based mostly around liquid HFO/HCFO. These are all similar in their properties and all seem to suggest a stepwise improvement in thermal performance over other low-GWP alternatives.

**Figure 2.17 Walk-in cooler under construction**

Foams are often sprayed or poured into a mold, but sandwich panels are also used in commercial refrigeration applications which consists of a foam core often between steel or aluminum facings. Sandwich panels are used for cold storage for garage doors, and controlled manufacturing environments, such as in electronics and food processing.2.3.3 Transport refrigeration

**Figure 2.18 Refrigerated transport**

HCs are used as the foam blowing agents in many polyurethane foam systems for transport refrigeration systems, especially those manufactured by medium and large enterprises. Hydrocarbons are non-ozone depleting substances (ODS) with low global warming potential (GWP) and are not controlled by the Montreal Protocol. HCs integrated into foam systems also provide good energy efficiency performance. Hydrocarbons can be blended with fluorocarbons to further enhance thermal efficiency.  However, even blended foam blowing agents containing hydrocarbons still create flammable mixtures and require that safety precautions, as do hydrocarbons in foam systems.

Sprayed foam into molds or sandwich panels are used for the manufacture of insulated trucks and refrigerated containers. The foams have good long-term thermal performance, physical strength and are self-adhesive in both A5 and non-A5 parties.

The table below shows FTOC's assessment of the most used HFC alternatives for refrigeration applications against the six Decision XXVI/9 criteria. Note that "Easy to Service" is marked as not applicable (NA) throughout the evaluation.

**Table 2.6 Summary of most used HFC alternatives for refrigeration foam insulation**

| **Decision XXVI/9 Criterion** | | **Alternatives** | | | |
|---|---|---|---|---|---|
| | | **HFOs/ HCFOs** | **HCs** | **Methyl formate: commercial refrigeration only** | **Water** |
| I | Commercially available | Y | Y | Y | Y |
| II | Technically proven | Y | Y | Y | N |
| III | Environmentally sound | Y | Y | Y | Y |
| IV | Economically viable and cost effective | Widely adopted in domestic and commercial refrigeration, and can be used to improve energy efficiency as required | Y | Adopted in commercial refrigeration<br><br>Can be blended with FCs to optimize cost and thermal performance | NA |
| V | Safe to use in densely populated areas | Y | May be limitations due to flammability properties and local safety codes and requirements | May be limitations due to flammability properties and local requirements Methyl formate in a foam system can be provided to foam manufacturers which may reduce limitations of use. | NA |
| VI | Easy to service | NA | NA | NA | NA |

## 2.10 Polyurethane boardstock

Polyurethane (PUR) and polyisocyanurate (PIR) slabs can be easily laminated to variety of facings including aluminium, paper, and other construction materials continuously or discontinuously for use generally as insulation and sheathing for buildings. Boardstock offers good long-term thermal performance and generally perform well in fire testing. Laminators allow for fast-paced production and are relatively lightweight for ease of installation. They also have the necessary compressive strength to allow for weight-bearing maintenance. These products were historically, primarily used in North America and Europe.

Hydrocarbons are generally the foam blowing agent in commercial use in PU Boardstock

(Polyisocyanurate or PIR). The larger facilities allow for the economy of scale benefit which is optimized with lower operating costs with higher capital investment for using pentanes. However, it is possible that HFO/HCFO blends with hydrocarbons may be considered in the future as increased thermal performance becomes more preferred or mandatory in building construction to reduce heating and cooling loads.

Most medium and large manufacturers of boardstock use hydrocarbon foam blowing agents. Please see summary on **Considerations Related to Hydrocarbons** in the beginning of section 3 for safety, cost, and other considerations.

The table below shows FTOC's assessment of the most used HFC alternatives for polyurethane boardstock against the six Decision XXVI/9 criteria.

**Table 2.7 Summary of most used HFC alternatives for PU Boardstock**

| **Decision XXVI/9 Criterion** | | **Alternatives** | | | |
|---|---|---|---|---|---|
| | | **HFOs/ HCFOs** | **HCs** | **Methyl formate** | **Water** |
| I | Commercially available | Y | Y | Y | Y |
| II | Technically proven | Y | Y | N | N |
| III | Environmentally sound | Y | Y | Y | Y |
| IV | Economically viable and cost effective | N | Y | NA | NA |
| V | Safe to use in densely populated areas | Y | May be limitations due to flammability properties and local safety codes and requirements | NA | NA |
| VI | Easy to service | NA | NA | NA | NA |

## 2.11 Polyurethane panels


**Figure 2.19 Polyurethane panels**

Hydrocarbons are generally the foam blowing agent in commercial use in PU Panels. The larger facilities allow for the economy of scale benefit which is optimized with lower operating costs with higher capital investment for using pentanes. However, it is possible that HFO/HCFO blends with hydrocarbons may be considered in the future as increased thermal performance becomes more preferred or mandatory in building construction to reduce heating and cooling loads.

Most medium and large manufacturers of panels use hydrocarbon foam blowing agents. Please see summary on **Considerations Related to Hydrocarbons** in the beginning of section 3 for safety, cost, and other considerations.

The table below shows FTOC's assessment of the most used HFC alternatives for PU panels against the six Decision XXVI/9 criteria.

**Table 2.8 Summary of most used HFC alternatives for PU Panels**

| Decision XXVI/9 Criterion | | Alternatives | | | |
|---|---|---|---|---|---|
| | | **HFOs/ HCFOs** | **HCs** | **Methyl formate** | **Water** |
| I | Commercially available | Y | Y | Y | Y |
| II | Technically proven | Y | Y | N | N |
| III | Environmentally sound | Y | Y | Y | Y |
| IV | Economically viable and cost effective | Some use when thermal performance needs to be enhanced | Y | NA | NA |
| V | Safe to use in densely populated areas | Y | May be limitations due to flammability properties and local safety codes and requirements | May be limitations due to flammability / properties and local requirements.<br><br>Methyl formate in a foam system can be provided to foam manufacturers which may reduce limitations of use. | NA |
| VI | Easy to service | NA | NA | NA | NA |

## 2.12 Polyurethane spray foam

Spray foams are field applied as rigid polyurethane thermal insulation for residential and commercial buildings, industrial storage tanks, cold storage facilities, piping, and ductwork, and refrigerated transport trailers and tanks, using a hand-held pressurized spray gun, combining polyol and isocyanate. In North America and in Southern Europe, spray foam is also used on roofs.

Recipes or formulations and installation instructions are designed to optimize specific desired properties such as compressive strength for roofing applications or dimensional thermal stability at high ambient temperatures. Spray foam application allows for use on complex surfaces. Multiple layers can be applied, with cooling time in between layers, to create a thicker foam.

Safety has been of primary importance in the application of spray foams. Historically, non-flammable foam blowing agents have been used because of concerns about flammable mixtures especially in enclosed spaces. In the past 10 years, there has also been research to confirm the appropriate timing to allow entry of other trades or occupants after chemicals have dissipated without protective equipment. These studies have focused on several emissive chemicals including foam blowing agents. Spray foam requires focused solutions because the foaming process essentially requires that small portable chemical application equipment be brought into residential and commercial settings during renovation or construction of new buildings.

One-component, two-component, high-pressure, low-pressure

One-component foams (OCF) are "moisture-cured" sealants, which can be challenging in dry weather.  The higher humidity and air temperature, the quicker curing of the foam. OCF is generally sold in small spray cans to seal small openings, Personal protective equipment is still needed to avoid contact with the chemicals in the foam system. Sometimes OCF is described as "low-expansion" foam because it expands at a much smaller rate than two-component foams.

**Figure 2.21 One-component foam**

Two-component foam undergoes curing due to a chemical reaction between its two components. Both OCF and two-component foams are closed-cell foams.

**Figure 2.20 Spray foam Application**

In recent years, there have been some trials using flammable foam blowing agents in spray foam including addition of the flammable foam agent into either portion of the foam formulation (either polyol or isocyanate or both). Concentrations above the lower flammability level (LFL) have been detected in some testing. FTOC does not have additional data related to further safety testing.

There has been additional focus on reducing heating and cooling loads in buildings in recent years which has led to increased use of spray foam to "seal" the building envelope to minimize air infiltration and increased focus on the energy efficiency of those foams. HFOs/HCFOs all seem to provide a stepwise improvement in thermal performance over other low-GWP alternatives. HFO-1233zd (E) and HFO-1336mzz (Z) are successfully in use, limited by

Spray foam installation

Spray foam often needs to be installed in layers or passes that require approximately 30 minutes of wait time between each pass to allow the foam to sufficiently cure and cool to ensure that the foam or the substrate don't ignite because of excess temperature build-up during the curing process. Multiple-pass application helps ensure the foam's physical properties and performance characteristics are optimized with even curing.

Some foam system manufacturers are testing new technologies to reduce installation time without compromising physical properties or safety.

supply chain issues and available capacities.

The cost of the alternatives remains the key concern, but cost is slightly reduced by the addition of water, which reacts with the isocyanate to form $CO_2$. In addition, $CO_2$ (water) is used alone as a foam blowing agent for spray foam as a lower cost alternative to HFOs/HCFOs. $CO_2$ (water) is frequently used in residential construction in North America. The reaction with water results in very high reaction temperatures (aka "exotherm") and can result in charring or burning of foams if layers are applied with insufficient time between applications to allow for cooling and for the reaction to be complete.

In addition, with the advent of the pandemic there is increasing focus on ventilation and air exchange in buildings which might cause some modifications to building design, including the procedures to apply foams.

The table below shows FTOC's assessment of the most-used HFC alternatives for PU spray foam against the six Decision XXVI/9 criteria.

**Table 2.9 Summary of most- used HFC alternatives for PU Spray Foam**

| Decision XXVI/9 Criterion | | Alternatives | | | |
|---|---|---|---|---|---|
| | | HFOs/ HCFOs | HCs | Methyl formate | Water |
| I | Commercially available | Y | Y | Y | Y |
| II | Technically proven | Y | N (flammability concerns) | Y | Y |
| III | Environmentally sound | Y | Y | Y | Y |
| IV | Economically viable and cost effective | Y in closed cell spray foam | NA | Y | Y |
| V | Safe to use in densely populated areas | Y | N | May be limitations due to flammability / properties and local requirements.<br>Methyl formate in a foam system can be provided to foam manufacturers which may reduce limitations of use. | Y |
| VI | Easy to service | NA | NA | NA | NA |

## 2.13 Polyurethane in-situ, pipe-in-pipe, and block foams

Foam-insulated pipe-in-pipe sections are typically installed underground to transport hot water from a central boiler to other buildings or in manufacturing and chemical. Foams must meet strength and durability requirements and are produced by injecting the foam chemicals into the cavity between the inner and outer pipes. Preformed pipes are produced by pouring or injecting the foam chemicals into half-section moulds.

**Figure 2.22 pipe-in-pipe foam**

Hydrocarbons are generally the foam blowing agent in commercial use in PU in situ and block foams. Larger facilities allow for the economy of scale benefit which is optimized with lower operating costs with higher capital investment for using pentanes. However, it is possible that HFO/HCFO blends with hydrocarbons may be considered in the future as increased thermal performance becomes more preferred or mandatory in building construction to reduce heating and cooling loads.

Most medium and large manufacturers of in-situ and block foams use hydrocarbon foam blowing agents. Please see summary on **Considerations Related to Hydrocarbons** in the beginning of section 3 for safety, cost, and other considerations. The table below shows FTOC's assessment of the most used HFC alternatives for PU in-situ and block foams against the six Decision XXVI/9 criteria.

**Table 2.10 Summary of most used HFC alternatives for PU In-situ and Block Foams**

| **Decision XXVI/9 Criterion** | | **Alternatives** | | | |
|---|---|---|---|---|---|
| | | **HFOs/ HCFOs** | **HCs** | **Methyl formate** | **Water** |
| I | Commercially available | Y | Y | Y | Y |
| II | Technically proven | Y | Y | N | N |
| III | Environmentally sound | Y | Y | Y | Y |
| IV | Economically viable and cost effective | Could be used if thermal performance needs to be enhanced | Y | NA | NA |
| V | Safe to use in densely populated areas | Y | May be limitations due to flammability properties and local safety codes and requirements | NA | NA |
| VI | Easy to service | NA | NA | NA | NA |

## 2.14 Polyurethane integral skin and other non-insulating foams

Integral skin polyurethane foams are used to make many automotive parts, exercise equipment, and furniture. The key feature of these foams is a very tough, abrasive resistant skin surrounding a more flexible core. This skin is created during the foaming process by a combination of mold pressure /temperature and blowing agent. Fluorochemical blowing agents have solubility and boiling point suitable for this process, and thus typically create a very thick abrasion-resistant skin surrounding the inner foam core. Integral skin is used for steering wheels, headrests, armrests, and other uses. Other automotive foams include energy absorbing foams for side impact and high-density foam for exterior body parts. Other common non-insulating foams include low-density packaging; floatation foam; and floral foams.

**Figure 2.23 Office chair with integral skin foam**

Cost and structural performance have been the most important considerations in selecting next generation foam blowing agents for non-insulating foams. As such, water and some hydrocarbons are generally used for these products. The major emerging technologies in the sector are based mostly around liquid HFOs/HCFOs. These are all similar in their properties and all seem to suggest a stepwise improvement in thermal performance over other low-GWP alternatives. HFO-1233zd(E) and HFO-1336mzz(Z) are successfully in use, limited by supply chain issues and available capacities. However, their high comparative cost to non-fluorinated alternatives has led to some market preference to use lower operating cost options or blending with hydrocarbons.

The cost of the alternatives remains the key question, but this consideration is slightly diffused by the fact that the CO2 (water) technology developed around HFC-245fa and HC-365mfc/227ea looks transferable to the HFO/HCFO blowing agents as well. $CO_2$ (water) has been increasingly used as a foam blowing agent as a lower cost alternative to HFOs/HCFOs.

The table below shows FTOC’s assessment of the most used HFC alternatives for non-insulating foams against the six Decision XXVI/9 criteria.

**Table 2.11 Summary of most used HFC alternatives for non-insulating foams**

| Decision XXVI/9 Criterion | | Alternatives | | | |
|---|---|---|---|---|---|
| | | **HFOs/ HCFOs** | **HCs** | **Methyl formate** | **$CO_2$ (water)** |
| I | Commercially available | Y | Y | Y | Y |
| II | Technically proven | Y | Y | Y | N |
| III | Environmentally sound | Y | Y | Y | Y |
| IV | Economically viable and cost effective | Could be used if structural performance or skin quality needs to be enhanced | Y | Y | Y |
| V | Safe to use in densely populated areas | Y | May be limitations due to flammability properties and local safety codes and requirements | May be limitations due to flammability properties and local requirements.<br>Methyl formate in a foam system can be provided to foam manufacturers which may reduce limitations of use. | Y |
| VI | Easy to service | NA | NA | NA | NA |

## 2.15 Extruded polystyrene (XPS)

Extruded polystyrene is generally selected as the insulation of choice due to a combination of properties beyond thermal conductivity, which varies by application.

- Long-term performance
- Closed-cell structure
- Low moisture/ water uptake for below grade applications
- Large cross-section, 20 to 200mm thick monolayer that can be bonded for thicker foams through thermal bonding
- Lightweight
- High mechanical strength under load
- Easy to fabricate
- Dimensional stability over a wide range of temperatures for roofing

**Figure 2.24 Extruded polystyrene foam boards for under grade (ground) construction**

HFC-134a use in XPS has been phased out in Europe where there is strong demand for XPS, despite high prices for XPS. This is important because XPS is competitively used in place of other materials. This is largely due to higher insulation requirements which have resulted in the use of XPS in new ways. The ability to use thermal bonding for XPS foams results in thicker foams with incrementally better insulating capability. The ability to use thicker foams below grade or on a roof allows for extensive use of liquid $CO_2$ as an FBA and compensate for its better insulating capability by using multiple layers of XPS.

Note that $CO_2$ is challenging to use alone and is generally combined with a co-blowing agent such as dimethyl ether (DME), ethanol, or HFC-152a to lower the foam density. Isobutane is used to improve thermal performance, but its use is limited due to challenges in passing fire testing of finished foams. It is anticipated that HFC-134a use in foams are likely to transition to HFO-1234ze(E) due to its similar properties. The high cost of HFOs makes it unlikely to be a direct replacement and will likely be used in combination with other FBAs.

XPS is also used in plaza decks because of the very high compressive strength. It is used for showers and other uses because its cutability while retaining its properties as well as its dynamic fatigue. Separately, there are some applications where thickness is contained, such as for insulated trucks in Europe. The floor of the truck is part of the chassis and there must be very high compressive strength, excellent thermal properties, and low dynamic fatigue. Certification requirements were just updated requiring better thermal performance. Fluorocarbons are likely to continue to be used in this application and in other applications that are subject to space constraints.

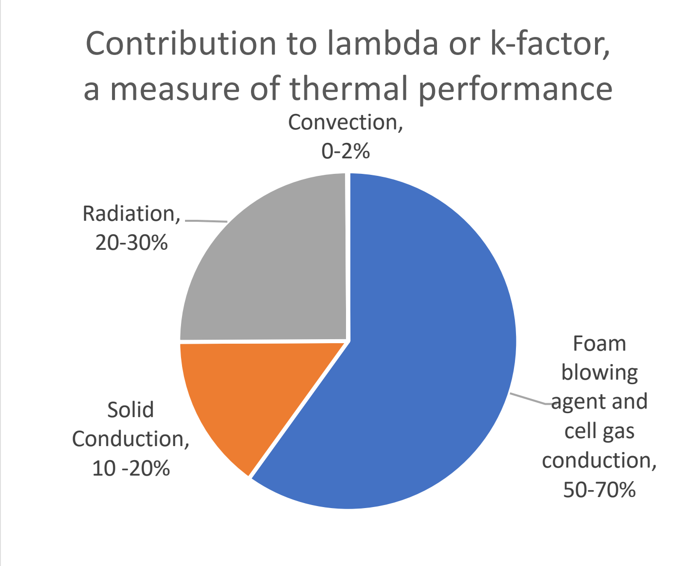
In other parts of Europe, beyond the European Union, there is high demand for very low-density (20-25 kilograms (kg) per cubic meter) foams for non-insulating foams to fill cavities or for other uses. The demand has been stable and is expected to remain stable in the coming years.

In contrast, the North American Market transitioned from HCFC-142b / HCFC-22 to HFC-134a to comply with a requirement of meeting a resistance (R-) value of 5 per inch. All building codes are based on this insulation requirement which makes HFOs the most likely replacement in a blend to meet this thermal performance. Insulation uses in North America include below grade use for basements and foundations and above grade sheathing in residential settings. Commercial buildings use XPS insulation below grade and in steel stud applications above grade. XPS is also used in cold chain floors and for roofing especially for plaza decks and green roofs where more compressive strength is needed.

It is anticipated that there will soon be regulations mandating the transition out of HFCs in the United States, where states have taken the lead with individual mandates. One fluorocarbon manufacturer has announced that they will shutter their HFC-134a facility to produce HFOs. However, due to HFO shortages, variances have been approved for GWP limits for XPS FBAs. Production of XPS in North America has been close to capacity in 2022. Blends of HFC-134a, HFO-1234ze(E), HFC-152a, carbon dioxide, and water have been approved for use in the United States under its EPA Significant New Alternatives Policy (SNAP) program. Shortages continue to impact transitions as of October 2022.

XPS manufacturers report that they will try to minimize the use of HFOs in blends due to cost. This impact their ability to make other changes because of the importance of the FBA to reducing heat transfer by gas conduction as shown in this figure.

**Figure 2.25 Importance of FBA to XPS thermal performance by reducing heat transfer through gas conduction.**




In China, $CO_2$ with ethanol seems to be the predominant commercial selection of the next generation FBA, based on case-studies from equipment vendors. The pre-pandemic volume of XPS was approximately 20-30 million cubic meters which represented approximately one-third of the foam insulation market divided among 7 to 10 thousand manufacturers.

Japan has a minimal number of manufacturers like North America, with a pre-pandemic volume of 2.3 to 2.5 million cubic meters of foam representing nearly 40% of the foam market. FBA blends include mixed butanes, DME, ethyl chloride, and carbon dioxide with significant volumes of flame retardant. The phase out of the fire retardant hexabromocyclododecane (HBCD) may cause manufacturers to move away from hydrocarbons to meet fire and smoke testing requirements under the building codes[38].

In Japan, under the 2000 Housing Quality Assurance Promotion Law, there is a 10-year warranty on defects, including insulation performance. However, the industry association promotes a twenty-year performance standard, which may impact FBA blends and selections. Europe and US have long-term thermal performance testing to meet building code requirements to reduce heating and cooling load in buildings. There is now some use of HFO to lower fire-retardant requirements and thermal performance needs. Of note, the fire test in Japan is different from other XPS qualification tests in that a candle is used as the flame source in contrast to Europe where a much higher energy ignition source is used.

**Considerations Related to Hydrocarbons** in the beginning of section 3 for safety, cost, and other considerations.
However, it should be noted that in parties where there are strict energy efficiency requirements, low GWP HFCs, HFOs/HCFO blends are generally used to manufacture XPS in blends. They are often

[38]Red phosphorous has recently been used in place of HBCD in some instances.

combined with other foam blowing agents and nucleating agents to reduce costs. There also can be limitations due to VOC restrictions in some jurisdictions.

It should be noted that all newly manufactured XPS, precautions should be taken to vent emissions of flammable FBAs, including hydrocarbons and HFC-152a to ensure that there is no ignition in storage. Off-gassing happens at a high rate in the days after production, except for HFC-134a and HFOs.

The table below shows FTOC's assessment of the most used HFC alternatives for XPS against the six Decision XXVI/9 criteria.

**Table 2.12 Summary of most used HFC alternatives for XPS**

| **Decision XXVI/9 Criterion** | | **Alternatives** | | | |
|---|---|---|---|---|---|
| | | **HFOs/ HCFOs** | **HCs** | **Methyl formate** | **Water** |
| I | Commercially available | Y | Y | Y | Y |
| II | Technically proven | Y | Y usually as co blowing agents except in some specific regions where codes allow | Y | Y in blends |
| III | Environmentally sound | Y | Y | Y | Y |
| IV | Economically viable and cost effective | Used to achieve desired thermal performance where needed | Y may require significant capital investment | Y | Y |
| V | Safe to use in densely populated areas | Y | Mitigation required, building codes may not allow use of hydrocarbons May be limitations due to flammability properties and local safety codes and requirements | May be limitations due to flammability properties and local requirements . | Y |
| VI | Easy to service | NA | NA | NA | NA |

## 2.16 Phenolic foam

Phenolic foams represent only a small portion of insulation materials. They are sometimes selected because of low smoke rates in fire testing, but their cost can be a competitive barrier as can challenges when exposed to moisture with compatibility. It is used more widely in Europe with growth in Japan and de-selection in North America. Open-celled phenolic foams are still used in some countries but most uses as insulation have converted to closed-cell technology. CFC-113 was once used competitively to CFC-11 in phenolic foams.

Figure 2.26 Phenolic foam used in insulated pipe

HCs are generally the foam blowing agent in commercial use in phenolic foams. The larger facilities allow for the economy of scale benefit which is optimized with lower operating costs with higher capital investment for using pentanes. However, it is possible that HFO/HCFO blends with hydrocarbons may be considered in the future as increased thermal performance becomes more preferred or mandatory in building construction to reduce heating and cooling loads. 2-Chloropropane is also used as a foam blowing agent for phenolic foam co-blown with hydrocarbons. This is a non-ozone depleting substance (ODS) with low global warming potential (GWP) and are not controlled by the Montreal Protocol.

Most medium and large manufacturers use hydrocarbon foam blowing agents, especially those manufactured by medium and large enterprises. Please see summary on **Considerations Related to Hydrocarbons** in the beginning of section 3 for safety, cost, and other considerations. The table below shows FTOC's assessment of the most used HFC alternatives for phenolic foam against the six Decision XXVI/9 criteria.

**Table 2.13 Summary of most used HFC alternatives for Phenolic Foam**

| **Decision XXVI/9 Criterion** | | **Alternatives** | | | |
|---|---|---|---|---|---|
| | | **HFOs/ HCFOs** | **HCs** | **Methyl formate** | **Water** |
| I | Commercially available | Y | Y | Y | Y |
| II | Technically proven | Y | Y | N | N |
| III | Environmentally sound | Y | Y | Y | Y |
| IV | Economically viable and cost effective | Some use when thermal performance needs to be enhanced | Y | NA | NA |
| V | Safe to use in densely populated areas | Y | May be limitations due to flammability properties and local safety codes and requirements | NA | NA |
| VI | Easy to service | NA | NA | NA | NA |

## 2.17 Other alternatives under development or used in small quantities

Dimethyl ether (DME), ethanol and butanes are used in extruded polystyrene. DME is also used in some one-component polyurethane foams that are dispensed from an aerosol can.

Methylene chloride is still used as a blowing agent in the production of flexible foams in A5 Parties. Japan no longer allows the use of methylene chloride in foams and the US SNAP program changed the status of methylene chloride to “unacceptable” for use in foams. Although, foam produced from methylene chloride in A5 Parties can be exported to the US provided the foam is open-celled.

Methylal[39] (Dimethoxymethane), is used as a co-blowing agent in low-resistance, high-density (“memory”) foams and in very low concentrations in combination with water in rigid foams. Flammability of the polyol blend is a limiting factor when used as a sole blowing agent.

Trans-1,2 dichloroethylene (1,2-DCE) is also used as a co-blowing agent, primarily in spray foam, with HFCs and is approved for use in the US and Europe. Flammability of the polyol blend is a limiting factor when used as a sole blowing agent.

In the PU hydrocarbon-blown sector, FTOC had previously become aware of two perfluorocarbon foam additives (FA-188 and PF-5056), both from the same manufacturer, which are being used to optimise cell formation to gain maximum thermal performance. FA-188 is a perfluorinated olefin, which is used in very small quantities and has a GWP of only around 100, but there are concerns about its potential breakdown products, which currently remain uncertain. PF-5056 has high GWP.

## 2.18 Summary

The table below summarises where alternatives to HFCs are available on a sector-by-sector basis. For an alternative to be available, it must have passed all Decision XXVI/9 criteria, i.e., it is commercially available, technically proven, environmentally sound, economically viable and cost effective, and safe to use, according to FTOC’s interpretation of these criteria.

**Table 2.14 Summary of alternatives for HFCs in foams applications**

| Sector | HFC Use Comment | HFCs being used? | Alternatives Available? |
|---|---|---|---|
| Domestic Refrigeration | Some use to improve thermal performance | Some | Yes |
| Commercial Refrigeration | Frequently used to improve thermal performance | Yes | Yes |
| Transport Refrigeration | Frequently used to improve thermal performance but cost sensitivity prevents some use | Yes | Yes |
| Polyurethane boardstock (PU) | Used to improve thermal performance | Some | Yes |
| PU Panels | Rarely used in continuous panels but could be used to improve thermal performance | Yes, in discontinuous panels) but rarely used in | Yes |

[39] The boiling point of methylal is 42C, Lambiotte

| Sector | HFC Use Comment | HFCs being used? | Alternatives Available? |
|---|---|---|---|
| | | continuous panels | |
| PU Spray Foam | Commonly used (safety and to improve thermal performance) | Yes | Yes |
| PU *in-situ* and Block Foams | Rarely used (could be used to improve thermal performance | Yes | Yes |
| PU Integral Skin | Some use for unique structural properties | Yes | Yes |
| Extruded polystyrene (XPS) | Some use for higher thermal or structural performance | Yes | Yes |
| Phenolic Foam | Some use for higher thermal or structural performance | Yes | Yes |

**Continuing Challenges Especially for Small and Medium Enterprises and Spray Foam**

The transition away from ODS foam blowing agents in some regions and market segments (e.g., spray foam) may be delayed because of cost, especially where local codes require higher thermal performance[40]. It should be noted that the price of HFC blowing agents has risen substantively during the pandemic and is nearly as high as HFO/HCFO prices were prior to the pandemic in some A5 parties. In locations where HFCs are used HFO/HCFO costs will be higher but more comparable than when replacing HCFCs.

Finally, small, and medium enterprises (SMEs) and spray foam manufacturers may still be facing challenges related to the adoption of HFOs/HCFOs, due to their operating cost, and hydrocarbons, due to potentially cost-prohibitive, capital investment or impractical safety requirements for field application. This continues to be an unresolved challenge for smaller companies and field applications for all foams for all parties.

**Figure 2.26 Insulated cookware**
Insulated cookware and food storage is built with a double-layer design encasing PU insulation material, which can keep food warm for several hours

[40] Although the cost of hydrochlorofluorocarbons (HCFCs) was approximately 20-30% of the cost of high-GWP HFCs, HCFC price is increasing as they are phased out globally. The low price of some high-GWP HFCs, particularly HFC-365mfc which is banned in some non-A5 parties, is leading to an increase in market share, which is slowing the conversion to low-GWP blowing agents

## 3.0 Low Global Warming Potential, Zero Ozone Depletion Potential (ODP) Alternatives Technical Advancements

Although there is no single foam blowing agent replacement for currently used HCFCs or hydrofluorocarbons (HFCs), there are different technical, economic, safety, and environmental performance properties for each low global warming potential (GWP), zero ozone depletion potential (ODP) alternative and different needs for each market subsector. There is a proliferation of blends across the whole of the foam sector which is an indication of the reality that there is no single best solution. Often a key factor is the size of the manufacturing plant since the economies of scale have a considerable bearing on the relative importance of capital and operational costs. Cost also is a major factor in the consideration of the major emerging technologies.

There continues to be a trend away from the use of fluorocarbon (FC) FBAs with every transition. It has been estimated that less than 20% of the FBA volume will be comprised of FCs after this transition globally. This is in part due to direct conversions to other FBAs and blends with lower concentrations of FCs, as is evidenced in the emissions of “liquid” FBAs as estimated through atmospherically derived emissions, which also shows that there continued to be potential for continued reductions in emissions of controlled FC FBAs

**Table 3.1 Low Global Warming Potential, Zero Ozone Depletion Potential Foam Blowing Agents**

| | **Thermal performance** | **Chemically Compatible with formulation and equipment** | **Commercially Available** | **Environmentally Sound** | **Economically Viable and Cost Effective** | **Safe to use due to Flammability and Toxicity** |
|---|---|---|---|---|---|---|
| **Hydrocarbons** | Better | Some differences in formulations | Some limitations due to supply chain issues | Low GWP<br>Zero ODP<br>Volatile organic compounds (VOC) | Low operating cost, but capital investment needed | Capital investment and training needed for safe operation |
| **$CO_2$ (water), super-critical $CO_2$** | Adequate in many situation | Generally compatible; use of supercritical $CO_2$ requires specialized equipment | No limitations to water | No concerns comparatively | Low cost for water, higher costs related to super-critical CO2 | High pressures related to supercritical CO2 |
| **HFOs/ HCFOs** | Better | Some challenges with stability requiring modifications to additive package for some (HCFO-1233zd)<br><br>Similar compatibility with components and metals | Some limitations due to higher demand than capacity and supply chain issues.<br><br>New capacity now on-line (2022) | Low GWP<br>Low (HCFO-1233zd) or Zero ODP<br>Lower Maximum Incremental Reactivity (MIR) (VOC) than hydrocarbons and considered non-VOC by some regulating agencies | Higher cost than other options, but provides additional thermal efficiency in many cases | Similar or same safety precautions as current alternatives |
| **Methyl formate, methylal, others** | Adequate in many situations | Generally compatible with formulations. Some challenges of corrosion reported, but can be addressed through formulation or changes in materials | No known issues | Low GWP<br>Low (HCFO-1233zd) or Zero ODP | Medium Cost (higher than water, lower than HFOs / HCFOs) | Some precautions may be needed due to flammability |

## Hydrocarbons

Hydrocarbons are a low GWP, low raw material cost alternative that have been available since an early stage of the transition from CFCs. Hydrocarbons have been available for large parts of the foam sector throughout that period, even at the time of the phase-out of CFCs in non-Article 5 Parties when approximately two-thirds of the market transitioned from fluorocarbons to hydrocarbons. In fact, hydrocarbons have been used in the foam industry without major incident since 1994 due to fastidious safety practices and the proper installation and use of explosion-proof equipment. Consequently, the account of the transition history since 1987 in the polyurethane and phenolic product sectors is dominated by whether a specific foam sub-sector could adopt hydrocarbon technologies or not. Improvement of insulation performance lead consideration of new foams for the use higher ratios of cyclopentane. Further HC foams have improved performance by using new injection systems which is leading to improved insulating performance.

As a focus on energy efficiency continues to require foam technology to increase thermal performance, there is an increasing use of blends of hydrocarbons with HFCs and HFO/HCFO equipment companies have developed equipment to blend multiple blowing agents into a polyol.

It should be noted that pre-blending hydrocarbons into polyol systems in very low hydrocarbon concentrations have been tested and used in small niche markets.  Testing indicates that even low concentrations of hydrocarbons in polyol blends (even below 2%) can exceed the explosivity limit during foam processing with isocyanate. The fully formulated polyol flash point will likely be classified as flammable; therefore, labels and transportation procedures must comply with the Global Harmonized System (GHS).

**Table 3.2 Flashpoint data for polyol blends containing flammable foam blowing agents**

| Intertox/ABIQUIM Presentation at FEIPUR 2010 - Brazil | | | | |
|---|---|---|---|---|
| **Flash Point Data for different blowing agents combined with Standard Formulated Polyol for PU rigid foam** | | | | |
| Formulated Polyol (Pbw) * | 100 | 100 | 100 | |
| Blowing Agent added to Formulated Polyol | | | | Flash Point, C # |
| HCFC-141b | 4 | | | No |
| | | 6 | | No |
| | | | 8 | No |
| HFC-365mfc/227ea | 4 | | | No |
| | | 6 | | No |
| | | | 8 | No |
| C-Pentane >95 | 4 | | | 18,5 |
| | | 6 | | 13,0 |
| | | | 8 | 7,0 |
| Methylal | 4 | | | 26,5 |
| | | 6 | | 13 |
| | | | 8 | 6 |
| Methyl Formate | 4 | | | >60 |
| | | 6 | | 53 |
| | | | 8 | 39 |

*Sucrose based polyol (Fm 4,4), combined with Glycerine initiated (Fm 3), with DMCHA catalyst, and standard Silicone Surfactant for PU rigid foam, containg 2,35% water in the formulated polyol composition
# ASTM D 56-05 "Standard Test Method for Flash Point by Tag Closed Cup Tester"
IPT Code: CMQ-LCL-PE-047)*

The dominance of the hydrocarbon technologies is even greater as the blowing efficiency of hydrocarbon blowing agents, due to the difference in molecular weights, is better than the CFCs and HCFCs that were replaced. This means that the amount of foam blown by the 290,000-295,000 tonnes of hydrocarbons predicted to be used in the foam industry in 2020 will be 30-40% greater than would be achieved by the same quantity of CFCs. The optimisation of hydrocarbon technologies over the years has also resulted in improvements in thermal performance through improved cell structure, thereby negating some of the earlier concerns about poorer thermal efficiency.

In general availability of hydrocarbon blowing agents is balanced to the global market demand. Nevertheless, while n-/iso-pentanes are local based refinery products without foreseeable limitations in availability, cyclopentane relies mainly on the chemical industry in Asia and Europe. At an increasing demand, disruptions in production of key manufacturers or global logistics could cause limitations.
Hydrocarbons are expected to play an increasing role in the coming years as means are found to cost effectively engineer hydrocarbon (HC) solutions for medium-sized enterprises (e.g., water heater manufacturers), in HC blends in extruded polystyrene, and appliance manufacturers. Interestingly, it is worth noting that cyclopentane, which has the lowest thermal conductivity and is used in refrigeration foams, is manufactured in the smallest, most limited quantities. Isopentane and normal pentane, largely used in discontinuous panels, are more plentiful, but still have limited supply options.

However, there currently are limitations in the available supply of pentanes and a limited number of manufacturers that produce foam grade pentanes[41]. There are additional requirements for shipping hydrocarbons than for other FBAs because of the safety risks. Finding qualified truckers during the pandemic proved challenging.

[41] Cyclopentane is a specialty grade produced by naphtha cracking. Pentanes are not produced in the hydraulic fracturing process and pentane production may be limited as decarbonization efforts reduce the use of fossil fuels.

The carbon footprint has gained importance for chemical products in the recent past. Selected companies are already able to apply mass balances in their chemical production processes to ensure the credibility of the "cradle to gate" statement. This comprehensive mass balance approach ensures that the use of sustainable resources to reduce the carbon intensity of the product is allocated throughout the value chain.[42]

Hydrocarbon solutions can be used as an FBA in many situations provided safety challenges are addressed, such as the following. Some of these concerns have either been addressed or largely discounted in recent years, but others continue to be of importance, and some are even growing in significance (e.g., waste management issues) as hydrocarbon blown foams reach end-of-life.

- The flammability risks associated with the production process, installation, and use
- The capital cost of flame-proofing measures for production processes in relation to the size of the manufacturing plant
- *In situ* field-applied flammable blends
- Local health & safety regulations
- Local regulations on volatile organic compounds (VOCs)
- Waste management issues

**"Renewable" hydrocarbons**

Hydrocarbons can be produced using renewable raw materials in their operations that are certified and allocated to the production of pentanes. Generally, they are only referred to as renewable if they are certified by a technical inspection body.

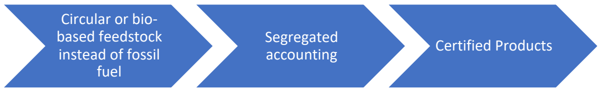



**Figure 3.1 Chemical manufacturing and operator**

There are several helpful resources available to address safe handling and use of hydrocarbons. Here are some of those resources.

ESIG Flammability Guide:
https://www.esig.org/flammability-guide-update-2022
https://www.esig.org/resources/videos

Hydrocarbon use in the manufacturing of polyurethane foams
http://www.multilateralfund.org/Our%20Work/DemonProject/Document%20Library/6617p6%20low%20cost%20PU%20foam.pdf

Facilities upgrades for safe storage and handling at manufacturing facilities

[42] **For more information on renewable hydrocarbons and circular economy** https://www.iscc-system.org/about/circular-economy/mass-balance-approach/

Safety consideration in the storage of flammable liquids in tanks
https://www.hse.gov.uk/pubns/books/hsg176.htm

**Supercritical Carbon Dioxide, Water as Carbon Dioxide**

Although carbon dioxide ($CO_2$) is generated by the reaction between isocyanates and water in polyurethane chemistry (so called $CO_2$ (water) technology), the focus of this section is on the external addition of supercritical $CO_2$ to create gaseous $CO_2$ as a blowing agent. This is a technology mostly practiced in the extruded polystyrene sector, where the main low-GWP and cost-effective alternative has been $CO_2$ injected into the extruder itself. Again, the main challenge throughout has been to understand why this solution could not be universal in its application. Reasons have included:

- Processing difficulties with $CO_2$ and even $CO_2$/HCO or $CO_2$/HC blends
- The higher gaseous thermal conductivity leading to poorer thermal efficiency of the foam
- Costs of conversion - including licensing constraints resulting from patents
- Loss of processing flexibility ruling out some board geometries completely

However, $CO_2$ -based blends are now dominant in the European extruded polystyrene (XPS) industry either alone or blended with other blowing agents. It is also used in the production of flexible polyurethane foams used for comfort applications in furniture, bedding, and automotive seating. In North America where the lower lambda product is required, HFCs still dominate. By contrast, much of the European XPS market is targeted at requirements, such as floor insulation, where its moisture resistance is particularly valuable. In these applications, board geometries are less critical.

Injected (super-critical) $CO_2$ is also used for PU spray foam applications – most notably in Japan, where PU spray foam is widely used. The technology is proprietary to several companies which have adopted this technology. There are also some shortcomings in thermal performance against other technological solutions in the sector, especially in relation to the emerging HFOs / HCFOs (see next section). Supercritical $CO_2$ is handled as a high-pressure gas in Japan and subject to equipment and safety requirements when used.

## Latest Status of HFC/HCFO Developments

Unsaturated HFCs and HCFCs (often commercially referred to as HFOs/HFCOs) are offering similar or better performance to HCFCs and saturated HFCs. In addition, they have the potential to replace some elements of the hydrocarbon and $CO_2$-based sectors, based primarily on improved thermal insulating properties.

In practice, and for cost reasons, blends of HFOs with other blowing agents (including increasing quantities of $CO_2$ (water) are also in commercial use or under development. Optimized foam formulations using HFO/HCFOs or blends of HFO/HCFOs with other blowing agents (such as HC and methyl formate) will often require product approval and qualification/certification testing, not

**Closed and open cells in foams**

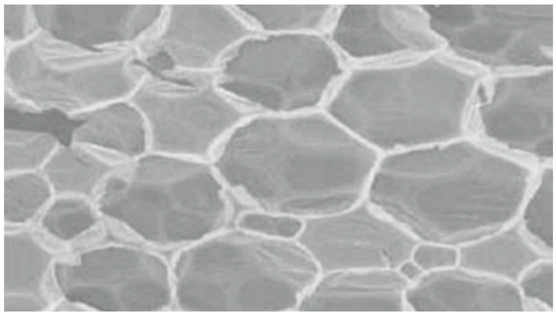


**Figure 3.2 open and closed cells in a foam matrix**

It may be helpful to note that there are different types of spray polyurethane foam insulation. Open cell and closed cell foam insulation are differentiated by the percentage of the foam structure that has broken cell walls. If more than 50% of the cells are broken or open, the foam is considered an open-cell foam. If more than 50% of the cells are closed, the foam is considered a closed-cell foam.

Closed-cell foams generally have higher density (2 pounds per cubic foot) and are used to “seal” the building envelope to minimize heating and cooling loads by reducing air infiltration into the building. Open-cell foams generally have lower densities (0.5 lbs per cubic foot) and are used in place of other insulation in homes in warmer climates.

Historically, water, which reacts with the other chemicals in the foams recipe to make carbon dioxide, has been used in the manufacture of open-cell foams while fluorocarbon foam blowing agents are used to make closed-cell foams. In recent years, some companies have worked to expand the range of products manufactured with water to make more dense foams that can be used in certain applications in colder climates to better seal the building envelope.

In cold climates, when warm moist air meets a cold surface, moisture condensation occurs. Closed-cell foam is so dense that condensation only occurs on the surface of the material. Moisture on the surface of the closed-cell foam evaporates quickly preventing severe moisture problems.

only for the blowing agent itself, but also for the foam products where the blowing agent is used. This foam formulation development, qualification and gaining of code approvals, where required, can take from 18 months to several years.

Nearly two-thirds of HFC/HCFO in Japan is used in spray foam. FC usage in spray foam or where foams are manufactured on-site use FCs due to safety concerns. In addition, thermal performance is better than water-blown ($CO_2$) foams as noted in this study by JRII.

> Spray foam blowing agent thermal performance:
>
> ➢ Water; residential houses & apartment / office buildings in mid and south Japan, the thermal performance or k-factor in milliwatts per meter per degree Kelvin (mW/m-K).
> - <34 mW/m-K（for high density foams)
> - < 40 mW/m-K (for low density)
>
> ➢ HFO/HCFO; residential houses & apartment / office buildings in north Japan and cold chain, K-factor;
> - < 26 mW/m-K

Commercial availability has been established for HFO-1234ze(E) (gaseous blowing agent), HFO1233zd(E) (liquid blowing agent), and HFO-1336mzz(Z) (liquid blowing agent). Markets which require improved thermal efficiency or are unable to use flammable alternatives (e.g., spray foam and SMEs) are more likely to adopt these technologies. In addition, the demand to leap-frog high GWP HCFC alternatives in other sectors could further accelerate distribution in Article 5 regions. However, cost remains a key issue and blending with other co-blowing agents may well be required to meet commercial needs.

HCFO-1224yd and HFO-1336mzz(E) have recently been commercialized in small quantities (less than 1000 tonnes) as alternative foam blowing agents. Additional information regarding use in various foam sectors may be available as commercialization progresses.

Another aspect of the change to HFO/HCFOs, is the continuing development by additive suppliers of catalysts and surfactants which helps optimize various performance parameters of HFO/HCFOs, such as thermal and mechanical properties and shelf stability of polyol blends. New catalysts and surfactant designed for use with HFOs have been introduced commercially into the market globally.

There continues to be a mismatch, at least locally, of supply and demand of HFO/HCFO foam blowing agents with shortages in NA5 and A5 parties delaying transitions or creating compliance challenges for companies that have selected this technology as their next generation solution. See the following timeline from Japan, as an example of the response to the HFO/HCFO shortages. Alternate insulations are replacing the spray foam market because of inability to comply with both the Energy Saving Law, which requires minimum thermal performance, and the requirement to comply with HFC bans.

**Recent research and announcements of commercialization announcements of new foam blowing agents**.

Since the last FTOC Assessment Report, there has been continued research and commercialization announcements of various uses of FBAs, despite the pandemic. Generally, there has been testing and qualifying of new uses, work to improve various properties, and testing of blends to improve properties or cost or both. Some of this research is summarized below.

- **Energy Efficiency –** HCFOs have been tested as replacement of HFCs in refrigerated containers[43] which requires testing related to stability of the polyol blend and long-term thermal performance, which helps to reduce fuel consumption by the trailer cooling

[43] Achievements Made Phasing out HFC Blowing Agents to HCFO Blowing Agents – Covestro – 2021 Center for Polyurethane (CPI) Conference

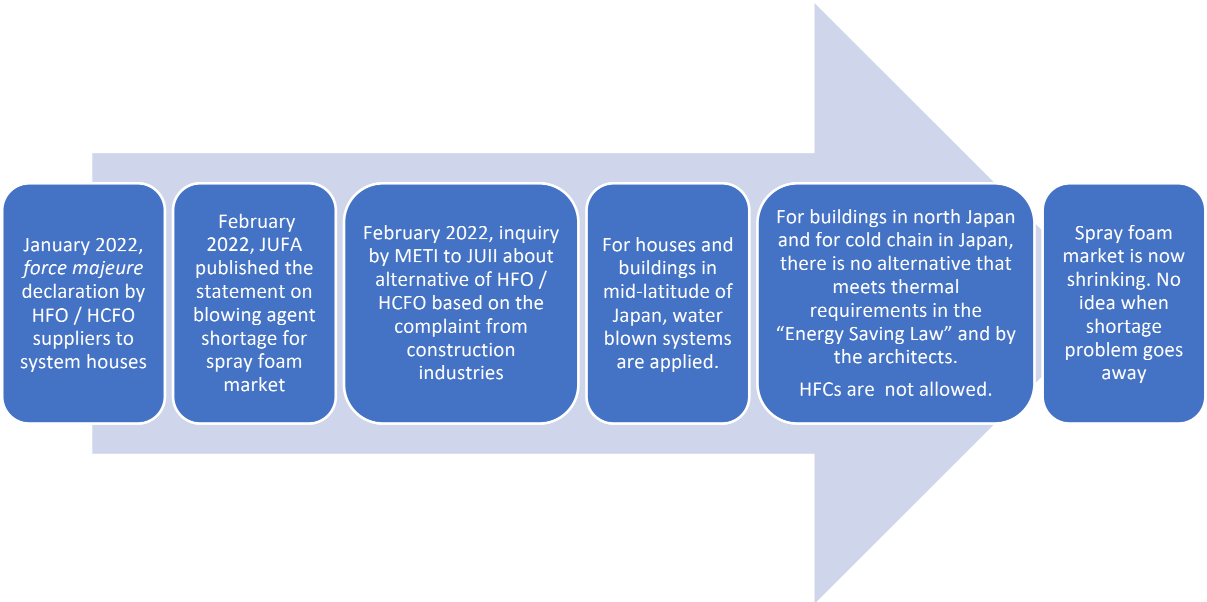
system. Research has highlighted mechanisms that create stability challenges. Also of note was that the high solubility of some FBAs in the polymer matrix may create challenges for compressive strength, dimensional stability, and poorer adhesion to metal and plastic. New catalysts and additive combinations may allow for improved performance.

- **Measuring Long-Term Thermal Performance** - Spray foam long-term thermal performance testing[44] was also examined for HFO-1336mzz-E isomer with estimates of degradation 16-30%, based on the current long-term thermal resistance (LTTR) test methods. Actual performance data indicates a degradation is much lower with a reduction of only 2.7% after 3.5 years. The study noted that LTTR methods may be a poor predictor of thermal performance in spray foam or thicker polyurethane foams. The hypothesis of the study is that there is slow motion of air and carbon dioxide through thicker foams. The conclusion is that ICC-ER AC377 is a better method for long-term aged k prediction, and that methods like EN 14315 might be more meaningful and should be explored.
  In contradiction, one study[45] suggest that continued use of the current LTTR method is appropriate based on a 6-month study except for a filled wall cavity.
  Thermal performance measurements[46] were also explored for insulated metal panels (IMPs) in a 5-year study started in 2014 by the Insulated Metal Panel Alliance to more accurately predict the long-term thermal resistance (LTTR). An independent, accredited, third-party lab completed the analysis of results from the two blind studies. The results suggested that a prescriptive calculation to predict 5-year insulation values from 6 months of measurements was plausible. The study showed that current method for LTTR, CAN/ULC S770, underpredicts the values for IMPs. Although current U.S. building energy codes do not have LTTR requirements, they are present in Canadian specifications. The IMP alliance aims to make a strong case for using a method specific for IMPs where LTTR is required.
- **Stability of blends -** There have also been continued analysis of catalysts[47], [48] and to improve stability of polyurethane systems containing HFOs/HCFOs problems with HFOs, especially 1233zd to reach 15 months shelf-life for low pressure foam systems. Innovations made to formulas, dispensing equipment (nozzle), and manufacturing redesigns. Formula optimization resulted in shelf stability of 15 months. Alternate approaches have been to clarify that foam systems have a shelf life of 12 months[49] for guidance to customers. Alternate metal catalysts and amines have also been tested for two-component[50] foams to select best options. Note that no testing was found to confirm any additional impacts for high ambient temperature (HAT) impact to stability.
- **Co-blowing Agents -** Co-blowing agents continue to be examined to reduce costs and improve properties of interest[51]. Performance of *(methylal or dimethoxymethane)* in

[44] 2. Spray Polyurethane foam Formulation Parameter and Their Effect on Long Term Thermal Conductivity – Chemours - – 2021 CPI Conference
[45] Comparison of Field vs Laboratory Long-term Thermal Conductivity of Closed-cell Spray Polyurethane Insulation – HW and NCFI - – 2021 CPI Conference
[46] Determination of Long-Term Thermal Resistance (LTTR) Values of Insulated Metal Panels – Metal Construction Association (MCA) and Huntsman Polyurethanes 2022 CPI Conference
[47] 4. Low GWP Two-component Low Pressure Spray Foam Using CO2 as a Blowing Agent – DuPont - – 2021 CPI Conference
[48] Quantitative Performance Evaluation of a Novel Strong Blowing Amine Catalyst for HCFO-1233zd(E) Blown SPF Application – Tosoh 2022 CPI Conference
[49] HFO Blown Low Pressure Two –component Spray Foam Insulation: A Challenging but Attainable Pursuit – ICP Building Solutions. – 2021 CPI Conference
[50] 5.Novel Concept to Improve Shelf Life of LP 2K SPF with HFO 1234ze – DuPont – 2021 CPI Conference
[51] Impact of Using a Coblowing Agent with HFO-1233zd(E) on the Performance and Properties of a Polyurethane Foam System – Arkema 2022 CPI Conference

blends with HFOs/HCFOs[52] has also been recently explored especially focusing on dimensional stability.

- **Fire Testing -** Analysis continues of scientific methods[53] to link small-scale laboratory methods and large-scale fire tests through materials characterization and fire modelling using the National Institute of Standards and Technology (NIST) Fire Dynamics Simulator (FDS) code. Fundamental pyrolysis from small scale testing was used to develop an innovative fire dynamic modelling to predict large scale ASTM E84 Steiner tunnel test results with good agreement between experimental and simulated FSI and SDI values




## Oxygenated Hydrocarbon Alternatives Developments

**Methyl Formate**
Pure or blended methyl formate is used in Latin America with limited adoption as it may have some challenges in some formulations with some concerns about blend stability limitations and challenged in achieving long term dimensional stability. Compatibility of manufacturing equipment and finished product should be to eliminate instances of chemical attack compared to other FBAs. This can be as simple as using more compatible materials of construction. Non-flammable formulated polyol blend can be achieved (>60 C of flash point). However, higher concentrations are classified as flammable for purposes of transportation (GHS) and handling/processing. However, methyl formate is low cost and available, so SMEs are re-evaluating its use in blends with HFCs or HCFOs.

**Methylal (Dimethoxymethane)** belongs to a class of chemicals referred to as acetals and is generally used as a co-blowing in low-resistance, high-density ("memory") foams and in very low concentrations in combination with water in rigid foams. Flammability of the polyol blend is a limiting factor when used as a sole blowing agent.

[52] Performance of Novicell (methylal or dimethoxymethane) Blowing Agent in Closed Cell Rigid Polyurethane Foams as offset for HFO 1336mzz(Z) – Troy Polymers and Lambiotte – 2021 CPI Conference
[53] Modelling the Performance of PU Rigid Foams in Large-scale Fire Tests – Huntsman 2022 CPI Conference

### Other Non-fluorinated Alternatives

**Dimethyl ether (DME), ethanol and butanes** are used in extruded polystyrene. DME is also used in some one-component polyurethane foams that are dispensed from an aerosol can.

**Methylene chloride** is still used as a blowing agent in the production of flexible foams in A5 Parties. Japan no longer allows the use of methylene chloride in foams and the US SNAP program changed the status of methylene chloride to "unacceptable" for use in foams. Although, foam produced from methylene chloride in A5 Parties can be exported to the US provided the foam is open-celled.

**Trans-1,2 dichloroethylene (1,2-DCE)** is also used as a co-blowing agent, primarily in spray foam, with HFCs and is approved for use in the US and Europe. Flammability of the polyol blend is a limiting factor when used as a sole blowing agent.

In the PU hydrocarbon-blown sector, FTOC had previously become aware of two perfluorocarbon foam additives **(FA-188 and PF-5056),** both from the same manufacturer, which are being used to optimise cell formation to gain maximum thermal performance. FA-188 is a perfluorinated olefin, which is used in very small quantities and has a GWP of only around 100, but there are concerns about its potential breakdown products, which currently remain uncertain. PF-5056 has high GWP.

# 4. 0 The Status of Banks and Stocks of Controlled Substances and the Options Available for Managing them to Avoid Emissions to the Atmosphere.

Foam blowing agents currently in use in insulating foams in buildings and appliances are described as "active" foam banks. Active banks of FBAs are fulfilling their intended technical and economic purpose, providing insulation for the duration of their useful lifetime. Waste management choices determine the extent of FBA emissions at a product's end-of-life (EOL).

The *most commonly* adopted disposal practice globally is to landfill foam waste. The foam is buried and often partially crushed in the process, leading to emissions of a portion of the FBA contained in the foam cells. Crushing the foam within the landfill reduces its displacement volume, where space has a value. Remaining FBA in the foam is emitted over time (estimated at 0.5% per year), except for possibly some relatively small amounts that may undergo anaerobic degradation (bacterial digestion, whereby the FBA may be chemically broken down) in the landfill.

The internalised costs of landfill disposal are relatively low, compared with the costs of recovery and destruction, making landfill disposal ostensibly attractive in market-based economies. The externalised costs associated with landfill disposal of foam products, passed on to governments and society in other ways, include the value of landfill space occupied by foam wastes (and associated need to build future landfills) and the costs associated with health, climate and other impacts arising from long-lived ODS emissions. As a result, some countries regulate and incentivise the management of waste foam products (and other demolition and equipment wastes) to drive market decisions that prioritise resource recovery or destruction and to mitigate the externalised long-term costs to society of landfill disposal of ODS wastes.

To recover controlled FBAs from appliance foams, the appliance is shredded within an airtight system to capture the foam blowing agent, which is partially released during the process. The shredded foam, still containing FBA, is separated from the metals and then is either incinerated to destroy the foam and FBA together, or the FBA can be separated from the foam for reclamation or destruction. This process is relatively energy and cost intensive. However, an analysis of the relative environmental impacts concludes that energy consumption for disposal processes, measured in $CO_2$ equivalents, has a negligible impact compared to the impact of emissions avoided from the destruction of high GWP FBAs[54].

Relative investment and operating costs in ODS waste recovery and destruction present a challenge compared with cheaper forms of disposition (venting and landfill disposal). The low internalised waste disposal costs for cheaper forms of recovery and disposal can be weighed against the externalised costs to society of future health and environmental impacts of ODS emissions from venting or landfill disposal. With long building lifetimes, the drivers for recovery and destruction of building insulation foams may change over time. The evolution of net zero carbon requirements and the circular economy may improve end-of-life choices.

Destruction costs represent a minor proportion of total costs of recovery and destruction, with recovery costs being the major portion and dependent on factors such as the sector waste type, infrastructure, logistics, and transport distances. It is also important to appreciate that the recovery and destruction of waste foam is essentially considered to be a broader waste management issue.

[54] GIZ Proklima, *Management and destruction of existing ozone depleting substances banks*, August 2015.

Since the 1990s, some polyurethane appliance foams have been shredded. Very little of the FBA has been recovered with mandatory recovery requirements of foams during the dismantling of equipment, where foams or FBAs are generally destroyed rather than reclaimed, which may be impractical as waste streams tend to be mixed.[55] The cost of recovery of FBAs from foams for reuse has generally been considered too high for broad implementation through current recycling and reuse or extended producer responsibility (EPR) programs.

**Voluntary destruction**

The Montreal Protocol encourages parties to destroy surplus or contaminated end-of-life ODS/HFCs through destruction technologies approved by parties; however, it is not mandated for ODS or Annex F Group I HFCs except for HFC-23[1]

Promotion of voluntary recovery of foams and FBAs for subsequent destruction occurs mainly for appliances, e.g., in Canada and the United States. Recovery and destruction is also practiced in Europe and Japan.

European Union Regulation 1005/2009 on substances that deplete the ozone layer sets out measures that CFCs in insulation foams shall be recovered for destruction, recycling, or reclamation if technically and economically feasible, or shall be destroyed without prior recovery using approved destruction technologies. For domestic appliances, these must be disposed of at a licenced treatment facility using contained processes that ensure that the CFCs or HCFCs are not emitted to atmosphere, by recovery followed by destruction. In Germany, treatment plants that meet the quality criteria are awarded the RAL GZ 729 quality mark (RAL Gütezeichen) for the de-manufacture of foam products containing ODS[1].

Mandatory recovery is generally limited to refrigeration appliances. Steel-faced panels and spray insulation foam, which is adhered onto building surfaces is not generally segregated without unreasonable effort or FBA emissions with some exceptions[56], e.g., Germany and Austria, have mandates to remove and treat insulation foam prior to the demolition of a building.

The challenge with building insulation foam is its separation and collection during building demolition. Depending on the foam type and application method, this might be feasible with medium effort, e.g., steel-faced panels or is not feasible without emitting the FBA, e.g., spray foams. The level of effort also relies on existing practices of segregating material during demolition. Building insulating foams can be collected with lower effort where the segregation of demolition material is common practice[57]. Based on these previous analyses, the cost of collection and destruction of steel-faced foam panels is between 3-15 times higher than the recovery and destruction of refrigerants from stationary AC (including chillers). By comparison, the cost of recovery and destruction of appliance foams is estimated to be as little as a quarter the cost, and up to a similar equivalent cost, as the recovery and destruction of steel-faced foam panels.

Up to 10-20% of closed-cell CFC-11 foam lifecycle emissions occur during dismantling and/or segregation processes, e.g., during the recovery and recycling of metals and plastics from insulating foam panels in buildings or from refrigerators in the instances where the process is not enclosed. The

[55] Bruce J. Wall, Appliance Recycling Centers of America, Inc., *CFCs in Foam Insulation: The Recovery Experience*, 1994, https://www.aceee.org/files/proceedings/1994/data/papers/SS94_Panel4_Paper28.pdf (accessed April 2021).

[56] GIZ Proklima, *Banks and Emissions of CFC-11 and CFC-12, Country data and possible consequences for global modelling*, 2020.

[57] Report of the Decision XX/7 TEAP Task Force on Environmentally Sound Management of Banks of Ozone-Depleting Substances, Phase 2 Report, October 2009. https://ozone.unep.org/sites/default/files/2019-05/teap-october-2009-decisionXX-7-task-force-phase2-report.pdf.

separated foam is rarely shredded before disposal by destruction or to landfill; instead, undivided portions of foam waste are supplied for disposal.

Foam waste is occasionally recycled for secondary uses, such as in road base, e.g., in China, where it is sometimes ground up and incorporated as road aggregate. If foam is shredded or ground as part of waste handling, up to about half of the FBA is estimated to be emitted. Adoption of destruction technologies varies by country, depending on the demand for destruction, the requirements of national regulations and related standards, national and local air quality guidelines, availability of appropriate technology, and viability of the market for destruction.

When destroyed, the foam is generally incinerated, e.g., in a rotary kiln incinerator, a cement kiln, or municipal solid waste incinerator. While some emissions will occur during associated waste transportation and handling, the FBA remaining within the foam product will be largely destroyed during the process, assuming optimal thermal destruction conditions apply. It should be noted that while cement kilns are not an approved destruction technology for ODS foams under the Montreal Protocol, there is no technical reason why they could not be utilised as an efficient and effective method of destruction for foams, assuming local requirements for air pollutants can be maintained. Developing countries that do not have incinerators might instead have cement kilns suitable for this purpose.

**End-of-life of foams in A5 parties**

In A5 parties, some refrigerators and freezers are dismantled, and rigid PU foam is collected, reused, or recycled. However, the percentage is relatively low due to difficulty in collecting and transporting. Exact percentage of foam collected is not available. In China, it is estimated that 99kt of rigid foam used in Appliances (only 7% of total) was collected – part of it is pulverized and used with concrete in construction for lighter weight and better thermal insulation. Due to strong government drive on decarbonization, PU foam reuse and recycle will most likely increase.

In A5 parties, e.g., Colombia has practiced recovery of waste foams from refrigeration equipment with an extended producer responsibility system. The recovery process requires segregation of waste and materials for separate processing. In the case of refrigeration appliances, refrigerant, metals, and plastics are separated from other components, often undertaken as part of a broader waste management program.

In Brazil, an appliance shredder is used to recover refrigerant, for recycling, and blowing agent, for destruction. Metals and plastics are separated and recycle. Polyurethane pellets are recycled or used to generate energy. During 10 years of operation, it has been estimated that 1 million units have been recycled, which is approximately 16% of annual production. In 2008, a project was initiated in Latin America to recycle 40-50 million appliances from 2010 to 2020 through dissembling units. The program was sunset due to logistics challenges and competing priorities.

### 4.1 Cost of Foam Blowing Agent Recovery

Relative investment and operating costs in ODS waste recovery and destruction present a challenge compared with cheaper landfill disposal. The low internalised waste disposal costs for cheaper forms of recovery and disposal can be weighed against the externalised costs to society of future health and environmental impacts of ODS emissions that result from venting of refrigerant wastes or landfill disposal of foam wastes.

Climate change benefits of recovery and destruction of thermal insulating foam wastes may decrease relative to costs over time. The European Commission analysis[58] of the recovery and destruction of CFCs emerging from thermal insulating foam sources suggested that relative GWP-based cost-effectiveness will decrease substantially with time. To illustrate the point, selecting foam products in the built environment that are the simplest to recover (i.e., continuous and discontinuous steel-faced panels), the cost of emissions abatement per tonne of $CO_2$ saved is predicted to increase with time. The reason for this is that insulating panels containing CFC-11 cannot be targeted in isolation from other steel-faced insulating panels containing other blowing

[58] Ibid., SKM ENVIROS, 2012.

agents; the average GWP of the waste stream decreases as the use of lower GWP blowing agents increases over time, thereby increasing the cost of emissions abatement per tonne of $CO_2$ saved and reducing the cost effectiveness of recovery and destruction when considered on a GWP basis.

These trends in cost effectiveness also show a window of opportunity for CFC-11 before around 2045 after which abatement costs per tonne of $CO_2$ saved for steel-faced panels show an accelerated increase, presumably as the average GWP of the foam waste decreases.

With long building lifetimes, the drivers for recovery and destruction of building insulation foams may change over time. The evolution of net zero carbon requirements and the circular economy may improve cost effectiveness and end-of-life choices.

In voluntary carbon markets, there is an opportunity for ODS (and HFC) recovery and destruction in the offsetting of Scope 3 greenhouse gas emissions within construction product supply chains. The impacts of the total lifecycle emissions must be accounted for as Scope 3 emissions in the year of manufacture, according to the current Greenhouse Gas Protocol. For decommissioned foams, these could be considered as an offset to stimulate extended producer responsibility and for those seeking to reduce their net carbon footprints.

A comprehensive study of ODS disposal by ICF[59] has defined five categories of challenges that hinder the effective collection and destruction of ODS in developing and developed countries and gives recommendations on how to address them. These challenges are informational, financial, technological, logistical, and legal. Some of the significant challenges for recovery and destruction in developing countries include the availability of, and access to, destruction facilities, transboundary movement of waste, recovery equipment, transportation infrastructure, and cost. According to the 2015 GIZ Proklima report on ODS banks[60], the most important factors that decide the success of ODS lifecycle management in developing countries are the creation of financial incentives for returning ODS or ODS-containing equipment, and regulatory controls for the management of ODS waste, including destruction if substances cannot be reused.

The October 2009 Decision XX/7 TEAP Task Force Report[61] concluded that recovery and destruction of a waste stream combining all ODS and HFCs would realise the largest economies of scale and accrue the greatest benefits. This approach also presents the best opportunity for recovery and destruction of CFC-11 waste streams.

There might be circumstances where the choice of technology to maximise destruction efficiencies and the accounting of destroyed ODS wastes are important, e.g., for voluntary carbon markets. This need not necessarily preclude the use of destruction technologies that are not approved by the Montreal Protocol to destroy controlled substances, apart from HFC-23 and countries that have introduced laws mandating ODS destruction using technologies approved by the Montreal Protocol.

Most destruction facilities are concentrated in developed countries, predominantly the European Union, Japan, and the United States. Developing countries are establishing and expanding their destruction capacities, e.g., Brazil, Cuba, and Mexico.

Depending on the technology, destruction capacities per facility range between 40 to 600 tonnes/year with average destruction costs of about US$7/kg[62]. An evaluation of pilot demonstration projects in

59 Ibid., ICF, 2008.
60 Ibid., GIZ Proklima, 2015.
61 Ibid., Decision XX/7 TEAP Task Force, 2009.
62 Ibid., ICF, 2008.

Article 5 parties for ODS disposal and destruction indicated average cost-effectiveness of a similar magnitude[63].

Destruction costs represent a minor proportion of total costs of recovery and destruction, with recovery costs being the major portion and dependent on factors such as the sector waste type, infrastructure, logistics, and transport distances.

### 4.1 Summary of foam blowing agent bank management

As early as 2005, the IPCC and TEAP Special Report[64] concluded, "*For CFC-11, recovery from foams is discouraged by the chemical's low market value and by laws requiring the destruction of CFCs. For HFCs, recovery may be more attractive due to the higher market values of the chemicals. Even if the chemicals are not recovered, however, a major abatement option will be the recovery of used foam products and their subsequent destruction*[65]*. Either destruction or chemical recovery could substantially reduce emissions of CFCs, HCFCs and HFCs from the banks in foams.*"

Identifying and capitalising on economies of scale are important in maximising the benefits and minimising the costs of any program for the recovery and destruction of FBAs and foams. This means that a program to recover insulation foams containing CFCs only, in isolation of foams containing other ODS or HFCs, is less practical and less likely to succeed. The October 2009 Decision XX/7 TEAP Task Force Report[66] concluded that a waste stream combining ODS and HFCs would realise the largest economies of scale and accrue the greatest benefits.

It is also important to note that the recovery and destruction of waste foam is essentially considered to be a broader waste management issue, with ODS emissions needing to be managed within a range of other waste management considerations. Foams might have some small value as waste derived fuel; however, the foam waste mass will be a low proportion of the waste feed, e.g., to a cement kiln, and therefore its relative contribution will be small or not significant as a qualified contribution for fossil fuel replacement. With long building lifetimes, the drivers for recovery and destruction of building insulation foams may change over time. The evolution of net zero carbon requirements and the circular economy may improve cost effectiveness and end-of-life choices.

In summary, there is inherently low efficiency in collecting FBAs from foams. There are significant losses in the reverse supply chain of foams through the dismantling process, including crushing and shredding of foams unless the foam blowing agent is extracted in a controlled and contained system. Remaining FBA is in a relatively small ratio to remaining foams (well under 10% by weight), and the density of foams is also very low. There are relatively small benefits in terms of captured controlled substance per cubic meter of foam waste. As a result, the overall cost per kilogram or cubic meter is consequently higher than for collection and destruction of other controlled substances, such as refrigerants.

The net result is poor efficiency relative to concentrated EOL ODS/HFC management in addressing End-of-Life (EOL) management in terms of mitigating emissions and their global impacts on ozone depletion and climate. These dilute waste streams are a less attractive target for carbon finance mechanisms.

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[63] UNEP/OzL.Pro/ExCom/84/11, *Final Report on the Evaluation of the Pilot Demonstration Projects on ODS Disposal and Destruction*, 14 November 2019, and its Corrigendum, UNEP/OzL.Pro/ExCom/84/11/Corr.1.
[64] Bert Metz, Lambert Kuijpers, Susan Solomon, Stephen O. Andersen, Ogunlade Davidson, José Pons, David de Jager, Tahl Kestin, Martin Manning, and Leo Meyer (Eds), *IPCC/TEAP Special Report: Safeguarding the Ozone Layer and the Global Climate System*, page 419, Cambridge University Press, UK. https://www.ipcc.ch/report/safeguarding-the-ozone-layer-and-the-global-climate-system/
[65] Destruction generally by incineration.
[66] Ibid., Decision XX/7 TEAP Task Force, 2009.

The Medical and Chemicals TOC reports further details in its 2022 Assessment Report about opportunities for ODS and HFC collection and destruction.

## 4.2 Update on Bank Estimates

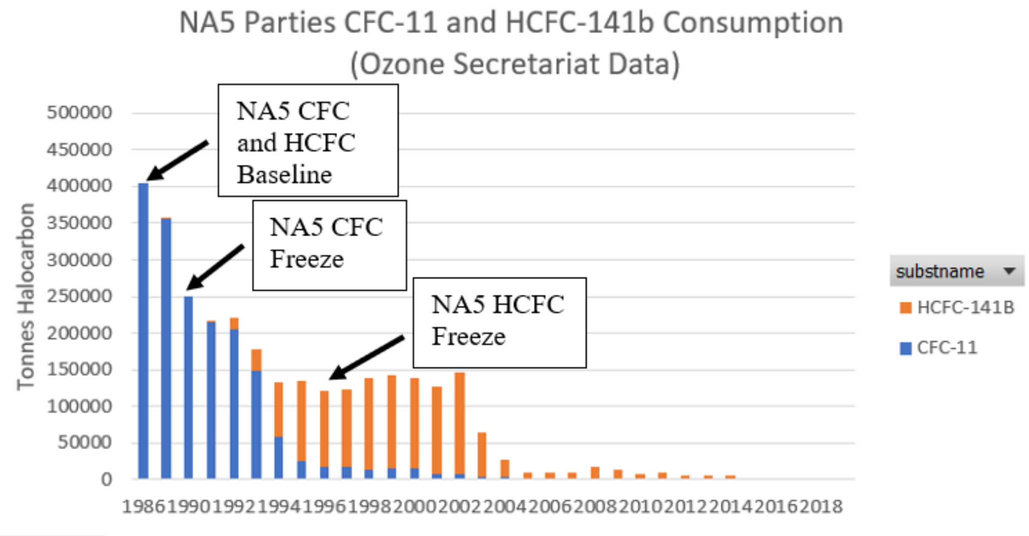
TEAP has been working to build a database of banks estimates to better respond to parties' requests. The modeling technique used is based on data reported to the Ozone Secretariat and into the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS)[67] and uses emissions rates, market information, lifetime of equipment and foams, economic influences, and other information to create these estimates. Emission estimates are compared to those from estimated emissions based on atmospheric chemical concentrations, when available. The same methodology was used by the TEAP Task Force on the Unexpected Emissions of CFC-11.
Examples of this work, showing the estimated banks and emissions of CFC-11 and HCFC-141b, are included in this report. More information will be provided in the TEAP Assessment Report.

After non-Article 5 parties banned the use of CFC-11 by 1996, except for essential uses, total quantities of CFC-11 production and consumption reported to the Ozone Secretariat by Article 5 parties from 1996 and beyond were much smaller than the early peak in reported data in 1986, which included non-Article 5 parties. The overwhelming majority of both the production and consumption of CFC-11 reported to the Ozone Secretariat prior to 1996 was in non-Article 5 parties specifically in North America and Europe. The use of CFC-11 in Article 5 parties gradually increased. Amid this gradual growth, the Montreal Protocol phase-out of CFCs in Article 5 parties was already underway.

HCFC-141b was introduced as a replacement for CFC-11 for use as a closed-cell foam blowing agent during the phase-out of CFC-11. HCFC-141b is also undergoing a phase-out as agreed by the parties to the Montreal Protocol. By 2006, Non-Article 5 parties were already transitioning from ozone depleting blowing agents. The phase-out of CFC-11 for non-Article 5 parties was completed by 1996 and reductions were already well under way for HCFC-141b prior to the phase-out scheduled to be completed by 2020, but many parties regulated HCFC-141b early using a "worst-first" strategy, given its higher ozone depletion potential. For example, the United States banned the use of HCFC-141b for use in foam for appliances in 2003 and then in imports of products containing HCFC-141b in 2015. It is important to note that each transition in non-Article 5 parties resulted in much lower use of halocarbons as foam blowing agents as foam manufacturers shifted to other alternatives including water and hydrocarbons.

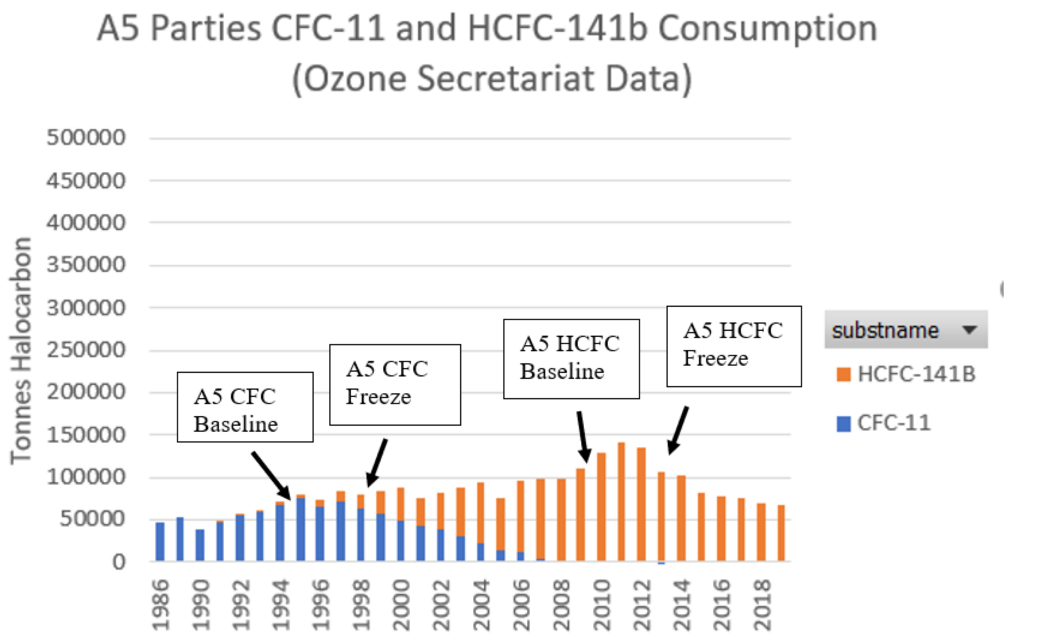
[67] The Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) collected data on several CFCs as reported by the producers. Data included market uses as well as estimated emissions. The data could be found here. https://agage.mit.edu/data/afeas-data

**Figure 4.1 Non-Article 5 party consumption of CFC-11 and HCFC-141b**




The Article 5 party baselines were determined in 1995-97 for CFCs and in 2009-10 for HCFCs. The Article 5 party freeze and phase-down started in 1999 for CFCs and in 2013 for HCFCs. Many parties again regulated HCFC-141b using the same "worst-first" approach that non-Article 5 parties used.

**Figure 4.2 Article 5 party consumption of CFC-11 and HCFC-141b**




The quantities of CFC-11 consumed in Article 5 parties were much smaller than the quantities consumed in non-Article 5 parties. The vast majority of CFC-11 production and consumption took place in non-Article 5 parties.

### 4.3 Estimated global use by foam type

The Flexible and Rigid Foams Technical Options Committee (FTOC) completed a detailed analysis of the use of foam blowing agents by foam sector by region in the 2006 FTOC Assessment Report. The 2006 FTOC Assessment Report provided regional estimates of the use of foam blowing agents.

The FTOC described large, mature foam markets in North America (NA) and Europe (EU) for the types of foams that historically used CFC-11 and HCFC-141b. Other regions all using less than one-third of the quantities used by either North America or Europe. Closed-cell foam markets in Article 5 parties had slowly been growing prior to 2006 as shown above.

**Table 4.1 Production and consumption phase-out schedule for Montreal Protocol Annex A, Group I, controlled substances: chlorofluorocarbons[68]**

| *Non-Article 5(1) Parties* | | *Article 5(1) Parties* | |
|---|---|---|---|
| Base level: | 1986 | Base level: | Average of 1995-97 |
| Freeze: | July 1, 1989 | Freeze: | July 1, 1999 |
| 75 per cent: reduction | January 1, 1994 | 50 per cent: reduction | January 1, 2005 |
| 100 per cent: reduction | January 1, 1996* | 85 per cent: reduction | January 1, 2007 |
| | | 100 per cent: reduction | January 1, 2010* |

**Except for essential use exemptions*

**Table 4.2 Consumption phase-out schedule for Montreal Protocol Annex B, Group II, controlled substances: hydrochlorofluorocarbons[69]**

| *Non-Article 5(1) Parties: Consumption* | | *Article 5(1) Parties: Consumption* | |
|---|---|---|---|
| Base level: | 1989 HCFC + 2.8 % 1989 CFC consumption | Base level: | Average 2009-10 |
| Freeze: | 1996 | Freeze: | January 1, 2013 |
| 35 per cent: reduction | January 1, 2004 | 10 per cent: reduction | January 1, 2015 |
| 75 per cent: reduction | January 1, 2010 | 35 per cent: reduction | January 1, 2020 |
| 90 per cent: reduction | January 1, 2015 | 67.5 per cent reduction | January 1, 2025 |
| 100 per cent: reduction | January 1, 2020<br><br>Allowance of 0.5 per cent of base level consumption until January 1, 2030, for servicing equipment existing on 1 January 2020. | 100 per cent: reduction | January 1, 2030<br><br>Allowance of 2.5 per cent of base level consumption when averaged over ten years 2030-40 until January 1, 2040, for servicing equipment existing on 1 January 2030. |

By 2006, NA5 parties had completed their phase-out of CFC-11 use as a blowing agent in 1996 and had started their phase-outs of HCFC-141b. The transition to HFCs would be minor compared to past usage of fluorocarbons with no more than 40,000 tonnes capacity globally of HFC-245fa and HFC-

[68] This includes CFC-11, CFC-12 and others.

[69] This includes HCFC-141b, HCFC-142b, HCFC-22 and others.

365mfc as late as 2015 as chemical producer patent limitations continued. Low GWP foam blowing agent commercialization was necessary for compliance with EUs HFC phase-down step in 2018, and regulations in North America and Japan.

**Figure 4.3 Estimated Liquid FBA usage in NA5 parties**


non-A5 parties completed their phase-out of CFC-11 use as a blowing agent in 1996 and have already completed their phase-outs of HCFC-141b. There are small volumes of HFCs used compared to past usage of fluorocarbons with no more than 40,000 tonnes capacity globally of HFC-245fa and HFC-365mfc as late as 2015 as patents limited production. Low GWP foam blowing agent commercialization was necessary for compliance with EUs major HFC phase-down step in 2018, with expectations of transitions largely taking place in other non-A5 parties by 2024 with the 40% reduction in HFC supply under the Kigali Amendment and the American Innovation and Manufacturing (AIM) Act.

**Figure 4.4 Estimated Liquid FBA usage in A5 parties**

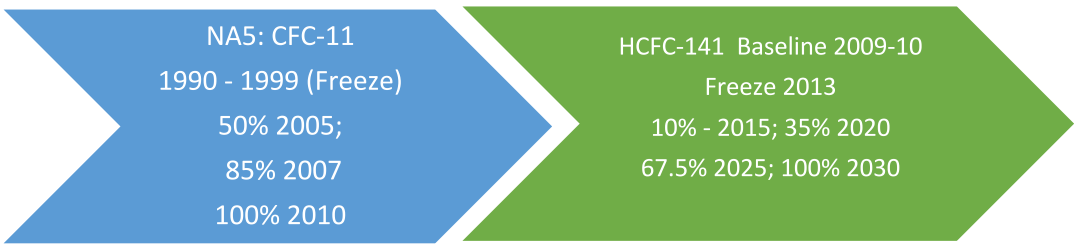
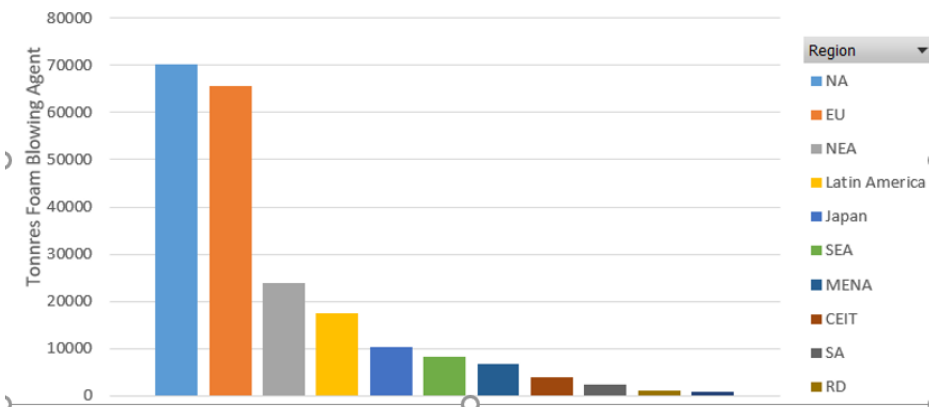



**Figure 4.5 2006 FTOC Assessment Report: Total foam blowing agent usage for foam sectors that historically used CFC-11 and HCFC-141b (tonnes)[70]**




The 2006 FTOC Assessment Report sectoral and regional analysis was used to create an estimate of foam use of blowing agents to estimate banks and emissions based on the losses of blowing agents during different foaming processes and foam lifetimes. The 2006 FTOC breakdown of products and regional uses of blowing agents skews CFC-11 quantities to be larger than they would have been for Article 5 parties as blowing agent usage in A5 parties would have been nascent and still growing from

[70] Note that the regions are listed in Appendix 5 as defined in FTOC 2006 Assessment Report.

1990 onward; however, the quantities are still very small. The pie chart below shows the relative size of the regional markets in 2006 showing the overwhelming majority of the closed-cell foam production took place in North America and Europe (non-Article 5 parties) even as late as 2006. An even larger percentage was produced in non-Article 5 parties in early years before the development of the closed-cell foam market in Article 5 parties.

**Figure 4.6 Historic foam production by region for 2006 FTOC Assessment Report, which estimated that approximately 360 kilotonnes/year of blowing agents were in use around the timeframe of that report**

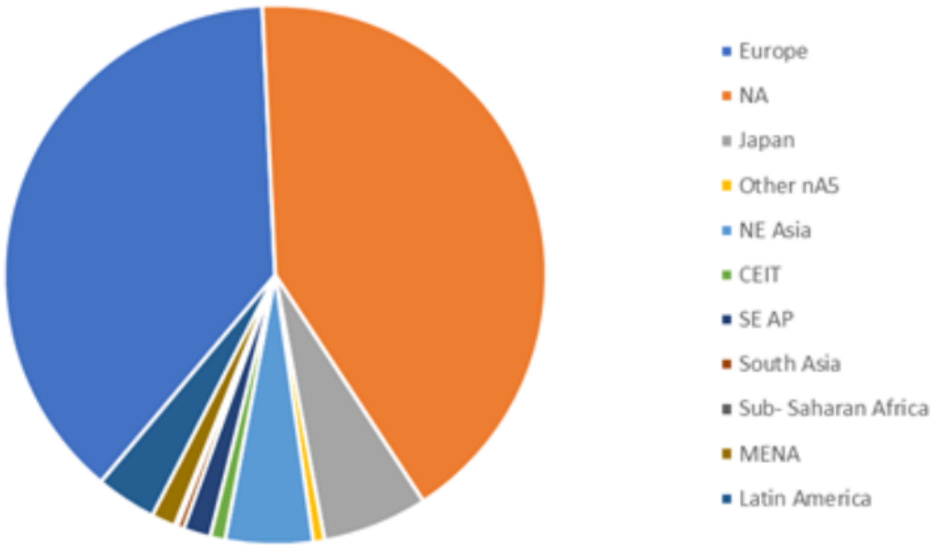
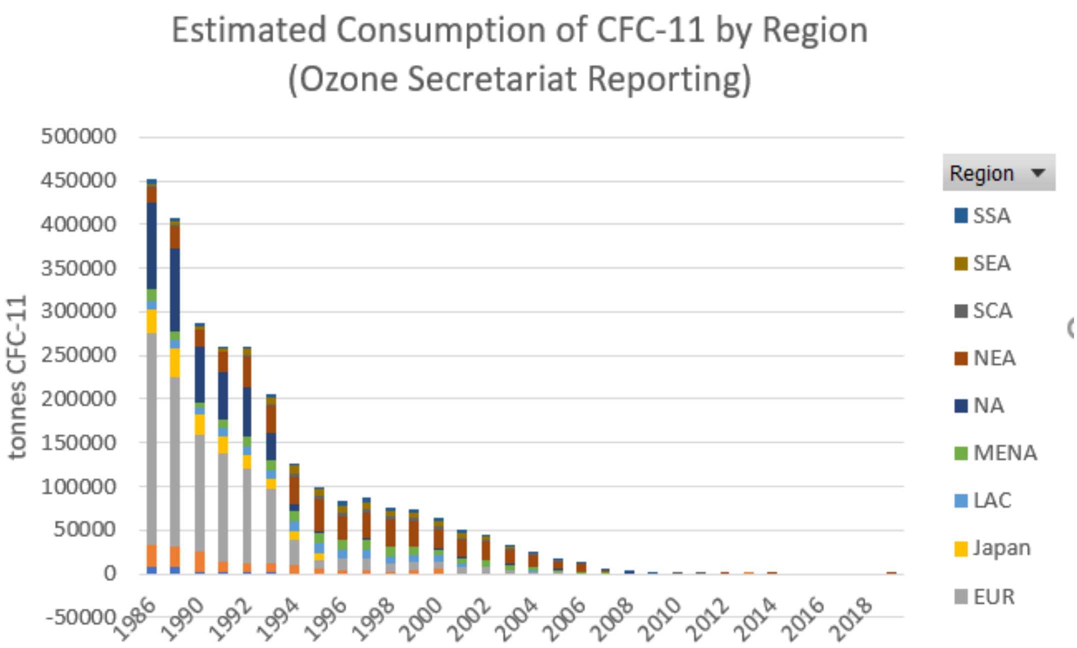



**Figure 4.7 Estimated consumption of CFC-11 by region (data reported to the Ozone Secretariat)**



## 4.3 HCFC-141b Model Development

Parties report the production, import, and export of controlled bulk chemicals and the quantity of chemicals contained in polyols under Article 7 of the Montreal Protocol. These reported values were used to estimate the use of various chemicals in different end-uses. In the case of foams, product sectors by region for CFC-11 and HCFC-141b were estimated based on the 2006 FTOC Assessment Report. Note that the calculated consumption based on reported production plus import minus exported HCFC-141b by year is generally smaller than the reported production as the total global quantity of imports was generally greater than reported exports. Over time this difference decreased over time and calculated consumption has been within 5% of reported production since 2013.

Most parties have used a "worst-first" combined with an "easiest-first" approach to ODS phase-outs. As a result, foams have often transitioned early in the phase-out process. Refrigeration foams have generally transitioned early. It has been assumed that all regions have shifted away from HCFC-141b in refrigeration uses by 2015.

The analysis in this report incorporated a Weibull function to create a probabilistic distribution of the life cycle of foams including the rate of decommissioning, estimated timing of various life stages, emissions, and the size of foam banks by types of closed-cell foam products. The same emissions rates and Weibull constants are used for CFC-11 and HCFC-141b except for integral skin where errors are introduced by the short timeframe of the Weibull constant.

It should be noted that for both CFC-11 and HCFC-141b models it is assumed that foam blowing agents are destroyed in Europe after 2001 for refrigeration uses, as required by regulation. Emissions from HCFC-141b production for feedstock use were also incorporated into the model. A 2% growth per year was assumed for feedstock use from 2020 and beyond.

### CFC-11 Results

There is a distinct bifurcation of lifetimes for foams used in refrigerating applications and foams used in construction of buildings. Nearly all the active bank of CFC-11 is comprised of foam panels and boardstock in buildings. Nearly all the remaining bank of foams used in refrigerating applications have been decommissioned and either landfilled or destroyed[71]. CFC-11 from the relatively small quantities of other types of foams have largely been decommissioned. By this analysis, there are an estimated 750 ± 50 kilotonnes of CFC-11 in active foams banks and 700 ± 50 kilotonnes in inactive banks in 2021[72].

As noted above, most of the remaining active CFC-11 bank is contained in panels and boardstock installed in buildings. Most remaining foams from refrigerating appliances along with a significant volume of decommissioned foams from building has been landfilled (inactive bank), or in Europe, appliance foams were destroyed.

The largest quantities of panels and boardstock containing CFC-11 were manufactured in North America and Europe as noted below. Also of note, significant numbers of appliances containing CFC-11 were sold, used, and ultimately decommissioned and landfilled in North America and Europe. Most of the remaining global CFC-11 bank is in North America and Europe in construction foams in buildings or in landfills.

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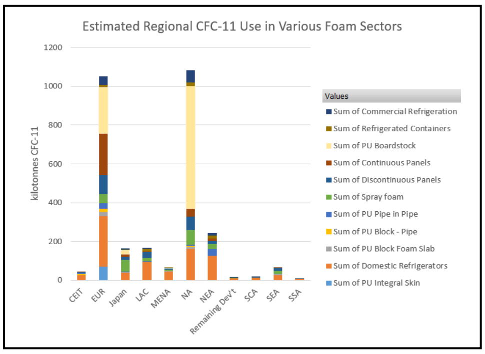
[71] Note that the European Union requires ODS blowing agents to be captured and destroyed under the WEEE Directive 2002/96/EC, ICF estimates that 78-88% of 55 kilotonnes could be destroyed between 2010 and 2030

[72] Excludes estimated additional bank resulting from unreported CFC-11 production and use.

**Figure 4.8 Estimated regional CFC-11 use in various foam sub-sectors (kilotonnes) using 2006 FTOC Assessment Report as a proxy**




in
be

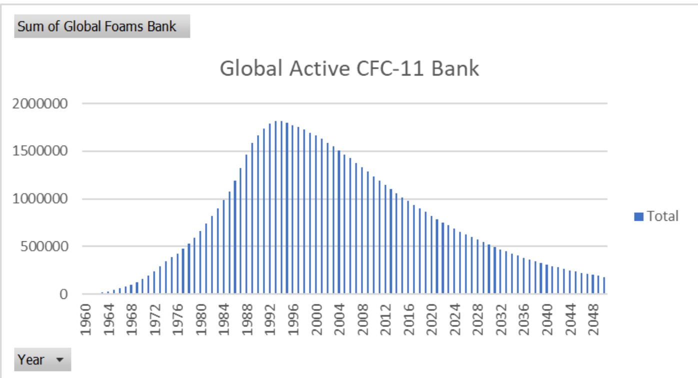
TEAP estimated at that time that the total active and inactive CFC-11 banks (foams, refrigerants, and storage) are estimated to be 1500 ± 100 kilotonnes 2021[73]. The total active CFC-11 bank is estimated to 800 ± 50 kilotonnes, 3.8 Gt $CO_2$eq, in 2021.

Most appliance foams containing CFC-11 have already reached their end-of-life leaving an estimated 100 kilotonnes in the active bank[74]. Note that most appliances containing CFC-11 foams were likely manufactured after 1995 in Article 5 parties, many of which may have been exported. CFC-11 foam products produced prior to 2010, with a lifetime of between 20 to 50 years, have been, and will continue to, reach their end-of-life, providing opportunities for recovery and destruction. Illegally produced CFC-11 was most likely recently used in insulation foam, which means that the resulting foam products' end-of-life could be in another 20 to 50 years. Recycling or reclamation and reuse provide opportunities for CFC-11 used in centrifugal chillers, with servicing requirements reducing as an increasing number of chillers reach their end-of-life, after which there are opportunities for recovery and ultimate destruction.

The SAP concluded in its 2018 Assessment Report that,

"*Emissions from current ODS banks continue to be a slightly larger future contribution than ODS production to ozone layer depletion over the next four decades, assuming maximum production levels allowed by the Montreal Protocol. Future business-as-usual emissions from HCFCs and from banks of CFCs and banks of halons are each projected to contribute roughly comparable amounts to EESC in the next few decades.*"

**Figure 4.10 Global Active CFC-11 Bank**



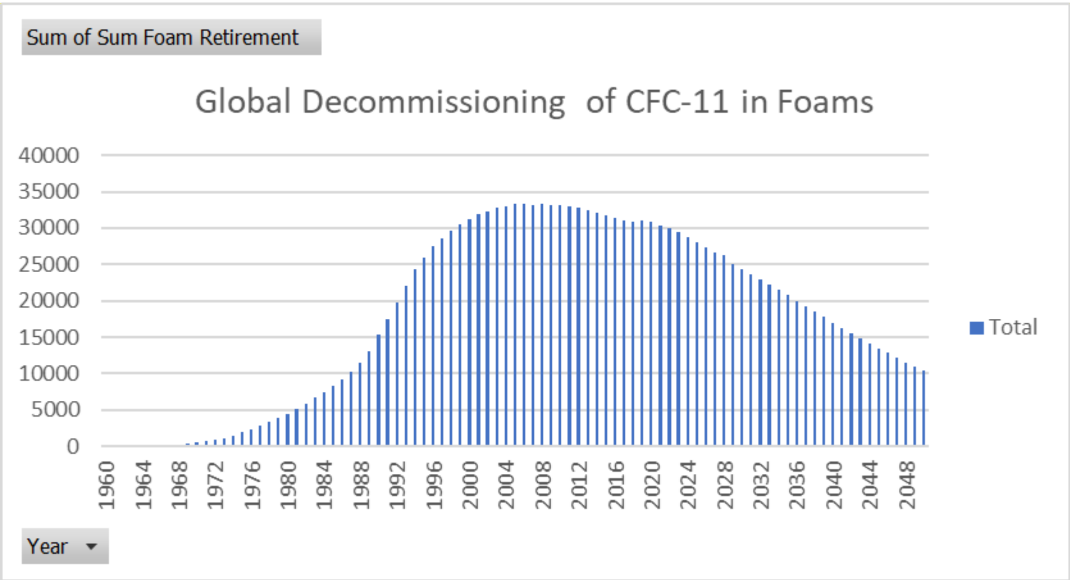

In TEAP's response to D*decision XXXI/3, paragraph 7(c): Types of CFC-11 products and their disposition, and opportunities for detection and potential recovery of CFC-11,* limited opportunities were identified to recover CFC-11 from products containing CFC-11 from foams to a few active banks, mainly of insulation foams. Most CFC-11 used in foams is located in landfills in inactive banks and do not present a readily available or economically feasible opportunity to recover the associated CFC-11 where the remaining CFC-11 will likely be slowly emitted over time.

[73] Excludes estimated additional bank resulting from unreported CFC-11 production and use.
[74] Excludes estimated additional bank resulting from unreported CFC-11 production and use.

TEAP estimated that the global peak of decommissioned CFC-11 from the largest portion of active banks (foams), when dismantled at end-of-life, is estimated to have occurred around the year 2010, at about 45 kilotonnes/year, then decreases slowly over time, to less than 10 kilotonnes by 2050. There are underlying variations to the regional peaks in CFC-11 foam decommissioning that are obscured within the global analysis, where some regions and foam types, are likely yet to reach their decommissioning peak, e.g., Europe for foam panels in buildings. The opportunity for CFC-11 recovery and destruction lies in higher management of active foam banks at end-of-life, with potential diversion of foam wastes away from landfill and emissive secondary usage towards destruction, which mitigates most emissions.

Figure 5.1 below shows the estimated timing of decommissioning of products containing CFC-11 from all active CFC-11 banks[75].

**Figure 4.11 Estimated CFC-11 decommissioned from all active CFC-11 banks, 1931-2050 (kilotonnes)**




The Task Force adopted assumptions for emissions and lifetimes based on the 2019 Report and adjusted by the Weibull distribution, which results in a prediction that most total global CFC-11 foams from refrigerating foams would likely have been decommissioned prior to 2021. The global peak of the CFC-11 decommissioned from the largest portion of active banks, i.e., all foams, when dismantled at end-of-life, is estimated to have occurred around the year 2010, at about 45 kilotonnes/year, and then subsequently decreases slowly over time to under 10 kilotonnes/year by 2050. These global peaks are dominated by the foam banks, foam products, and decommissioning patterns in the United States and Europe, owing to their overwhelming size.

There are underlying variations to the regional timing of peaks in foam decommissioning and/or variations for different foam product types, that are obscured within this global analysis. For example, studies and surveys estimate a 30-year lifetime of construction foams in Northeast Asia (NEA)[76] and a

[75] Excludes estimated additional bank resulting from unreported CFC-11 production and use.
[76] Zhou *et al*., Estimating Lifetimes and Stock Turnover Dynamics of Urban Residential Buildings in China, https://www.mdpi.com/2071-1050/11/13/3720/pdf#:~:text=The%20specified%20Weibull%20distribution%20had,design%20lifetime%20of%2050%20years.

portion of foams used in commercial buildings in the United States[77],where premature demolishing of buildings prior to the expected lifetime has been recorded.

Most foam banks are in developed countries, and assuming an average building lifetime of 50 years, GIZ Proklima concluded in 2020 that, for insulation foam waste from buildings, there was the opportunity to avoid an estimated 870 kilotonnes of CFC-11 and CFC-12 emissions, equivalent to 4.5 Gt $CO_2$eq.[78]

In other studies that reported the estimated flow of ODS reaching the waste stream in any given year, the 2018 MCTOC Assessment Report[79] highlighted that the annual amount of *all ODS* reaching the waste stream, and potentially available for ODS management and destruction, was estimated to have peaked in 2016 at ~200 kilotonnes, based on an earlier 2015 report on ODS banks by GIZ Proklima[80]. These reports' estimations were based on the same earlier data used to derive Figure 3-1 of the October 2009 Report of the Decision XX/7 TEAP Task Force[81], which predicted ODS waste arisings for 2010 to 2030.

TEAP estimated in 2021 that the total active and inactive CFC-11 banks (foams, refrigerants, and storage) are estimated to be 1500 ± 100 kilotonnes in 2021[82]. The total active CFC-11 bank is estimated to be 800 ± 50 kilotonnes, 3.8 Gt $CO_2$eq, in 2021.

Most appliance foams containing CFC-11 have already reached their end-of-life leaving an estimated 100 kilotonnes in the active bank[83]. Note that most appliances containing CFC-11 foams were likely manufactured after 1995 in Article 5 parties, many of which may have been exported.

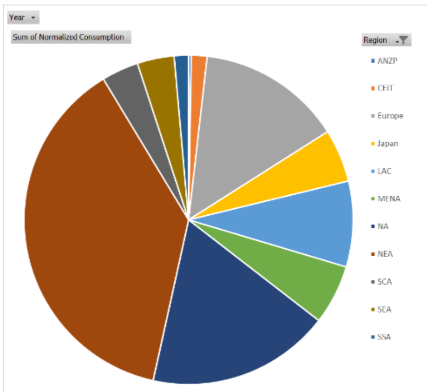


Figure 3.12 Regional division of consumption of HCFC-141b

**HCFC-141b Results**

HCFC-141b consumption peaked around 2000 in non-A5 parties and in 2011 in A5 parties with the majority used to manufacture foams in North America (NA) and in Northeast Asia (NEA). However, much of the production of foams in NEA was used in domestic appliances which were exported to other regions of the world.

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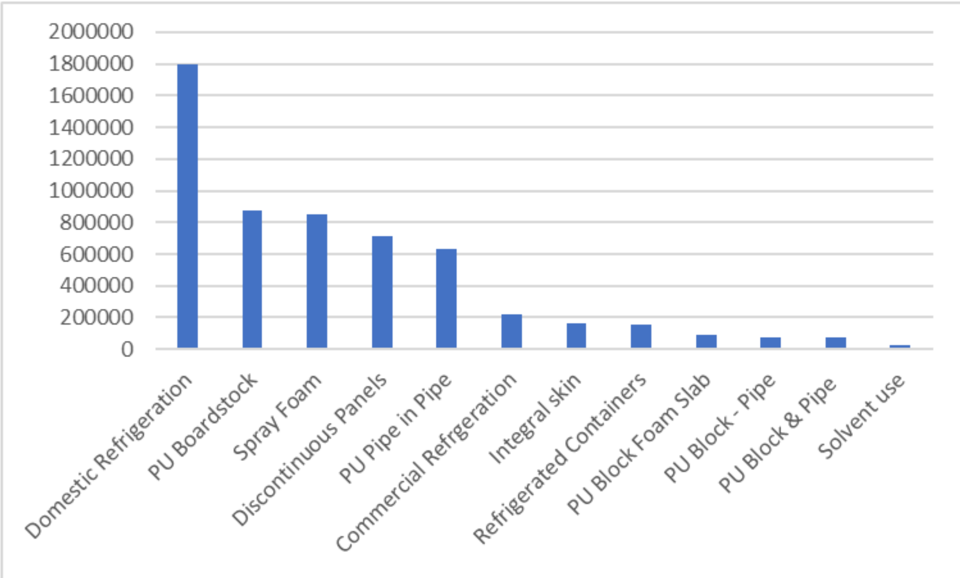
[77] Aktas, Can and Bile, M, Lifetime on U.S. Residential Building LCA Results, https://digitalcommons.newhaven.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1002&context=civilengineering-facpubs.
[78] Ibid., GIZ Proklima, 2020.
[79] Report of the Medical and Chemicals Technical Options Committee, 2018 Assessment Report, December 2018.
[80] Ibid., GIZ Proklima, 2015.
[81] Ibid., Decision XX/7 TEAP Task Force, 2009.
[82] Excludes estimated additional bank resulting from unreported CFC-11 production and use.
[83] Excludes estimated additional bank resulting from unreported CFC-11 production and use.

**Figure 4.13 Sectoral consumption of HCFC-141b**

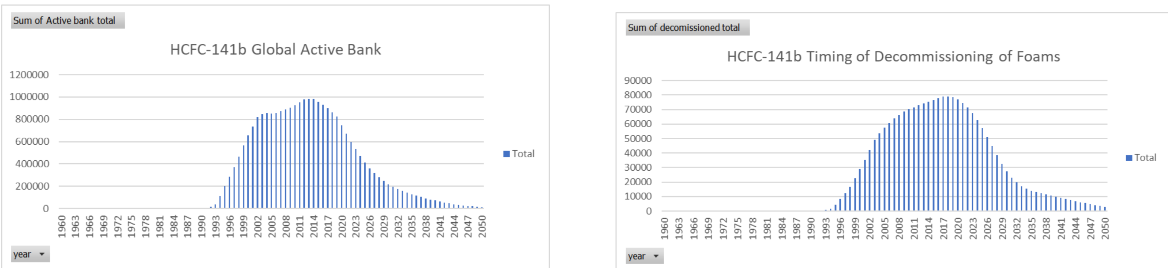



Note that most of the foam blowing agents were used in domestic refrigeration products, which historically have much shorter lifetimes than foams in buildings.

### Global consumption and emissions

There are two distinct peaks in the production and consumption of HCFC-141b as policies allowed for its use and then mandated its phase-out in non-A5 and then A5 parties. Policies have also generally mandated bans in the use of HCFC-141b in domestic refrigeration manufacture by 2015 in much of the world. The inactive bank of HCFC-141b is believed to have been used largely in foams in refrigerators, while the active bank is now shifting to be largely related to construction foams globally. The global active bank peak is now estimated to have occurred with continued decommissioning of appliances and buildings containing HCFC-141b being greater than new HCFC-141b usage to create new foams. The global peak timing for decommissioning of foams containing HCFC-141b is estimated to occur over the next 5 years.

**Figure 4.14 Global Model Results: Total Reported Production by Foam Type, Cumulative Sales by Sector, HCFC-141b Banks, Active and Inactive Banks**



### A5 Consumption, Banks, and Emissions

Peak reported production and consumption of HCFC-141b in A5 parties occurred by 2012 and was largely used in domestic refrigeration foams until 2015 when mandated bans in the use of HCFC-141b in domestic refrigeration occurred in much of the world. The inactive bank of HCFC-141b is believed to have been used largely in foams in refrigerators, as has the active bank of foams manufactured in A5 parties. The A5 active bank peak is estimated to have occurred between 2015 and 2020 with continued decommissioning of appliances and buildings containing HCFC-141b being greater than new HCFC-141b usage to create new foams. The peak timing for decommissioning of foams manufactured in A5 parties containing HCFC-141b is estimated to occur over the next 5 years.
It should be noted that a significant volume of the appliances manufactured in A5 parties have been exported to various regions where emissions during the lifetime of equipment, during decommissioning, and from inactive banks will occur in other regions.

### Non-A5 Consumption, banks, and emissions

Peak reported production and consumption of HCFC-141b in non-A5 parties occurred by 2000 and was largely used in domestic refrigeration foams. The inactive bank of HCFC-141b is believed to have been used largely in foams in refrigerators, as has the active bank of foams manufactured in non-A5 parties. The non-A5 active bank peak is estimated to have occurred between 2000 and 2005 with continued decommissioning of appliances and buildings containing HCFC-141b being greater than new HCFC-141b usage to create new foams. The peak timing for decommissioning of foams manufactured in non-A5 parties containing HCFC-141b is estimated to occur prior to 2015.

# 5.0 Challenges Facing Parties to the Montreal Protocol in Implementing obligations and Maintaining the Phase-outs Already Achieved, especially those on Substitutes and Substitution Technologies, and Potential Technical and Economically Feasible Options to Face Those Challenge

Significant progress has been made by parties to phase-out the use of HCFCs in foams. As shown in previous sections, there are FBAs that are not controlled substances for nearly every foam sector in use commercially today. However, there are some technical and economic challenges remaining for A5 parties and especially for SMEs, as highlighted below.

Separately, there continues to be insufficient supply of HFO/HCFO FBAs to meet demand and there seems to be a risk to supply chains impacting availability related to hydrocarbons.

## 5.1 Low-Pressure Spray Foam

Spray foam pressure impacts the rate of foam application. High-pressure systems are used in larger projects because they have a much faster application rate than lower pressure systems. Low-pressure polyol blends are stored in pre-pressurized tanks at low pressure and often contain a liquid and a gaseous blowing agent to propel the blend into the cavity. The pressurized foam system can create challenges in maintaining stability of low-GWP blowing agents and catalysts.[84] However, recent research shows improved stability of polyol blends[85] Low-pressure spray foam doesn't cure as fast as high-pressure, meaning that more time would be needed to apply additional layers.

Low-pressure foams kits do not have air constantly moving through the application hose and nozzle, which means that liquid product will begin to cake up and clog them if the spray process is stopped and re-started. Low-pressure kits are generally used for small projects around doors and windows, or to fill small spaces.

## 5.2 Extruded Polystyrene (XPS) Foam Blowing Agents

Some XPS manufacturers note that there continue to be challenges for the conversion of XPS foam blowing agents for some foams and regions depending on specific product needs noting that new foam blowing agents cannot directly replace current products and that the need to maintain density does not necessarily allow for reduced loading of higher cost blowing agents. They further note that preparation for conversion to flammable blowing agents, which at the processing temperatures of XPS brings some blowing agents generally classified as non-flammable by required room temperature or near room temperature testing requirements into the flammable range requires approximately18 to 36 months for capital investment and product qualification based on the specific end use (e.g., walls, roofs, structural support, transportation, cold storage. It was also noted that at least one non-flammable, mid-range (750 GWP) blend, containing HFC-134a, is currently under consideration for use.

In China there are Chinese equipment vendors offering both $CO_2$ based and HFC solutions for medium to large enterprises. It is expected that $CO_2$ based systems will predominate for the phase out of HCFCs.

Other blowing agents and co-blowing agents continue to be used in small quantities. Isopropyl chloride (2-Chloropropane) is blended with isopentane generally for phenolic foam. Foam additives FA188 and

[84]Recent papers focus on catalysts for the trimerization reaction.

[85] Koh et al, Novel Concept to Improve Shelf Life of LP 2K SPF with HFO 1234ze 2021 Center for Polyurethane Institute Conference; Thomas et al' Low GWP Two-Component Low Pressure Spray Foam Using CO2 as a Blowing Agent; 2021 Center for Polyurethane Institute Conference

PF-5056 are highly fluorinated, $C_5$ or greater olefins whose GWPs are close to 100 and have been thought to be potential nucleating agents. However, based on the European Norm standard (EN13165), this material can be found in the cell gas after 6 months @ 70°C in polyisocyanurate (PIR) foam, so then it is also classified as a blowing agent.

A patented chemical blowing agent (trade named CFA8[86]) is being promoted, as a foam blowing agent, to the polyurethane market by China's Butian New Materials and Technology Company. It is expected that other innovative chemical and physical blowing agents may be introduced in the near future, although no specific materials or technologies have been announced.

### 5.3 Phenolic Foams

Phenolic foam insulation was developed in the early 80s in response to the energy-crisis, which called for greater insulation efficiency, especially in roofing material. This cost-effective solution was used in conjunction with built-up roof membranes, and commonly referred to as "tar and gravel" roofs on low-slope commercial buildings. Phenolic foam was manufactured in board form

In early uses, acid was produced when the phenolic foams were exposed to moisture that damaged metal decking. Re-design of systems occurred, and roofing was replaced. Newer formulations seem to have addressed those concerns[87].

In closed-cell phenolic foams, the thermal performance of the foam is directly related to the blowing agent that is present in the final product. High quality closed cell phenolic foam has a very high percentage of closed cell content which can provide up to double the thermal performance of open cell foams.

### 5.4 Challenges Related to Supply, Availability, and Cost of Alternatives

**HFOs/HCFOs** provide an alternative to HCs that can eliminate or reduce the flammability or use of flame retardant for polyurethane, polyisocyanurate, and extruded thermoplastic foam production, eliminating the capital investment required to address safety when using HCs as a blowing agent. In addition, HFOs/HCFOs can result in improved foam insulating values compared to HC blown foams. There have been significant improvements in the development and availability of additives, co-blowing agents, equipment and formulations enabling the successful commercialization of foams containing low GWP blowing agents.

The transition by SMEs to HFOs/HCFOs is currently slowed by both their greater direct expense and limited but improving supply in A5 parties. HFO/HCFOs are sometimes blended with other blowing agents to reduce costs in both A5 and non-A5 parties.

Manufacturers of HFO/HCFOs have increased capacity of some of the HFOs/HCFOs to meet the demand for low GWP blowing agents that is expected to result from the implementation of low GWP regulations. Continued coordination could be helpful to ensure that there is adequate supply as regulations are implemented.

In Japan, shortages of HFOs/HCFOs slowed HFC conversions in rigid polyurethane foams in 2021 and volumes of HFOs/HCFOs reaching 3700MT in 2021. Markets also contracted in 2021, particularly in spray foam. In 2020 HCFO-1224yd(Z) was commercialized in Japan[88]. The boiling point of HCFO-1224yd(Z) is the same as that of HFC-245fa. HCFO-1224yd(Z) is also used as a refrigerant and solvent

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[86] PCT/CN2017/083948 (WO2017206692 A1) 201610393108.0 (CN107089927A)

[87] Yost "Phenolic Foam Insulation Revisited. Can we put to bed the corrosion concerns with this insulation?" https://www.greenbuildingadvisor.com/article/phenolic-foam-insulation-revisited

[88] Its boiling point is 15ºC and its molecular weight is 149

in addition to blowing agent. However, it is not in sufficient supply to compensate for the shortages in other HFOs/HFCOs.

Significant testing remains to be completed for HCFO-1224yd (Z) in spray foam including stability and system optimization. It will take 3-4 years to demonstrate sufficient stability of the polyol blend containing the foam blowing agent and to determine the aged thermal performance of manufactured spray foam. Spray foam systems must also successfully comply with JIS A9526 (Spray-applied rigid polyurethane foam for thermal insulation),

The Multilateral Fund published outcomes from a demonstration project at foam system houses[89] to formulate pre-blended polyols for spray polyurethane foam applications using new catalyst packages that resulted in foam properties comparable to those blown with HCFC-141b. The cost of the foam was 22-46% greater than the cost prior to the pandemic.

Methyl formate used as a sole blowing agent continues to increase around the world in rigid foam applications and integral skin foam applications. It is also being used in A5 parties as a co-blowing agent with HFCs for various rigid foam applications. Methyl formate blends with HFCs are also being used in the United States for manufacturing XPS boards and in some cases blends with HFCs and HCFOs for rigid polyurethane foams

[89] http://www.multilateralfund.org/Our%20Work/DemonProject/Document%20Library/8311ax5_Thailand.pdf

# 6.0 The Impact of Sustainable Development on the Phase-out of Controlled Ozone-Depleting Substances and the Phase-down HFCs.

**Decarbonization and Energy Efficiency Trends**
Insulation creates a resistance to heat flow that reduces the heating and cooling load of buildings and refrigeration systems. The implication is that smaller equipment can be used to maintain temperatures at the same level and less energy, and associated power source and greenhouse gases, is needed due to this benefit. Heat flow resistance or “R-value”, or its inverse, heat conductivity or “lambda value” or “k-factor” are used to describe the insulation properties of insulating foams.

Foam insulation can also be used to seal building envelopes from air infiltration further reducing heating and cooling loads. Foam density is of particular importance as a property to consider in balancing cost and thermal performance. More density costs more and provides more air barrier.

Building science trends toward efforts to reduce cooling and heating loads increase the amount of foam and its associated FBA usage and selection. It should be noted that a careful balance of air infiltration and ventilation has been identified as a key aspect of “healthy buildings” as a result of the pandemic, and it is anticipated that more information will become available in the coming years that better balance these needs.

Increases in minimum efficiency performance standards (MEPS) also impact foam formulations and quantities of foam blowing agents used. Insulation selection is considered a “design feature” in performance-based MEPS metrics where manufacturers can select from a variety of options to meet new, higher MEPS levels. This is especially true for refrigeration equipment used in cold chains including transportation and processing of food and medicine.
Thermal bridging is a key loss in thermal performance that affords an opportunity for improvement in performance. Finally, there may be limitations to the adoption of insulation with lower thermal conductivity because of its cost or the availability of FBAs with better thermal performance. In addition, space limitations limit additional layering of insulation and optimization must be based on foam formulation and blowing agent selection, as well as elimination of thermal bridging.

**Life Cycle Analysis**

Concern about climate change has created demand for FBAs with low GWP as well as improved thermal properties. A life cycle analysis can be used to fully understand the impact an FBA will have on climate change potential (CCP)[90] in spray polyurethane foam, panels, or refrigeration applications. For installations where thickness is constrained or set equal, optimized blends to maximize thermal performance can have lower CCP evaluated on a cradle-to-grave (CTGr) basis due to the lower GWP of direct emissions of FBA during installation, use, and at end-of-life due to lower energy requirements during the use phase. Generally, results remain consistent, showing lower CCP across changes to several variables, such as regional climates and FBA loading across sensitivity and uncertainty analyses with respect to FBA emissions during use and end-of-life, FBA formulation variability and life cycle inventory uncertainty, house size, and electricity grid mix. Direct emissions more than off-set the energy benefits relative to water/$CO_2$ blown foam, leading to higher CTGr CCP.[91]

Life cycle analyses over the past decade have continued to confirm that the GWP of FBAs with GWPs less than 50 have less impact on the holistic life cycle GHGs of a foam while HFC-based blowing agent, the GWP values affect the overall lifecycle GHGs significantly heavily dominating the

[90] Climate Change Potential is defined further in section 1.7 of this report as per the TRACI impact assessment method
[91]Krieger et al; *Low GWP Spray Foam Expansion Agents: Why Performance also Matters*

calculation compared to the embodied carbon of the foam. With efficient blowing agents and greater penetration of renewables into the electricity grid, the overall lifecycle GHG emissions may also be reduced further[92]

**Circular economy**

In addition to some local mandates to destroy controlled foam blowing agents, an increased focus on extended producer responsibility (EPR) has resulted in foam manufacturers working to develop technologies to increase mechanical recycling of foam scraps and to invest in research to chemically break down rigid polyurethane foam into its molecules and then recompose them through pyrolysis, enzymatic breakdown, chemical processes or by other means. It is not yet clear whether these technologies will become commercial or how they may impact FBA selection and use.

**Potential restrictions of FC FBAs**

Finally, there is one local jurisdiction within a single party that has required an exemption to continue to use FC FBAs after 2030. The state of Maine in the United States will require reporting of use of FC FBAs and approved exemptions for continued use after 2030.  This is slowing selection of FBAs in some jurisdictions as they consider similar requirements.

[92] Wysong et al; *GWP Values of Blowing Agents: What Do They Really Mean and the Important Implications for SPF Insulation Sustainability*

# 7.0 Technical Advancements in Developing Alternatives to HFCs Suitable for Usage in Countries with High Ambient Temperatures, particularly regarding Energy Efficiency and Safety.

There are some unique challenges faced by companies manufacturing foams in high ambient temperature (HAT) conditions. Hot temperatures affect raw material storage, product selection, method of application, and can impact foam quality. For example, dry conditions mean that moisture-curing, one-component foams may be challenging or impossible to use.

Liquid FBAs are generally used in polyurethane foam formulations, unless a propellant is needed, such as for low pressure foams. Some liquid FBAs are listed below with their BPs. The lower BPs indicate that higher pressures must be withstood in systems and in storage.

**Table 7.1 Boiling points of some liquid foam blowing agents**

| Liquid FBAs | CFC-11 | HCFC- 141b | HFC-245fa | Methyl Formate |
|---|---|---|---|---|
| **Boiling point (°C)** | 24 | 33 | 15 | 40 |

Higher temperatures mean that foam blowing agents will expand, increasing the pressure in storage drums alone (neat) or in blended polyol systems. Some distributors and manufacturers address this challenge by cooling warehouses or be partially loading drums so that there is more room for foam blowing agent.

Foam systems have a limited shelf-life that is shortened by high temperatures. Spray foam insulation components have a six-month shelf life, after which the catalyst may begin to degrade which may make the resulting foam more brittle.

In addition, some manufacturers caution against installing foam systems at temperatures greater than .49 C. Although many of these challenges have been important in HAT parties and regions during previous transitions, they continue to be important factors in the design of new systems.

Except for polyisocyanurate (PIR), resistance to heat transfer tend to decrease at higher temperatures[93] for historic and current foam blowing agents. FTOC is unaware of azeotropic blends that provide different results. However, foam insulation can be used to seal the building envelope limiting the ingress of high temperatures.

Finally, another important safety consideration in HAT and other parties for use of foams in buildings is best practices and updated building codes in building design for fire safety. Best practices such as (seems like something is missing)

[93]Berardi, Umberto "The impact of temperature dependency of the building insulation thermal conductivity in the Canadian climate" 11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

# 8.0 FTOC membership and administration

The disclosure of interest (DOI) of each member can be found on the Ozone Secretariat website at: https://ozone.unep.org/science/assessment/teap. The disclosures are normally updated at the time of TEAP's annual meeting (normally in April/ May). TEAP's Terms of Reference (TOR) (2.3) as approved by the Parties in Decision XXIV/8 specify that

*"… the Meeting of the Parties shall appoint the members of TEAP for a period of no more than four years…and may re-appoint Members of the Panel upon nomination by the relevant party for additional periods of up to four years each."*. TEAP member appointments end as of 31 December of the final year of appointment, as indicated in the following tables.

TEAP's TOR (2.5) specifies that *"TOC members are appointed by the TOC co-chairs, in consultation with TEAP, for a period of no more than four years…[and] may be re-appointed following the procedure for nominations for additional periods of up to four years each.*" New appointments to a TOC start from the date of appointment by TOC co-chairs and end as of 31st December of the final year of appointment, up to four years.

**TEAP Flexible and Rigid Foams Technical Options Committee (FTOC)**
FTOC members currently have expertise in: Producing and handling foam blowing agents; foam formulation; foam production (XPS, Spray Foam, appliance etc.) and life cycle analysis; emissions and banks modeling; certification testing for foams; regulations related to foams; global foam markets including forecasting future production; historical knowledge of foams, foam blowing agents, regulations, and the Montreal Protocol; the building envelope and reducing energy demand from buildings; appliance design and production energy efficiency.
**Needed expertise:**
FTOC is seeking additional experts to provide expertise in A5 extruded polystyrene production in India and China replacing experts that left the FTOC. FTOC also seeks polyurethane system house technical experts from southern Africa, the Middle East, or Mexico (especially from small and medium enterprises) as they seem to continue to face challenges in the transition from HCFC-141b. FTOC seeks additional foam chemistry experts globally and expertise in building science related to energy efficiency from A5 or non A5 parties.

***Table 8.1 FTOC Membership at May 2022***

| Co-chairs | Affiliation | Country | Appointed through |
|---|---|---|---|
| Helen Walter-Terrinoni | The Air Conditioning, Heating and Refrigeration Institute | US | 2025 |
| Paulo Altoé | Independent Expert | Brazil | 2024 |
| **Members** | **Affiliation** | **Country** | **Appointed through** |
| Paul Ashford | Anthesis | UK | 2023 |
| Kultida Charoensawad | Covestro | Thailand | 2023 |
| Roy Chowdhury | Foam Supplies | Australia | 2025 |
| Joseph Costa | Arkema | US | 2026 |
| Gwyn Davis | Kingspan | UK | 2024 |
| Gabrielle Dreyfus | Climate Works | US | 2025 |
| Rick Duncan | Spray Polyurethane Association | US | 2023 |
| Ilhan Karaağaç | Kingspan | Turkey | 2024 |
| Shpresa Kotaji | Huntsman | Belgium | 2023 |
| Simon Lee | Independent Expert | US | 2023 |
| Yehia Lotfi | Technocom | Egypt | 2024 |
| Smita Mohanty | CIPET: School for Advanced Research in Polymers | India | 2024 |
| Miguel Quintero | Independent Expert | Colombia | 2025 |
| Sascha Rulhoff | Haltermann | Germany | 2026 |

| Co-chairs | Affiliation | Country | Appointed through |
|---|---|---|---|
| Enshan Sheng | Huntsman | China | 2026 |
| Koichi Wada | Japan Urethane Industry Institute | Japan | 2024 |
| David Williams | Independent Expert | US | 2023 |
| Ernest Wysong | Natural Polymers | US | 2024 |

# 9.0 Conclusion

Although there is no single foam blowing agent replacement for currently used HCFCs or hydrofluorocarbons (HFCs), there are different technical, economic, safety, and environmental performance properties for each low global warming potential (GWP), zero ozone depletion potential (ODP) alternative and different needs for each market subsector. There is a proliferation of blends across the whole of the foam sector which is an indication of the reality that there is no single best solution. Often a key factor is the size of the manufacturing plant since the economies of scale have a considerable bearing on the relative importance of capital and operational costs. Cost also is a major factor in the consideration of the major emerging technologies.

Significant progress has been made by parties to phase-out the use of hydrochlorofluorocarbons (HCFCs) in foams. There are Foam Blowing Agents (FBAs) in use commercially today for nearly every foam sector that are not controlled substances. However, there are some technical and economic challenges remaining for A5 parties and especially for Small and Medium Enterprises (SMEs) and the safety requirements related to field applied foams

Low-global warming potential (GWP) foam blowing agent shortages continue in both Article 5 (A5) and non-Article 5 (non-A5) parties which may be due to pandemic-related supply chain issues, raw material and supply chain shortages, manufacturing issues, and severe weather. Undisclosed manufacturing issues from at least one HFO/HCFO supplier have led to *force majeure* declarations, according to several foam manufacturers. As a result, there has been a significant increase in the use of hydrofluorocarbon HFC-365mfc / HFC-227ea or HFC-365mfc/ HFC-245fa blends in some A5 parties and a reversion to HFC-365mfc blends and HFC-245fa in some non-A5 parties. Prices of HFCs have also increased during the pandemic. There have also been reported shortages of hydrocarbons, such as cyclopentane.

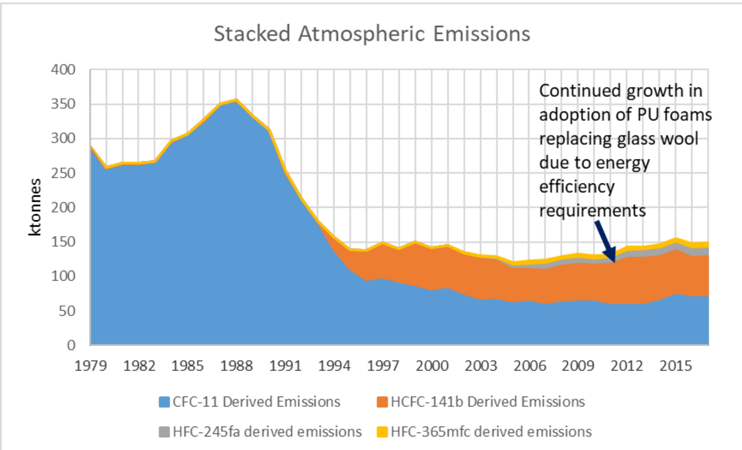


Figure 8.1 Stacked graph showing atmospheric derived emissions of CFC-11, HCFC-141b, HFC-245fa and HFC-365mfc (kilotonnes)[1]

The transition away from ODS foam blowing agents in some regions and market segments (e.g., spray foam and extruded polystyrene [XPS]) may be delayed because of cost, especially where local codes require higher thermal performance[94]. It should be noted that the price of HFC blowing agents has risen substantively during the pandemic and is nearly as high as hydrofluoroolefin/hydrochlorofluoroolefin (HFO/HCFO) prices were prior to the pandemic in some A5 parties.

There continues to be a trend away from the use of fluorocarbon (FC) FBAs with every transition. It has been estimated that less than 20% of the FBA volume will be comprised of

[94] Although the cost of hydrochlorofluorocarbons (HCFCs) was approximately 20-30% of the cost of high-GWP HFCs, HCFC price is increasing as they are phased out globally. The low price of some high-GWP HFCs, particularly HFC-365mfc which is banned in some non-A5 parties, is leading to an increase in market share, which is slowing the conversion to low-GWP blowing agents

FCs after this transition globally. This is in part due to direct conversions to other FBAs and blends with lower concentrations of FCs, as is evidenced in the emissions of “liquid” FBAs as estimated through atmospherically derived emissions, which also shows that there continued to be potential for continued reductions in emissions of controlled FC FBAs

UN environment programme | ozone secretariat