Technology and Economic Assessment Panel

2018 Assessment Report

Montreal Protocol on Substances that Deplete the Ozone Layer

UN environment
United Nations Environment Programme
Ozone Secretariat

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1 Introduction

At the 27th Meeting of the parties to the Montreal Protocol in November 2015, parties adopted Decision XXVII/6 requesting the Scientific Assessment Panel (SAP), the Environmental Effects Assessment Panel (EEAP) and the Technology and Economic Assessment Panel (TEAP) to update their 2014 Assessment Reports in 2018 for consideration by the forty-first Open-Ended Working Group (OEWG-41) and the thirty-first Meeting of the parties in 2019 (MOP-31). In paragraph 8 of that decision, the parties requested the TEAP, in its 2018 Assessment Report to consider the following topics:

(a) The impact of the phase-out of ozone-depleting substances on sustainable development;

(b) Technical progress in the production and consumption sectors in the transition to alternatives and practices that eliminate or minimize emissions to the atmosphere of ozone-depleting substances, taking into account those factors stipulated in Article 3 of the Vienna Convention;

(c) Technically and economically feasible choices for the reduction and elimination of ozone-depleting substances in all relevant sectors including through the use of alternatives, taking into account their performance, and technically and economically feasible alternatives to ozone-depleting substances in consumption sectors, taking into account their overall environmental performance;

(d) The status of banks containing ozone-depleting substances and their alternatives, including those maintained for essential and critical uses, and the options available for handling them;

(e) Accounting for production and consumption for various applications and relevant sources of ozone-depleting substances in inventories; ozone depleting substances and their alternatives.

In response to Decision XXVII/6, the Panel's Flexible and Rigid Foams Technical Options Committee (FTOC), Halons Technical Options Committee (HTOC), Methyl Bromide Technical Options Committee (MBTOC), Medical and Chemicals Technical Options Committee (MCTOC), and Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC) have each produced a 2018 Assessment Report, which address new developments as well as global progress in the transition away from ozone depleting substances (ODS) in the various sectors of use. The main findings from the TOCs are integrated into this 2018 TEAP Assessment Report.

The 2018 TEAP Assessment Report comprises Executive Summaries from each TOC 2018 Assessment Report. Key findings identified by each TOC are included in this introductory section. In addition, this report provides a list of Task Force and Working Group reports that TEAP has produced in response to specific decisions of parties for the period 2014–2018.

1 Overall key findings

The Montreal Protocol continues to be effective because control measures have created incentives for new technology, because enterprises and organizations have worked diligently to implement new technology and because the Multilateral Fund (MLF) has financed the agreed incremental costs of the transition for Article 5 parties. As each production and consumption phase-out milestone have been achieved, the implementation of new phases of technology have further ratcheted down the production, use, and emissions of ODSs most of which are also potent greenhouse gases. Through these efforts, the world has avoided the substantial economic, environmental and health consequences of increases in both ultraviolet radiation and global warming.

Since the 2014 TEAP Assessment Report, important technical developments have taken place as the parties to the Montreal Protocol continue working toward key ODS production and consumption phase-out milestones. The Kigali Amendment, which was adopted in 2016 and entered into force in 2019, creates new challenges and additional milestones for parties to achieve the phase-down of certain hydrofluorocarbons (HFCs). Regular assessments by TEAP highlight the challenges and provide the necessary information to transition to alternatives and technologies across the various sectors of use. The sector and technology-specific challenges include phase out of remaining uses of ODS in specific sectors, some specific uncontrolled and growing ODS uses, and emerging options for the use of more climate-friendly alternatives.

A key message of the Assessment Panels from their 2014 assessment remains relevant today: *"The sustained success of the Protocol hinges on continued vigilance by the parties to fulfil their commitments and prevent any future actions that threaten to nullify the ozone and climate benefits achieved under the agreement. Success also depends on continuing the lessons of collaboration, leadership, innovation, and shared investment in our global environment that was the promise made to future generations under the Protocol."*

1.1 HFC phase down under the Kigali Amendment

The Kigali Amendment established a strong link between ozone protection and climate and set a clear path in protecting our planet's environment through the control of HFCs. The measures taken to phase-down production and consumption of HFCs is expected to avoid up to 0.4 °C of warming by the end of the century. Improvements in the energy efficiency in the refrigeration and air conditioning sector in parallel with HFC phase-down could double that climate benefit.

The TEAP and TOC expertise is evolving to meet the new challenges dictated by the Kigali Amendment. The planned HFC phase-down under the Kigali Amendment, as well as national and regional regulations, are driving industry towards lower-GWP HFC alternatives or not in kind, particularly in refrigeration, air conditioning, and foam applications. However, the range of new, lower GWP products creates challenges in finding the best solution for each application, considering factors such as flammability, toxicity, availability and operating conditions (e.g., high ambient temperatures, HAT).

Around 90% of the potential improvement in energy efficiency of refrigeration and air-conditioning (RAC) equipment comes from technological innovation of equipment, rather than the refrigerant itself. On the other hand, the overall drive to reduce energy demand will lead to increasing energy efficiency of RAC equipment. These twin drivers create an enhanced synergy for HFC phase-down.

1.2 Significant technical progress

Progress continues in every consumer, commercial, industrial, agricultural, medical, and military sector, with ODS no longer used in many applications worldwide. CFC-containing MDIs have been successfully phased out worldwide and replaced by a range of CFC-free inhalers.

The phase-out of HCFC-22 in non-Article 5 parties is essentially complete and is progressing in Article 5 parties.

The phase-out of ozone depleting refrigerants in new chillers is nearly complete. HCFC-22 in new, small chillers has been phased out in non-Article 5 parties, but limited production continues in Article 5 parties.

The year 2015 marked the final production and consumption phase-out date for controlled uses of methyl bromide (MB) in Article 5 parties, and there only a small number of critical uses still being sought by these parties in 2019. This milestone for A5 parties was reached showing steady progress under the Protocol, the successful conclusion of many investment projects, and clear demonstration of how far key sectors, previously dependent on MB, had come in their transition to alternative options and technologies.

1.3 Continuing uses of ODS

Continued vigilance through atmospheric monitoring and regular assessments of ODS consumption and use and inventories (banks) is needed to monitor the progress and achievements under the Montreal Protocol. Continuing use of already phased out ODS and recent reporting of unexpected emissions of CFC-11 reinforce this importance.

CFC-11 remains a major source of ozone-destroying chlorine to the stratosphere. Its concentration in the atmosphere has been declining over several decades because of the Montreal Protocol, but recent measurements indicate that this decline has recently become slower than expected under the Montreal Protocol. CFC-11 was used primarily as a foam-blowing agent, as a refrigerant, and in a range of other smaller uses, including asthma medical inhalers and in tobacco expansion. However, alternative chemicals or products are available as replacements for all applications, and have been from the mid-1980s onwards. Production of CFC-11 in non-Article 5 parties was phased out in 1996; production of CFC-11 in Article 5 parties was phased out in 2010. Production of CFC-11 to supply essential uses was less than 400 tonnes each year after 2010 and ceased altogether after 2014. No feedstock uses of CFC-11 have been reported from parties.

Despite these controls, an increase in global CFC-11 emissions after 2012, at least part of which is strongly suggested to originate from eastern Asia, was derived from measurements by two independent networks. In response to Decision XXX/3 (November 2018), SAP and TEAP have coordinated efforts to provide additional information regarding atmospheric monitoring and modelling, with respect to the unexpected emissions, and on potential sources of emissions of CFC-11 and related controlled substances, respectively.

Contrary to the general perception that the halon sector issues are all resolved, in fact the demand from on-going, enduring uses (e.g., civil aviation, oil & gas facilities, nuclear facilities, and military installed base/reserves, etc.), and the growing civil aviation demand of halon-1301 resulting from the lack of replacements for new designs for engine and cargo compartment applications, will likely soon exceed the supply from stockpiles. Emission estimates derived from atmospheric abundances suggest that there were more emissions than previously estimated and therefore there is significantly less stockpiled halon-1301 available to support ongoing needs. It was previously projected that available halon-1301 supplies will run out by the years 2032 to 2054. However, there are regional imbalances, which could mean that for those without dedicated, long-term stockpiles, the run-out date will occur much earlier. Therefore, TEAP anticipates that this will require action under the Montreal Protocol with the strong likelihood that essential use nominations for the production of new halon-1301 will be submitted in the foreseeable future to supply these important fire-fighting uses, and especially for civil aviation.

Atmospheric concentrations of MB have stopped declining, indicating possible continued use of MB larger than is currently reported for QPS (exempted) uses. An estimated 40% of reported QPS uses have immediately available alternatives, but are not being adopted because QPS uses are exempted under the Protocol. Further, around 70% of current MB emissions derived from reported QPS uses could be avoided, by using re-capture or destruction for QPS commodity uses and barrier films for the QPS pre-plant soil fumigation uses. The resulting reductions in atmospheric concentrations of MB would provide near-term benefits for the ozone layer.

2 Progress and challenges by sector

2.1 Foams

- There have been significant improvements in the development and availability of additives, co-blowing agents, equipment and formulations enabling the successful commercialisation of foams and foam systems containing low GWP blowing agents.
- Growth in the construction sector and the cold chain in Article 5 parties, coupled with the adoption of enhanced energy efficiency criteria for buildings has led to a growth in demand for thermal insulation materials.
  - Total global production of polymeric foams continues to grow (3.9% per year) at a slightly lower rate than noted last year (4.0%), from an estimated 24 million tonnes in 2017 to 29 million tonnes by 2023. Production of foams used for insulation is expected to grow in line with global construction and continued development of refrigerated food processing, transportation and storage (cold chain).
  - Based on average blowing agent percentages of 5.5% w/w (weight by weight or mass fraction) for polyurethane and 6%[1] w/w for XPS, this leads to an estimated demand of greater than 400,000 tonnes with a further 10,000 tonnes being consumed by other

1 Compound Annual Growth Rate

foam types. Further, it is estimated that blowing agent demand would grow to above 500,000 tonnes by 2023 based on the growth rates presented below.

- Article 5 parties (A5 parties) face common challenges in phasing out production and consumption of hydrochlorofluorocarbons (HCFCs) and phasing down high global warming potential (GWP) HFC blowing agents.
- The conversion from HCFC-141b in insulation foam applications has been largely successful within larger and some medium enterprises where the critical mass of the operation is sufficient to justify investment in hydrocarbon technologies.
- Managing foams transition for the multitude of SMEs in both Article 5 and non-Article 5 parties remains a challenge. The low GWP alternatives are mostly flammable, and SMEs may find the necessary fire precautions unaffordable. Unless there is industrial rationalisation, this leaves high GWP solutions as the only option, often with considerable emissions.
- The unexpected emissions of CFC-11 requires revisiting previous assessments of this transition in the foams sector and the many factors that may influence selection of foam blowing agent including foam blowing agent cost, safety (flammability, toxicity), ease of use, compatibility with equipment and other raw materials (etc.).

2.2 Halons

- There is great concern regarding the general perception that the halon sector issues are all resolved. Increasing demand for on-going and enduring uses (e.g., civil aviation, oil & gas facilities, nuclear facilities, and military installed base/reserves, etc.) will soon exceed supply from stockpiles. The stockpile of halon-1301 may be less than previously estimated, because atmospheric abundances suggest higher emissions than previously estimated, and this will be exacerbated by regional imbalances in stocks. Taken together these factors suggest that for users without access to significant stockpiles, halon-1301 supplies will run out well before the previously estimated 2032 to 2054 timeframe. The growing civil aviation demand for halon-1301 will require action under the Montreal Protocol, with likely submission of essential use nominations for the production of new halon-1301 in the foreseeable future.
- Implementation of 2-BTP as a halon-1211 replacement in hand-held portable extinguishers on board civil aviation aircraft is currently on-going. (This represents approximately 10% of the halon installed in aircraft.) In contrast, the fact that civil aviation has only implemented a replacement for halon-1301 in lavatory fire extinguishing systems, its smallest use by far, is a remarkably disappointing result, given the level of research and testing efforts performed by governments and fire protection companies for the past 25+ years.
- Since the 2014 Assessment Report, little further progress on additional low-GWP alternatives for total flooding systems (to replace halon-1301, HFC-227ea and/or HFC-125) has been reported. Although research to identify potential new fire protection agents continues, it could be five to ten years before a viable agent could have significant impact on the fire protection sector.

2.3 Methyl Bromide

- MBTOC considers that technical alternatives exist for almost all remaining controlled uses of methyl bromide. Ninety-nine per cent of the reported controlled consumption has been phased out, with only 141 t being presently approved for critical use exemptions. Concern exists that a much greater amount of MB used for controlled purposes is presently unreported.
- In recent years some countries have reported steep increases in QPS consumption, whilst others have significantly declined. Owing to this, there has been no overall sustained reduction in QPS use over the last twenty years. MBTOC estimates that alternatives to MB are immediately available for about 40% of QPS uses, particularly pre-shipment.
- Methyl bromide used for QPS purposes is almost entirely emitted to the atmosphere. Control of these emissions by use of barrier films (for any remaining pre-plant soil fumigation) or recapture and destruction technologies would eliminate more than 70% of these emissions, providing a significant near-term gain to the reduction of ODS substances in the stratosphere.

2.4 Medical and Chemical

- CFC-containing metered dose inhalers (MDIs) have been successfully phased out worldwide. A range of alternative treatment methods is available. The choice of the most suitable treatment method is a complex decision and may be enhanced with an increase in publicly available information about the environmental impact, including carbon footprint, of different inhaler products.
- Based on a recent study, an increase in CFC-11 emissions of 13,000 ± 5,000 tonnes per year is suggested for the period 2013 to 2016. The increase in emissions of CFC-11 appears unrelated to past production. Losses of 13,000 tonnes per year of CFC-11 are not economical from a chemical production process. At the upper end of possible emission levels (5 per cent losses) for an economically run process, this would equate to production of 260,000 tonnes CFC-11 per year. The fate of any CFC-12 produced as a by-product of CFC-11 production is not yet clear.

2.5 Refrigeration and Air Conditioning

- The phase-out of HCFC-22 in non-Article 5 parties is essentially complete and is progressing in Article 5 parties.
- There is no single “ideal” refrigerant. Refrigerant selection results from balancing several factors which include: suitability for the targeted use, availability and cost of the refrigerant, the availability and cost of the RAC equipment, the cost and effectiveness of servicing, energy efficiency, safety, ease of use, and environmental issues. Since the publication of the RTOC 2014 Assessment Report, 35 new refrigerants have received a standard designation and safety classification of which five are single-compound refrigerants, and 30 are blends
- The HFC phase-down under the Kigali Amendment, as well as regional and national regulations, are driving the industry towards the use of low GWP refrigerants.

Alternatives to high GWP refrigerants exist and new lower GWP refrigerants have been proposed. Finding the best refrigerant for each application is a continuing challenge. Refrigerants with low direct impact on climate change are often flammable and may have higher toxicity. In order to maintain the current safety levels new technologies are being developed and an increased level of training will be needed.

- In domestic refrigeration, HC-600a (predominantly) or HFC-134a continue to be the refrigerant options for new production and currently, more than 1 billion domestic refrigerators use HC-600a. In commercial refrigeration, lower GWP HFC/HFO blends and non-halocarbon options like R-744, HC-290, HC-600a and R-717 are growing in use, especially as research and development improves system performance; this trend will further increase with new safety standards and codes which will come into effect in the next few years. In larger industrial refrigeration plants, while R-717 has been extensively used, current technological advances include the use of low charge R-717 systems, as well as cascade systems using R-717 together with R-744. In transport refrigeration, some regions have experienced a significant migration from R-404A to lower GWP alternatives. R-404A has been completely replaced by R-452A in new truck and trailer equipment in Europe. R-744 and R-513A have been introduced in intermodal container applications. R-744 is being field tested on trucks and trailers.
- In air-to-air air conditioners and heat pumps, there is an almost continuous introduction of new refrigerants for use, but few match or exceed the performance of HCFC-22 regardless of the GWP. Nevertheless, market transformation for lower GWP refrigerants as replacement to R-22 has occurred; currently millions of R-32 AC are commercially available, especially in Asia. Despite the reported low risk for certain applications, safety standards remain restrictive to several low GWP flammable refrigerants in certain product types, but are under revision for all refrigerants. Water and space heating heat pumps are a dynamic market with a number of lower GWP options.
- The phase-out of ozone depleting refrigerants in new chillers is nearly complete. HCFC-22 in new, small chillers has been phased out in non-Article 5 parties, but limited production continues in Article 5 parties.
- Due to the enforcement of regulations, HFO-1234yf is rapidly increasing its market share in US and Europe in new AC equipped passenger cars, while HFC-134a remains widely used in other regions. Although the transition away from CFC-12 has been successful, there are still some luxury or special types of vehicles (built before year 2002) in operation in A5 countries with MACs operated on CFC-12. The CFC-12 quantities used are minimal and are resulting from the recycling of CFC-12 contained in old products.
- Comprehensive sustainable selection criteria for refrigerants have been introduced and include: energy efficiency, impact on climate and hydrosphere, usage of renewable energy, and other options to reduce GHG emissions and consumption of natural resources, adaptability for thermal energy storage, costs, technological development level, safety, flammability and liability.
- Not-In-Kind (NIK) technologies do not primarily use mechanical vapour compression (MVC) technology to produce air conditioning or refrigeration. NIK technologies are expected to provide savings in operating costs. Their unique ability to use waste and renewable energy sources makes their application potentially highly energy efficient.

- Research done at HAT conditions has identified viable low-GWP refrigerant alternatives. There is more awareness of the challenges faced at HAT conditions in the design, implementation, and servicing of equipment using low-GWP refrigerants that are capable of delivering a high level of energy efficiency.

3 TEAP role, organisation and challenges

The role of TEAP and its TOCs continues to evolve in meeting the current needs of parties.

The parties have placed significant importance on the TEAP's Terms of Reference (TOR) and on the smooth operation of this body of experts towards achieving the parties' goals of the Montreal Protocol. Parties dedicated over four continuous years (2010–2013) for discussions and a number of key decisions, resulting in the requirements outlined in the current TOR that the TEAP has been implementing.

TEAP is successfully implementing the TOR including: a review of membership and re-appointment process throughout all the TOCS, which was first completed in 2014 and is now on-going; developed guidelines for nominations to the TOCs; developed standard disclosure of interest/ disclosure of conflict forms and guidance; standardised the practice of reviewing TOR requirements with members at the opening of each TEAP, TOC and TSB meetings.

TEAP and its TOCs continue to review membership and work in order to identify the needed expertise to meet current and new demands relevant to decisions, including the implementation of the Kigali Amendment. TEAP continues its efforts in achieving A5 and non-A5 balance, taking into account geographical and gender balance. TEAP welcomes the assistance of parties in identifying appropriate candidates with the needed expertise and the time, capacity, and support to share in the workload of the TOCs.

TEAP members have a broad experience of collective responsibility and of consensus-building. Their collective know-how includes understanding the history of the Protocol, its decisions, its issues, and the way in which the technical outputs developed by the TOCs and the TEAP underpin the Protocol. This is in addition to the individual technical expertise each member brings to the Panel. Some TOCs have experienced attrition, through the retirement of members or the lack of support for their participation, with increasing loss of expertise. The challenge for TEAP and for the parties, is both to maintain the needed expertise and to recruit volunteers with needed technical expertise, the ability to reach consensus, and the necessary time, energy and ability to write clearly. One mechanism to identify new volunteers are task forces, which bring in new technical experts, familiarise them with the process, and allows them to determine their interest in future participation. This also allows TEAP to consider their capability and suitability for TOC and possible future TEAP membership.

Over the last four years, TEAP has responded to a major increase in its workload as parties negotiated the Kigali Amendment, among other topics. TEAP is concerned with the significant administrative burden related to the work of TEAP, and also related in particular with its TSBs (e.g., Task Forces) when multiple and increasingly complex requests of the parties have included the production of two reports, one for the OEWG and one for the MOP. In most cases, the work required to address parties' comments on the first report has essentially doubled the workload of the Task Force for the year, which is unsustainable, particularly in years where other standing reports must also be delivered to parties. This situation, if unaddressed, will increasingly affect the delivery and timeline and possibly quality, of TEAP's outputs. TEAP is also concerned with retaining the independence and neutrality of its assessments if the trend continues to require delivery of interim reports to the OEWG, where changes to the scope of the original decision may be introduced through a less formal feedback processes.

TEAP will continue to review its operations, organisation, and planning as it moves forward in the next phase of progress implementing the Montreal Protocol.

2 Key TOC sector findings

The key TOC sector findings are summarised in the following sections.

1 Flexible and Rigid Foams TOC (FTOC)

1.1 Global Foam Production

Total global production of polymeric foams continues to grow (3.9% per year) at a slightly lower rate than noted last year (4.0%), from an estimated 24 million tonnes in 2017 to a projected 29 million tonnes by 2023. Production of foams used for insulation is expected to grow in line with global construction and continued development of refrigerated food processing, transportation and storage (cold chain).

Based on average blowing agent percentages of 5.5% w/w (weight for weight or mass fraction) for polyurethane and 6%[2] w/w for XPS, this leads to an estimated current demand of greater than 400,000 tonnes with a further 10,000 tonnes being consumed by other foam types. By 2023, it is estimated that blowing agent demand for XPS will exceed 500,000 tonnes with hydrocarbons representing over 50% of the total

1.2 Use in Construction

Growth in the construction sector in Article 5 parties, coupled with the adoption of enhanced energy efficiency criteria for buildings has led to a growth in demand for thermal insulation materials in these regions. Insulation foams have been the material of choice, although concerns over flammability have hindered adoption in some key markets, particularly where construction methods expose hazards. Differentiation between product types is increasingly occurring.

In non-Article 5 parties, there has been an increasing focus on insulation use in existing buildings, where solutions are required to be both efficient and cost-effective. PU spray foam has made considerable inroads as a result.

1.3 Introduction of Low GWP Blowing Agents

Regulations continue to evolve regarding the use of controlled hydrofluorocarbons (HFCs) in foams driving transitions to low GWP alternatives in several regions and especially in many non-Article 5 parties (nA5 parties) in the last two years. There have been significant

2 Compound Annual Growth Rate

improvements in the development and availability of additives, co-blowing agents, equipment and formulations enabling the successful commercialisation of foams and foam systems containing low GWP blowing agents.

1.4 Article 5 parties

A5 parties face common challenges in phasing out hydrochlorofluorocarbons (HCFCs) and phasing down high global warming potential (GWP) HFC blowing agents.

HPMPs continue to drive transitions in foams.

- In general, HCFCs are less than half of the cost of high GWP HFCs. Hydrofluoroolefin / hydrochlorofluoroolefin (unsaturated HCFCs and HFCs) blown foams remain more expensive than HFC foams, due to the total cost of the blowing agent and required additives.
- In some A5 parties, import of HCFC-141b itself is controlled or under license, but polyols containing HCFC-141b can be imported without controls. To counter this, some A5 parties have implemented regulations that would ban or restrict import of HCFC-containing polyol systems.
- Decisions on transition for some segments (e.g. spray foam and extruded polystyrene [XPS]) may be delayed because the cost of transition is still being optimized for some regions.
- Capacity planning for alternatives will require continued communication between regulators, producers and users to ensure smooth transitions.
- SMEs have difficulty in affording the investment in safety needed for flammable alternatives, leaving high GWP alternatives as the only option, often with considerable emissions.
- Oxygenated hydrocarbons, such as methyl formate, are being increasingly used in some Article 5 parties, especially in integral skin applications[3], although flammability remains an issue.

The focus of HCFC phase-out in the foam sector to date has been HCFC-141b based on the “worst-first” principle. However, this has led to a significant tail of HCFC-142b/22 use in the XPS sector which has continued to grow rapidly, particularly in Asia.

1.5 Banks

Banks of blowing agents are expected to exceed 5 million tonnes, inclusive of hydrocarbons by 2020. Much of the ODS component of these banks will already be in the waste stream by then as products containing them (e.g. appliances) will have already reached end of life. In addition, the economic justification for recovery will become more challenging as the average GWP of blowing agents in banks declines.

3 Water (carbon dioxide) is largely used as a foam blowing agent for integral skin

2 Halons TOC (HTOC)

Implementation of the halon-1211 replacement 2-BTP in hand-held portable extinguishers on board civil aviation aircraft is on-going. However, the fact that civil aviation is only now implementing this replacement for halon-1301 in lavatory fire extinguishing systems, (its smallest use by far), is a remarkably disappointing outcome, considering the enormous amount of research and testing performed by governments and fire protection companies for the past 25+ years.

The HTOC remains very concerned about the general perception that all halon sector issues are resolved, when high demand for halon-1301 will likely require future action under the Montreal Protocol. The HTOC anticipates that EUNs will likely be submitted in the future owing to the high demand of halon-1301 to support both on-going uses (e.g., civil aviation, oil & gas facilities, nuclear facilities, and military installed base/reserves, etc.) and the growth of the civil aviation fleet. For users that do not have dedicated, long-term stockpiles, the estimated available halon-1301 supplies are projected to run out by the years 2032 to 2054.

Parties may wish to consider re-addressing the need for awareness programmes / capacity building in the fire protection sector, in particular for estimating long-term needs for their enduring uses of halon-1301 (e.g., civil aviation, oil & gas facilities, nuclear facilities, military, etc.), eliminating barriers to trade, and implementing proper storage and handling practices.

The HTOC continues to recommend that destruction as a final disposition option should be considered only if the halons are contaminated and cannot be technically and/or economically reclaimed to an acceptable purity. The HTOC further recommends extending this same practice to all gaseous, halogenated fire extinguishants.

Since the 2014 Assessment Report, little further progress on additional low-GWP alternatives for total flooding systems (to replace halon-1301, HFC-227ea and/or HFC-125) has been reported. The HTOC is of the opinion that although research to identify potential new fire protection agents continues, it could be five to ten years before a viable agent could have significant impact on the fire protection sector.

3 Methyl Bromide TOC (MBTOC)

3.1 Controlled non QPS uses

Since 1992, when controls were implemented on MB use, alternatives have been identified that have led to a reduction of over 99% of the baseline consumption, including soil fumigation and treatment of commodities and structures. The critical use nominations (CUN) for MB have fallen from 18,700 tonnes in 2005 to 150 tonnes in 2019/2020. Concern exists that a much larger amount of MB used for controlled applications may be unreported.

In non-Article 5 parties, MB under a CUN is only used for strawberry runner production. However, some parties have changed the national legislation to re-classify some uses from CUN to QPS, which is not yet controlled under the Protocol. (e.g. forest nurseries, strawberry runners).

In A5 parties, CUNs were submitted in 2014 for strawberry fruit and runners, raspberry runners, ginger and tomatoes, however in 2018 only strawberry fruit and tomatoes remained. Many Article 5 parties who used large quantities of MB reported complete phase-out by 2015.

3.2 QPS Use

In 2017 global use of MB for QPS was seventy-fold larger than controlled, non-QPS consumption

In 2017, the following five uses accounted for over 80% of the MB used for QPS: 1) Sawn timber and wood packaging material (ISPM-15); 2) Grains and similar foodstuffs; 3) Pre-plant soils use; 4) Logs; and 5) Fresh fruit and vegetables.

Between 2012–2014 there appeared to be a decline, but between 2014–2017 global QPS consumption increased substantially from 8,500 tonnes to over 10,000 tonnes (31% non-A5 versus 69% A5 parties), Of the 50 countries still regularly using MB for QPS, 14 show significant reductions in their MB consumption for QPS but 13 other countries have shown sharp increases.

MBTOC considers that available alternatives are ready for adoption and use in pre-shipment fumigation (e.g. irradiation, cold and heat treatments, modified atmospheres, cool temperature phosphine treatment, sulfuryl fluoride, ethane dinitrile and ethyl formate). This is because this pre-shipment use targets cosmopolitan pests, where these alternatives have already been shown to be effective for the same pests under the phase-out of controlled uses. Several parties have already made policy decisions leading to the reduction and/or phase-out of MB for some QPS applications. These policies have benefits in terms of worker safety and local air quality, in addition to ozone.

Parties may wish to reconsider whether it is now timely for the exemption of this section of the QPS exemption should be reviewed.

3.3 MB Emissions

Since 1998, MBTOC estimates that overall anthropogenic emissions of MB from reported consumption should have declined to 8,500 tonnes almost all from QPS use, a reduction of 80–85% from the peak emissions of around 48,000 tonnes in 1998. The atmospheric levels of MB have flattened but have varied since 2013, and there is uncertainty over the actual size of the contribution of anthropogenic emissions.

Improvements in recapture technologies and approval by the parties of the first destruction technology for MB now offer a means to reduce MB emissions, but are expensive to implement. Some countries are imposing regulations for MB recapture/destruction. Barrier films for any remaining pre-plant soil fumigation, together with recapture and destruction for many QPS uses, could reduce current emissions of MB by over 70%.

4 Medical and Chemical TOC (MCTOC)

4.1 Metered dose inhalers

CFC-containing metered dose inhalers (MDIs) have been successfully phased out worldwide. A range of alternative treatment methods is available. The choice of the most suitable treatment method is a complex decision and may be enhanced with an increase in publicly available information about the environmental impact, including carbon footprint, of different inhaler products.

4.2 Aerosols

Technically and economically feasible alternatives to ODS propellants and solvents (CFCs and HCFCs) are available for aerosol products. Small uses of HCFCs remain in a few countries for specific medical aerosol products. A small proportion of aerosols migrated to HFC propellants. In many cases, HFC propellants and solvents can be substituted with low-GWP options, and not-in-kind technologies where suitable.

4.3 Sterilants

The use of CFC-12 in sterilization has been successfully phased out in non-Article 5 parties, and in most, if not all, Article 5 parties, and only then from remaining stockpile. The complete phase-out of HCFCs in sterilization to meet the Montreal Protocol schedule is readily achievable.

4.4 Feedstocks

In 2016, total ODS production for feedstock (and process agent) uses was 1,189,536 tonnes, with estimated emissions 2,194 ODP tonnes. The largest feedstock uses currently are HCFC-22, CTC, and HCFC-142b.

4.5 Process agents

Most of the process agent uses are long-standing processes built around the unique solvent properties of an ODS, making it difficult or impossible to convert to alternatives in a cost effective and timely manner. For some of the remaining applications, no alternatives are available to date. There exists a suite of measures that operators need to consider in minimising consumption and emissions.

4.6 Solvents

CFC-113 and 1,1,1-trichloroethane uses for solvent cleaning have been phased out in both Article-5 and non-Article 5 parties, with the exception of CFC-113 in aerospace applications until stockpiles are depleted. HCFC-141b and HCFC-225 uses for solvent cleaning have been largely phased out in non-Article 5 parties, with the exception of aerospace and military applications. In A5 parties, HCFC use for solvent cleaning is declining. Many solvents and technologies developed as CFC alternatives are also candidates for HCFC alternatives.

4.7 Other chemicals issues

The discrepancy between carbon tetrachloride (CTC) emissions calculated from atmospheric observations and those estimated from industrial activity can be explained by revised estimates of previously unaccounted emission sources and partial CTC lifetimes (stratosphere, ocean, or soil). Parties may wish to consider examining potential sources of CTC emissions (including unreported non-feedstock emissions from CTC production, feedstock fugitive emissions, legacy emissions (e.g. from historic landfill) and unreported inadvertent emissions (e.g. from chlorine production and uses)) to increase the understanding of those emissions and the accuracy of emissions estimates.

Dichloromethane (DCM), which is not a controlled substance, contributes a small percentage to current total stratospheric chlorine loading. Given predicted market trends in chemical production and DCM usage, global DCM production and atmospheric concentrations are unlikely to increase significantly. Dichloroethane (EDC) is a very short-lived substance, is also not controlled under the Montreal Protocol. Based on predicted EDC consumption, the background atmospheric concentration of EDC could double by 2030.

Based on a recent study, an increase in CFC-11 emissions of 13,000 ± 5,000 tonnes per year is suggested for the period 2013 to 2016. The increase in emissions of CFC-11 appears unrelated to past production. Losses of 13,000 tonnes per year of CFC-11 are not economical from a chemical production process. At the upper end of possible emission levels (5 per cent losses) for an economically run process, this would equate to production of 260,000 tonnes CFC-11 per year. The fate of any CFC-12 produced as a by-product of CFC-11 production is not yet clear.

4.8 Laboratory and analytical uses

In 2016, the reported global production of all reported ODS for laboratory and analytical uses was relatively small (151 tonnes). Many standards still require the use of small quantities of ODS. Parties may wish to consider additional measures to facilitate the replacement of ODS in standards.

4.9 Destruction

Cumulatively, over 300,000 tonnes of ODS have been destroyed since 1996, of which the majority was CTC. Based on reported ODS (excluding CTC) destruction, it is estimated that a global destruction rate of about 3 per cent was achieved in 2016.

5 Refrigeration and Air Conditioning and Heat Pumps TOC (RTOC)

5.1 Refrigerants

Since the publication of the RTOC 2014 Assessment Report, 35 new refrigerants have received a standard designation and safety classification and five are single-compound refrigerants.

There is no single “ideal” refrigerant. Refrigerant selection is a balanced result of several factors, which include suitability for the targeted use, availability, cost of the refrigerant and associated equipment and service, energy efficiency, safety, ease of use, and environmental issues.

The planned HFC phase-down under the Kigali Amendment, as well as regional and national regulations, are driving the industry towards low GWP HFC refrigerants and not in-kind alternatives. Alternatives to high GWP refrigerants exist and new lower GWP refrigerants have been proposed, which creates a challenge to finding the best refrigerant for each application. Many of the newly introduced refrigerants may only play an interim role in the phase-down process, as their GWP may still be high for long term use.

Refrigerants with low direct impact on climate change are often flammable and may have higher toxicity. In order to maintain or improve the current safety levels, new technologies are being developed, and increased training will be needed.

5.2 Domestic appliances

HC-600a (predominantly) or HFC-134a continue to be the refrigerant options for new production and currently, more than 1 billion domestic refrigerators use HC-600a. None of the other new refrigerants has matured to become an energy-efficient and cost competitive alternative.

5.3 Commercial refrigeration

Lower GWP HFC/HFO blends and non-halocarbon options like R-744, HC-290, HC-600a and R-717 are growing in use, especially as research and development improves system performance. This trend will further increase with new safety standards and codes, which will come into effect in the next few years.

5.4 Industrial refrigeration and heat pump systems

In larger industrial refrigeration plants, R-717 has been extensively used for more than 150 years. Current technological advances include the use of low charge R-717 systems, and cascade systems using R-717 together with R-744.

5.5 Transport refrigeration

In some regions, a significant migration from R-404A to lower GWP has occurred since the last assessment. Today, R-404A has been completely replaced by R-452A in new truck and trailer equipment in Europe. This trend might extend across the rest of the world.

R-744 and R-513A have been introduced in intermodal container applications. R-744 is being field tested on trucks and trailers.

5.6 Air-to-air air conditioners and heat pumps

The phase-out of HCFC-22 in non-Article 5 parties is essentially complete and is progressing in Article 5 parties.

There is an almost continuous introduction of new refrigerants for use in air-to-air air conditioners and heat pumps, but few match or exceed the performance of HCFC-22 regardless of the GWP. Component and system optimisation can be a design challenge. Nevertheless, Market transformation for lower GWP refrigerants as replacement to R-22 has occurred. There are millions of R-32 AC commercially available, especially in Asia.

5.7 Water and space heating heat pumps

Water and space heating heat pumps are a dynamic market with a number of options. Low GWP refrigerant HC-290 and the medium GWP refrigerant HFC-32 are commercially available, and other medium and low-GWP HFC blends may become commercially available. R-744 based water heating heat pumps have been mainly developed and commercialised in Japan, where around 6 million units have been installed since 2001. In Europe, commercial sized units are being installed for multi-family houses and hotels. R-717 is also being introduced in a small number of reversible heat pumps as well as in absorption heat pumps

5.8 Chillers

The phase-out of ozone depleting refrigerants in new chillers is nearly complete. HCFC-22 in new, small chillers has been phased out in non-Article 5 parties, but limited use continues in Article 5 countries.

5.9 Vehicle air conditioning

At present, more than one refrigerant is used for new car and light truck air conditioning: HFC-134a will remain widely accepted world-wide while, due to regulations, the use of HFO-1234yf will continue expanding mainly in the US, Europe and Japan. R-744, currently available for very few car models, is expected to be considered as an option for electrified vehicles, when used at the same time for a heat pump function.

5.10 Energy efficiency and sustainability applied to refrigeration systems

[Industry and policymakers may consider the methods, tools and incentives described in this RTOC assessment report chapter to stimulate and support improvements on energy efficiency and sustainability. A wider range of relevant environmental and social aspects is briefly described in this chapter while keeping focus on possible environmental impacts of refrigeration systems.]

5.11 Not-in-Kind technologies

Not-In-Kind (NIK) technologies do not primarily use mechanical vapour compression (MVC) technology for cooling applications.

NIK technologies are expected to provide savings in operating costs. Their unique ability to use waste and renewable energy sources, makes their application potentially highly energy efficiency.

5.12 High ambient temperature (HAT)

Research done at HAT conditions reveals viable low-GWP refrigerant alternatives that can be effectively used.

There is more awareness of the challenges faced at HAT conditions in the design, implementation, and even servicing of equipment using low-GWP refrigerants that are capable of delivering a high level of energy efficiency.

5.13 Modelling

Determination of current and future refrigerant demand has been a task for RTOC experts when involved in recent Task Force reports. The demand follows from "bottom-up" calculations of banks and emissions that give good insight into future developments, albeit that these imply assumption of a large number of parameters. This includes economic growth, equipment base and composition, leakage, end-of-life characteristics, recovery and recycling.

The methodology used by the RTOC to model banks and emissions from the global sector transitions is described in significant detail for the first time in this assessment report.

3 Special Reports Prepared in Response to Decisions from the Parties

Aside from its annual Progress Reports and bi-annual reports on Critical Use Nominations for methyl bromide, in the 4 years since the 2014 Assessment Report, TEAP has prepared forty-one special reports in response to various Decisions issued by the parties to the Protocol.

Full versions of these reports can be found on the Ozone Secretariat website http://ozone.unep.org/science/assessment/teap.

Table 3.1 below provides a full list of reports prepared by TEAP during the last quadrennium in response to various decisions issued by the parties.

Table 3.1 **Technology and Economic Assessment Panel reports produced in response to parties' requests during the period 2015–2018**

Issue	Request by parties to TEAP	Report produced
2015		
Progress update		
Technical progress update by TEAP and its TOCs	**Decision IV/13** – Report annually to OEWG on technical progress in reducing the use and emissions of controlled substances and assess the use of alternatives, particularly their direct and indirect global-warming effects	June 2015 progress report Addendum to the progress report
	Decision XI/17 – Report on any important new developments	
Thematic		
Critical-use nominations	**Decision IX/6** – Review nominations for critical use exemption of methyl bromide and make recommendations based on the criteria established in the decision (and other relevant decisions)	2015 interim report 2015 final report
Essential-use nominations	**Decision IV/25** – Review any submitted nominations and make recommendations in accordance with the criteria established in the decision	June 2015 progress report
Alternatives to ODS	**Decision XXVI/9** – 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 decision are not available	June 2015 Task Force report September 2015 Task Force updated report

Issue	Request by parties to TEAP	Report produced
2015		
Process agents	**Decision XXII/8** – Review progress made in reducing process-agent uses and make any additional recommendations on further action to reduce uses and emissions of process agents	Considered. No new information available, no report prepared
Destruction technologies for controlled substances	**Decision XXIII/12** – Continue to assess the plasma destruction technology for methyl bromide in the light of any additional information that may become available and to report to the parties when appropriate	Considered. No new information available, no report prepared
Laboratory and analytical uses of controlled substances	**Decision XV/8** – Report on laboratory and analytical procedures that can be performed without controlled substances in Annexes A, B and C (groups II and III) of the Montreal Protocol	Considered. No new information available, no report prepared
	Decision XVII/10 – Report on laboratory and analytical procedures that can be performed without the controlled substance in Annex E of the Montreal Protocol	Considered. No new information available, no report prepared
	Decision XXIII/6 – Continue reviewing international standards that mandate the use of ozone-depleting substances and work with the organizations that promulgate such standards to include non-ozone-depleting substances and procedures as applicable	Considered. No new information available, no report prepared
n-Propyl Bromide	**Decision XIII/7** – Report on use and emissions of n-propyl bromide	Considered. No new information available, no report prepared
New substances	**Decision IX/24** – Report on any new substances with ozone-depleting potential including an evaluation of the extent of use or potential use and, if necessary, the potential alternatives, and make recommendations on actions the parties should consider taking	Considered. No new information available, no report prepared
Periodic assessment		
Quadrennial assessment	**Decision XXIII/13** – Prepare and present the assessment panels' synthesis report	TEAP 2014 Assessment Report (submitted in 2015) 2014 Synthesis report of the 3 Panels*.
	Number of reports produced in 2015:	8

* The three Panels of the Montreal Protocol – EEAP, SAP and TEAP prepared their joint 2014 Synthesis Report (submitted in 2015) even though the Decision does not specifically require it.

Issue	Request by parties to TEAP	Report produced
2016		
Progress update		
Technical progress update by TEAP and its TOCs	**Decision IV/13** – Report annually to OEWG on technical progress in reducing the use and emissions of controlled substances and assess the use of alternatives, particularly their direct and indirect global-warming effects	June 2016 progress report
	Decision XI/17 – Report on any important new developments	
Thematic		
Critical-use nominations	**Decision IX/6** – Review nominations for critical use exemption of methyl bromide and make recommendations based on the criteria established in the decision (and other relevant decisions)	2016 interim report 2016 final report
Essential-use nominations	**Decision IV/25** – Review any submitted nominations and make recommendations in accordance with the criteria established in the decision	June 2016 progress report
HFC climate benefits and costs	**Decision Ex.III/1** – prepare a report for consideration by the 28th MOP containing an assessment of the climate benefits, and the financial implications for the Multilateral Fund for the Implementation of the Montreal Protocol, of the schedules for phasing down the use of HFCs contained in the amendment proposals discussed by the parties at the 38th meeting of the OEWG and the 3rd Extraordinary MOP	TEAP September 2016 Working Group Report, additional clarifications (addendum) and updated information on spreadsheet 5 of Annex III to the Working Group report
Alternatives to ODS	**Decision XXVII/4** – Prepare a report for consideration by the OEWG at its 37th meeting, and thereafter an updated report to be submitted to the 28th MOP in 2016, that would update, where necessary, and provide new information on alternatives to ODS, including not-in-kind alternatives, based on the guidance and assessment criteria provided in subparagraph 1 (a) of decision XXVI/9 and taking into account the most recent findings on the suitability of alternatives at high-ambient temperatures; Update and extend to 2050 all the scenarios in the decision XXVI/9 report	March 2016 Task Force report June 2016 Task Force report September 2016 Task Force report
HCFC phase-out	**Decision XXVII/5** – Submit a report to the 37th meeting of the OEWG in 2016 on HCFC-related issues set out in the decision	June 2016 Working Group report
Carbon tetrachloride discrepancies	**Decision XXVII/7** – TEAP and SAP to continue their analysis of the discrepancies between observed atmospheric concentrations and reported data on carbon tetrachloride and to report and provide an update on their findings to the 28th MOP	TEAP-SAP September 2016 report

Issue	Request by parties to TEAP	Report produced
2016		
Process agents	**Decision XVII/6** – Review information submitted by parties on process-agent use exemptions, on insignificant emissions associated with a use, and process-agent uses that could be added or deleted from table A of decision X/14; review emissions in table B of decision X/14, taking into account parties' submissions, and recommend any reductions to the make-up and maximum emissions	June 2016 progress report
Destruction technologies for controlled substances	**Decision XXIII/12** – Continue to assess the plasma destruction technology for methyl bromide in the light of any additional information that may become available and to report to the parties when appropriate	Considered. No new information available, no report prepared
Laboratory and analytical uses of controlled substances	**Decision XV/8** – Report on laboratory and analytical uses that can be performed without controlled substances in Annexes A, B and C (groups II and III) of the Montreal Protocol	June 2016 progress report
	Decision XXIII/6 – Continue reviewing international standards that mandate the use of ozone-depleting substances and work with the organizations that promulgate such standards to include non-ozone-depleting substances and procedures as applicable	Considered. No new information available, no report prepared
n-Propyl Bromide	**Decision XIII/7** – Report on use and emissions of n-propyl bromide	June 2016 progress report
New substances	**Decision IX/24** – Report on any new substances with ozone-depleting potential including an evaluation of the extent of use or potential use and, if necessary, the potential alternatives, and make recommendations on actions the parties should consider taking	Considered. No new information available, no report prepared
Periodic assessment		
–	–	–
	Number of reports produced in 2016:	9

Issue	Request by parties to TEAP	Report produced
2017		
Progress update		
Technical progress update by TEAP and its TOCs	**Decision IV/13** – Report annually to OEWG on technical progress in reducing the use and emissions of controlled substances and assess the use of alternatives, particularly their direct and indirect global-warming effects	May 2017 progress report
	Decision XI/17 – Report on any important new developments	
Thematic		
Critical-use nominations	**Decision IX/6** – Review nominations for critical use exemption of methyl bromide and make recommendations based on the criteria established in the decision (and other relevant decisions)	2017 interim report 2017 final report
Essential-use nominations	**Decision IV/25** – Review any submitted nominations and make recommendations in accordance with the criteria established in the decision	May 2017 progress report
Energy efficiency	**Decision XXVIII/3** – Review energy efficiency opportunities in the RACHP sectors related to a transition to climate-friendly alternatives, including not-in-kind options and assess the information submitted by parties	October 2017 Working Group report
Safety standards	**Decision XXVIII/4** – Report on safety standards relevant for low-GWP alternatives	May 2017 Task Force report
Process agents	**Decision XXII/8** – Review progress made in reducing process-agent uses and make any additional recommendations on further action to reduce uses and emissions of process agents	May 2017 progress report
Destruction technologies for controlled substances	**Decision XXIII/12** – Continue to assess the plasma destruction technology for methyl bromide in the light of any additional information that may become available and to report to the parties when appropriate	Considered. No new information available, no report prepared
Laboratory and analytical uses of controlled substances	**Decision XV/8** – Report on laboratory and analytical uses that can be performed without controlled substances in Annexes A, B and C (groups II and III) of the Montreal Protocol	Considered. No new information available, no report prepared
	Decision XVII/10 – Report on laboratory and analytical uses that can be performed without the controlled substance in Annex E of the Montreal Protocol	May 2017 progress report
	Decision XXIII/6 – Continue reviewing international standards that mandate the use of ozone-depleting substances and work with the organizations that promulgate such standards to include non-ozone-depleting substances and procedures as applicable	Considered. No new information available, no report prepared
n-Propyl Bromide	**Decision XIII/7** – Report on use and emissions of n-propyl bromide	Considered. No new information available, no report prepared

Issue	Request by parties to TEAP	Report produced
2017		
New substances	**Decision IX/24** – Report on any new substances with ozone-depleting potential including an evaluation of the extent of use or potential use and, if necessary, the potential alternatives, and make recommendations on actions the parties should consider taking	Considered. No new information available, no report prepared
Periodic assessment		
Replenishment study for 2018–2020	**Decision XXVIII/5** – Prepare a report on the appropriate level of the 2018–2020 replenishment of the Multilateral Fund	Replenishment Task Force report (2018–2020) Supplement to the replenishment Task Force report
	Number of reports produced in 2017:	7

Issue	Request by parties to TEAP	Report produced
2018		
Progress update		
Technical progress update by TEAP and its TOCs	**Decision IV/13** – Report annually to OEWG on technical progress in reducing the use and emissions of controlled substances and assess the use of alternatives, particularly their direct and indirect global-warming effects	May 2018 progress report
	Decision XI/17 – Report on any important new developments	
Thematic		
Critical-use nominations	**Decision IX/6** – Review nominations for critical use exemption of methyl bromide and make recommendations based on the criteria established in the decision (and other relevant decisions)	May 2018 interim report September 2018 final report
Process agents	**Decision XVII/6** – Review information submitted by parties on process-agent use exemptions, on insignificant emissions associated with a use, and process-agent uses that could be added or deleted from table A of decision X/14; review emissions in table B of decision X/14, taking into account parties' submissions, and recommend any reductions to the make-up and maximum emissions	May 2018 progress report
Destruction technologies for controlled substances	**Decision XXIX/4** and additional guidance by OEWG (40th meeting) – Assess destruction technologies for controlled substances	April 2018 Task Force report May 2018 supplemental Task Force report Addendum to May 2018 supplemental report
Halon availability	**Decision XXIX/8** – Report on the work of a possible joint working group with ICAO on future availability of halons and their alternatives	September 2018 report
HCFCs in non-Article 5 parties	**Decision XXIX/9** – Assess requirements for HCFCs in non-Article 5 parties for the period 2020–2030	March 2018 Working Group report
Energy efficiency	**Decision XXIX/10** and additional guidance by OEWG (40th meeting) – Report on issues related to energy efficiency while phasing down HFCs	May 2018 final Task force report September 2018 updated final Task force report
Laboratory and analytical uses of controlled substances	**Decision XV/8** – Report on laboratory and analytical procedures that can be performed without controlled substances in Annexes A, B and C (groups II and III) of the Montreal Protocol	May 2018 progress report
	Decision XXIII/6 – Continue reviewing international standards that mandate the use of ozone-depleting substances and work with the organizations that promulgate such standards to include non-ozone-depleting substances and procedures as applicable	September 2018 report
	Decision XXVI/5 – Report on the development and availability of laboratory and analytical procedures that can be performed without using controlled substances	

Issue	Request by parties to TEAP	Report produced
2018		
n-Propyl Bromide	**Decision XIII/7** – Report on use and emissions of n-propyl bromide	May 2018 progress report
New substances	**Decision IX/24** – Report on any new substances with ozone-depleting potential including an evaluation of the extent of use or potential use and, if necessary, the potential alternatives, and make recommendations on actions the parties should consider taking	Considered. No new information available, no report prepared
Periodic assessment		
Quadrennial assessment	**Decision XXVII/6** – Prepare the TEAP 2018 quadrennial assessment	TEAP and TOCs 2018 quadrennial assessment reports (6)
	Number of reports produced in 2018:	17

Abbreviations: EEAP – Environmental Effects Assessment Panel, HCFC – hydrochlorofluorocarbon, HFC – hydrofluorocarbon, ICAO – International Civil Aviation Organization, MOP – Meeting of the Parties, OEWG – Open-ended Working Group, TEAP – Technology and Economic Assessment Panel, SAP – Scientific Assessment Panel, TOCs – technical options committees.

4 The Impact of the Phase-out of Ozone-Depleting Substances on Sustainable Development

Paragraph 8 of Decision XXVII/6 requested the TEAP, in its 2018 Assessment Report, to consider the *"impact of the phase-out of ozone-depleting substances (ODS) on sustainable development."* The approach taken by the TEAP to respond to this paragraph of the decision has been to consider certain key United Nations decisions and reports related to sustainable development and also to consider the global transition away from ozone-depleting substances in the various sectors of use, as assessed in the quadrennial assessments of the TOCs.

1 Introduction

CFCs, which were listed in the first group of controlled substances by the Protocol, were considered wonder chemicals. They were considered almost chemically inert, and invaluable for safe refrigeration, among other properties. Annual production was in excess of 1 million tonnes per year through the 1970's.

Concerns on CFCs were first raised in the early 1970s when CFCs were found in the stratosphere in northern latitudes. In 1974, Rowland and Molina wrote their landmark paper which hypothesized that CFCs would catalyze the breakdown of stratospheric ozone (i.e., the CFCs themselves remain intact until they reach the stratosphere). Taken together with the very long atmospheric lifetime (50–100 years), Rowland and Molina cautioned about the threat to the atmosphere from the huge amounts of CFCs that were being made and emitted. However, the chemical industry actively campaigned against controls on CFCs. As a result, no concerted international action took place for over a decade, during which over 10 million tonnes of CFCs were manufactured.

In the early 1980s, most scientists believed that the impact of CFCs on ozone would be small, slow in onset, and generalized over the stratosphere. No one predicted localized depletion of ozone – known as the "Antarctic Ozone Hole" – which was identified in 1985. The discovery of severe ozone depletion and the very graphic images of the ozone hole was the trigger that persuaded politicians to take action, and industry to respond responsibly. The Montreal Protocol was signed in 1987, with initially a 50% reduction in CFC production and consumption, and the establishment of its unique funding mechanism, the Multilateral Fund (MLF), to assist developing countries. As solid evidence on the hazards of CFCs and other ODS accumulated, controls were gradually ratcheted up, by consensus agreement.

The Montreal Protocol was signed in 1987, when the politicians were persuaded to act by the first evidence of the Antarctic Ozone Hole. Once the ozone hole was discovered in 1985, the political response was remarkably speedy. The Protocol controlled CFCs and other ODS, on the basis of the *hypothesis* that they were the cause, but without solid proof of the role of CFCs, which emerged later that year. So, in signing the Montreal Protocol in 1987, the first 30 signatories were adopting the "precautionary principle", because at that time, both the size of the problem and the role of CFCs were unclear.

2 Sustainable Development and the Montreal Protocol

In each annual review of the eight Millennium Development Goals of the United Nations (MDGs) between 2000 and 2015, the success of the Montreal Protocol was highlighted under MDG#7 (To ensure environmental sustainability).

In 2000, the Millennium Assembly of the United Nations received a presentation from former UN Secretary General late Kofi Annan, entitled *"We the peoples: the role of the United Nations in the twenty-first century", in which he stated "Perhaps the single most successful international environmental agreement to date has been the Montreal Protocol"*.

In 2015, the concluding report on the Millennium Development Goals presented to the UN General Assembly, further highlighted the contribution of the Montreal Protocol to Sustainable Development. It stated *"Virtual elimination of ozone-depleting substances represents an unequivocal success of an intergovernmental effort. It reflects achievements in both integrating sustainable development principles into national policies and developing global partnerships for development."*

World leaders in United Nations Summit, in September 2015, embraced a sweeping 15-year global plan of action along with its set of 17 Sustainable Development Goals (SDGs). The SDGs were proposed to build on the momentum that had been created by the Millennium Development Goals (MDGs). MDGs had an end date of 2015. The 2015 SDGs were adopted as a decision of 193 members of the United Nations entitled *"Transforming our world: The 2030 Agenda for Sustainable Development"*. The implementation of SDGs commenced on 1 January 2016 with an end date in 2030.

In 2018, the President of the Conference of the Parties to the Vienna Convention for the Protection of the Ozone Layer (Vienna Convention) and the President of the Twenty-Ninth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) jointly submitted a report[4] to the High Level Political Forum on Sustainable Development (HLPF), in response to the invitation from the President of the United Nations Economic and Social Council.

The report describes the contribution of the Vienna Convention and its Montreal Protocol (the ozone treaties) towards those SDGs which are most relevant to the work of the two treaties. The contributions are summarized below. TEAP has built on this report, and other reports including the reports of TOCs, to present below the impact of the phase-out of ozone-depleting substances on sustainable development.

4 https://sustainabledevelopment.un.org/content/documents/18021Ozone_Treaties_Input_to_2018_High_Level_Political_Forum.pdf

3 Montreal Protocol: Progress in ODS phase-out

The near elimination of the production and consumption of ODS and the projected recovery of the stratospheric ozone layer has been one of the biggest environmental success stories of the 21st century. The Scientific Assessment Panel (SAP) of the Montreal Protocol has predicted the recovery of the ozone layer to pre-1980 levels by the middle of this century. In preventing the exponential increase in ODS and especially CFCs, which are potent and long lasting GHGs, the world avoided a projected average temperature increase of ~2.5° C by 2070 (~2°C in the tropics, 6°C in the Arctic, 4° C in Antarctica; Garcia RR, Kinnison DE, Marsh RM, 2012: https://doi.org/10.1029/2012JD018430). The twin impacts of the Protocol, on climate and on the ozone layer not only saved the world from catastrophe, but also contributed to sustainable development.

After the initial signing in 1987, the Montreal Protocol moved forward by universal consensus through a series of amendments to tighten controls. The rate of phase-down varied between different ODS. Some ODS and ODS technologies had relatively straightforward alternatives whilst others were more complex, with wider implications, longer consideration and delayed implementation. In many instances, developed countries could move faster than developing countries, which needed assistance. Sometimes, industrial rationalization was needed, with market winners and losers. In all cases, the initial priority was to phase out ODS and stop destruction of the ozone layer.

In phasing down ODS, the choices of ozone friendly alternatives in each sector often presented complex decisions. They have always been a step towards sustainable development, although not always the final step. For example:

- CFCs in domestic refrigeration have been replaced initially by HFC-134a (zero ODP, but high Global Warming Potential, GWP), and then to hydrocarbons (both zero-ODP and low GWP). HCFCs in domestic air conditioners have so far been replaced by HFC-410A with significant GWP. This has now required a response in terms of the Kigali Amendment, to phase down HFCs to reduce the potentially substantial increase in global temperature through their use.
- In foam blowing, CFCs were replaced in a single step by hydrocarbons as a blowing agent in Developed Countries. However, many SMEs in developing countries have been unable to switch in one step to hydrocarbon blowing agents because of the expensive fire protection required for safe production, and have been using HCFCs.

There are a number of examples where careful technical assessments have been important in determining the pace of safe phase-out of ODS in some sectors:

- Pharmaceutical grade CFCs used for many drugs in inhalers for Asthma/Chronic Obstructive Pulmonary Disease (COPD) have required annual essential use exemptions for two decades. Patients benefitted by a careful evidence-based approach during the development and safe introduction of CFC-free inhalers.
- Methyl bromide (MB) has been subject to annual assessments of diminishing amounts nominated for critical uses, whilst successful alternatives have been identified and adopted for virtually all controlled uses of the past. In 2018, 99% of the reported original volume of MB for controlled uses had been phased out. Substantial volumes of MB are however still used for exempted quarantine and pre-shipment (QPS) applications, which

are emitted directly to the atmosphere. Emissions could be reduced drastically by using barrier films, or via re-capture and/ or destruction technologies. Some challenges remain, including some pests potentially becoming resistant to the MB alternatives adopted for controlling them, and some key chemical alternatives to MB being restricted or even deregistered, putting their future availability in question.

- Halons remain essential for fire-protection in civil aviation. So far, there have been adequate supplies through stockpiles combined with re-cycling to avoid the need for new manufacture. However, no near-term alternatives have yet been identified for engine and cargo bays, the two largest uses of halons, in spite of substantial R&D. The challenge is to avoid complacency, carefully manage available banks of halons, and accelerate R&D efforts to identify safe and effective alternatives, in order to defer or avoid the need for new manufacture of halon-1301.

4 Montreal Protocol: Impact on Sustainable Development Goals

The TEAP has considered the impact of the phase-out of ODS under the Montreal Protocol on sustainable development by considering how the sector transitions relate to certain SDGs as discussed below.

4.1 Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture

Preventing the increase in UV radiation has avoided the adverse impacts on plant growth and agricultural production.

The challenge of phasing out Methyl Bromide (MB) generated as a side-benefit, a wealth of information and experience on agricultural production systems, including pest and disease control, fertilization and watering practices, cultural practices and others. This is particularly relevant to intensive agriculture (where MB was primarily used), but has been applicable to agriculture in general. Integrated Pest Management (IPM) and Integrated Crop Management programmes (ICM), non-chemical alternatives (grafting, soil-less culture, bio-fumigation), crop rotation and others were widely evaluated from technical and economical standpoints, and successfully implemented commercially in many countries around the world. Large numbers of growers and other key stakeholders were trained. This directly translates into agriculture production practices that are sustainable in the long term by protecting non-renewable resources, increasing productivity and resilience of different crops, enhancing food security, spurring economic development, and positively impacting human health.

Renewed attention to ODS alternatives and increasing energy efficiency in refrigeration, together with improved insulating properties of foam has helped the development of ozone-friendly and efficient cold chains for perishable foodstuffs. These have enabled developing countries to avoid loss of perishable foods. Setting up of cold chains for perishable foodstuffs, has enabled both developed and developing countries to reduce food loss.

Improved cold chains impacted food security and human health and availability by delaying food spoilage.

4.2 Goal 3: Ensure healthy lives and promote well-being for all at all ages

Near complete ODS phase-out has resulted in the stratospheric ozone layer starting on the path to recovery. By preventing the destruction of the ozone layer, the major increases in UV radiation largely has been avoided. This will result in the avoidance of millions of skin cancers and eye cataracts each year.

Some alternatives to MB are inherently safer for human health (integrated pest management promotes non-chemical alternatives and rational use of pesticides). Phase out of MB has improved worker safety.

Enhanced energy efficiencies in refrigeration and air conditioning appliances has resulted in reduced need for energy generation, with reduced air-pollution. The improved cold chain has meant safer storage of pharmaceuticals and vaccines making them more accessible for people in developing countries.

In medicine, the transition to CFC-free inhalers for asthma and COPD occurred in parallel with the development of a much wider range of inhalers, which has increased patient choice and contributed to improved disease control.

4.3 Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all

The ODS phase-out has driven the global transformation to both ozone-friendly and energy efficient refrigeration and air conditioning. Manufacturers and research institutes have used the opportunity to improve design and manufacturing practices and develop more energy efficient products and new technologies. For the consumer, the energy bills have been reduced.

The efficiency of refrigerators doubled between 1994 and 2015 in parallel with the transition to zero–ODP refrigerants and improved foam insulation. Considering the current annual production of 100 million refrigerators of latest energy consumption of 375 kWh per year, 10 new power plants of 500 MW capacity each are avoided per year, just due to energy efficient domestic refrigerators.

Currently the RACHP (refrigeration, air conditioning and heat pumps) sectors together account for 7.8% of total global greenhouse gas emissions[5]. Following the Kigali amendment, in parallel with the development and implementation of zero-ODP refrigerants, the RACHP industry will simultaneously improve the energy efficiency of many components and systems.

5 Int. Institute of Refrigeration, (2017). The Impact of Refrigeration Sector on Climate Change. 35th Info Note on Refrigeration Technologies, Nov 2017, IIR Paris. http://iifiir.org/userfiles/file/publications/notes/NoteTech_35_EN_uz7bwths.pdf.

4.4 Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

The phase-out of ODS had positive impact on the global economy, which is estimated to be nearly half a trillion USD between 1987 and 2060. The increased UV radiation resulting from the depletion of the ozone layer would have caused a range of damage extending from agriculture and fisheries, through to degradation of materials such as plastic and wood. There are further benefits due to lives saved and diseases prevented.

Some alternative technologies have needed investments in new, modified and retrofitted production lines, which avoided adverse impacts on the economic growth of the manufacturing and service industries in developing countries.

The MB phase-out process contributed to improving market access and opportunities for A5 parties in international trade of many products. Modern production technologies increased competitiveness; efficient, reliable cold chains allowed producers to extend the shelf life of their products and reach distant markets, with large economic benefits.

Access to cooling is increasing especially in regions with large economic development, improving the quality of indoor air, and the productivity of office workers. Air conditioning using cost effective ODS alternatives has been introduced, including in countries experiencing high ambient temperature and high air humidity.

There have been major opportunities in job training. For example, large numbers of growers and other key stakeholders were trained in sustainable agriculture production practices in the pursuit of MB phase-out. Many RAC technicians were trained or retrained globally in recycling, reclaiming and servicing of the alternative chemicals and technologies.

4.5 Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

In response to the Montreal Protocol control schedules, there was a major R&D effort in every sector to identify and commercialise ODS and ODS technology alternatives. Many new patents related to alternative products and technologies were filed in the short time period after 1987, as a direct result of the ODS phase-down and phase-out. These patent filings are testimony to the innovations that took place globally mainly by the initiative of the industry and research institutes. The patents led to commercial opportunities for the innovator companies, but required substantial investment. For example, the development costs for the pharmaceutical industry to reformulate drugs in CFC-free inhalers have been estimated well in excess of $2 billion USD.

The phase-out of ODS has encouraged climate-friendly and safer alternatives, some of which are not-in-kind technologies (e.g., agriculture – soil-less crop production, bio-fumigation and grafting; reduced-cooling-requirements through building design; innovation in refrigeration with absorption and adsorption refrigeration, natural refrigerants; solvent-free cleaning methods). Broad innovation across the range of alternatives has bought down the costs, and made them more affordable.

ODS phase-out also drove the innovative infrastructure for recycling, reclaiming, more efficient production practices, market access, competitiveness, etc. Effective gaseous fire protection that leaves no residue, minimizes damages and is compatible with energized electrical systems has enabled continued growth in telecommunications, cloud applications, server, and data centres for digital technologies such as the Internet of Things.

4.6 Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable

Many heavily populated cities of the world in high temperature or high humidity regions need efficient RAC. High pollution levels, which come at least in part from coal-fired power stations, have been mitigated by the reduced energy requirements that come with efficient RAC equipment. Many communities who live and work outdoors have been protected from the adverse effects of excessive UV exposure.

4.7 Goal 12: Ensure sustainable consumption and production patterns

Part of the unsustainable replacement of ODS, that resulted into the global warming is now being addressed under the Kigali Amendment of the Montreal Protocol to phase down high-GWP HFCs. HFCs are being replaced by ozone-friendly and climate-safe alternatives thereby setting the example of the long term sustainability of the production and consumption patterns.

The phase-out of ODS has driven technological improvements, such as better foam insulation and improved energy efficiency of refrigerators. These have contributed to the extending the food chain, which has reduced food waste.

For many environmentally damaging but essential chemicals, sustainable management systems have been developed which minimise production, avoid unnecessary emissions, with recycling or destruction of banks where appropriate. For example, halon-1301, which is a potent ODS and GHG, is essential for fire protection in civil aviation, and for some legacy military systems, and oil and gas production facilities. Through judicious management of stockpiles, with minimization of emissions, it has been possible to avoid any new production of halon-1301 for fire protection in non-Article 5 parties for over for 25 years and in Article 5 parties for almost 10 years.

4.8 Goal 13: Take urgent action to combat climate change and its impacts

The phase-out of ODS has had a major impact on mitigating climate change. First, it avoided the direct global warming of CFCs and HCFCs, which are extremely potent GHGs. The phase-out of ODS has already mitigated an estimated 135 billion tonnes of CO_2 equivalent emissions between 1990 and 2010, the most effective measures in climate change mitigation. Without the Protocol, CFC abundances would have increased exponentially, and it is estimated that the world has avoided a projected temperature increase of ~2.5°C by 2070.

During the ODS phase-out there has been substantial efficiency improvements of RAC equipment. Domestic refrigerators have already more than doubled their energy efficiency. The energy efficiency of AC is improving around the world, and will continue to do so in parallel with the HFC phase-down. The phase-out of ODS has driven energy efficient technological improvements, such as better foam insulation which add to the energy efficiency benefits in mitigating climate change.

After the Kigali Amendment, the phase-down of HFCs in the RAC sector is already occurring in equipment that is more energy efficient. This will partially offset the huge increase in demand for energy generation that will be needed in the developing world as they acquire increasing amounts of AC.

4.9 Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development; and

Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

The eventual recovery of the Ozone layer as a result of phase out of ODS will remove the potentially catastrophic threat of excessive UV radiation on the land and oceans which are the key parts of the Earth's ecosystems. Many micro-marine organisms including phytoplankton, fish larvae and small fish are sensitive to UV radiation. It has also protected the economies of countries and sectors that rely on those resources.

There have been other unanticipated benefits in terms of sustainability from the Montreal Protocol. The phase-out of methyl bromide has provided a unique opportunity to develop integrated pest management programmes, which lead to reduced and rationalised use of chemical fumigants and other chemical products.

4.10 Goal 17: Partnerships for the Goals

The Montreal Protocol is an outstanding example of how global partnerships can be forged with the relevant stakeholders, and then effectively be implemented at national and global level.

The financial mechanism of the Montreal Protocol, the Multilateral Fund (MLF), provides technical and financial resources to Article 5 parties to help them meet their Montreal Protocol obligations. The MLF has supported technology transfer projects that have replaced ODS with ozone-friendly substitutes and technologies in Article 5 parties. So far, it has allocated approximately USD $3.6 billion to assist 147 Article 5 parties. As result of MLF project implementation processes and the search for new alternatives suitable to conditions in Article 5 parties, partnerships were consolidated, with the participation of MLF, governments and industries.

The partnership with the Global Environment Facility (GEF) was instrumental in effective phase out of ODS in countries with economies in transition (CEIT) which were not funded by the MLF. It also assisted countries in all regions to transform their markets for energy efficiency products during the CFC and HCFC phase-out.

The Ozone Secretariat has acted as a catalyst for the transparent reporting and tracking of MP compliance. Following decisions of the parties, it has developed partnerships with other important international organizations such as the United Nations Framework Convention on Climate Change, the International Plant Protection Convention, the International Civil Aviation Organisation, the International Maritime Organisation and the World Meteorological Organisation, and with industry associations and other non-governmental organisations (NGOs).

TEAP and its TOCs provide policy-neutral, technical and economic information to support the decisions and priorities determined by the parties. TEAP consists of independent and voluntary experts who come mainly from industry, academia, NGOs etc. They are politically independent, and work by consensus to provide policy-relevant, technical and economic information to the parties to the protocol, on the feasibility and timing of the phase-out of ODSs, as well as the introduction of alternative non-ODS chemicals and technologies.

The partnerships formed between the multilateral environmental treaties have assisted the Montreal Protocol in managing the ODS phase-out.

5 Could the Montreal Protocol have done better in terms of Sustainable Development?

5.1 Slow initial response

The application of the precautionary principle a decade earlier could have prevented the continued production of around 10 million tonnes of CFCs over the decade between the Rowland and Molina paper and the signing of the Montreal Protocol. The long atmospheric lifetime of CFCs means that they will slowly decline over coming decades, and this will eventually return ozone levels to pre 1970's levels by around 2060. However, because of the up to 40 years delay between exposure to UV in early life and skin cancer in later life, skin cancer rates associated with the increased UV radiation will not normalize until 2100. People will still be dying of skin cancer as a result of ozone layer depletion over 100 years after the initial environmental insult.

5.2 High GWP ODS alternatives

The strong link to climate change from some of the ODS alternatives with high GWP, such as HFCs, has been apparent for some time, but the responsibility for the emissions control was outside the scope of the Montreal Protocol. Following agreement within UNEP, and with the support of the United Nations Framework Convention for Climate Change, the Montreal Protocol took responsibility by a consensus decision of parties to phase down the consumption and production of HFCs under the Kigali Amendment in 2016. In some sectors in A5 parties (e.g., foam blowing), there is still the opportunity to leapfrog to low GWP alternatives. But for large sectors such as AC in A5 parties, it has been difficult to prevent the accelerated increase of high GWP refrigerants during the phase-out of CFCs and HCFCs. Nevertheless, the parties to the Protocol now have an opportunity for a double success in terms of sustainable development – the substitution of inefficient AC equipment using HFCs, by increasingly energy efficient AC using low GWP alternatives, through the effective implementation of the Kigali Amendment.

5.3 Industry response

Industry has generally recognized the need to drive innovation to protect the environment, and responded to demands for environmentally neutral technologies. It is therefore disappointing that recent evidence has indicated new production of CFC-11, well after its phase-out under the Montreal Protocol in 2010. Continued vigilance through on-going and increased atmospheric monitoring can provide alerts for current and future threats, so that parties can monitor global compliance, as part of the obligations to the Montreal Protocol.

6 Building partnerships to phase down HFCs

The Montreal Protocol is uniquely placed to build the global partnerships described above in SDG 17 to phase down HFCs and mitigate their climate change threats. It has the opportunity to build partnerships to phase in safe low-GWP alternatives. The Montreal Protocol can support and coordinate efforts by individual parties to introduce energy efficient technologies in parallel with the HFC phase-down. It could partner with climate funding bodies and continue to use the MLF to drive technology transfer, so that Article 5 parties are not disadvantaged during the transition. It can coordinate the information from atmospheric monitoring to show that HFC levels are declining appropriately, and if they are not, it has the capacity to monitor compliance.

7 Conclusion

The Montreal Protocol has been a remarkably effective mechanism to prevent global catastrophe, from the twin threats of ozone depletion and climate change. The near elimination of ODS under the Montreal Protocol has made a major and effective contribution to sustainable development. It should remain vigilant and ensure compliance with the final phase-out of ODS. When ODS replacements such as HFCs have been phased down and replaced by environmentally neutral, safe and sustainable alternatives, the Montreal Protocol will have made its full contribution to sustainable development.

5 TEAP and TOC membership information

1 TEAP and TOC Membership Lists – Status at December 31st, 2018

The following lists include members who were active until 31 December 2018, and participated in the preparation of the TOC 2018 Assessment Reports.

Table 5.1 **Technology and Economic Assessment Panel (TEAP)**

TEAP Co-chairs	Affiliation	Country
Bella Maranion	US Environmental Protection Agency	USA
Marta Pizano	Independent Expert	Colombia
Ashley Woodcock	Manchester University NHS Foundation Trust	UK

Senior Expert Members	Affiliation	Country
Mohamed Besri*	Institut Agronomique et Vétérinaire Hassan II	Morocco
Suely Carvalho	Independent Expert	Brazil
Marco Gonzalez	Independent Expert	Costa Rica
Rajendra Shende	Terre Policy Centre	India
Sidi Menad Si-Ahmed	Independent Expert	Algeria
Shiqiu Zhang	College of Environmental Sciences and Engineering, Peking University	China

TOC Chairs	Affiliation	Country
Paulo Altoé	Dow Chemical	Brazil
Adam Chattaway	Collins Aerospace	UK
Sergey Kopylov	All Russian Research Institute for Fire Protection	Russian Federation
Roberto de A. Peixoto	Maua Technological Institute	Brazil
Fabio Polonara	Marche Polytechnic University	Italy
Keiichi Ohnishi	AGC Inc.	Japan
Ian Porter	La Trobe University	Australia

TOC Chairs	Affiliation	Country
Helen Tope	Energy International Australia	Australia
Daniel Verdonik	Jensen Hughes Inc.	USA
Helen Walter-Terrinoni	Air-conditioning, Heating and Refrigeration Institute	USA
Jianjun Zhang	Zhejiang Chemical Industry Research Institute	PR China

* Membership ended December 31, 2018

Table 5.2 **FTOC – Flexible and Rigid Foams Technical Options Committee**

Co-chairs	Affiliation	Country
Paulo Altoé	Dow Chemical	Brazil
Helen A Water Terrinoni	Air-conditioning, Heating and Refrigeration Institute	US

Members	Affiliation	Country
Samir Arora	Industrial Foams	India
Paul Ashford	Anthesis Group	UK
Angela Austin	Independent Expert	UK
Kultida Charoensawad	Covestro	Thailand
Roy Chudhury	Foam Supplies	Australia
Joe Costa	Arkema	US
Gwyn Davies	Kingspan Group	UK
Rick Duncan	Spray Polyurethane Foam Association	US
Rajaran Joshi	Owens Corning	India
Ilhan Karaagac	Izo Can	Turkey
Shpresa Kotaji	Huntsman Corporation	Belgium
Simon Lee	Independent Expert	US
Yehia Lofty	Techno Cam	Egypt
Lisa Norton	Solvay	US
Miguel Quintero	Independent Expert	Colombia
Sally Rand	Independent Expert	US
Sascha Rulhoff	H-C-S Group	Germany
Enshan Sheng	Huntsman Corporation	China
Kooichi Wada	Japan Urethane Industry Institute	Japan
David J Williams	Honeywell	US
Guolian Wu	Samsung	US
Wentao Allen Zhang	Independent Expert	China

Table 5.3 **HTOC – Halons Technical Options Committee**

Co-chairs	Affiliation	Country
Adam Chattaway	Collins Aerospace	UK
Sergey Kopylov	All Russian Research Institute for Fire Protection	Russian Federation
Daniel P. Verdonik	Jensen Hughes Inc.	USA

Members	Affiliation	Country
Jamal Alfuzaie	Independent Expert	Kuwait
Johan Åqvist	FMV (Swedish Defence Materiel Administration)	Sweden
Youri Auroque	European Aviation Safety Agency	France
Seunghwan (Charles) Choi	Hanchang Corporation	South Korea
Michelle M. Collins	Independent Expert- EECO International	USA
Khaled Effat	Modern Systems Engineering – MSE	Egypt
Carlos Grandi	Embraer	Brazil
Laura Green	Hilcorp	USA
Elvira Nigido	A-Gas Australia	Australia
Emma Palumbo	Safety Hi-tech srl	Italy
Erik Pedersen	Independent Expert	Denmark
R.P.Singh	Centre for Fire, Explosives and Environment Safety, Defence Research and Development Organisation	India
Donald Thomson	MOPIA	Canada
Mitsuru Yagi	Nohmi Bosai Ltd & Fire and Environment Prot. Network	Japan

Consulting Experts	Affiliation	Country
Pat Burns	Retired	USA
Thomas Cortina	Halon Alternatives Research Corporation	USA
Matsuo Ishiyama	Nohmi Bosai Ltd & Fire and Environment Prot. Network	Japan
Nikolai Kopylov	All Russian Research Institute for Fire Protection	Russian Federation
Steve McCormick	United States Army	USA
John G. Owens	3M Company	USA
John J.O'Sullivan	Bureau Veritas	UK
Mark L. Robin	Chemours	USA
Joseph A. Senecal	FireMetrics LLC	USA
Ronald S. Sheinson	Independent Expert	USA
Robert T. Wickham	Independent Expert	USA

Table 5.4 **MBTOC – Methyl Bromide Technical Options Committee**

Co-chairs	Affiliation	Country
Marta Pizano	Independent Expert	Colombia
Ian Porter	La Trobe University	Australia

Members	Affiliation	Country
Cao Aocheng	Institute for Plant Protection, Chinese Academy for Ag. Sci.	China
Jonathan Banks	Independent Expert	Australia
Fred Bergwerff	Eco2, Netherlands	Netherlands
Mohamed Besri	Institut Agronomique et Vétérinaire Hassan II	Morocco
Sait Erturk	Turkish Ministry of Agriculture	Turkey
Ken Glassey	Senior Advisor Operational Standards Biosecurity	US
NZ, Min. of Agriculture and Forestry Wellington	New Zealand	UK
Alfredo Gonzalez	Independent Expert/ Fumigator	Philippines
Rosalind James	United States Department of Agriculture	USA
Takashi Misumi	MAFF	Japan
Christoph Reichmuth	Humboldt University	Germany
Jordi Riudavets	IRTA – Department of Plant Protection	Spain
Akio Tateya	Japan Fumigation Technology Association	Japan
Alejandro Valeiro	Department of Agriculture	Argentina
Nick Vink	University of Stellenbosch	South Africa

Table 5.5 **MCTOC – Medical and Chemicals Technical Options Committee**

Co-chairs	Affiliation	Country
Kei-ichi Ohnishi	Asahi Glass	Japan
Helen Tope	Energy International Australia	Australia
Jianjun Zhang	Zhejiang Chemical Industry Research Institute	China

Members	Affiliation	Country
Emmanuel Addo-Yobo	Kwame Nkrumah University of Science and Technology	Ghana
Fatima Al-Shatti	Consultant to the International Ozone Committee of the Kuwait Environmental Protection Authority	Kuwait
Paul Atkins	Oriel Therapeutics Inc. (A Novartis Company)	USA
Bill Auriemma	Diversified CPC International	USA
Olga Blinova	Russian Scientific Center "Applied Chemistry"	Russia
Steve Burns	AstraZeneca	UK
Nick Campbell	Arkema	France
Jorge Caneva	Favaloro Foundation	Argentina
Nee Sun (Robert) Choong Kwet Yive	University of Mauritius	Mauritius
Rick Cooke	Man-West Environmental Group Ltd.	Canada
Davide Dalle Fusine	Chiesi Farmaceutici (seconded at Chiesi China)	Italy
Maureen George	Columbia University School of Nursing	USA
Kathleen Hoffmann	Sterigenics International Inc.	USA
Eamonn Hoxey	E V Hoxey Ltd	UK
Jianxin Hu	College of Environmental Sciences & Engineering, Peking University	China
Ryan Hulse	Honeywell	USA
Biao Jiang	Shanghai Institute of Organic chemistry, Chinese Academy of Sciences	China
Javaid Khan	The Aga Khan University	Pakistan
Andrew Lindley	Independent consultant to Mexichem (UK) Ltd. and to the European Fluorocarbon Technical Committee	UK
Gerald McDonnell	DePuy Synthes, Johnson & Johnson	USA
Robert Meyer	Independent Consultant to Greenleaf Health	USA
John G. Owens	3M	USA
Jose Pons Pons	Spray Química	Venezuela
Hans Porre	Teijin Aramid	Netherlands
John Pritchard	Private Consultant	UK

Members	Affiliation	Country
Rabbur Reza	Beximco Pharmaceuticals	Bangladesh
Paula Rytilä	Orion Corporation Orion Pharma	Finland
Surinder Singh Sambi	Indian Institute of Chemical Engineers (Northern Region)	India
Rajiev Sharma	GSK	UK
Roland Stechert	Boehringer Ingelheim	Germany
Jørgen Vestbo	University of Manchester	Denmark
Kristine Whorlow	Non-Executive Director	Australia
Ashley Woodcock	University Hospital of South Manchester	UK
Yizhong You	Journal of Aerosol Communication	China

Consulting Experts	Affiliation	Country
Archie McCulloch	Independent Consultant to European Fluorocarbon Technical Committee (EFCTC)	UK
Hideo Mori	Tokushima Regional Energy	Japan
Tim Noakes	Mexichem (UK) Ltd.	UK
Lifei Zhang	National Research Center for Environmental Analysis and Measurement	China

Table 5.6 RTOC – Refrigerants Technical Options Committee

Co-chairs	Affiliation	Country
Peixoto, Roberto	Maua Institute, IMT, Sao Paulo	Brazil
Polonara, Fabio	Universita delle Marche, Ancona	Italy

Members	Affiliation	Country
Britto, Maria C	Johnson Controls, JCI	Brazil
Calm, James M.	Calm Consultancy	USA
Cermák, Radim	Ingersoll Rand	Czech Republic
Chen, Guangming	Zhejiang University, Hangzhou	PR China
Chen, Jiangpin	Shanghai JiaoTong University	PR China
Colbourne, Daniel	Re-phridge Consultancy	UK
De Vos, Richard	GE Appliances	USA
Devotta, Sukumar	Independent Expert	India
Dieryckx, Martin	Daikin Europe N.V,	Belgium
Dorman, Dennis	Trane Co.	USA
Elassaad, Bassam	Independent Expert	Lebanon
Gluckman Ray	Gluckman Consulting	UK
Godwin, Dave	U.S. EPA	USA

Members	Affiliation	Country
Grozdek, Marino	University of Zagreb	Croatia
Hamed, Samir	Petra Industries	Jordan
Herlin, Herlianika	PTAWH	Indonesia
Janssen, Martien	Re/genT B.V.	Netherlands
König, Holger	Independent Expert	Germany
Kauffeld, Michael	Fachhochschule, University Karlsruhe	Germany
Koban, Mary E.	Chemours Co	USA
Köhler, Jürgen	University of Braunschweig	Germany
Kuijpers, Lambert	Independent Expert	Netherlands
Lawton, Richard	Cambridge Refrigeration Technology CRT	UK
Li, Tingxun	Guangzhou San Yat Sen University	PR China
Malvicino, Carloandrea	FCA (Fiat)	Italy
Mohan Lal D.	Anna University, Chennai	India
Mousa, Maher	Independent Expert	Saudi Arabia
Nekså, Petter	SINTEF Energy Research	Norway
Nelson, Horace	Independent Expert	Jamaica
Okada, Tetsuji	JRAIA	Japan
Olama, Alaa M.	Independent Expert	Egypt
Pachai, Alexander C.	Johnson Controls, JCI	Denmark
Pedersen, Per Henrik	Independent Expert	Denmark
Rajendran, Rajan	Emerson	USA
Rusignuolo, Giorgio	UTC Carrier	USA
Vonsild, Asbjørn	Independent Expert	Denmark
Yana Motta, Samuel	Honeywell (USA)	Peru
Yamaguchi, Hiroichi	Toshiba Carrier Co	Japan

6 Annex – Executive Summaries of all TOCs

1 Flexible and Rigid Foams TOC (FTOC)

- Regulations continue to evolve regarding the use of controlled hydrofluorocarbons (HFCs) in foams driving transitions to low GWP alternatives especially in many non-Article 5 parties (nA5 parties).
- There have been significant improvements in the development and availability of additives, co-blowing agents, equipment and formulations enabling the successful commercialisation of foams and foam systems containing low GWP blowing agents.
- Article 5 parties (A5 parties) face common challenges in phasing out hydrochlorofluorocarbons (HCFCs) and phasing down high global warming potential (GWP) HFC blowing agents.
  - HPMPs continue to drive transitions in foams.
  - In general, HCFCs are less than half of the cost of high GWP HFCs and hydrofluoroolefin / hydrochlorofluoroolefin (unsaturated HCFCs and HFCs) blown foams remain more expensive than HFC foams due to the total cost of blowing agent and required additives.
  - In some A5 parties, import of HCFC-141b itself is controlled or under license, but polyols containing HCFC-141b can be imported without controls. To counter this, some A5 parties have implemented regulations that would ban or restrict import of HCFC-containing polyol systems.
  - Decisions on transition for some segments (e.g. spray foam and extruded polystyrene [XPS]) may be delayed because the cost of transition is still being optimized for some regions.
  - Capacity planning for alternatives will require continued communication between regulators, producers and users to ensure smooth transitions.
- Total global production of polymeric foams continues to grow (3.9% per year) at a slightly lower rate than noted last year (4.0%), from an estimated 24 million tonnes in 2017 to 29 million tonnes by 2023. Production of foams used for insulation is expected to grow in line with global construction and continued development of refrigerated food processing, transportation and storage (cold chain).
- Based on average blowing agent percentages of 5.5% w/w for polyurethane and 6% w/w for XPS, the estimated demand of greater than 400,000 tonnes with a further

10,000 tonnes being consumed by other foam types. Further, it is estimated that blowing agent demand would grow to above 500,000 tonnes by 2023 based on the growth rates presented below.

1.1 Global Markets for Foams

Table 1 **Estimated Global Polymer Foam Production 2017–2023 (tonnes)**

Estimated Global Polymer Foam Production (tonnes)	2017	2023	CAGR[6]%
Polyurethane			
Rigid	**5,352,900**	**6,831,808**	**5.00%**
Flexible	**7,447,700**	**9,100,541**	**4.09%**
Total PU Foam Production	12,800,600	15,641,391	4.54%
Polystyrene			
EPS	**8,523,575**	**9,890,000**	**3.02%**
XPS	**1,750,000**	**1,850,000**	**1.12%**
Total Polystyrene Foam Production	10,273,575	11,740,000	2.70%
Phenolics, Polyolefins, EVA, ENR	1,613,000	2,150,000	5.92%
Total Estimated Polymeric Foams	24,687,175	29,531,391	3.87%

The market size of polymer foam is projected to grow at a Compound Annual Growth Rate of 3.9% from 2017 to 2023 in volume from just over 24 million tonnes to 29 million tonnes. The rate of growth is estimated to be slowing due to concerns about plastics in the environment and legislation regarding disposal of polymeric foams.[7] Additional details related to polyurethane foams are provided in Table 1.1 below.

6 Compound Annual Growth Rate

7 Market & Market Global Polymeric Foam Report 2017–2022

Table 1.1 **Estimated Global Polyurethane Foam Production 2017 (tonnes)**[8]

	EMEA	NAFTA	CHINA	APAC	LATAM	Global
2017						
Global Rigid PU (Tonnes)						
Panels	**990,000**	**610,000**	**120,000**	**90,000**	**50,000**	**1,860,000**
Slabstock	**7,000**	**22,000**	**60,000**	**6,000**	**1,000**	**96,000**
Pipe Insulation	**75,000**	**18,000**	**190,000**	**30,000**	**1,000**	**314,000**
Spray Foam	**115,000**	**320,000**	**80,000**	**50,000**	**5,000**	**570,000**
Pour in place & OCF	**45,000**	**30,000**	**260,000**	**15,000**	**5,000**	**355,000**
Total Construction	1,232,000	1,000,000	710,000	191,000	62,000	3,195,000
Total refrigeration	**365,000**	**265,000**	**1,002,500**	**250,000**	**108,000**	**1,990,500**
Others*	**80,000**	**27,000**	**40,000**	**10,400**	**10,000**	**167,400**
Total Rigid PU Foam	1,677,000	1,292,000	1,752,500	451,400	180,000	5,352,900
Global Flexible PU						
Slabstock	**1,700,500**	**835,000**	**2,080,000**	**600,000**	**420,000**	**5,635,500**
Total Automotive	**440,000**	**354200**	**380,000**	**278,500**	**75,000**	**1,527,700**
Non-Automotive	**50,000**	**57,000**	**150,000**	**45,000**	**6,000**	**308,000**
Total Moulded Foam	**490,000**	**411,200**	**530,000**	**323,500**	**81,000**	**1,835,700**
Total Flexible Foam	**2,167,000**	**1,246,200**	**2,610,000**	**923,500**	**501,000**	**7,447,700**
Total Foams	3,844,000	2,538,200	4,362,500	1,374,900	681,000	12,800,600

*Others rigid packaging, moulded furniture, craft and hobby, miscellaneous

8 Estimated Global PU Foam Production (ICF, Technical Experts, EPA, HPMPs

1.2 Global Drivers for Foams

The increasing disposable incomes of the growing global, urban middle class remain the main drivers of the global polymeric foam market. Demand is driven by its wide range of end-use industries, building & construction, the cold chain, furniture & bedding, packaging and automotive industries. Rigid polymeric foams are most often used for thermal insulation and packaging. These foams historically have used blowing agents controlled by the Montreal Protocol.

Polyurethane, polystyrene and phenolic foams contribute substantially to the energy efficiency in buildings. Global construction is forecast to increase by USD 8 trillion by 2030, creating a global annual growth in demand for thermal insulation of 4–5%[9]. The main drivers for thermal insulation are legislation and building standards to reduce heat loss. The EU and North America are currently leading proponents of building codes to reduce energy consumption in the construction industry. Emerging countries in Asia Pacific are fast growing markets for polymeric foams that offer thermal insulation.[10]

In all buildings, the demand for thermal insulation has increased substantially as their role in reducing energy dependency and greenhouse gas emissions has been recognised. New or improved thermal insulation requirements have emerged across the Middle East and throughout India, China, South Africa and Latin America. Even though there has been some shift between fibre (mineral/slag wool) and foam market shares in China during the period, mostly as a result of fire concerns, the production of polyurethane chemicals had grown globally. Other competing foam insulation materials are expanded polystyrene (never used ozone depleting substances), extruded polystyrene (XPS), phenolic and polyethylene foams. The demand for XPS foams is also growing. There is also recognition that, in most non-Article 5 parties, over 50% of the buildings that will be operational in 2050 have already been built. If progress on building energy efficiency and related CO_2 emissions is going to be made in A5 parties, then significant renovation will be necessary.

Current foam projections[11] predict on-going growth to 2019 of 4% per year. On this basis global blowing agent consumption will exceed 520,000 tonnes by 2020 unless there are further gains in blowing efficiency as technologies develop. Based on these trends, the historic, current and future demand for physical blowing agents is summarised in Figure 1 below:

Rigid polyurethane foam accounts for 30% of the total estimated polymeric foam produced, the major drivers being regulation and energy efficiency, especially in construction and the cold chain.[12]

An estimated one third of global food production requires refrigeration. The Food and Agricultural Organization estimates that food production needs to increase globally by 70% to feed an additional 2.3 billion people by 2050, therefore refrigeration has an increasing role to play in food preservation.[13]

9 Oxford Economics – Global Construction Trends to 2030

10 Ialconsultants.com – EU Thermal Insulation Markets 2018

11 RAPRA Report 'The Future of Polymer Foams: Market Forecasts'

12 JRC Technical Report on the Competition Landscape of Thermal Insulation

13 Cooling and refrigeration sector: the centre of the EU's energy system, CORY ALTON MAY 2017, PUBLISHED IN BLOG

1.3 Trends in Global Foam Use and Impacts on Blowing Agent Consumption

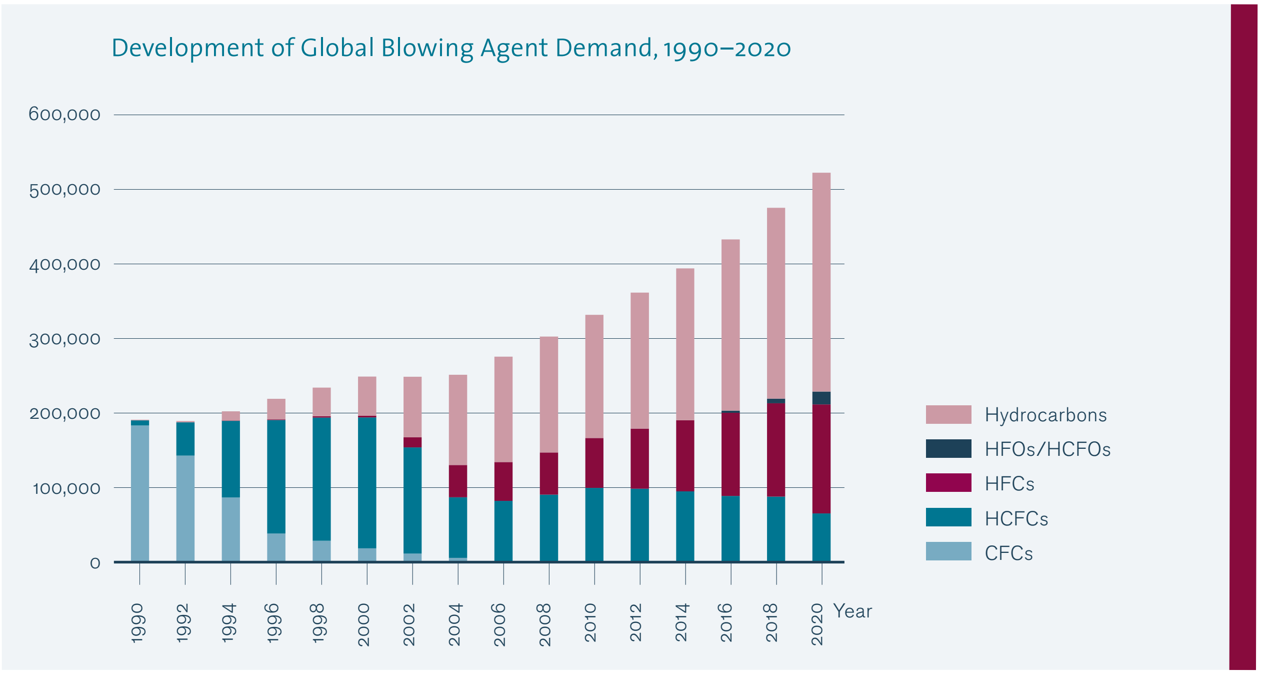

Figure 1 **Growth in the use of Physical Blowing Agents by Type over the period from 1990 to 2020. Source: FTOC 2014 Assessment Report**

1.4 Update on Bank Estimates and Emerging Management Strategies

1.4.1 Overview of Progress and Challenges Related to Blowing Agent Transitions

The major blowing agent transitions being driven by regulation currently are those in Article 5 parties resulting from Decision XIX/6 and being funded under national HCFC Phase-out Management Plans (HPMPs). First phase HPMP implementation is generally running smoothly, although there have been delays in the initiation of some plans owing to the significant administration involved. Since Decision XIX/6 requires a "worst first" approach, the phase-out of HCFC-141b has been particularly targeted over the period covered by this report. This has been broadly successful within larger enterprises where the critical mass of the operation is sufficient to justify investment in hydrocarbon technologies, often with individual enterprises often willing to co-fund the investment where the funding thresholds available under the Multilateral Fund have been insufficient.

Foams manufactured using other blowing agents, notably extruded polystyrene (XPS), have not typically been part of the first phase of most HPMPs. This is because there are no proven low-GWP alternatives to HCFC-142b/22 currently available. Although CO_2 based technology is prevalent in Europe, it is still not clear whether it is sufficiently versatile for the variety of manufacturing plants operating in Article 5 parties. Other alternatives include hydrocarbons and ethers, but the flammability of these blowing agents is problematic when coupled with polystyrene as brominated flame retardants are also being phased out in some countries. The concern about flammability has increased in Asia since 2010 following a series of major building fires, which occurred during the construction of some high-rise buildings. Despite these concerns, investment in XPS manufacturing capacity is increasing in response to demand for inexpensive and effective insulation. This has particularly been the case in Russia, the Middle East and parts of Eastern Europe and North Africa. The current choices of blowing agent in these regions are blends of HFC-134a/HFC-152a, which have a GWP of 1430 and 124 respectively. The manufacturing process is typically quite emissive. Blends based on a combination of hydrofluoroolefins (HFOs) and/or hydrochlorofluoroolefins (HCFOs) together with hydrocarbons, ethers or other low GWP blowing agents may ultimately provide a solution for XPS, but the continuing development is causing delay on conversions for some parties. The net impact of these trends is projected in the Figure 2 below:

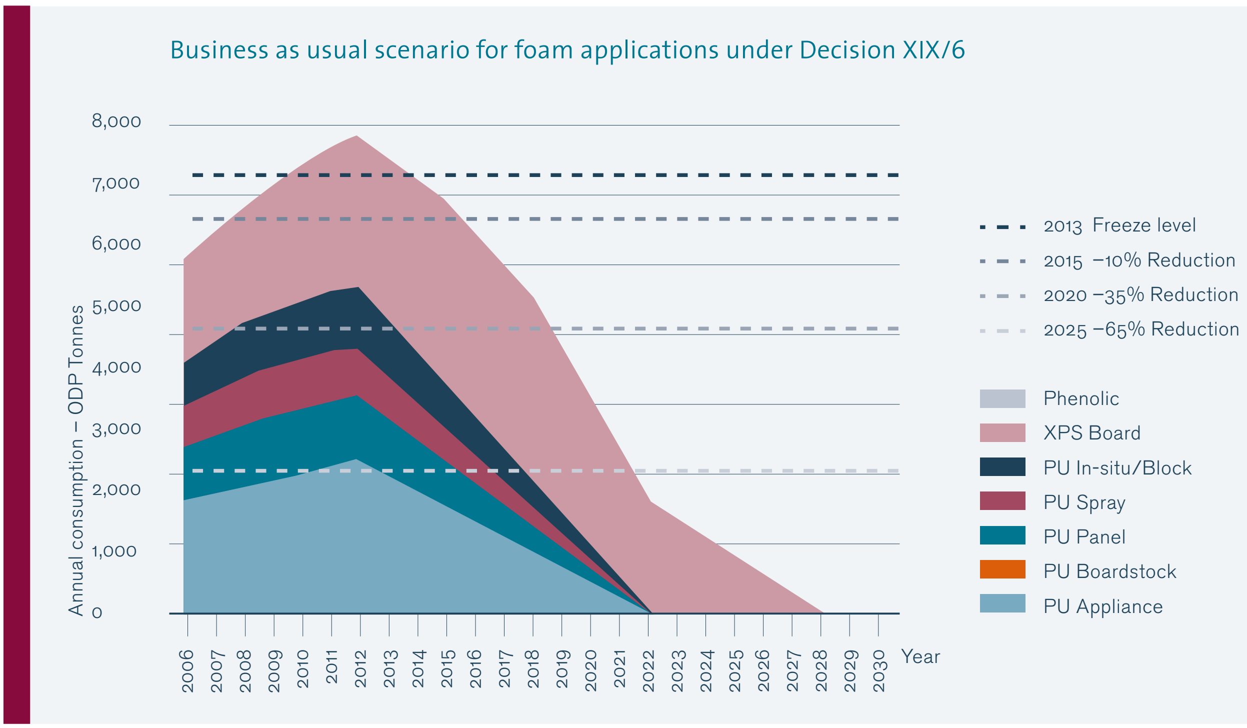

Figure 2 **Evolution of consumption patterns for blowing agents in Article 5 parties with time. Source: FTOC 2014 Assessment Report**

The growth in XPS could have resulted in a possible breach of the 2013 HCFC Freeze in the foam sector. However, parties noted no issues with non-compliance with the Protocol, and there is always the potential to compensate in other sectors or require other transitions in foams to meet the required levels.

In addition, there are challenges remaining for small and medium enterprises (SMEs). Lack of economies of scale prevents the adoption of hydrocarbons, while the adoption of high GWP alternatives results in high climate impact within processes, which are typically less well engineered or are unavoidably emissive. Although transitions from HCFCs to HFCs were largely unavoidable in many non-Article 5 parties during phase-out of HCFCs, there is increasing pressure to switch to low-GWP technologies. In view of hydrocarbon flammability, the focus is on the potential role of less flammable blowing agents such as unsaturated HCFCs and HFCs or all water-blown formulations. For integral skin applications, oxygenated hydrocarbons such as methyl formate are becoming the blowing agent of choice while the major PU Spray Foam markets of the USA and Canada, seem to be adopting unsaturated HCFCs and HFCs, with commercial systems now emerging.

During the negotiation of the HFC amendment, parties discussed patented low GWP products and the challenges that parties might face in converting to those patented products due to access and potential cost. Unsaturated HFCs and HCFCs are patented in some parties; however, there are also many parties where there are no patents related to unsaturated HFCs and HCFCs. Unsaturated HFCs and HCFCs have been commercialized in many parties including in some of those where they are patented. Some members of the committee noted that adoption of patented products might be slower in some countries and some foam products for some parties while other members note that this may not be an issue as evidenced by some of the adoption in already.

Non-Article 5 parties in North America, Europe and Japan are now pursuing regulatory strategies to encourage the phase-out of HFC use in the foam sector. In Europe, this has been enacted under the re-cast F-Gas Regulation, while in the USA, the existing Significant New Alternatives Program (SNAP) is being explored as a tool for the de-selection of some blowing agent options. These regulatory initiatives could place particular pressure on the XPS industry in these regions, since universally acceptable alternatives are still to emerge. In Japan, GWP limits have been set on PU Spray foam from 2020 and reporting requirements continue for HFC-245fa and HFC-365mfc.

Global banks of blowing agents in foams are estimated to have grown from around 3 million tonnes in 2002 to an estimated 4.45 million tonnes in 2015[14]. Based on current consumption estimates, these will grow to well in excess of 5 million tonnes by 2020. This is in spite of the fact that some of the bank will have moved into the waste stream (typically landfill) by then. i.e. the relative proportion of ODS and GWP chemicals to the total bank is declining. ODS-containing foam is being increasingly treated as hazardous waste, but monitoring shipments is difficult when no simple way of determining the blowing agent within a foam exists. The search for appropriate detection equipment continues for both the characterisation of waste and the monitoring of cross-border trade. One option is to encourage voluntary intervention at decommissioning by assigning value to the process. However, the average global warming potential (GWP) of the waste stream will decrease with time making this less economically viable. Figure 3 illustrates this trend:

14 Data adapted from Special Report on Ozone and Climate (2005) – values include hydrocarbons

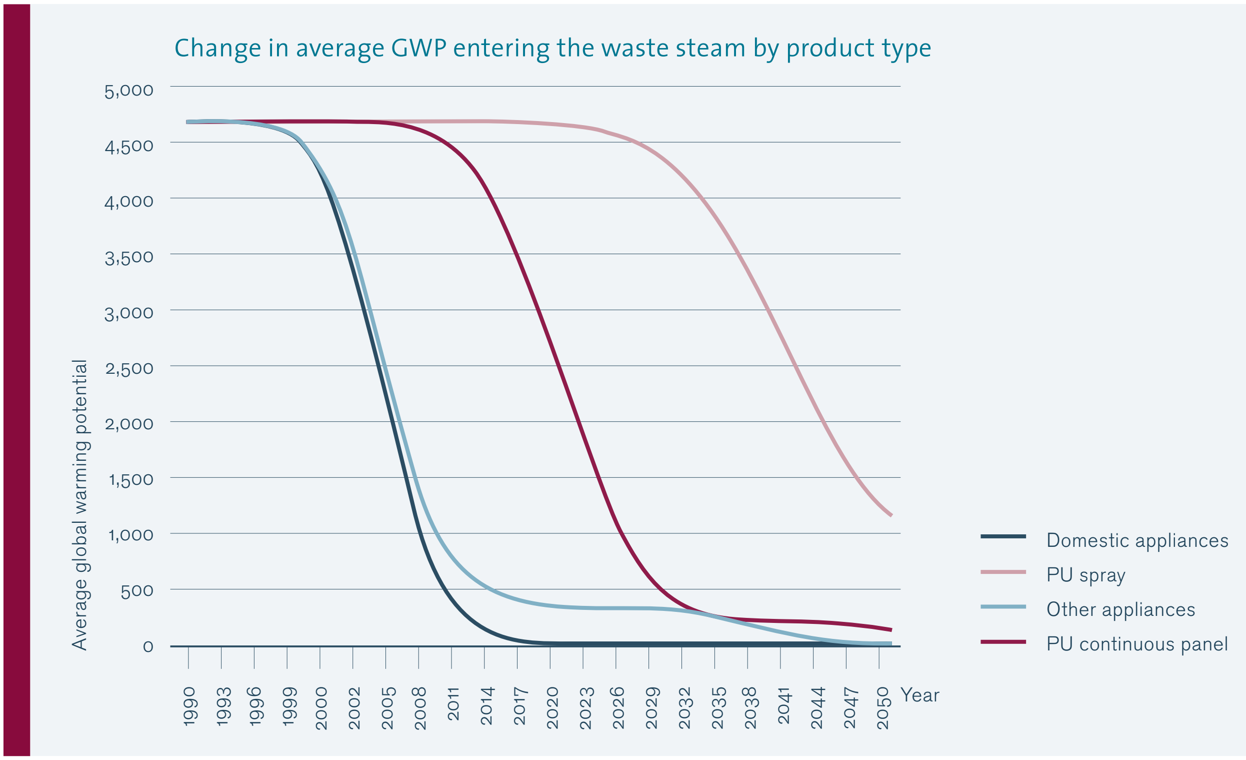

Figure 3 **Expected decline in average GWP of the waste streams for typical foam applications**

These trends imply that there is an urgent need to introduce effective waste management practices. Indeed, much of the climate benefit arising from appliances foams has already passed as lower GWP alternatives have been commercialized. This is being borne out in practice for many appliance recycling plants, where the associated climate benefit is not sufficient justification for capital investment. As a result, contractors are interested in minimising their upfront investment costs by adopting manual dismantling practices, even though there are associated emissions. This is especially the case in areas of low population density, where the economies of scale are more limited.

1.5 A History of CFC-11

The FTOC has been made aware of the marketing of CFC-11 for use in foams. A brief summary of the technical feasibility of reverting to CFC-11 in foam use is provided below.

CFC-11 conversion to HCFC-141b required significant adjustments to the formulation because of its 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.

Until phase-out, CFC-11 was used historically in PU flexible and rigid foams through 1996 in nA5 parties and through 2010 in A5 parties. CFC-11 was not known to be used in XPS where CFC-12 was used. PU foam formulations generally contained between 3% CFC-11 in flexible slab foams to 12% in rigid PU foams. It has been approximated that 86% to 100% 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.

Historically, CFC-11 was low cost and widely used in most polyurethane foam applications. The boiling point was 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 (e.g. long shelf-life). CFC-11 foams had good dimensional stability, compressive strength and insulation capability.

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

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 (e.g. Polycat 8, Dabco 33LV, DC193) were used for CFC-11 foams and are still used today.

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

In addition to marketing CFC-11 in foams, a significant number of patent applications 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.

There are a significant number of patents describing a method to make fire retardant high strength materials for exterior walls. Historically, CFC-11 did not demonstrate capability as a fire suppression agent and is not likely to reduce flammability when used in or sprayed on foams. FTOC has not been made aware of the commercialization of the products described in the patents.

A small sample of the patents includes:

Preparation method of environment-friendly fireproof and heat-insulating material for building external wall CN 108070166 A 20180525,

- Preparation method of fire-resistant board CN 107814543 A 20180320
- Preparation method of cement foaming agent CN 107777913 A 20180309,
- Sandwich panel using quasi-incombustible resin composition and method for manufacturing the same KR 1823003 B1 20180131
- Preparation method of Arenga engleri fibre foam mattresses CN 107513266 A 20171226
- Method for preparing synthetic latex foam mattress CN 107501667 A 20171222
- Heat-insulating fireproof material for external wall CN 107383761 A 20171124

2 Halons Technical Options Committee (HTOC)

2.1 Impact of the Kigali Amendment

1. Following the Kigali Amendment to the Montreal Protocol, the role of the Halons Technical Options Committee (HTOC) has broadened in that it now has to cover alternatives to high- Global Warming Potential (GWP) hydrofluorocarbons (HFCs) as well as halons and hydrochlorofluorocarbons (HCFCs) and their alternatives. This has a number of consequences for the HTOC:
   (a) Each of the chapters in this report has been revised to cover this expanded scope
   (b) All Supplementary Reports and Technical Notes have been revised to cover this expanded scope
2. The initial Kigali production phase down of 10% in non-Article 5 parties is unlikely to have a significant impact on the availability of HFCs for fire protection.

2.2 Alternatives to Halons, HFCs and HCFCs

1. Halons are remarkably good fire extinguishants. Following their production phase-out, only 25% of system applications were replaced with "in-kind" solutions (vaporizing liquids that left no residue and acceptable toxicity), the other 75% being various other "not-in-kind" solutions (e.g., sprinklers, water mist, foam, dry chemical, CO_2). For portable extinguishers, the split is approximately 20% "in-kind" and 80% "not-in-kind".
2. Since the 2014 Assessment Report, no substantial progress on potential alternatives has been reported. A hydrochlorofluoro-olefin, HCFO-1233zd(E) (HClC = $CHCF_3$), was proposed but has subsequently been withdrawn. More recently, the manufacturer has proposed a blend of this agent with the fluoroketone FK-5-1-12 ($CF_3CF_2COCF(CF_3)_2$). A recent interest has been growing for trifluoroiodomethane (CF_3I) as a total flooding agent in aviation-related normally unoccupied spaces such as Engine/ auxiliary power units (APU) applications.
3. Nevertheless, the HTOC is of the opinion that although research to identify potential new fire protection agents continues, it could be several years before a viable agent could possibly have significant impact on the fire protection sector. This could be as little as five years if the agent has undergone some development (e.g. CF_3I) or as much as ten years if the agent is only in the research and development phase.

2.3 Civil Aviation

1. The fire extinguishant 2-bromo-3,3,3-trifluoroprop-1-ene, $CH_2{=}CBrCF_3$, (2-BTP) is now commercialized and qualified for civil aviation use to replace halon-1211. Although it does contain a bromine atom, it degrades in the troposphere, meaning that it has a short atmospheric lifetime and thus a low GWP and Ozone Depletion Potential (ODP). It is the closest to a "drop-in" replacement for halon-1211 in portable extinguisher

applications. Two companies now offer portable extinguishers containing 2-BTP and have started supplying major aircraft manufacturers on a platform-by-platform basis. The transition to 2-BTP for newly produced aircraft is ongoing.

2. Despite over 20 years of research, the civil aviation industry has failed to find any replacements for halon-1301 that they deem to be acceptable from an efficiency perspective (i.e., space and weight), a toxicity perspective or both. Given the anticipated 25–40-year lifespan or more of a newly produced civil aircraft, halon-1301 dependency is likely to continue beyond the time when recycled halon is readily available.

3. Although the HTOC has previously reported that this situation might result in civil aviation submitting an Essential Use Nomination (EUN), the impact could be broader. Since most other enduring users of halon-1301 do not have long-term, dedicated stockpiles, they are also vying for the same halon supplies that civil aviation is reliant on. The timeframe when halon is no longer available to civil aviation could also be the timeframe when halon is no longer available to other users that do not have dedicated, long-term stockpiles, who might then also feel the need to submit an EUN(s).

4. To determine the potential availability of halon-1301 to support civil aviation and other enduring users, a model using various scenarios was developed to estimate halon-1301 resources needed to service the existing aviation fleet, account for aviation growth through 2060, and to also service continuing non-aviation applications. Based on the results of this analysis, the estimated available halon-1301 supplies for replacing halon emitted from most existing active fire protection systems in aviation and non-aviation applications (e.g., oil and gas facilities, nuclear facilities, and military installed/reserves) as well as new aviation demand are projected to run out by years 2032 to 2054, depending on estimates of the initial total worldwide supply in 2018 and annual emission rates used in the model. It should be noted that organizations that have long term, dedicated stockpiles such as certain militaries may be capable of providing support for their specific applications well beyond this timeframe.

5. Work is ongoing in the Halon Alternatives for Aircraft Propulsion Systems (HAAPS) Industry Consortium, whose aim is to define common non-halon fire extinguishing solution(s) for use in engine nacelles and APUs. The industry Cargo Compartment Halon Replacement Advisory Group is conducting a technical assessment on alternatives and will report to ICAO next year.

6. A recent Technology and Economic Assessment Panel (TEAP) Working Group Report concluded that there was some likelihood that there might be Aircraft Rescue and Firefighting (ARFF) applications that would continue to need clean agents (i.e., those that vaporize and leave no residue) in the 2020–2030 timeframe that currently can only be met through the supply of halon-1211 or HCFC Blend B (mostly HCFC-123, with PFC-14[15] and argon). The most recent estimate is that between 120 and 450 tonnes of HCFC Blend B will be required per year. FK-5-1-12 has recently been evaluated in ARFF vehicle applications but the results have not been published at the time of writing this report.

15 PFC-14 is an extremely stable compound with an estimated atmospheric life time of 50,000 years and a GWP of 7,390(AR4) / 6,630 (AR5)

7. In November 2018, the parties to the Montreal Protocol agreed to adjust the Protocol and adopted a corresponding Decision XXX/2 to allow the use of newly produced HCFCs for the servicing of niche applications such as fire suppression and fire protection equipment existing on 1 January 2020 for the period 2020–2029 for non-A5 parties and also on existing equipment in 1 January 2030 for the period 2030–2039 for A5 parties.

2.4 Military Applications

1. Military fire protection systems are unique in that besides protecting against 'peacetime' fires from routine use, they must protect personnel and platforms from the consequences of combat damage. These fires are generally very fast-growing and relatively large and military fire protection systems must counter these threats and, in many cases, while allowing occupants to remain in the affected spaces.

2. Alternatives have been adopted where they have been found to be technically and economically feasible. For new designs, there are virtually no applications where a halon must be used although there are many applications where the only alternative is a high GWP HFC, i.e., there are no low-GWP alternatives for those applications. In legacy (existing) designs, there are several applications where neither suitable halon nor HFC alternatives exist. Therefore, in these applications halons and high-GWP HFCs are the only viable fire and explosion protection solutions that maintain parties' levels of national security and safety of their military personnel and equipment. This will, in all likelihood, continue to be the case for both new designs and legacy systems for the foreseeable future.

2.5 Oil & Gas Operations

1. Generally speaking, halon-1301 is only required to support enduring legacy facilities for the foreseeable future and all new facilities are halon-free but depending upon the climate (i.e., low temperature), might require HFC-23 which is a very high GWP (12,400 in Intergovernmental Panel on Climate Change Assessment Report 5).

2. Legacy facilities in certain geographic locations will continue to require the use of halons in occupied spaces owing to severe ambient (very low temperature) conditions.

2.6 Telecommunications and Computer Rooms

1. In the early 1990s, the HTOC estimated that telecommunications and computer rooms accounted for about 65% of the annual use of halon-1301. Since then a wide range of "in-kind" and "not-in-kind" alternatives have been adopted for new applications. Only a portion of the halon replacement went to high GWP HFCs, mainly HFC-227ea and lesser amounts of HFC-125.

2. There is significant geographical variation in the type of alternatives being employed; in some regions the HFCs are the market leader, whereas in others inert gas systems predominate. The fluoroketone FK-5-1-12 is also a significant alternative.

2.7 Merchant Shipping

1. Under International Maritime Organization (IMO) resolution MSC.27(61), halon-1301 ceased being installed in merchant shipping at the end of 1993. It has been estimated that the total halon-1301 installed at that time was 3,775 metric tonnes. As the ships with halon-1301 installed come to the end of their lives, they are decommissioned and some fraction of that halon-1301 becomes available for other applications, but this fraction is not known. Depending on the assumed lives of the ships containing halon-1301, this limited supply is estimated to continue to be available through 2023 (assuming 30-year lives) to 2033 (assuming 40-year lives).

2.8 Global Estimates of Halons and HFC Fire Extinguishing Agent Quantities

1. The estimated size of the global halon banks at the end of 2018 are: halon 1301 – 37,750 metric tonnes; halon-1211 – 24,000 metric tonnes; and halon-2402 – 6,750 metric tonnes. Although regional disparities in the distribution of a halon itself does not necessarily constitute a regional imbalance, it is anticipated that imbalances may result in shortages in one country or region with excesses in other countries or regions.

2. The rates of halon-1301 emissions based on atmospheric measurements of halon-1301 concentrations are generally similar to the emission rates based on the HTOC model. However, emissions based on atmospheric measurements appear to have been higher for short periods of time. This suggests additional emissions but HTOC is unaware of any singular current fire protection use that could account for the higher levels of emissions as they are at least an order of magnitude higher than the largest single fire protection systems known to exist. One potential source of emissions is from shipbreaking activities. Additionally, halon-1301 continues to be produced as a feedstock for the pesticide Fipronil, whose emissions are not be accounted for in the HTOC model but are included in the emission estimates based on atmospheric measurements.

3. A possible consequence of this discrepancy is that the overall size of the halon-1301 bank might be up to ~25% smaller and the global emissions higher than estimated through the HTOC model. As halon-1301 stocks continue to be depleted this difference becomes even more significant. The combination of a potential higher emission rate than assumed by the HTOC and a smaller bank of halon-1301 could also imply that there is going to be significantly less halon-1301 available to support on-going needs in civil aviation, oil and gas, militaries, etc., which could result in a much sooner “run-out date” of 2032 to 2054 as discussed in the Civil Aviation section.

4. The rates of halon-1211 emissions based on atmospheric measurements of halon-1211 concentrations were generally similar to the rates of emissions based on the HTOC model up to approximately 2002. Thereafter the emissions estimated by the two

techniques diverge, with emissions based on atmospheric measurements being higher.

5. HTOC is aware that in some places in the world, large amounts of halon-1211 were not allowed to be re-used so there was no economic reason to prevent emissions. As the HTOC model is based on the best handling practices over time, the lack of handling by professional servicers makes the estimation of emission factors difficult at best. Therefore, HTOC believes that it is certainly possible that the emissions are higher than the HTOC model predicts. The HTOC model might come back into closer agreement with emissions estimated from atmospheric measurements once the non-professionally managed halon-1211 is emitted and emission rates are more predictable.

6. The HTOC estimates that the majority of halon-2402 remains in the former Countries with Economies in Transition. The HTOC model's emissions estimates are generally higher than those based on atmospheric measurements but are within the range of uncertainty of the atmospheric data.

7. A model was developed to estimate HFC-227ea (the main HFC used to replace halon-1301) emissions from fire protection and the size of the bank. As of the end of 2018, the total estimated emissions from fire protection applications is about 3,400 metric tonnes. Assuming a global average annual emission rate of 2.5%, the global HFC-227ea fire protection bank at the end of 2018 is estimated to be about 130,000 metric tonnes. While there is insufficient information available to estimate the emissions and banks of the other HFCs used in fire protection, the HTOC believes that they are much smaller than the HFC-227ea emissions and bank.

8. Many parties have halon banking programs that are fully operational, but more parties have implemented only partial programs, or none at all, and may not be aware of the increasing need to establish a means of meeting the long-term needs for their remaining users. Those parties who have established banking programmes have a distinct advantage in that it is a straightforward step to expand those programs, practices, and processes to include HCFCs and HFCs. Use of HCFCs in fire protection is much smaller than the use of HFCs and as of now recovery of HCFCs is somewhat limited. The banking of HCFCs is in its infancy. Recovery of HFCs in fire protection is meeting as much as 75% of servicing requirements for existing fire protection equipment. Some banking of HFCs is occurring, primarily in parties who have well-established halon banking programs such as Australia, Japan, and the U.S.

9. The HTOC has a continuing concern regarding the historical knowledge that has been lost due to the length of time over which the Montreal Protocol activities have been implemented. A significant number of individuals are new to the Protocol, finding themselves now responsible for fire extinguishing agent management but not being familiar with the issues surrounding halocarbon use, recycling, and banking. The HTOC notes that this is becoming more and more challenging as it works with various parties and organizations on issues related to acquiring halons to meet their continuing needs. Parties may wish to consider addressing awareness programmes to re-establish this apparent loss in institutional memory.

2.9 Recycling, Emission Reduction Strategies and Destruction

1. Many, if not all, of the recommended practices for recycling or reclaiming halons will also apply to other halogenated gaseous fire extinguishing agents. Quality testing of blended agents is needed to determine whether recycling or reclamation processes will need to be applied to return them back to their original quality specifications. Where agents are made up of halogenated blends, recycling will reduce physical contaminants like acidity, water content, particulate matter and nitrogen (if the agents have been pressurized). On the other hand, reclamation procedures involving a form of distillation may be required to separate the blended components and rectify their respective purities before they are re-blended in order to meet the overall purity requirements of the agent. From time to time, depending on the agent's overall quality, it may need to be subjected to both recycling and distillation. Virtually all of the recommended halon emission reduction strategies will also apply to other halogenated gaseous fire extinguishing agents.
2. Owing to the continued global demand in applications such as civil aviation, oil and gas, and militaries, the HTOC continues to recommend that destruction as a final disposition option should be considered only if the halons are contaminated and cannot be reclaimed to an acceptable purity. The HTOC recommends extending this same practice to all halogenated fire extinguishants.
3. Destruction of halons presents some unique considerations. Therefore, technologies that are recommended for CFC and HCFC destruction, but have not been tested for halon destruction, are described as only being potential technologies for halon destruction. As there is nothing particularly different with the HFC fire extinguishants, much less concern with their destruction is anticipated. The one exception to this general principle is HFC-23, which was considered by the Task Force on Destruction Technologies to be in a separate category from the other HFCs, as it is more thermally stable.

3 Methyl Bromide Technical Options Committee (MBTOC)

3.1 Mandate and report structure

Under Decision XXVII/26 taken at the Twenty-Third Meeting of the parties to the Protocol in 2015, the parties requested the Assessment Panels to update their 2014 reports in 2018 and submit them to the Secretariat by 31 December 2018 for consideration by the Open-ended Working Group and by the Twenty Seventh Meeting of the parties to the Montreal Protocol, in 2019.

As required under Decision XIII/13, the MBTOC 2018 Assessment reports on advances since 2014 to replace Methyl Bromide (MB) used under Critical Use by both A5 and non-Article 5 parties. It also reports on QPS uses, which are presently exempt from controls under the Montreal Protocol. It further reports on technically and economically feasible alternatives for non-QPS and QPS uses of MB and gives actual examples of their successful commercial adoption around the world. It shows trends in methyl bromide production and consumption in both Article 5 and non-Article 5 parties, estimated levels of emissions of MB to the atmosphere, and strategies to reduce those emissions.

3.2 The Methyl Bromide Technical Options Committee (MBTOC)

As at December 2018, MBTOC had 16 members: seven (44%) from Article 5 parties and nine (56%) from non-Article 5 parties. Members come from seven Article 5 and eight non-Article 5 parties. MBTOC is seeking new members, especially from non-A5 parties; several members from this group of parties have stepped down due to lack of funding.

3.3 Methyl bromide control measures

Methyl bromide was listed under the Montreal Protocol as a controlled ozone depleting substance in 1992. Control schedules leading to phase-out were agreed in 1995 and 1997. There are a number of concerns apart from ozone depletion that also led countries to impose severe restrictions on methyl bromide use including toxicity to humans and associated operator safety and public health, and detrimental effects on soil biodiversity. In some countries, pollution of surface and ground water by methyl bromide and its derived bromide ion are also of concern.

The control measures, agreed by the parties at their ninth Meeting in Montreal in September 1997, were for phase out of methyl bromide by 1 January 2005 in non-Article 5 countries. For parties operating under Article 5 of the Protocol (developing countries) the control measures were for a 20% cut in production and consumption, based on the average in 1995–98, from 1 January 2005 and phase out by 1 January 2015. Since 2003, nine non-Article 5 parties have submitted nearly 150 applications for 18,700 tonnes for ‘critical uses’ after 2005 for non-QPS purposes under Article 2H of the Montreal Protocol. By 2018 the number had declined to two applications for approximately 33 tonnes for use in 2018 and 2019. Use of methyl bromide under the ‘Critical Use’ provisions became available to Article 5 countries in 2015 and initially four countries applied for 590 tonnes of MB after 2014. Presently, two parties have requested 118.5 tonnes of MB under the CUE provisions for use in 2019.

Although QPS uses must be officially reported under Article 7 of the Protocol they continue to be exempt from controls under Article 2H.

3.4 Production and consumption trends

At the time of writing this report, all parties had submitted data to the Ozone Secretariat for controlled uses in 2017. Although a few cases of data gaps remain from the early years, reported data has become much more complete. All tonnages are given in metric tonnes in this report.

In 2017, global *production* for the methyl bromide uses controlled under the Protocol was 245 tonnes, which represented 0.4% of the 1991 reported production of 66,430 tonnes.

Global *consumption* of methyl bromide for controlled uses was reported to be 64,420 tonnes in 1991 and remained above 60,000 tonnes until 1998. By 2013, global consumption was estimated at about 2,953 tonnes in 2013 and fell to 245 tonnes in 2017. Historically, in non-

Article 5 regions, about 91% of methyl bromide was used for pre-plant soil fumigation and about 9% for stored products and structures.

The official aggregate baseline for non-Article 5 countries was 56,083 tonnes in 1991. In 2005 (the first year of critical use provisions), non-Article 5 countries consumption had been reduced to 11,470 tonnes, representing 21% of the baseline. Many non-Article 5 countries achieved complete phase-out for controlled uses before 2010 (New Zealand, Switzerland and countries of European Community). Israel and Japan phased-out for controlled uses (pre-plant soil fumigation) in 2011 and 2012 respectively. The USA, which was the largest non QPS user of MB historically, submitted its last CUN in 2014 for 2016 use for its remaining pre-plant soil use in the strawberry fruit sector. Non-A5 parties requested CUEs from 2003 and in 2018 only two – Australia and Canada – remain (99% of the controlled baseline has been replaced). Many Article 5 previously included among the largest users reported complete phase-out by 2015 (i.e. Brazil, Egypt, Turkey, Lebanon, Zimbabwe, Morocco) and did not submit CUNs. Only four Article 5 parties requested CUNs since 2014, and two – Argentina and South Africa – remain in 2018. Almost all (97.5%) of the controlled use baseline (15,870 tonnes) for A5 parties has been replaced.

3.5 Alternatives to methyl bromide

MBTOC assumes that an alternative (Refer Decision IX/6 1(a)(ii)) demonstrated in one region of the world would be technically applicable in another unless there were obvious constraints to the contrary e.g., a very different climate or pest complex. Additionally, it is recognised that regulatory requirements, or other very specific constraints or circumstances may make an alternative available in one country but unavailable in another specific country or region. When evaluating CUNs, MBTOC accounts for the specific circumstances of each Party.

Since controls were implemented on MB use in 1992, parties have been able to identify alternatives for over 99% uses of the baseline consumption. Only 141 tonnes of the original 72,000 tonnes of MB used by non-A5 and A5 parties for controlled uses remain. The rest of the uses have taken up a wide range of non-chemical and chemical alternatives or developed new production systems or technologies which do not require MB fumigation. Of the remaining uses, MBTOC considers alternatives are available, but these may require time for adaptation and adoption.

3.5.1 Alternatives for soil treatments

The reduction in consumption of methyl bromide for soil fumigation has been the major contributor to the overall reduction in global consumption of methyl bromide for controlled uses with amounts used in 2017 falling 99.5% from about 57,400 tonnes in 1992 to about 33 tonnes, in non-A5 parties and 119 tonnes in A5 parties in 2019.

Methyl bromide is presently used in non-Article 5 countries for strawberry runner production only. Some uses previously considered under the CUN process have been partially reclassified as QPS in one country under national legislation outside of the Montreal Protocol (e.g. forest nurseries, strawberry runners). Since 2014, A5 parties submitted CUNs for strawberry fruit and runners, raspberry runners, ginger and tomatoes. In 2018 only strawberry fruit and tomatoes remained.

Over the years, MBTOC has identified a range of key chemical and non-chemical alternatives that perform consistently across most regions and sectors. Chemical fumigants (e.g. Metham sodium, dazomet, 1,3 D alone or combined with chloropicrin (Pic,) dimethyl disulfide (DMDS) and others) are widely used around the world and have successfully replaced MB. A wide range of non-chemical alternatives to MB continue to be trialled around the world including disease-resistant cultivars and grafting desirable varieties onto resistant rootstocks; soil-less culture; anaerobic soil disinfestation; biofumigation and organic amendments; solarisation and biosolarisation; trap cropping; hot water; biological control; and microwaves. A combination of treatments within an IPM program continues to be reported as the most effective approach.

Since 2003, quantities of MB requested for critical use (120 critical use nominations from 10 non-A5 parties plus the European Union) have fallen from 18,700 t for use in 2005 to 150 t for 2019/2020 use (four CUNs from 3 parties, two A5 and two non-A5).

This chapter of the 2018 Assessment report focuses on leading economically and technically feasible chemical and non-chemical alternatives for pre-plant soil fumigation adopted in the past by sectors in countries which previously used MB, particularly under the CUE process. It also focuses on alternatives for the remaining MB uses in the soil sector: strawberry fruit and tomato in Argentina, strawberry runner production in Australia and Canada. In the past, many tomato, strawberry fruits and runner industries around the world relied on MB soil fumigation to produce fruits and disease-free strawberry transplants, but most of them have phased-out MB and successfully implemented alternatives. Research is currently underway to evaluate different alternatives and it is expected that MB will be very soon phased-out from soil disinfestations in these 3 remaining countries still using MB: Argentina, Australia and Canada.

3.5.2 Alternatives for treatment structures and durable commodities (non-QPS)

Uses remaining in the Structures and Commodities sector (non-QPS) are anticipated to consume less than 41 tonnes in 2019. At the time of the Copenhagen Amendment (1992), this sector is estimated to have consumed an estimated 6,500 tonnes per year, with much of the reduction attributable directly to the application of the Montreal Protocol measures.

Methyl bromide CUEs in this sector totalled 27.27 tonnes for 2014, all from non-A5 countries, and all phased-out by 1 January 2018. The first Article 5 CUEs, were granted for 2016 use of 74.062 tonnes for South Africa. Of these 41.00 tonnes have been granted for use in 2019. The main alternatives adopted were fumigants. In this sector and in those countries where MB has been phased-out, mainly phosphine and sulfuryl fluoride have taken its place with phosphine has mainly been adopted for disinfestation of durable products and sulfuryl fluoride mostly for disinfestation of empty structures. In some countries, ethyl formate, hydrogen cyanide and propylene oxide have also been registered and are in use for certain fields of application. The MB phase-out was in general associated with changes in application technology, logistics and use of additional IPM measures. There has been some adoption of not-in-kind alternatives (e.g. heat, cold, controlled atmospheres, contact pesticides, biological control). Adoption of particular alternatives has been situation and commodity dependant.

There are continued efforts to improve and register existing alternatives, including fumigants falling into disuse and to develop and register new or more environmentally friendly non-MB approaches. These include systems to avoid pressures to return to MB-dependence.

Several alternatives are under threat and may require replacement or further adaptation within the next few years, at least on a local basis. There is increasing reliance on phosphine treatment for protection of many postharvest durable products in store (e.g. cereal grains, pulses, cocoa beans). However, resistance to phosphine in several pest species has developed, to levels where phosphine is uneconomic due to the very high dosages necessary to control resistant strains. Sulfuryl fluoride fumigation, a potential alternative for the control of insect pests in infested empty structures (warehouses, mills, food and feed factories, wooden structures in houses), has a high GWP that may change its widespread acceptability for use as an alternative to both phosphine and methyl bromide. Sulfuryl fluoride is also used for disinfestation of some selected durable products, but these applications are under revision due to the risk of exceeding the maximum residue limits for fluoride. The risk of losing this fumigant for pest control in structures poses difficult challenges for the MB phase out program of the last decades, in particular the disinfestation of large mills and food factories which would remain without feasible pest control measures. Regulatory issues also impact treatment of foodstuffs. Chemical alternatives (and methyl bromide itself) are under increasing regulation with potential to making their use infeasible in particular situations.

3.6 Alternatives to methyl bromide for Quarantine and Pre-shipment (QPS) applications (exempted uses)

Article 2H exempts methyl bromide used for QPS treatments from phase-out for quarantine and pre-shipment purposes. Methyl bromide fumigation is often the preferred treatment for certain types of perishable and durable commodities in trade worldwide, as it has a well-established, successful reputation amongst regulatory authorities to prevent the spread of quarantine pests.

Parties to the Montreal Protocol are nevertheless encouraged to minimize and replace MB for QPS whenever possible, ensuring, among others, that their official lists of quarantine pests are regularly updated and that MB is applied in the most efficient way possible (i.e. observing appropriate dosages, avoiding duplicate treatments, ensuring gas-tightness of fumigation chambers). Considering that in the past MBTOC has identified opportunity for replacing between 30 and 45% of QPS uses with immediately available alternatives, parties may wish to step up efforts to reduce and replace QPS uses, particularly those for pre-shipment uses.

Since the MBTOC 2014 Assessment Report (MBTOC, 2015), several parties have made significant technical advances and taken strict policy decisions leading to reductions and even phase-out of MB for some QPS applications. Such policies may go further that agreed per Montreal Protocol control measures, and are mainly driven by concerns for worker safety and local air quality. In 2010, the European Union phased-out all uses of MB, New Zealand has recently implemented a policy of requiring recapture for all QPS uses of MB and North Carolina in the US has also imposed recapture technologies.

Quarantine treatments for host plants of potentially damaging plant quarantine pests are generally approved on a pest and product specific basis following extensive bilateral or regional negotiations, which may require years to complete. This process helps ensure safety against the incursion of harmful pests. For this and other reasons, replacing MB for quarantine treatments can be a complex issue. Many non-methyl bromide treatments are, however, published in countries quarantine regulations, but they are often not the treatment of choice due to cost or availability.

Nevertheless, since the 2014 Assessment report there has been acceptance under domestic quarantine (biosecurity) protocols, bilateral arrangements and IPPC regulations that a number of technical alternatives are as effective as MB for specific commodities. These include irradiation, cold and heat treatments, modified atmospheres, cool temperature phosphine treatment, SF, EDN and ethyl formate.

Global production of methyl bromide reported for QPS purposes in 2017 was 10,217 tonnes, increasing by about 15% from the previous year. Although there are substantial variations in reported QPS production and consumption on a year-to-year basis, there is no obvious long-term increase or decrease. Production occurs in five parties, China, India, Israel, Japan and USA.

In 2009 the QPS consumption exceeded non-QPS for the first time, being 46% higher. By 2017, reported QPS consumption was 70 times larger than controlled consumption. From 2012- 2014 it appeared that there was a trend towards reduced QPS use, but over the last three years (since the global phase out for controlled uses) QPS consumption has increased substantially from 8,500 tonnes to over 10,000 tonnes.

Of the 50 countries still regularly using MB for QPS, 14 show significant reductions in their methyl bromide consumption for QPS but 13 others have shown sharp increases. This is possibly due to increased pest risks and trade in commodities requiring treatment, such as pulses and logs. Countries with significant increases include Australia, China, India and New Zealand. Owing to this increase in use for QPS by some countries, the major reductions obtained in others, some greater than 50% (EU, Japan, Thailand, USA and others) have been offset and there has been no overall sustained reduction in QPS use in the last twenty years.

Reported consumption shows that MB used for QPS now exceeds the baseline levels set for controlled uses in 16 countries, particularly for Australia, Pakistan, New Zealand and Vietnam. In addition some of these countries, five countries (El Salvador, Fiji, India, Korea and Nicaragua) never used any methyl bromide for controlled uses, but now have significant uses under QPS. Regulations have existed which prevent any new uses for pre-shipment applications, but MBTOC is unclear if this has occurred due to unreliable reporting.

In 2017, QPS consumption in A5 parties (6,617 tonnes) represented 69% of global consumption; non-A5 Party consumption of 3,343 tonnes was 31%. Overall, MB consumption for QPS in Article-5 parties has trended upward over the past 15 years, whereas consumption in non-A5 parties has a downward trend. Global consumption averaged 9,617 tonnes over the period 2010 to 2017 and in 2017 has increased to about 10,000 metric tonnes.

On a regional basis, since 1999 consumption in the Latin America and the Caribbean, Africa and Eastern Europe regions has remained much lower since 1999 than in Asia and in North America. In 2017, Asian countries accounted for 55% of global QPS consumption.

In 2017, QPS use of MB contributed over 97% of the global emissions of methyl bromide (Chapter 4) which is approximately 34 times greater than the emissions from the consumption for critical uses controlled under the Montreal Protocol. Control of these emissions is the biggest immediate gain that can be made under the Montreal Protocol to the reduction of ODS substances in the stratosphere. parties who have reduced emissions of MB for QPS have either regulations which speed up the uptake of alternatives or are adopting recapture technologies.

Improvements in recapture technologies and approval by the parties of the first destruction technology for methyl bromide (TEAP 2018) mean that technologies are now available to reduce the level of MB emissions. As the implementation of these technologies imposes a cost on the user, their uptake will most likely only occur if parties impose regulations mandating their use. To date, parties who have reduced emissions of MB for QPS have either regulations, which speed up the uptake of alternatives or are adopting recapture technologies.

Accurate reporting (as noted, for example by the sudden jump in MB use by India) and classification of use is still a major problem. Some parties continue to express concerns over difficulties in interpreting the categories of MB uses between controlled and exempted uses and some of the QPS reported use appears to be wrongly reported. MBTOC also still has difficulty in determining the actual pests and commodities for which MB is used in QPS and parties may wish to consider improved means with which parties can obtain and report this information more effectively.

While there remain some data gaps and uncertainties, information supplied by the parties allowed MBTOC to estimate that five uses consumed more than 80% of the methyl bromide used for QPS in 2017: 1) Sawn timber and wood packaging material (ISPM-15); 2) Grains and similar foodstuffs; 3) Pre-plant soils use; 4) Logs; and 5) Fresh fruit and vegetables. On the basis of these estimates and currently available technologies to replace methyl bromide for QPS, MBTOC has estimated that between 30 and 45% of the MB used for QPS purposes could be replaced with immediately available alternatives.

The International Plant Protection Convention (IPPC) recently approved sulfuryl fluoride as a treatment for compliance with ISPM-15 (wood packaging materials). Heat (including dielectric heating) and non-wooden pallets provide additional options. Alternatives under consideration by IPPC for logs include phosphine, sulfuryl fluoride, ethane dinitrile (EDN, cyanogen); heat (including vacuum steam), and debarking provide further options. Ethane dinitrile has been registered or is close to registration in several countries and with a growing body of efficacy data has potential to replace a significant portion of QPS use for non-food items, particularly if accepted by the IPPC.

In contrast to quarantine treatments, MBTOC considers that a range of alternatives are available and ready for use for pre-shipment fumigation. This is because pre-shipment use targets cosmopolitan pests, where alternatives have generally been shown by the country to be effective under the phase-out of controlled uses or critical uses. Parties may wish to reconsider whether this part of the QPS exemption from controls could be reviewed. This category contains a high proportion of durable commodities for which MBTOC considers alternatives are more suitable and more effective. The pre-shipment exemption is often a confusing issue for parties. MBTOC is aware of MB uses, which do not fall within the pre-shipment category, nor the broader QPS exemption but are nevertheless reported as such.

For pre-plant soil quarantine treatments, alternative fumigants are available, provided the alternatives meet certification standards; substrates also may be used at least partially in the propagation systems.

For perishables, there are various approved treatments, depending on product and situation, including heat (as dry heat, steam, vapour heat or hot water dipping), cold (sometimes combined with modified atmosphere), modified and controlled atmospheres, alternative fumigants (e.g. ethyl formate), physical removal, chemical dips and irradiation. Irradiation of fresh food continues to grow in trade between countries.

The technical and economic feasibility of alternatives to methyl bromide used for QPS in all countries mainly depend on achieving the high level of efficacy required against quarantine pests of concern.

In the absence of regulatory or economic incentives to adopt alternatives, methyl bromide is often the lowest cost-effective option at present, an alternative would not be voluntarily adopted unless it performed as well or better at a similar market cost. However, increasing health and safety concerns are driving the market to alternatives and QPS consumption is in decline in many countries. Those concerns are also increasing the use of recapture equipment of QPS methyl bromide.

3.7 Emissions from methyl bromide use and their reduction

The large reduction in consumption of methyl bromide (MB) since 1999 has resulted in a significant decline in atmospheric emissions of MB, mostly in line with the reduction measures imposed on parties) under the Montreal Protocol. Based on reported consumption data under Article 7 of the Protocol, MB emissions to the atmosphere from known current usage are expected to be around 8,500 tonnes in 2017 (see Table 4.2). Since 1998, MBTOC estimates that anthropogenic emissions of MB have declined by 80–85% from the peak emissions of around 48,000 tonnes in 1998. Owing to the reported phase-out of nearly all controlled uses of MB (i.e. for soil fumigation and domestic commodity and structural fumigation) the bulk (98%) of the present emissions should now only be from QPS (quarantine/pre-shipment) uses. These QPS uses are predominantly to support international trade of durable and perishable commodities and some structural fumigations, but also some pre-plant soil fumigation to produce high health nursery/turf products moving across jurisdictional boundaries in the US. MBTOC has estimated that most (i.e. nearly 80%) of the MB used for QPS is presently emitted after treatment directly to the atmosphere. Some countries (e.g. New Zealand) have imposed regulations to prevent emissions and instead ensure that MB is recaptured/destroyed as much as practical from fumigation operations.

As anticipated, the decline in the atmospheric concentration of MB due to restrictions on MB consumption has slowed since 2015 as 98% of the reported consumption for controlled uses occurred prior to 2015, the final phase-out date for A5 countries. The remaining emissions are now supposedly only from the small amounts used for critical uses (Critical Use Exemptions – CUEs), i.e. 290 tonnes of MB consumed in 2017 for CUEs and 10,100 tonnes from QPS use in 2017. The emissions from the 4,000 tonnes of MB used for feedstocks are considered insignificant (probably less than 100 tonnes). Fugitive emissions from industrial syntheses continue to be a cause of concern.

Recently (2013 to 2017) changes in global atmospheric MB concentrations do not appear to be explained by global production and consumption data (Figure 3.3). From 2013 to 2015 there appeared to have been a 5 ktonne rise in emissions of MB, followed by a similar magnitude fall in emissions (2015 to 2017). The reason for this are unclear and potentially indicates that there may be some consumption which is unreported or other sources of MB which are now more predominantly influencing emissions.

The Montreal Protocol has set several policy steps to minimise emissions of MB. (Article 2H, Decisions VII/5(c), and XI/13(7), where parties are encouraged to adopt emission control technologies. As a consequence, emission reduction steps have been developed for all controlled uses. For pre-plant soil uses, barrier films were widely adopted by the parties for controlled uses and for commodity uses recapture technologies have been available but not widely used. MBTOC considers that barrier films should be mandatory for any remaining pre-plant soil fumigation of MB globally and that recapture/destruction technologies should be considered for all remaining commodity uses where practically feasible.

Since the last assessment, MBTOC estimates that alternatives to MB are available for approximately 40% of the MB used for QPS uses. Even if alternatives are not adopted and MB continues to be used, MBTOC considers that recapture and destruction technologies are available for many QPS uses and that their adoption could reduce at least 70% of the existing emissions of MB for those uses.

Mandatory recapture and destruction for all remaining uses of MB for QPS, together with identification and stopping any unreported uses are considered important factors to return MB concentrations in the atmosphere to natural levels. Owing to the relatively short lifetime of MB in the atmosphere, recapture/destruction would have an immediate benefit in reducing MB levels in the atmosphere and an important step currently available to parties of the Montreal Protocol to enhance ozone layer recovery.

3.8 Economic issues

In the case of most CUNs relatively simple partial budget analyses are sufficient to establish economic (un?)feasibility.

Australian and Canadian parties may shift the emphasis in their respective nominations to the issue of economic infeasibility. MBTOC also anticipates that it may be asked to comment on the type(s) of economic evaluation that will be required with QPS uses of methyl bromide.

4 Medical and Chemical Technical Options Committee (MCTOC)

4.1 Metered Dose Inhalers

Asthma and chronic obstructive pulmonary disease (COPD) are the most common chronic diseases of the respiratory tract. Inhalation therapy is the mainstay of treatment for asthma and COPD. There are two common types of inhalation devices for the delivery of respiratory drugs: (pressurised) metered dose inhaler (MDI) and the dry powder inhaler (DPI) in single- or multi-dose. In different markets, the proportion of MDIs to DPIs differs. These proportions vary for many reasons including prescribing practices, cost, availability, patient preference, and national government guidance. Other methods of delivering drugs to the lung include soft mist inhalers and nebulisers.

MDIs that use chlorofluorocarbons (CFCs) as a propellant were historically the inhaled-delivery device of choice as they were affordable, reliable and extremely effective. Under the Montreal Protocol, the manufacture of pharmaceutical grade CFCs for MDIs has been successfully phased-out worldwide without significant adverse impact to human health. Pharmaceutical companies have replaced the CFC propellants in MDIs with hydrofluorocarbons (HFCs, namely HFC-134a and to a lesser extent HFC-227ea). Three low-GWP (global warming potential) chemicals are under development as potential propellants for MDIs (isobutane, HFC-152a, and a hydrofluoroolefin, HFO-1234ze(E)).

Following the Kigali Amendment to the Montreal Protocol, HFCs, including -134a, -152a, and -227ea, are now listed as controlled substances under Annex F. Approximately 800 million HFC MDIs are currently manufactured annually worldwide, using approximately 11,500 tonnes HFCs in 2018. HFC-134a makes up the major proportion of MDI manufacture (~10,600 tonnes in 2018), with HFC-227ea accounting for about 8 per cent (~900 tonnes in 2018). This corresponds to direct emissions with a climate impact of approximately 18,000 $ktCO_2$-eq. For the year 2016, HFC propellant consumption for MDI manufacture corresponded to direct emissions that are estimated to be about 2 per cent of global GWP-weighted total emissions of HFCs. The use of HFC MDIs is projected to increase, especially with increasing use of MDIs in developing countries.

Dry powder inhalers (DPIs) are devices that deliver powdered medication (active ingredient mixed with excipient) without the need for a propellant. Most commonly used respiratory drugs have been formulated successfully for DPIs and are now widely available. Almost all new drugs are being developed in the DPI format, often exclusively.

In many circumstances, DPIs are technically and economically feasible alternatives that could substantially reduce the use of HFC MDIs. Nebulisers and emerging technologies may also be technically feasible alternatives for avoiding the use of some HFC MDIs. The main exception is salbutamol, where salbutamol multi-dose DPIs are generally more expensive than salbutamol HFC MDIs, which remain an essential and affordable therapy. It is not yet technically or economically feasible to avoid HFC MDIs completely in this sector because, currently: for salbutamol, there are economic impediments in switching from some HFC MDIs to multi-dose DPIs; and some patients (young children and frail elderly) cannot use DPI alternatives to HFC MDIs.

By moving from CFC MDIs to HFC MDIs and DPIs, not only have emissions of ozone depleting substances been eliminated, but there have also been benefits for climate change. The carbon footprint of HFC MDIs is about one-eighth the carbon footprint of CFC MDIs. DPIs have an even lower comparative climate impact, about one-hundredth of the impact of CFC MDIs and less than one-tenth the impact of HFC MDIs. For a given dose, the carbon footprint of HFC inhalers can vary threefold. The carbon footprint of an HFC-152a MDI is projected to be about 90 per cent less than an HFC-134a MDI. Aqueous mist inhalers also have much lower carbon footprints than current HFC MDIs.

The choice of the most suitable treatment method is a complex decision taken between the health care provider and the patient. MDIs, DPIs and other delivery systems all play an important role in the treatment of asthma and COPD, and no single delivery system is considered universally acceptable for all patients. Similarly, not all active ingredients are available equally as either an MDI or DPI. Healthcare professionals continue to consider that a range of therapeutic options is important. Complex considerations are necessary when patients and healthcare professionals make an informed choice about a patient's inhaled therapy, taking into account therapeutic options, patient history, patient preference, ability (e.g., dexterity, inspiratory flow, vision) and adherence, patient-borne costs, as well as environmental implications, with the overall goal of ensuring patient health.

While acknowledging these complex considerations, including patient health and broader public health implications, it is possible to minimise the carbon footprint of inhaled therapy use through certain choices. These choices include: minimising the use of MDIs containing the highest volumes of HFC-134a and those containing HFC-227ea; and giving preference to lower GWP propellants (if and when they become available, e.g. HFC-152a) and lower carbon footprint therapies (e.g. DPIs and aqueous mist inhalers). Patient choice may be enhanced with an increase in publicly available information about the environmental impact of different inhaler products. Healthcare professionals and their patients may benefit from this information in order to take environmental impact into account, among other important considerations, in their choice of inhaler.

4.2 Aerosols

Aerosols are used in a wide range of different applications. Aerosols incorporate propellants and solvents with the appropriate technical properties and characteristics in formulations designed to deliver a product for its intended purpose. Propellants include compressed gases (nitrogen, nitrous oxide, carbon dioxide), or liquefied gases, which are liquid inside the pressurized container; these liquefied gas propellants include chlorofluorocarbons (CFCs) (no longer used), hydrochlorofluorocarbons (HCFCs, e.g. HCFC-22) and hydrofluorocarbons (HFCs) (e.g. HFC-134a, HFC-152a), hydrofluoroolefins (HFOs, e.g. HFO-1234ze(E)), hydrocarbons, and dimethyl ether (DME). Some aerosol products also contain solvents, including HCFCs, HFCs, hydrofluoroethers, aliphatic and aromatic solvents, chlorinated solvents, esters, ethers, alcohols, ketones, and hydrochlorofluoroolefins (HCFOs, e.g. HCFO-1233zd(E)). CFC solvents are no longer used in aerosols.

Technically and economically feasible alternatives to ozone-depleting propellants and solvents (CFCs and HCFCs) are available for aerosol products. Small uses of HCFCs remain in a few countries (China and the Russian Federation) for specific medical aerosol products. A significant proportion of aerosol propellants have migrated to hydrocarbons and DME, which dominate in the consumer aerosol market. Hydrocarbons and DME are highly flammable propellants. Hydrocarbons and oxygenated hydrocarbons (such as DME) are volatile organic compounds (VOCs) that contribute to photochemical smog generation. In some jurisdictions, strict VOC controls can have an impact on the choice of propellant, where hydrocarbons are avoided. The use of compressed gases as propellants has increased as a result of VOC controls and the availability of better cans.

A smaller proportion of aerosols migrated to HFC propellants where: emissions of VOCs, such as hydrocarbons and DME, are controlled; a non-flammable propellant is needed; and/or a propellant is necessary that is safe to inhale, such as HFC-134a. HFC-134a is used more commonly as a propellant in technical and non-MDI medical aerosols where its non-flammable and inhalation safety properties have advantages. HFC-152a is used more commonly as a propellant in consumer aerosols. HFC-152a has moderate flammability, and is used alone, or in blends with hydrocarbons to meet VOC regulations. HFC-152a is also blended with HFC-134a to produce a propellant with lower GWP (than HFC-134a) and lower flammability (than HFC-152a). HFO-1234ze(E) is starting to be used as a propellant in technical and consumer aerosols where non-flammable and low-GWP properties are needed. HFO-1234ze is also used in jurisdictions that have VOC emission controls.

ODS solvents (CFC-113, methyl chloroform, HCFC-141b) used in aerosols have migrated to hydrofluorocarbons (HFC-43-10mee, -365mfc, -245fa), hydrofluoroethers (HFEs), aliphatic and aromatic solvents, chlorinated solvents, oxygenated organic chemicals, and low-GWP chemicals, such as hydrofluoroolefins and hydrochlorofluoroolefins, including methoxytridecafluoroheptene (MPHE) and HCFO-1233zd(E).

There are also not-in-kind (NIK) technologies that compete with aerosol products to perform the same or similar functions, including trigger sprays, finger pumps, squeeze bottles, roll-on liquid products (e.g., for deodorants), and non-sprayed products (e.g., for polishes and lubricating oils). NIK alternatives are sometimes not as easy to use or achieve lower performance for some applications.

HCFC use in China for medical aerosols for Traditional Chinese Medicines could be about 2,000–2,500 tonnes HCFC-22 or HCFC-22/HCFC-141b blend (HCFC-22: 1,500–2,000 tonnes and HCFC-141b: 500 tonnes). HCFC-22 is used as propellant, and HCFC-141b is used for its solvent properties. Flammability safety concerns with some economically feasible alternatives, such as DME or LPG, are currently a barrier to their use in this application. Other potential technical alternatives, such as HFC-134a, currently present an economic impediment in this particular application. In the Russian Federation, topical medical aerosol applications also use HCFC-22 and -141b as propellant and solvent, respectively, in quantities of around 20 tonnes per year. The products are aerosol foams used to provide local anti-inflammatory and antiseptic action, and to stimulate healing. Regarding the use of HCFC-141b in topical medical aerosols, it is worth noting that the National Institute for Occupational Safety and Health (NIOSH) have presented the immediately dangerous to life or health (IDLH) air concentration value for HCFC-141b to be 1,700 ppm (8,245 mg/m^3) on the basis of cardiac sensitization.

Global HFC demand in aerosols was estimated to be around 45,000 tonnes (~15,000 tonnes HFC-134a; ~30,000 tonnes HFC-152a) in 2015. This corresponds to a warming impact from direct emissions of about 25,000 ktCO_2-eq. HFC propellant consumption for aerosol manufacture corresponds to direct emissions that are estimated to be about 3 per cent of global total GWP-weighted emissions of HFCs. HFC demand in aerosols is dominated by the North American market, which consumes about 85 per cent of the global total. The Asia and Asia-Pacific region is the next most significant, consuming around 10 per cent of global total of HFCs in aerosols. Production is expected to expand in Article 5 parties.

HFC use is limited, either owing to cost, safety or regulatory reasons, or to applications where VOC controls might limit hydrocarbon use, or where a propellant with low flammability and/or proven safety is needed. HFC consumption in this sector is ranked as the third largest after the refrigeration and air conditioning and foams sectors, where aerosols are a totally emissive use. There would be environment benefits in promoting low-GWP and climate-friendly alternatives and by avoiding high-GWP propellants and solvents. In many cases, HFC propellants and solvents can be substituted with low-GWP options, and NIK alternatives are commercially available where they are suited for the purpose.

4.3 Sterilants

Sterilization is an important process in the provision of good quality healthcare services. Sterilization of medical devices can be performed in facilities ranging from industrial settings to smaller facilities including hospitals. It is also a process that requires strict application of the principles of quality management, reliability and long-term materials compatibility.

Ethylene oxide (EO) can be used as a sterilant either alone or diluted with other gases to make non-flammable mixtures. A mixture of 12 per cent by weight EO and 88 per cent dichlorodifluoromethane (CFC-12) (12/88) was once widely used for this purpose. CFC-12 use for sterilization has been successfully phased-out in non-Article 5 parties, and in most, if not all, Article 5 parties, and only then from any remaining stockpile. Although it is difficult to be certain, global total use of CFCs for this application is believed to be zero.

EO/hydrochlorofluorocarbon (HCFC) mixtures (10 per cent by weight EO in a mix of HCFC-124 and HCFC-22) were virtual drop-in replacements for the 12/88 mixture using CFC. They were introduced as transitional products for sterilization in those countries that employed 12/88 extensively. Estimated global use of HCFCs in sterilization is now considered less than 50 metric tonnes, which amounts to less than 2 ODP tonnes worldwide. EO/HCFC use has been significantly reduced by using less gas per sterilizer load, 100 per cent ethylene oxide, and by hospital conversion to other technologies.

The complete phase-out of HCFCs in sterilization uses to meet the Montreal Protocol schedule is readily achievable. The useful lifetime of existing EO/HCFC sterilizers is about 20 years when well maintained. Therefore, by 2030 at the latest, any remaining sterilizers should be ready for replacement with available alternative technologies that do not use ozone-depleting substances. Hospital procurement should take the HCFC phase-out, and the coming redundancy of EO/HCFC sterilization equipment, into consideration in making future investment decisions.

There is a range of commercially available sterilization methods including: heat (moist heat or dry heat), ionizing radiation (gamma ray, electron beam, x-ray), alkylating processes (such as EO, formaldehyde) and oxidative processes (including hydrogen peroxide gas, gas plasma systems, liquid or gaseous peracetic acid, and ozone). Many of these alternative technologies provided significant advances, such as better safety profiles and turn-around times, and reduced cost per cycle. Further sterilization methods based on these and other chemical agents are under investigation for commercialization. Hydrofluorocarbons (HFCs) were investigated as alternative replacement diluents but were not widely adopted for technical reasons and the environmental impact of the use of HFCs. Any alternative to the use of ozone-depleting substances in sterilization needs to be well proven and tested to avoid putting the health of patients unnecessarily at risk. It is legal requirement in pharmaceutical and medical devices industries that any change in manufacturing processes, including sterilization, must be validated using appropriate guidelines before implementation.

4.4 Feedstocks

Ozone-depleting substances (ODS) feedstocks are chemical building blocks that allow the cost-effective commercial synthesis of other chemicals. The use of ODS as feedstocks, including carbon tetrachloride (CTC), 1,1,1-trichloroethane (TCA) (also referred to as methyl chloroform), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), allows incorporation of chlorine and fluorine atoms into molecule structures. The resulting products, such as refrigerants, blowing agents, solvents, polymers, pharmaceuticals and agricultural chemicals, find important uses that benefit society.

As raw materials, ODS feedstocks are converted to other products, except for de minimus residues and emissions of unconverted raw material. Emissions from the use of ODS feedstock consist of residual levels in the ultimate products, and fugitive leaks in the production, storage and/or transport processes. Significant investments and effort are spent to handle ODS feedstocks in a responsible, environmentally sensitive manner and, in most countries, are regulated through national pollution control measures.

In 2016, total ODS production for feedstock uses was 1,189,536 tonnes, representing a total of 438,712 ODP tonnes. Use of ODS as feedstock grew significantly between 1990 and 2011. Since 2011, use has been roughly constant, fluctuating around a mean total of 1,116,000 (±44,000) tonnes per year. The largest feedstock uses currently are HCFC-22 (45 per cent of the total mass quantity), CTC (19 per cent), and HCFC-142b (11 per cent). CFCs, mainly CFC-113, have shown a long-term decline in use as feedstock.

The sophistication of the operating facility can heavily influence emission levels. Highly automated, tight and well-instrumented facilities with proper, closely observed, procedures can have ODS emission levels as low as 0.05 per cent of the ODS amount used as feedstock. At the other extreme, batch processes of limited scale with less tight facilities, with less concern for operational excellence, could have emission levels up to 5 per cent of the ODS amount used as feedstock. Producers can follow specifically defined responsible use practices, which, inter alia, define equipment to control processes, closed-loop loading and recovery, and thermal destruction of vapour emissions. When strictly followed, these responsible use practices can limit ODS emissions to about 0.1 per cent of the ODS amount used as feedstock in continuous processes. Close cooperation between producers and regulators can continue to make these operations safe and environmentally sustainable.

Emissions are not reported by parties, and the estimation of ODS emissions is also inexact. The Intergovernmental Panel on Climate Change default emission factor of 0.5 per cent for HFC production has been applied as a surrogate emission factor for ODS feedstock (and process agent) use. For guidance purposes only, estimated emissions associated with ODS feedstock (and process agent) uses in 2016 can be calculated as 5,948 tonnes, or 2,194 ODP tonnes.

4.5 Process agents

Process agents have been characterised as controlled substances that, because of their unique chemical and/or physical properties, facilitate an intended chemical reaction and/or inhibit an unintended (undesired) chemical reaction. Process agent uses can be differentiated from feedstock uses, where controlled substances undergo transformation in processes in which they are converted from their original compositions except for insignificant trace emissions.

Parties have made a range of decisions relating to the use of controlled substances as process agents. Decision X/14 established that: the term "process agents" should be understood to mean the use of controlled substances for applications listed in Table A in that decision; and to treat process agents in a manner similar to feedstock and not to include them in the calculation of production and consumption provided that emissions from these processes were reduced to insignificant levels, as defined by Table B. Subsequent decisions have updated Tables A and B with new information.

The process agent uses first defined in Table A included 25 applications of ozone-depleting substances (ODS), including carbon tetrachloride, trichlorotrifluoroethane (CFC-113), trichlorofluoromethane (CFC-11), and dichlorodifluoromethane (CFC-12), with total maximum emissions limits of about 200 tonnes for 4,500 tonnes of make-up or consumption. In subsequent decisions, Table A grew to more than 40 applications, adding halon-1011 (bromochloromethane, BCM) to the group of controlled substances used in these applications. Table B emissions reached a maximum of 511 tonnes in decision XXIII/7 in 2011. From 2010 onwards, Article 5 parties were included in the measures for process agent uses. By 2017, when Table A was last updated, the number of process agent applications had reduced to 11 across 4 parties.

Most of the process agent uses are long-standing processes, where the ODS are used as solvents to create unique yields, selectivity and/or resistance to harsh chemical environments, with the result that production is achieved with high efficiency. Legacy processes built around these properties make it difficult or impossible to convert to alternatives in a cost effective and timely manner, and only a few examples are known. In this regard, the process agent uses have much in common with feedstock uses.

Almost all of the removals of process agents from Table A have resulted from plant closures, rather than substitution of other substances for the ODS process agent. For some of the remaining applications, no alternatives are available to date. The lifetime of a chemical production plant could be as long as 50 years. If the product is important enough to warrant continued production, and the plant is maintained in good condition, then the large investment required to put into operation a new ODS-free process is unlikely to be justified.

There exists a suite of measures that can be applied to minimize make-up/consumption and emissions and each one needs to be considered by an operator. These measures include limiting make-up/consumption to the essential minimum, ensuring tight systems (no leaking valves and joints); evacuation and purging with recovery, prior to opening equipment; closed-loop transfer systems; proximity of production and use of the ODS; monitoring sensors at potential leak locations to provide alerts for prompt repair; use of absorbents such as activated charcoal on vents; and destruction of vent gases.

4.6 Solvents

The main applications of solvents are metal cleaning where metal working oil, grease, pitch wax, etc., are cleaned, electronics cleaning where flux is mainly cleaned, and precision cleaning where particulate or dust is mainly cleaned.

Among controlled substances, trichlorotrifluoroethane (CFC-113) and 1,1,1-trichloroethane (TCA) use as solvents has been phased-out in both of Article-5 and non-Article 5 parties, with the exception being the use of CFC-113 as a cleaning solvent in aerospace applications until stockpiles are depleted.

Hydrochlorofluorocarbons (HCFCs) have been used in several different industries, for example in aerospace, micro-mechanical part manufacturing, plating, aerosol cleaners, circuit flushing, electronics defluxing/cleaning, oxygen service cleaning and the medical industry in deposition. The use of HCFC-141b and HCFC-225 for solvent cleaning has been largely phased-out in non-Article 5 parties, with the exception of aerospace and military applications. In Article 5 parties, HCFC use for solvent cleaning has declined and will continue to reduce further as more critical uses of HCFCs, such as in refrigeration, are given priority and as available quantities decline under the HCFC phase-out schedule of the Montreal Protocol.

Many alternative solvents and technologies developed for chlorofluorocarbon (CFC) alternatives since 1980s are also the candidates for HCFC alternatives. These include not-in-kind technologies such as aqueous cleaning, semi-aqueous cleanings, hydrocarbon and alcoholic solvents, and in-kind solvents such as chlorinated, fluorinated and unsaturated solvents, including hydrofluorocarbons (HFCs) and low-GWP HCFO-1233zd(E) and hydrofluoroethers (HFEs), with various levels of acceptance. Alternatives to HCFCs are being used for automotive, aerospace, precision component and optical cleaning where high levels of cleanliness are required.

Each application has its own set of specific cleaning requirements and associated test procedures to ensure the cleaned parts are acceptable for use. The consequences of incomplete cleaning can include decreased product lifetime or performance in electronics cleaning, and even large potential safety concerns, such as when parts are cleaned for use in oxygen services. When transitioning, it is important to match cleaning requirements with the new solvent or cleaning system.

n-Propyl bromide is being used as a solvent in a range of applications. *n*-Propyl bromide is used as an electrical cleaning agent, degreaser or carrier solvent, as an intermediate in chemical manufacture, in spray adhesives, dry cleaning, insulation, and as a refrigerant flushing agent. *n*-Propyl bromide has also appeared in consumer aerosol cans as electronics cleaning and degreasing products, as adhesive products, as textile spot removers, and as paintable mould release agents.

n-Propyl bromide is not a controlled substance under the Montreal Protocol, however, due to the presence of bromine in the molecule, concerns have been expressed based both on its potential for ozone depletion and its toxicity. The relatively low workplace exposure standards indicate that use of *n*-propyl bromide in solvent applications is likely to be problematic, and its use will likely be limited to applications where worker exposure is controlled and will require significant emission control. Nevertheless, *n*-propyl bromide continues to appear as a marketed solvent at trade exhibitions with demand in a number of markets.

4.7 Other chemicals issues

Information is included about carbon tetrachloride (CTC), dichloromethane (DCM), dichloroethane (EDC), and trichlorofluoromethane (CFC-11) and their emissions, in response to scientific atmospheric observations and their analysis, and concerns about their potential for ozone depletion.

Regarding the reported discrepancy between emissions of CTC calculated from atmospheric observations and those estimated from industrial activity, experts under the auspices of Stratosphere-troposphere Processes And their Role in Climate (SPARC[16]) concluded that some of the discrepancy could be explained by unreported emission sources, including from contaminated soils and industrial waste, and from chloromethanes production, and by revised estimates of partial CTC lifetimes (stratosphere, ocean, or soil). With the new total lifetime, the global top-down emissions calculation decreases to 40 (25–55) ktonnes per year. The new industrial bottom-up emissions estimate (including unreported emissions from chloromethanes plants, feedstock fugitive emissions, legacy emissions and unreported inadvertent emissions, for example from use of chlorine as disinfectant) could be up to 25 ktonnes per year.

The CTC discrepancy has been further reduced by recent estimates of uncontrolled CTC emissions from China, calculated using atmospheric measurements at Gossan Island, Korea, and giving a new source-based estimate of 36 ktonnes per year, consistent with SPARC's 40 ktonnes per year top-down estimate. These studies have almost closed the gap between top-down and bottom-up estimates of CTC emissions. However, much of the apportionment of sources is uncertain and subjective, and most of the emissions appear to arise from unregulated sources. Parties may wish to consider examining potential unregulated sources of CTC emissions with a view to increasing the understanding of those emissions and accuracy of emissions estimates.

DCM has widespread use as an industrial solvent, in applications such chemicals and pharmaceuticals production, and to a lesser extent as a food extraction solvent, and for

16 Liang, Q., Newman, P.A., Reimann, S. (eds.), SPARC Report on the Mystery of Carbon Tetrachloride, 2016, SPARC Report No. 7, WCRP-13/2016.

metal cleaning and paint removal. It is also a component of special adhesives and has been used in polyurethane foam blowing, in aerosols, paint strippers and as a laboratory agent. Many of these uses are emissive. More recently, smaller quantities of DCM have been used as chemical feedstock to produce HFC-32 (CH_2F_2, difluoromethane), although this does not result in significant emission of DCM. The current level of DCM emissions, inferred from atmospheric measurements, is about 1.3 million tonnes per year, contributing less than 1 per cent to the current total stratospheric chlorine loading (within the uncertainty of the total chlorine loading estimate).

Most of the global production of DCM is from chloromethanes plants that also make methyl chloride, chloroform and carbon tetrachloride. Carbon tetrachloride and chloroform are primarily used as feedstocks. More than 95 per cent of chloroform is used as a chemical feedstock for HCFC-22 production. The ratio of DCM to chloroform can be changed from 60 per cent DCM: 40 per cent chloroform to 40 per cent DCM: 60 per cent chloroform. With current low demand for carbon tetrachloride, the resulting product mix contains relatively higher amounts of DCM, even if chloroform is the more commercially desirable product. Given the reductions in HCFC-22 production, and other trends in DCM usage, global DCM production and atmospheric concentrations are unlikely to increase significantly. The short atmospheric lifetime of DCM means that any reduction in emissions would have a very rapid impact in reducing atmospheric levels.

A recent scientific study contains scenarios with high growth rates in DCM emissions that would give rise to significant stratospheric ozone depletion. These scenarios are extrapolations of short-term sub-sets of historic measurements that are difficult to reconcile based on a commercial and technical analysis of the DCM market.

EDC is the principal raw material for the production of vinyl chloride, which is the monomer for polyvinylchloride (PVC). About 40 million tonnes per year of vinyl chloride is currently consumed, requiring about 65 million tonnes per year of EDC. EDC is also used as a chemical feedstock for ethylene diamines. Estimated fugitive global emissions of EDC from feedstock uses are 65,000 tonnes per year. EDC is a very short-lived substance, with a global average atmospheric lifetime of 65 days (range 41–555 days). Using the global average atmospheric lifetime, possible emission of 65,000 tonnes per year results in a calculated atmospheric burden of 11,000 tonnes, yielding an average global atmospheric concentration of less than 1 ppt (part per trillion). Reported observed concentrations in the remote atmosphere near 9 ppt are substantially higher. The discrepancy could be due to a number of uncertainties. Further investigation of these uncertainties is required to resolve this apparent discrepancy. Based on predicted growth rates for EDC consumption of about 6 per cent per year, the background atmospheric concentration of EDC could double by 2030.

In a recent scientific study, measurements showed that, up until 2012, the atmospheric concentration of CFC-11 had declined at a rate consistent with the low emissions expected from a declining bank in equipment and zero production. However, since then, observations show that the rate of decline in concentration has slowed. Using atmospheric models, the study's authors infer that an additional 13,000 ± 5,000 tonnes per year of CFC-11 has been released into the atmosphere from 2014 to 2016, with the increase (from zero to this level) occurring over the course of a year. Using back trajectories of winds, the authors indicate that evidence strongly suggests increased CFC-11 emissions from eastern Asia after 2012.

Historically, CFC-11 was used primarily as a foam blowing agent (for flexible and polyurethane insulating foams) and as a refrigerant for air conditioners (centrifugal chillers, used in large commercial buildings), and in a range of other smaller or less common uses. Alternative products or technologies have replaced the use of CFC-11 in these uses. Nevertheless, a significant "bank" of CFC-11 remains in products and systems, particularly in foam insulation where the emission rate into the atmosphere from an installed foam is very low.

Commercial CFC-11 production installations consist most simply of a heated reaction vessel charged with a pentavalent antimony catalyst dissolved in partly fluorinated organic intermediates. The system is pressurised and totally enclosed. Anhydrous hydrogen fluoride and CTC are fed into a reactor, and simultaneously hydrogen chloride and the desired organic products (CCl_3F and CCl_2F_2, CFC-11 and CFC-12) are removed as the products of reaction. The relative proportions of CFC-12 and CFC-11 can be controlled by varying the operating conditions, with 100 per cent CFC-12 achieved relatively easily and 100 per cent CFC-11 more difficult to achieve but not impossible. Until around 1990, most processes were operated to achieve around 50:50 CFC-12 and CFC-11, with a comfortable operating range of 30:70 either way. Due to unpredictability and the potential for corrosive attack of the reaction vessel, operators are cautious about changing process conditions drastically. Nevertheless, it is possible to produce almost 100 per cent CFC-11 in a detuned CFC-11/-12 plant. There would be limited scope to recycle any by-produced CFC-12 to extinction, implying use/disposal of any remaining CFC-12.

Losses of 13,000 tonnes per year of CFC-11 are not economical from a chemical production process. At the upper end of possible emission levels (5 per cent losses) for an economically run process, this would equate to production of 260,000 tonnes CFC-11 per year. By comparison, CFC-11 production in the 1980s peaked between about 350,000–400,000 tonnes per year.

The fate of any CFC-12 produced as a by-product of CFC-11 production is not yet clear. Neither is it yet clear whether the observed unexplained increase in CFC-11 emissions is associated with CFC-11 production to supply emissive CFC-11 uses, or whether CFC-11 is being produced as a by-product of CFC-12 production for the purpose of supplying CFC-12 uses.

Montzka suggested that inadvertent CFC-11 production is possible from the fluorination of chlorinated methanes (for example, to produce HCFC-22). CFC-11 produced as a by-product in other chemical manufacturing pathways is unlikely for technical reasons. Under normal operating conditions, CFC-11 production as a by-product of HCFC-22 production is negligible (around 0.1 per cent). Any CFC-11 produced in this manner is more likely to be captured and recycled or destroyed.

Any stockpile accumulated from ODS production is not reported under the Montreal Protocol. Consumption of CFC-11 stockpile after the production phase-out is not prohibited under the Montreal Protocol. However, there is not likely to be enough CFC-11 in the stockpile inventory to account for the total amount of unaccounted CFC-11 emissions.

Decision XXX/3 requests the Technology and Economic Assessment Panel (TEAP) to provide parties with information on potential sources of emissions of CFC-11 and related controlled substances from potential production and uses, as well as from banks, that may have resulted in emissions of CFC-11 in unexpected quantities. A preliminary report will be provided to the Open-ended Working Group at its 41st meeting and a final report to the 31st Meeting of the Parties.

4.8 Laboratory and analytical uses

Laboratory and analytical uses of controlled substances have included: equipment calibration; extraction solvents, diluents, or carriers for specific chemical analyses; inducing chemical-specific health effects for biochemical research; as a carrier for laboratory chemicals; and for other critical purposes in research and development where substitutes are not readily available or where standards set by national and international agencies require specific use of the controlled substances.

At the 6th Meeting, parties authorised an essential use exemption for laboratory and analytical uses, according to conditions that authorise essential use production for laboratory and analytical purposes only if the controlled substances are manufactured to high purity and supplied in re-closable containers and in small quantities; this became known as the global essential use exemption. Various decisions have subsequently extended the global laboratory and analytical use exemption under these specified conditions, and/or excluded specific uses from the global exemption. Decision XXX/8 includes Annex C, group I, substances in the global laboratory and analytical use exemption.

In 2016, the global production of all reported controlled substances for laboratory and analytical uses was relatively small (151 tonnes). Carbon tetrachloride is the main controlled substance produced for these uses (more than 99.9 per cent); the production of other controlled substances is relatively very small. Reported total production in non-Article 5 parties was 21 tonnes (about 14 per cent of the reported global total) in 2016. Article 5 parties began reporting production data for laboratory and analytical uses in 2009, with a gradual overall decrease in reported production, from a peak of 257 tonnes in 2010 to 130 tonnes (about 86 per cent) in 2016.

Parties may wish to consider removing some additional listed procedures from the global exemption for laboratory and analytical uses of ozone-depleting substances (ODS), at a date to be determined by parties. Parties may also wish to consider establishing cooperation with standards organisations, to facilitate and accelerate the development or revision of standards for the replacement of ODS in analytical uses. Parties may also wish to consider providing: more comprehensive data (e.g. on consumption); sharing information on alternatives and on the revision of standards that use ODS; possible support for the development and/or revision of standards, and/or training, where needed.

Many standards still require the use of small quantities of ODS. There may come a point when the continued exclusion of specific laboratory and analytical uses on a case- by- case basis from the global exemption creates potential confusion for practitioners and regulators. Monitoring of, and adherence to, specific authorised uses of ODS in laboratory and analytical applications may become increasingly challenging as the exclusion list expands. At the 30th Meeting of the Parties, a number of parties noted the relatively insignificant quantities of ozone-depleting substances produced to supply laboratory and analytical uses, and the suggestion that excluding specific uses on a case- by- case basis could be confusing. In light of those considerations, parties discussed a proposal to take a fresh look at how to continue to reduce the use of ODS in laboratory and analytical procedures without sacrificing clarity or introducing excessively complicated measures for such as small quantity of ODS. Parties agreed to consider a draft decision on laboratory and analytical uses at the 41st meeting of the Open-ended Working Group.

4.9 Destruction technologies

Under the Montreal Protocol, the definition and data reporting requirements for production of controlled substances require parties to determine the quantity of ozone-depleting substances (ODS) destroyed in destruction facilities, in order to meet their reporting and compliance obligations. These definitions require parties to determine the quantity of ODS destroyed in destruction facilities, in order to meet their reporting and compliance obligations. The Montreal Protocol also allows remanufacture of ODS to replace a portion of ODS destroyed under specific conditions (within the same year as destruction, within the same group of substances, etc.). In practice, parties have not typically remanufactured ODS to offset quantities otherwise destroyed. In addition to these obligations, ODS destruction has been implemented to meet regulatory requirements and voluntary objectives to help protect stratospheric ozone and climate. In 2016, the Kigali Amendment to the Montreal Protocol included hydrofluorocarbons (HFCs) as controlled substances with obligations for their destruction.

Parties have taken a number of related subsequent decisions to approve destruction technologies for the purposes of Montreal Protocol requirements. Decision XXX/6 confirmed a range of approved destruction technologies for their applicability to HFCs and approved thermal decay for the destruction of methyl bromide.

Non-Article 5 parties generally have well established requirements to minimise emissions of ODS, including through the destruction of ODS. Recently, the Multi-lateral Fund of the Montreal Protocol (MLF) supported pilot destruction projects in Article 5 parties with an objective of overcoming some of the barriers to ODS destruction in those countries.

Cumulatively, over 300,000 tonnes of ODS have been destroyed since 1996, of which the majority was carbon tetrachloride (CTC) (70 per cent). The amount of ODS, excluding CTC, potentially available for management and destruction has been projected to peak globally at 200,000 tonnes in 2016. Based on ODS (excluding CTC) destruction reported to the Ozone Secretariat, a global destruction rate of about 3 per cent, of the total amount potentially available for destruction, was apparently achieved in 2016.

In 2015, the Executive Committee of the MLF reviewed a total of 15 approved ODS destruction demonstration projects approved in 2009, involving 12 countries, two regions, and one global project. The results of this review indicated that there were only two main approaches to destruction selected by countries, namely domestic destruction through local facilities and export of the ODS waste abroad for destruction in another country. In terms of the environmental performance of the destruction technologies evaluated in the MLF demonstration program, these were specific to the facility and the location. National standards/regulations impose emission limits for destruction facilities. However, destruction technologies were generally qualified for ODS destruction consistent with or similar to performance criteria used by the Technology and Economic Assessment Panel (TEAP) in assessing destruction technologies for the Montreal Protocol, which were sometimes more stringent than national standards.

Typically, waste HFCs are destroyed using the same processes that are used for ODS destruction. Many non-Article 5 parties already undertake and report on destruction of waste HFCs.

5 Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC)

5.1 Refrigerants

The Refrigerants chapter discusses and provides tabular summaries for refrigerant designations or identifiers, as well as physical, safety, and environmental data for refrigerants.

Refrigerant selection is a balanced result of several factors which include, suitability for the targeted use, availability, cost of the refrigerant and associated equipment and service, energy efficiency rating, safety, ease of use, and environmental issues.

There is no single "ideal" refrigerant. Due to the phase-down under the Kigali Amendment, the target refrigerants for main applications will include low GWP refrigerants such as R-717, R-744, hydrocarbons (HCs), unsaturated halochemicals such as hydrofluoroolefins (unsaturated HFCs sometimes referred to as HFOs) and hydrofluorochloroolefins (unsaturated HCFCs, sometimes referred to as HCFOs), and blends of these refrigerants, some even with traditional refrigerant fluids. Alternatives to high GWP refrigerants exist and new more efficient refrigerants are being proposed which creates a challenge to finding the right refrigerant for each application. Many of the proposed alternatives are seen as intermediate solutions in the HFC phase-down.

A system redesign or an update to the system topology will be required for most systems to begin using the newer refrigerants, but in some cases, this update may be as simple as changing the refrigerant and lubricant. As examples, the earlier transition from CFC-12 primarily to HFC-134a required only changes to lubricants and some elastomeric seals, while the shift from HCFC-22 to R-410A required those changes along with extensive compressor, heat exchanger, control, and other modifications. The search is a trade-off between cost, safety, energy efficiency, environmental impacts, and limiting the need for redesign.

One aspect of particular importance is that refrigerants with low direct impact on climate change are often flammable and may have higher toxicity. In order to maintain current safety levels, new technologies are being developed and increased levels of training will be needed.

Since the publication of the 2014 RTOC Assessment Report, 35 new refrigerants, most of them blends, have received a standard designation and safety classification. Among the 35 new fluids there are five single-compound refrigerants, HCC-1130(E), HFO-1132a, HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z). The newly introduced molecules, HCC-1130(E), HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z) have relatively high boiling points, making them relevant for high temperature heat pumps and centrifugal chillers. HFO-1132a is a lower toxicity flammable (safety class A2) high pressure fluid, with a boiling point of –86.7 °C; it has the potential to be used in cryogenic applications, as well as a component in new refrigerant blends, for instance those that will replace R-410A.

5.2 Domestic appliances

Under the domestic appliance category, the domestic refrigeration sub-sector is the major component and includes appliances that are broadly used domestically, such as refrigerators, freezers and combined refrigerator/freezer products. Small beverage dispensing machines are also included in domestic refrigeration, but represent only a small fraction of total units.

Globally, the movement away from the use of ODS in new refrigerator production was essentially completed by 2008. HC-600a (predominantly) or HFC-134a continues to be the refrigerant options for new production and currently, more than 1 billion domestic refrigerators use HC-600a. None of the other new refrigerants has matured to become an energy-efficient and cost competitive alternative. Refrigerant migration from HFC-134a to HC-600a is expected to continue, driven either by local regulations on HFCs or by the desire for reduced global warming impact from potential emissions. Significant progress is being made to convert the remaining applications of HFC-134a to HC-600a. With the market introduction of freezers and small refrigerators in the United States, service infrastructure is being developed. It is projected that by 2020 about 75% of new refrigerator production will use HC-600a (possibly with a small share by unsaturated HFC refrigerants) and the rest will use HFC-134a.

According to some industrial sources, initial developments to assess the use of HFO-1234yf in domestic refrigeration have begun, but it is not being pursued with high priority. No recent activity has been observed for the use of HFO-1234yf in refrigerators. Given the cost disadvantage, flammability, and investment requirements for product development, HFO-1234yf suffers significant disadvantages. With the lack of activity by manufacturers, HFO-1234yf is not likely to displace HC-600a or HFC-134a in the foreseeable future.

Alternative refrigeration technologies for domestic refrigeration continue to be pursued for applications with unique drivers such as, very low noise, portability, or no access to the electrical grid. In the absence of unique drivers, there are no known systems that are more efficient or cost effective than conventional vapour-compression technology for mass-produced domestic refrigerators.

The Association of Home Appliance Manufacturers (AHAM) of North America has announced a voluntary goal to phase out HFC-134a in household refrigerators and freezers after 2024 with HC-600a as the leading alternative. Based on recent studies, HFO-1234yf and HFO-1234ze and their blends with HFC-134a as drop-in refrigerants, may be possible alternatives. And after system optimization, the energy consumption may also be comparable. However, one also has to consider all safety issues with respect to flammability of these refrigerants.

The other domestic appliance covered in this chapter is the heat pump clothes (laundry) dryer (HPCD). Heat pump clothes (laundry) dryer (HPCD) sales are rapidly growing in the EU with manufacturing in EU, Japan and China, but the current market share of HPCDs in Article 5 countries is still insignificant. HPCDs are still predominantly based on HFC-134a and refrigerant charge amounts vary from 200 to 400 g. HPCDs using HC-290 are available in the market. Low GWP refrigerant solutions, including R-744, HC-600a and HFOs are still being explored.

5.3 Commercial refrigeration

Commercial refrigeration, used for storing and displaying food and beverages at different temperature levels within commercial stores. Two main levels of temperatures are generated by refrigeration systems from around 0 °C to 8 °C for the conservation of fresh food and beverages, and around -18 °C for frozen food and ice cream. HCFC-22, and more recently, R-404A are the commonly used refrigerants in these applications. Traditionally, commercial refrigeration applications are prone to significant refrigerant leakage due to the fact that most large systems are field installed. For all these reasons, the progressive phase-out of HCFC-22 in developing countries, and the phase-down of high GWP HFCs in many countries, requires making informed choices on the best replacement options.

Equipment can be classified as direct or indirect systems, or as stand-alone, condensing unit, centralised and distributed systems. The choice of a lower GWP alternate refrigerant depends greatly upon the type of equipment. In addition, since the equipment operates year-round and the condensing coils are typically located outdoors, the ambient temperature also plays a major role in equipment selection, this is particularly true for the high ambient regions of the world. Efficiency considerations are also a major factor due to the life cycle climate performance of such equipment tends to be dominated by the power consumed and the source of that energy. Commercial equipment typically has a life span of fifteen years or greater, and retrofit (changing refrigerant) is a common occurrence. Therefore, both new and existing equipment have to be considered when reviewing the refrigerant candidates for lower GWP. The table below gives a high-level summary of the types of refrigerants available for these applications:

	Stand alone	Condensing Unit	Centralised
High GWP HFC (current)	DX	DX	DX
Lower GWP HFC/HFO	DX	DX	DX/ with HTF
R-744	DX	DX	DX
R-717	---	With HTF	With HTF
HC	DX	DX / with HTF	With HTF

AHRI in the USA has conducted studies comparing lower GWP HFC/HFO refrigerants used as drop-in candidates with little modification to system design and the results have been encouraging. Numerous other conferences and studies have also reported similar findings for all climatic regions. In the past few years, non-halocarbon refrigerants like R-744 and R-290 systems have become common in global commercial refrigeration. While the adoption of new HFC/HFO blends is growing slowly and gradually, due to availability and to A2L standards and codes development, the growth of R-744 has not been uniform globally; this is due initially to cost and efficiency considerations in high ambient conditions. The growth in use of R-290 has followed a similar path, mainly due to the flammability of the refrigerant, which restricts the amount of refrigerant that can be used.

More recently, concerns about the efficiency of these alternate refrigerants have surfaced, but a study of field trials and existing literature on this topic shows that, in general, systems with the lower GWP alternate refrigerants can be as efficient as the high GWP HFC refrigerants they replace. Also, the methods of improving efficiency are not unlike those lower GWP refrigerant options.

In summary, several lower GWP refrigerant options have been identified for commercial refrigeration and more options are being announced as research and development continues. As the use of alternates increases globally, their availability, knowledge of use criteria, and the cost of the equipment can all be expected to improve. Refrigerant changes also give an opportunity to experiment with new system architectures that are aimed at reducing the total life cycle cost and climate impact of these equipment.

5.4 Industrial refrigeration and heat pump systems

Industrial refrigeration and heat pump systems are an integrated part of the global food chain from harvest to table. Industrial refrigeration is used for cooling a variety of food from ambient temperature to just above the freezing point of water or well below. Food and beverage (F&B) are important markets for industrial refrigeration, but industrial refrigeration is also used in a range of other industries such as fishing ships, pharmaceuticals, petrochemicals, airport cooling, and heating systems.

The majority of the world's large industrial systems use R-717 refrigerant. Where R-717 is not acceptable for direct systems, options include R-744 or glycol and brine in secondary systems, or HCFCs, or HFCs in direct systems. In countries where R-717 is not the preferred solution, or in market segments with smaller systems, the transition from HCFC-22 is not always straightforward, since most of the HFC alternatives are blends with a temperature glide. Due to accumulation of the separate components of a refrigerant blend in different parts of the system, blends form a challenge in industrial pumped and two stage systems. In larger systems, conversion to R-290 has been performed successfully e.g., in petrochemical installations where one more system with flammable gas does not raise any questions. It requires acceptance of higher cost fluorochemicals in similar system types or the adoption of more expensive systems with the cheaper refrigerants R-717 and R-744. This transition is slow and is constrained by a lack of trained personnel and lack of experience of the local end-users. It has been facilitated by corporate policy from multinational food and beverage manufacturers. The process of moving from HCFCs to zero ODP, low GWP alternatives would be accelerated by a concerted education and training program for operators and service technicians including operational experience and lessons learned from existing systems, and following ISO 22712. This conclusion has been reinforced by several fatal accidents that have occurred in recent years.

Suitable safety standards already exist such as those published by EN, ASHRAE, and ISO, including ISO 5149. ISO 5149 is also available as regional standards via EN 378 and ASHRAE 15. Once again, employee training on the higher standards is key to ensure safety of the systems in use. In markets where R-717 has been accepted as the preferred refrigerant, there is little to no indication that new refrigerants will gain any significant market share. The market use of the current HFC fluids has been limited due to their high cost and long-term availability. This does not give hope that new refrigerant fluids will be successful because they are expected to have a higher cost.

In large district heating systems HFO-1234ze (E) has shown to be a possible replacement for HFC-134a, however higher swept volumes and higher surface areas for the heat exchangers are required and its performance is not significantly better than that of HFC-134a. HFO-1234ze (E)) has also been demonstrated in centrifugal chillers, which could be used in process cooling or in district cooling installations. This may be a key player in addressing the challenge of a rapid market growth in the Gulf Co-operation Countries over the coming years.

Large size heat pumps are gaining market acceptance due to increased knowledge of the relevant technology benefits. There are several industrial processes where cooling and heating are needed at the same time, for example the dairy industry. These cases demonstrate how to fully use the potential of cooling and heating capabilities of heat pumps simultaneously.

The industrial sectors covered by this chapter are too diverse to facilitate the level of development expenditure required to bring a new fluid to market. It can therefore be stated that if any new development gains market share in industrial systems, it will be a fluid developed for some other purpose, either as a refrigerant in smaller mass-market systems or as a foam-blowing agent, solvent or other speciality chemical.

5.5 Transport refrigeration

Transport refrigeration is a small segment, mainly focused on the delivery of chilled or frozen products. This segment has specific challenges such as; shock, vibration, corrosion and broad operating conditions. Because of this, the refrigerant selection may be substantially different from other segments.

In truck and trailer refrigeration, one major development since the last assessment has been the introduction of R-452A as the alternative to R-404A. Because R-452A is non-flammable and a simple drop-in, its penetration in Europe has been substantial, whereas Asia and North America are continuing using R-404A.

As Europe continues its planned phase-down, significate steps have been taken to ensure long-term solutions have been put into place. The first step has been to transition to R-452A, but due to its GWP of 2000, it will most likely not become a long-term solution. A list of non-flammable blends with GWPs of around 1400 (such as R-448A, R-449A) are being evaluated and could potentially represent a second step of the phase-down. And finally, R-744, HC-290 and other mildly flammable refrigerants with ultra-low GWP are undergoing research activity and field trials for the final step.

In intermodal refrigerated containers, some manufacturers have proposed R-513A as an alternative to HFC-134a. Also, the first production units running on closed loop R-744 have entered the market. R-744 is attractive for its non-flammable characteristics and ultra-low GWP. The challenge in finding a comparable alternative mainly lies in the efficiency at moderate and high ambient temperatures.

Interest in flammable refrigerants as possible longer term, ultra-low GWP solutions, is evident given the significant activity in codes and standards updates and in the formation of the ISO 20854 working group for thermal containers. At the same time, flammability mitigation still represents a major challenge. No product solutions are currently available in transport applications that rely on flammable refrigerants.

The shipping industry is another sector that has made design changes to incorporate new refrigerants. Some new ships now use R-717 or R-744 either alone or in cascade, while the majority of the global fleet (other than those trading in Europe) will likely continue to operate using HCFC-22.

Although railway air conditioning applications continue to relying heavily on HFC-134a and R-407C, alternatives such as R-513A and R-449A are being evaluated. Also, alternative air cycles and R-744 systems are being tested in niche applications.

5.6 Air-to-air air conditioners and heat pumps

Air conditioners, including reversible air heating heat pumps (generally defined as "reversible heat pumps"), range in size from 1 kW to 1,100 kW although the majority are less than 70 kW. The most populous are non-ducted single splits, which are produced in excess of 110 million units per year. All products sold within non-Article 5 countries use non-ODS refrigerants. There is an increasing proportion of production of air conditioners in Article 5 countries that do not use HCFCs. Approximately one half of all units produced globally use non-ODS refrigerants.

Enterprises within non-Article 5 regions are continuing to evaluate and develop products with various HFC/unsaturated HFC blends, such as those comprising HFC-32, HFC-125, HFC-134a, HFC-1234yf and HFC-1234ze. In addition to the introduction of HFC-32 in residential split air conditioners in Japan, increased production and uptake is continuing in South East Asia, India, and in Europe. Further production lines conversion to HC-290 in China is underway, and (except for small and portable units) there is limited market introduction. This is contributed to by the restrictive safety standard requirements for certain product groups. In India, production of HC-290 split air conditioners is continuing, with production line conversions underway in several other, high ambient, countries. Some enterprises within the Middle East still see R-407C and HFC-134a as favourable alternatives to HCFC-22.

Acknowledging that almost all medium and low GWP alternatives are flammable, there has been significant progress with the development of new requirements for safety standards, although as yet the published standards remain restrictive for several low GWP refrigerants. Numerous research activities are investigating a variety of aspects related to the application of flammable refrigerants in air conditioning equipment.

5.7 Water and space heating heat pumps

Within the category of water and space heating heat pumps there are heat pump water heaters, space heating heat pumps, and combined space and hot water heat pumps. The required warm water temperature affects the selection of refrigerant. For the same source temperature, heat pump systems are more efficient at lower sink temperatures, but each product must fulfil the required operating temperature. The main use of heat pumps is to replace fossil fuel water heating systems. This is done with the purpose of reducing life time cost and/or to reduce the impact of greenhouse gas emissions. To compete with fossil fuel water heating systems, cost and energy efficiency are the most important factors and these will have a direct impact on the selection of the refrigerant.

Most heat pumps commercialised today make use of non-ODS refrigerants, such as R-410A, HFC-134a, R-407C, HC-290, HC-600a, R-717, R-744 and recently HFC-32, with the majority of new equipment using R-410A. In some Article 5 countries, HCFC-22 is being used due to its favourable thermodynamic properties and high efficiency. There are no technical barriers in replacing HCFC-22 by non-ODS refrigerants. The technical and process changes related to pressure, lubrication and contamination control are well known. Replacements are commercially available, technically proven and energy efficient, and all replacements have a similar or lower environmental impact. The issue of high ambient temperature conditions is of minor or no importance for water heating heat pumps. The main parameters required to select the HCFC-22 alternatives are efficiency, cost effectiveness, economic impact, safe use and easiness of use. Replacements consisting of low GWP HFC blends are under way to become commercially available.

HFC-134a, R-744 and HFC blends R-407C, R-417A and R-410A are commercially available solutions that have the highest grade of safety and easiness to use. Due to the quota requirements, low or lower GWP solutions like HC-290 and HFC-32 show a growing use in Europe. Temperature operation ranges for HC-290 and HFC-32 are better than those for R-410A and their efficiency is similar or better. R-410A, HFC-32 and HC-290 are most cost effective for small and medium size systems, while for large systems, HFC-134a is the most efficient option. R-407C and R-417A are the easiest alternatives for HCFC-22 from a design point of view, but cannot compete with the other HFC solutions.

5.8 Chillers

The phase-out of ozone-depleting refrigerants in new chillers is nearly complete, and globally, CFCs have been phased-out in new equipment. The use of HCFC-22 in new, small chillers has been phased-out in non-Article 5 countries as of 2010, yet there are still some Article 5 countries that are still manufacturing chillers that use HCFC refrigerants. However, global production of such chillers is very small. Despite these positive changes, there is a considerable number of existing chillers worldwide which use CFCs (notably CFC-11, CFC-12 and R-500) and HCFCs (notably HCFC-22 and HCFC-123) as refrigerants and, will remain in service for years to come, unless government regulations or financial incentives drive them to earlier retirement.

The current generation of chillers using zero-ODP refrigerants, dominated by HFCs, was introduced without sacrificing reliability or energy efficiency. Though most HFCs in use today are considered to have high GWPs, this is not a governing factor for chillers, because emissions are minimal and emissions related to their energy consumption dominate the environmental impact. None-the-less, the Kigali Amendment, which has entered into force, is a global agreement to phase-down HFCs and this will include change to refrigerants that have lower GWP.

Investigations into alternative refrigerants with lower GWP started several years ago and is now nearly complete. Understanding the trade-offs between GWP, efficiency, safety, and applied cost, along with the possibility of new single component refrigerants and blends, was a large task and yielded several acceptable alternatives. It is encouraging to report that the introduction of chillers with new lower GWP refrigerants has started and that chiller manufacturers will make that transition. However, the pace and intensity of the change is uncertain. Manufacturers are reluctant to change quickly, because product development costs are high and consumer demand is relatively low in most countries. Also, government regulations and financial incentives today provide little to accelerate change. As a result, the complete change to lower GWP refrigerants is likely to take several years. It is noteworthy that chillers that use non-fluorinated refrigerants are available today and will be part of a changing mix of commercially available products.

Vapour compression technology dominates all chiller products. Absorption chillers using lithium bromide/water or ammonia/water are available today, just as they have been for decades. Broader use is limited by cost and comparatively lower efficiency. They can be used effectively where there are favourable utility rates or in hybrid systems where waste heat or steam is available. It is unlikely that chillers using not-in-kind technologies will be commercialised in the foreseeable future.

The energy consumption of chillers dominates their environmental impact because the latest generation of chillers has low leak rates and, therefore, low direct global warming impact. The issue then is to introduce complete lines of chiller products, both air and water-cooled, with new refrigerants, while not sacrificing performance. It goes without saying that there can be no compromise in reliability or safety for those products that use flammable refrigerants. Safety codes and standards that give complete requirements for the application of flammable refrigerants are not yet published in all regions.

Regulators and customers alike are demanding higher performing, reliable chillers regardless of the refrigerant that is used. As most chillers are applied in large, multiple chiller systems, various application and control strategies are available that can significantly reduce the overall energy consumption of the system.

5.9 Vehicle air conditioning

Due to the enforcement of regulations, HFO-1234yf is rapidly increasing its market share in US and Europe in new AC equipped passenger cars, while HFC-134 remains widely used in other regions. Although the transition away from CFC-12 has been successful, there is still a transitional lag in selected Article 5 countries in that their existing automobiles still use CFC-12.

It is expected that as of 2019 and beyond, air conditioning for cars and light trucks will be met by several refrigerants such as HFC-134a, HFO-1234yf for use in new car models, and R-744. R-744 is expected to be considered as an option for electrified vehicles, when used at the same time for a heat pump function.

The de-carbonization of road transport and its progressive electrification will lead to a change of MAC (Mobile Air Conditioning). The vapour compression cycle will, by far, remain the most adopted technology; however, it will be implemented using different configurations, where the direct expansion will be in part be replaced by liquid cooled systems, to allow the electric and battery thermal management.

The global vehicle air conditioning market will be significantly governed by additional considerations such as safety, costs, regulatory approval, system reliability, heat pump capability (especially for electric driven vehicles) and servicing. The transition to new and more expensive refrigerants is driven by regulations; that is, where there are, or will be specific regulations, HFO-1234yf will be further adopted. Otherwise the old refrigerant (HFC-134a) will continue to be the main option unless (or until) less expensive solutions are available. Within this framework, it should be mentioned that there are studies to evaluate the adoption of less expensive, but flammable, low GWP refrigerants in Article 5 countries (e.g., in India).

Finally, it is unclear whether the bus and heavy-duty truck MAC will follow the passenger vehicle evolution, utilising for example HFO-1234yf or other options (HFO blends, R-744, etc.)

5.10 Energy efficiency and sustainability applied to refrigeration systems

The term sustainable refrigeration is linked to understanding and assessing the efficient use of resources, especially energy for operating refrigeration systems. Energy efficiency considerations were one of the considerations for the introduction of the chapter on sustainable refrigeration in the UNEP assessment reporting period 2010–2014. During 2014–2018, the importance for the selection of refrigerants has increased significantly.

This chapter moves beyond the traditional approach to refrigerant sustainability and uses a more holistic look of an air conditioning and refrigeration system lifecycle, with consideration given to the assessment tools and the aspects of efficient equipment and building design. Other opportunities were identified to achieve sustainability improvements along the lifecycle of a refrigeration system. Reduction in the use of raw materials and the establishment of codes of ethical conduct for suppliers along the value chain are two notable improvements.

Refrigeration, air conditioning, and heat pump equipment are vital means for sustainability in order to address the fundamental needs of humans in areas such as food conservation, food security, healthcare, water heating, and thermal comfort worldwide. There are, however, a number of negative environmental impacts from the use of this equipment that need to be minimised through careful consideration of design, operation, and end of life aspects of these equipment and the refrigerants they use. While keeping focus on possible environmental impacts of refrigeration treated throughout the report – namely the depletion of the stratospheric ozone layer and global warming – a wider range of relevant environmental, as well as social considerations, are briefly described in this chapter, for attention by decision makers.

Sustainable selection criteria, such as energy efficiency, climate impact, and adaptability for thermal energy storage, costs, technological level, safety, flammability and finally liability and responsibility for refrigerants are introduced in this chapter for the first time. Two environmental metrics – life cycle climate performance (LCCP) and total equivalent warming impact (TEWI) are used to select refrigerant options for reducing direct emissions and the sustainable use of refrigerants in service, maintenance, recycling, recovery, and disposal are described.

TFA, as a degradation product of several HFOs and HFCs used (as well as other chemicals containing a CF_3 group), is, and will be increasingly emitted to the ambient, thereby polluting aquatic soil layers and drinking water systems, with largely unknown impacts on the biosphere. Emission estimates for 2030 for HFOs *that are TFA related,* made in this report, are at about 60 ktonnes for non-Article 5 countries and at about 90 ktonnes for Article 5 countries. Even with a large number of studies done, adequate knowledge of HFOs decomposing to TFA and TFA pollution impacts is lacking. It implies that substantially more research is needed, particularly in light of the observed rapid, widespread uptake of HFO-1234yf in MAC applications and certain HFOs in other R/AC sectors between now and 2030.

The effects of political and regulatory measures, industry commitments, labelling of energy efficient products and other factors are explained using general technological and regional examples. It is emphasised that sustainable developments often conflict with the goal of minimising investment costs versus minimising energy consumption, thereby increasing energy efficiency.

For the first time, chapter 11 also addresses lifecycle considerations related to sustainable equipment design, sustainability within the refrigeration and air-conditioning servicing, the cold chains, sustainable building concepts and thermal energy storage.

This chapter also describes environmental impacts of refrigeration systems, which can be minimised by:

(a) The proper management of the selected refrigerants in response to growing environmental, regulatory, and economic concerns associated with refrigerant emissions, through:

- Charge minimization through simple measures such as checking the amount of refrigerant being charged, or by innovative technologies such as cascade systems and secondary loops;

- Improved design for leak tightness;
- Care taken during manufacturing, installation, service, and maintenance;
- Refrigerant conservation, using commercially available equipment for recovery, recycling and recovery, as well as destruction of refrigerants at the end of life.

(b) The reduction of CO_2 emissions from energy use, achievable through:

- Minimum energy efficiency performance standards applied through national regulation;
- The use of renewable energy sources; and
- Better energy management related to smart grid technologies, waste energy analysis, heat recovery, and anti-cyclical storage.

(c) The adoption and enforcement of responsible national and regional policies, legal requirements, and voluntary initiatives aiming to reduce refrigerant emissions through ban on venting and other measures.

(d) Environmentally sound end-of-life procedures in response to the growing demand of national and regional regulations.

5.5 Not-in-Kind technologies

This chapter analyses technologies that do not employ mechanical vapour compression (MVC) technology and further explores those Not-In-Kind (NIK) technologies that offer at least 15% energy savings compared to MVC technology. The chapter compares their attributes and properties. The technologies are classified as follows:

Commercially Available: At least one manufacturer produces this technology.

Widely Commercially Available: Available at more than one manufacturer.

Emerging: Passed R&D phase and is now established prior to commercial availability.

R&D: In research and development phase, not yet established.

All NIK technologies can be divided into three types:
- Solid state based,
- Electro-mechanical based, or
- Thermal based.

In all, 17 technologies were chosen for evaluation. Thermally based technologies are the ones that are most widely mentioned.

Thermally based technologies: nine technologies examined.

Commercially available or widely available. Examples are Absorption heat pumps, Adsorption heat pumps, Ejector heat pump, Duplex-Stirling heat pump for cryocooling (low temperature cooling) and Stand-Alone Solid Desiccant AC. Primarily for space cooling and some industrial applications. Four other technologies are in the Emerging or R&D stages.

Electro-Mechanical based technologies: five technologies examined.

Evaporative Cooling-both direct/indirect, also used in conjunction with other cooling systems to improve efficiency and reduce water consumption, for space cooling primarily.

Bryton cycle Heat Pump for aircraft AC systems, liquefaction of natural gas and for freezing tunnels. Three other technologies are in the R&D stage.

Solid-State based technologies: three technologies examined.

Magnetocaloric and Thermoelectric are widely commercially or commercially available. One technology is in R&D stage.

A table at the end of the chapter describes all technologies. In conclusion, the future is bright for NIK technologies. Plans are underway for assembling a one TR (3.52 kW) window air conditioner prototype operating on Thermoelastic technology (Electro-Mechanical Driven Technologies), at the University of Maryland, USA. In the US, one manufacturer developed a one TR (3.52 kW) prototype space-conditioning system that operate on Membrane Heat Pump technology (Electro-Mechanical technologies) using this two-stage, latent and sensible stages technology. High EER is predicted here.

Absorption heat pumps are commercially available and have an inherent advantage since they can operate on heat energy, thus saving precious peak electric power. Evaporative cooling has always been an attractive alternative in hot-dry conditions. In addition, Indirect/Direct evaporative cooling extended the use of this technology in mostly hot humid as well as hot dry conditions. Its water consumption rates have improved. Evaporative Liquid Desiccant technology (Thermal Based) a R&D technology, also consumes water. Careful selection is needed in regions where water is scarce. Ground coupled Solid Desiccant AC (Thermal Based Technologies) is also in R&D, and uses thermal energy. Magnetocaloric technology (solid-state based technologies) is available commercially for commercial refrigeration, although only one company claims production, therefore cannot be considered widely commercially available. Vuilleumier Heat Pump technology (thermal based technologies) is in the emerging phase and can be considered a promising technology.

Absorption fuel fired technology and Vuilleumier heat pumps (thermal based technologies) both use heat energy and serve both cooling and heating modes. For colder climates where cooling efficiency is offset by a much-improved heating efficiency, those technologies will offer important energy savings despite their lower cooling efficiency.

5.6 High ambient

The high ambient temperature (HAT) condition requires a design at 46°C (T3 in ISO 5151:2014) with appropriate operation up to 52°C ambient temperature. At HAT conditions, the heat load of a conditioned space can be up to six times more than that of moderate climates. Larger capacity refrigeration systems are needed which also implies larger refrigerant charges.

As ambient temperatures increase, the system capacity decreases due to higher condensing temperatures and thus compressor discharge temperatures also increase, leading to higher risks of reliability problems. This impacts the efficiency of the system installed, which will lead to a higher energy consumption for the cooling capacity to be provided.

HAT product should be specifically designed for HAT conditions, using a refrigerant suitable for that application and should also have all the safety measures incorporated for appropriate operation. Designing to meet the Minimum Energy Performance Standards (MEPS) in HAT countries is another important factor, as most of these countries have new and upgraded MEPS in place. This requires special design of bigger, more efficient units with an obvious impact on the unit size and cost to meet these new MEPS.

5.7 Modelling

There are a number of models used to calculate data for refrigeration and air conditioning applications, such as (1) thermodynamics based models that calculate energy efficiency and energy consumption, (2) combined thermodynamic, flow and heat transfer models used to investigate the impact of various refrigerant properties, (3) models that focus on total (climate relevant) emission reductions from the application of RACHP equipment, departing from assumptions or data on the number of pieces of equipment of certain types in the RAC(HP) subsector, and (4) inventory (bottom-up) models that calculate the amounts of refrigerant charged into RACHP equipment (i.e., the demand), where the equipment numbers are based on sales data of various types of equipment for a country or region; this can also be defined as the (global or regional) bank of refrigerants. A description of the latter model is given in the Annex to the 2010 RTOC Assessment Report. This type of model has been applied for the scenario calculations up to the year 2050 in various TEAP Task Force reports that investigated possible future high GWP HFC as well as low GWP refrigerant demand. Reports were published in the period 2012–2016.

It is quite challenging to find good data on the production of various types of equipment and the related sales for domestic use and export; needless to say, that these are extremely important data for any "bottom-up" inventory method. Good progress has been made up to 2018 in determining these parameters; it is expected that the availability of all the data and parameters will enable to develop adequate "bottom-up" scenarios for the refrigerant demand (as well as the related banks and emissions) during the next assessment period (2019–2022).

In 2014 and 2015, the RTOC inventory model was used for studies described in the XXV/5 and XXVI/9 Task Force reports. In 2016, the inventory model was used in the Decision XXVII/4 Task Force report, in order to further investigate the demand for high GWP HFCs and low GWP fluids for the RACHP sector until 2050. In particular, the impact of the length of the conversion period of the manufacturing in certain refrigeration and AC sub-sectors was considered. In 2016, the results of the RTOC inventory model were used to create a sort of database for the demand of all RACHP subsectors for a business as usual scenario for the period 2015–2050; this was done separately for non-Article 5 and Article 5 parties. Next to the RACHP sectors, data estimates were generated (and extrapolated into the future) for other HFC consuming sectors (foams, aerosols, fire protection). Using all these data, the HFC amendment proposals available in 2016 were evaluated and compared, this in particular where it concerns their climate benefits compared to a BAU scenario. Growth rates assumed for the various subsectors for the period until 2050 were given in the XXVII/4 Task Force report. This report paid a great deal of attention to the length of the manufacturing conversion period and its impact on total (manufacturing and servicing) demand, dependent on various mitigation scenarios. All scenarios were determined for the groups of both non-Article 5 and Article 5 parties. It will be clear that this method can also be used for separate countries, once sufficient input data on the equipment base and past refrigerant demand will be available.

The adoption and ratification of the Kigali Amendment is expected to drive new studies on the impact of the use of lower and low GWP fluids. This is likely to also include further emphasis on the impact of energy efficiency and the consequences for energy demand and related CO_2 emissions. The quality of rapidly evolving technical data will be important. This for modelling all aspects needed to provide timely conclusions on mitigation offered by lower and low GWP fluids and by lower indirect emissions, thereby enabling to prioritise policies.