Technology and Economic Assessment Panel

2022 Assessment Report

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Montreal Protocol on Substances that Deplete the Ozone Layer

Montreal Protocol
On Substances that Deplete the Ozone Layer
UNEP
2022 Assessment Report of the
Technology and Economic Assessment Panel

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1 INTRODUCTION

At the 31st Meeting of the Parties to the Montreal Protocol (MOP-31) in November 2019, parties adopted Decision XXXI/2 requesting the Scientific Assessment Panel (SAP), the Environmental Effects Assessment Panel (EEAP) and the Technology and Economic Assessment Panel (TEAP) to update their 2018 Assessment Reports in 2022 for consideration by the forty-fifth Open-Ended Working Group (OEWG-45) and the 35th MOP in 2023 (MOP-35). In paragraph 8 of that decision, the parties requested the TEAP, in its 2022 Assessment Report to consider the following topics:

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

b) *The status of banks and stocks of controlled substances and the options available for managing them so as to avoid emissions to the atmosphere;*

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

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

e) *Technical advancements in developing alternatives to HFCs suitable for usage in countries with high ambient temperatures, particularly with regard to energy efficiency and safety.*

In response to Decision XXXI/2, the Panel's Flexible and Rigid Foams Technical Options Committee (FTOC), Fire Suppression (formerly Halons) Technical Options Committee (FSTOC), 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 2022 report, which address new developments as well as global progress in the transition away from ozone depleting substances (ODS) and hydrofluorocarbons (HFCs) in the various sectors of use. The main findings from the TOCs are integrated into this 2022 TEAP Assessment Report.

The 2022 TEAP Assessment Report comprises Executive Summaries from each TOC. Key findings identified by each TOC are included in Chapter 2. 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 2019-2022.

1.1. Overall key findings

Since the 2018 TEAP Assessment Report, important technical developments have taken place to meet key ODS production and consumption phase-out milestones under the Montreal Protocol. The Kigali Amendment has created new challenges and additional milestones to phase down certain HFCs. Regular assessments by TEAP highlight the technical and economic challenges and provide useful information to transition to alternatives and technologies across the various sectors of use. The key sector and technology-specific challenges include phase-out of remaining uses of ODS in specific sectors, the phase-down of HFCs, uncontrolled and growing ODS uses, responsible management of banks and stocks of controlled substances, and emerging options for the use of more climate-friendly alternatives.

1.1.1. Significant technical progress

Actions under the Montreal Protocol support continued progress in consumer, commercial, industrial, agricultural, medical, and military sector, with ODS no longer used in many applications worldwide, e.g. no longer likely used in sterilisation. The phase-out of HCFC-22 in non-A5 parties is essentially complete and progressing in A5 parties. Under the Kigali Amendment, parties are progressing with national regulations to phase down HFCs, which is spurring market demand for lower-global warming potential (GWP) alternatives and simultaneously improving efficiency of equipment, stimulating innovative technologies and creating solutions to address new challenges for some applications.

Ultralow-, low-, and/or medium-GWP alternative refrigerants are available for all refrigeration, air conditioning, and heat pump (RACHP) applications and are being widely applied in some RACHP applications and regions. Most ultralow-, low-, and medium-GWP refrigerants have different flammability classes (lower flammability, flammable, and higher flammability). The RACHP sector continues to update the relevant safety standards to enable their use.

Significant progress has been made to phase-out the use of hydrochlorofluorocarbons (HCFCs) in foams. There are foam blowing agents (FBAs), that are not controlled substances, in use commercially today in nearly every foam sector.

Phase-out of controlled uses of methyl bromide (MB) is virtually complete. Parties report that greater than 99.8% of the baseline consumption of 66,428 tonnes for these controlled non-Quarantine and Pre-shipment (QPS) uses has been phased out by 1 January 2023.

Technically and economically feasible alternatives to controlled substances are commercially available for all aerosols, although not all alternatives are suitable across all aerosol applications in all locations. Parties may wish to consider the advantages of reducing the use of HFCs in the aerosol sector, where that is technically and economically feasible. Given that aerosols are totally emissive, any action taken would provide rapid reduction in HFC consumption and emissions.

Successful collaboration of experts across the Assessment Panels has supported the work of parties under the Montreal Protocol. The recent identification of unexpected increase in chlorofluorocarbon (CFC)-11 emissions between 2013 and 2018 led to coordinated research and analyses. In reports in 2019 and 2021, analysis by the TEAP Task Force on Unexpected Emissions of CFC-11 indicated that emissions from the CFC-11 banks alone could not explain the unexpected increase in emissions and indicative of unreported CFC-11 production and use in this period, most likely for use in closed-cell foams. Unreported production would also seem to have been occurring earlier in the period from 2007 to 2012. While this was a successful demonstration of scientific and technical collaboration providing answers on sources of unexpected emissions, it also highlighted the continuing challenge of compliance under the Montreal Protocol and the need for vigilance and continued support by parties.

1.1.2. Continuing challenges

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 technologies, 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.

Supply shortages of low-GWP alternatives in some sectors are understood to have started in 2020 due to COVID-19 related supply chain and logistics issues, raw material shortages, manufacturing issues, and severe weather, at the same time as increasing global demand. While these supply issues are less severe now, these will need careful monitoring as extended shortages in supply could delay transition away from HFCs across the various sectors of use.

In RACHP applications which use more than 90% of all HFCs, the HFC phase-down schedule focuses on addressing direct greenhouse gas (GHG) emissions by reducing HFC production and consumption. However, indirect GHG emissions from RACHP applications are equally or potentially more impactful to climate change. Some new low GWP RACHP equipment is more efficient by design, and reduces national energy demand. This will have a greater impact on climate change mitigation through synergy with reduced demand in high-performance buildings and cold-chain, and reduced carbon intensity of the electricity network.

In most A5 parties, but especially in low- and very low-volume consuming countries (LVC and VLVCs), the majority of ODS and HFC refrigerants is used for servicing. Cold food chains require a systematic approach, and are especially vulnerable, with a scarcity of trained personnel along supply chains delaying their implementation. Establishing proper servicing, described in codes and applied by trained and certified technicians, would reduce direct emissions of ODS/HFC refrigerants, and reduce the loss in energy efficiency in RACHP equipment over time.

In specific foam applications, some challenges remain, particularly for smaller enterprises in some A5 parties. These include shortage of supply and cost of alternatives, especially hydrocarbons and hydrofluoroolefins (HFOs). The proportion of fluorocarbons (FCs) used as foam blowing agents declines with each transition and is predicted to eventually be around 20% of total foam blowing agent use. However, fluorocarbon foam blowing agents will still be needed long term in some applications, to mitigate fire risk.

The overall increase in ODS feedstock uses through the last decade has been mostly due to the increase in feedstock uses of HCFCs, while uptake of HFOs is driving a more recent increase in carbon tetrachloride (CTC) feedstock use. In 2020, the proportions of the largest ODS feedstocks were HCFC-22 (48% of the total mass quantity), CTC (20%), and HCFC-142b (11%). HCFC-22 is by far the largest feedstock used, with 713,536 metric tonnes reported in 2020. It is important to monitor the increasing use of controlled substances as feedstock, as these contribute to overall global emissions.

Global consumption of HFCs for electronics manufacturing (HFC-23, HFC-32, HFC-41) and magnesium production (HFC-134a) is relatively small, although increasing for electronics manufacturing. Alternatives to HFC use include other fluorinated gases, many of which have higher GWPs.

Pressurised metered dose inhalers (pMDIs) for asthma and COPD contain HFC-134a and HFC-227ea as propellants. Lower GWP HFC-152a and HFO-1234ze(E) are under development as replacement propellants. DPIs and SMIs, where available, affordable and suitable, have much lower carbon footprints than pMDIs with high GWP propellants. Complex considerations are necessary when patients and healthcare professionals make an informed choice about a patient's inhaled therapy. Transition away from high GWP HFC pMDIs is a major undertaking with serious potential public health risks unless it is carefully managed. Parties may wish to consider the range of technical and economic issues associated with the transition from high GWP HFC pMDIs to ensure adequate supplies of pMDIs and other inhalers during HFC phase-down.

All aircraft continue to depend on halon from stocks for most of their fire protection applications, even though research and development has been ongoing for many years. The updated, estimated timeframe of between 2030 and 2049, when halon would be no longer available to civil aviation (or other fire suppression applications), means that the civil aviation industry (and others) must look either to their own stockpiles of halon or to the limited amounts of recycled halon available on the open market to avoid grounding aircraft because of a lack of appropriate fire protection. New aircraft designs in the military sector may only be able to use halon or a high-GWP HFCs to meet stringent design requirements.

In 2021, 100% of reported MB production was for QPS purposes, and MB production for controlled uses was reported to be zero, although a small amount is still used under the critical use exemption. Consumption for QPS uses remain at an average of 10,000 tonnes per year. Alternatives are available for most pre-shipment uses and if adopted, could result in replacing 30-40% (i.e. 3,000-4,000 tonnes) of the total QPS MB. Technical alternatives to both Q and PS purposes are becoming increasingly available, with new chemicals such as ethane dinitrile and hydrogen cyanide showing good efficacy against pests. Controlling emissions from QPS uses can be managed through use of recapture technologies.

The largest banks overall are currently in non-A5 parties and will rapidly reach end-of-life in the next decade. While ODS banks have been more concentrated in non-A5 parties, HFC banks are currently more evenly distributed between non-A and A5 parties. Banks in A5 parties are growing rapidly and will dominate global banks volumes by the early 2030s, resulting from declining banks in non-A5 parties and the rapid uptake of HFC-containing equipment in A5 parties. With quantities potentially available for recovery and management expected to increase in A5 parties, timely efforts to establish effective end of life (EOL) management capacity to prevent HFC emissions would have a significant impact, given the predicted size and growth of these banks in larger industrialised A5 parties. Addressing the barriers to the transboundary movement of EOL ODS/HFCs will be important in supporting preferential recovery/recycling and environmentally sound destruction of EOL ODS/HFCs, thereby minimising their emissions. Parties may wish to consider how relevant international treaty bodies can work together to facilitate transboundary movement of EOL ODS/HFCs.

1.2 Summary of Responses to Previous Decisions

A series of additional decisions taken by the parties during the 2018-2022 quadrennium are summarised in this section and further discussions in the relevant TOC report are indicated in Table 1.1. A brief summary of the responses to each of these decisions is provided following the table below.

Table 1.1. Additional decisions addressed in the 2022 TEAP Assessment Report:

Decision	Task	Source
XXVIII/2: Decision related to the amendment to phase-down HFCs	To request the Technology and Economic Assessment Panel to conduct periodic reviews of alternatives, using the criteria set out in paragraph 1 (a) of decision XXVI/9, in 2022 and every five years thereafter, and to provide technological and economic assessments of the latest available and emerging alternatives to hydrofluorocarbons;	See the following 2022 Reports: TEAP September 2022: Decision XXVIII/2 TEAP Working Group Report - Information on Alternatives to HFCs (Volume 5) Assessment Reports (updates): FSTOC, FTOC, MCTOC, and RTOC
XXIX/12: Consideration of HFCs not listed as controlled substances in Annex F to the Protocol	To request the assessment panels under the Montreal Protocol to provide in their quadrennial reports to be presented to the Thirty-Fifth Meeting of the Parties, in 2023, and every four years thereafter, information on the consumption and production of hydrofluorocarbons not listed in Annex F of the Protocol which have global warming potential no less than the lowest global warming potential of the hydrofluorocarbons listed in Annex F, noting that this is for information purposes only, given that the substances referred to in the present paragraph are not included in Annex F;	See 2022 MCTOC, Ch. 2 (2.11)
XXX/2: Adjustments to the Montreal Protocol	To request the Technology and Economic Assessment Panel to provide in its quadrennial reports to be presented to the Thirty-Fifth Meeting of the Parties in 2023 and to the Thirty-Ninth Meeting of the Parties in 2027 information on the availability of Annex C, Group I substances, including amounts available from recovery, recycling and reclamation, and best available information on country-level and total known stocks, as well as availability of alternative options for the applications described in Article 2F paragraphs 6 (a) and 6 (b);	See this report as well as the following 2022 Reports: FSTOC, FTOC, MCTOC, and RTOC

Decision XXX/6 paras 2 and 3, Destruction Technologies	To request the Technology and Economic Assessment Panel to assess those destruction technologies listed in annex II to the report of the Thirtieth Meeting of the Parties as not approved or not determined, as well as any other technologies, and to report to the Open-ended Working Group prior to the Thirty-Third Meeting of the Parties, with the understanding that if further information is provided by parties in due time, in particular regarding the destruction of Annex F, group II, substances by cement kilns, the Panel should report to an earlier meeting of the Open-Ended Working Group. To invite parties to submit to the Secretariat information relevant to paragraph 2 of the present decision	See 2022 MCTOC, Ch. 8.
XXX/15: Review of the TOR, composition, balance fields of expertise and workload of the TEAP	Further to request the Technology and Economic Assessment Panel, following the submission of the report called for in decision XXX/6, to provide a review of destruction technologies, if new compelling information becomes available; To request the Technology and Economic Assessment Panel to provide information to the parties on n-propyl bromide (nPB) if new compelling information is available, and on possible new substances if any previously unreported substances are identified that may have a likelihood of substantial production;	See 2022 MCTOC, Ch. 8 See 2022 MCTOC, Ch. 4 (4.3)
XXXI/5: Laboratory and analytical uses	To request the Technology and Economic Assessment Panel to report in its quadrennial report on any progress made by parties in reducing their production and consumption of ozone depleting substances for laboratory and analytical uses, on any new alternatives to those uses, and on laboratory standards that can be performed without such substances, on the understanding that, should new compelling information become available, including opportunities for significant reductions in production and consumption, that information should be reported in its annual progress report;	See 2022 MCTOC, Ch. 7
XXXI/6: Process agents	To request the Technology and Economic Assessment Panel to report in its quadrennial reports on any progress made by parties in reducing their use and emissions of controlled substances as process agents and on any new alternatives to such uses, including new production processes and emissions-reduction techniques, on the understanding that should new compelling information become available, that information should be reported in its annual progress report.	See 2022 MCTOC, Ch. 3

1.2.1. Decision XXVIII/2: amendment to HFC phase-down

Decision XXVIII/2, "Decision related to the amendment to phase-down hydrofluorocarbons", included a request to the TEAP under paragraph 4 "to conduct periodic reviews of alternatives, using the criteria set out in paragraph 1 (a) of decision XXVI/9, in 2022 and every five years thereafter, and to provide technological and economic assessments of the latest available and emerging alternatives to hydrofluorocarbons."

To respond to paragraph 4 of Decision XXVIII/2, TEAP considered that the first year of the requested review of alternatives to hydrofluorocarbons in 2022 coincided with the preparation of 2022 quadrennial assessment report of the TEAP. Decision XXXI/2, "Potential areas of focus for the 2022 quadrennial reports of the Scientific Assessment Panel, the Environmental Effects Assessment Panel and the Technology and Economic Assessment Panel", included a request for the TEAP "to assess and evaluate…technical advancements in developing alternatives to HFCs." In 2022, TEAP established a working group from within its membership, including the co-chairs of relevant TOCs FTOC, FSTOC, MCTOC, and RTOC). TEAP prepared a report[1] responding to Decision XXVIII/2 and presented this information to the 34th Meeting of the Parties. TEAP noted information contained in that report may be further updated as part of the TEAP 2022 quadrennial assessment. The information on alternatives to HFCs contained in the September 2022 Decision XXVIII/2 TEAP Working Group Report remains much the same as in the 2022 RTOC, FTOC, FSTOC, and MCTOC Assessment Report.

1.2.2. Decision XXIX/12: Consideration of HFCs not listed as controlled substances in Annex F to the Protocol

Decision XXIX/12, "Consideration of HFCs not listed as controlled substances in Annex F to the Protocol," requests the assessment panels "to provide in their quadrennial reports to be presented to the Thirty-Fifth Meeting of the Parties, in 2023, and every four years

[1] UNEP, "Report of the Technology and Economic Assessment Panel, Volume 5: Decision XXVIII/2 TEAP Working Group Report Information on Alternatives to HFCs," September 2022.

thereafter, information on the consumption and production of hydrofluorocarbons not listed in Annex F of the Protocol which have global warming potential no less than the lowest global warming potential of the hydrofluorocarbons listed in Annex F, noting that this is for information purposes only, given that the substances referred to in the present paragraph are not included in Annex F."

The 2022 MCTOC Assessment Report, Chapter 2, provides information relevant to this decision. Those HFCs that are not included in Annex F and that have GWPs above the threshold of 53 (based on IPCC AR6[2]) are included in Table 2.19 of that report. The reader is also referred to the MCTOC Executive Summary in Annex 1 of this report. The MCTOC noted that parties may wish to consider any actions that they might want to take concerning those HFCs not listed in Annex F with GWPs above 53 (IPCC AR6) with known commercial use (HFC-245cb, HFC-245eb, HFC52-13p, HFC-76-13sf, HFC-c447ef, cis-1,1,2,2,3,4-hexaflurorocyclobutane). Similarly, parties may also wish to consider whether to take any actions concerning anaesthetics that are halogenated ethers and other halogenated ethers with GWPs greater than 53 (IPCC AR6) with known commercial use.

1.2.3. Decision XXX/2: Adjustments to the Montreal Protocol

Decision XXX/2, "Adjustments to the Montreal Protocol," paragraphs 4, requests the TEAP "to provide in its quadrennial reports to be presented to the Thirty-Fifth Meeting of the Parties in 2023 and to the Thirty-Ninth Meeting of the Parties in 2027 information on the availability of Annex C, Group I substances, including amounts available from recovery, recycling and reclamation, and best available information on country-level and total known stocks, as well as availability of alternative options for the applications described in Article 2F paragraphs 6 (a) and 6 (b)."

Chapter 4 of this report provides a summary of information on banks and stocks of ODS and HFCs, and end-of-life management and destruction options contained in the 2022 Assessment Reports of the respective TOCs. The 2022 FSTOC, MCTOC and RTOC Assessment Reports also outline the alternatives options to Annex C, Group I substances and, where feasible, the amounts available from recovery, recycling and reclamation for the applications described in Article 2F paragraphs 6 (a) and 6 (b), which are the servicing of refrigeration and air-conditioning equipment; the servicing of fire suppression and fire protection equipment; solvent applications in rocket engine manufacturing; and topical medical aerosol applications for the specialised treatment of burns.

1.2.4. Decision XXX/6: Destruction Technologies

Parties have taken several decisions to approve destruction technologies that are used for the destruction of controlled substances for the purposes of Montreal Protocol production data reporting requirements under Article 7 and destruction of HFC-23 under Article 2J. The list of destruction technologies approved by parties has been updated, with the most recent list of approved destruction processes contained in Annex II to the 30th MOP under decision XXX/6. Decision XXX/6 on destruction technologies for controlled substances requests TEAP to assess destruction technologies listed as not approved or not determined, as well as any other technologies, and to report to parties. A summary of recommendations follow that are further elaborated in Chapter 8 of the 2022 MCTOC Assessment Report. The reader is also referred to the MCTOC Executive Summary in Annex 1 of this report.

MCTOC is not currently aware of new test data relating to already approved destruction technologies or new technologies that would allow an assessment. MCTOC notes that several mainstream destruction technologies continue to lack specific data on demonstration of DRE for Annex F HFCs. MCTOC is aware of some developments, including in the scale and application of existing approved destruction technologies and emerging interest in chemical transformation, that are noted in its 2022 Assessment Report. MCTOC also raises issues regarding already approved technologies for the consideration of parties.

MCTOC notes that parties may wish to consider removing the category, Portable Plasma Arc, as a separate approved technology to rationalise and consolidate the list of approved destruction technologies. Similarly, MCTOC notes that parties may wish to consider inclusion of cement kilns as an approved destruction technology for dilute sources of ODS and Annex F, Group 1, HFCs, for which there is already approval for concentrated sources. National and/or local governments require their own performance standards to meet emissions limits, and it is expected that any technology is required to meet local emissions standards on an installation specific basis.

1.2.5. Decision XXX/15: Review of the TOR, composition, balance fields of expertise and of the TEAP

Decision XXX/15, "Review of the Terms of Reference, composition, balance, fields of expertise, and workload of the Technology and Economic Assessment Panel," paragraphs 5 and 6 requests the following from the TEAP:

5. Further to request the Technology and Economic Assessment Panel, following the submission of the report called for in decision XXX/6, to provide a review of destruction technologies, if new compelling information becomes available;

6. To request the Technology and Economic Assessment Panel to provide information to the parties on n-propyl bromide (nPB) if new compelling information is available, and on possible new substances if any previously unreported substances are identified that may have a likelihood of substantial production;

[2] IPCC, 2021, Climate Change 2021, The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 7 Supplementary Material, Table 7.SM.7, contains metrics for substances including greenhouse gas lifetimes, radiative efficiencies and Global Warming Potentials (GWPs).

Information addressing paragraph 5 on review of destruction technologies is provided in Chapter 8 of the 2022 MCTOC Assessment Report. The reader is also referred to the MCTOC executive summary in Annex 1 of this report. Decision XXX/6 on destruction technologies for controlled substances requests TEAP to assess destruction technologies listed (in annex II to the report of the Thirtieth Meeting of the Parties) as not approved or not determined, as well as any other technologies, and to report to parties. MCTOC made the following recommendations based on its review: that parties may wish to consider 1) that parties may wish to consider removing the category, Portable Plasma Arc, as a separate approved technology in that no difference is seen from the currently approved full-size technology, and 2) inclusion of cement kilns as an approved destruction technology for dilute sources of ODS and Annex F, Group 1, HFCs, for which there is already approval for concentrated sources. The basis for these recommendations are elaborated in the chapter.

Information addressing paragraph 6 on nPB is provided in Chapter 4 of the 2022 MCTOC Assessment Report. The reader is also referred to the MCTOC executive summary in Annex 1 of this report. MCTOC noted that nPB is not a controlled substance under the Montreal Protocol and the continuing concerns regarding its use being based both on its potential for ozone depletion and its toxicity. Primarily due to health and safety risk characterisations for nPB, several countries regulate its use. Nevertheless, nPB continues to appear as a marketed solvent at trade exhibitions with demand in several markets (e.g., China, Japan, and the United States).

1.2.6. Decision XXXI/5: Laboratory and analytical uses

Decision XXXI/5, "Laboratory and analytical uses," paragraph 7, requests the TEAP "to report in its quadrennial report on any progress made by parties in reducing their production and consumption of ozone depleting substances for laboratory and analytical uses, on any new alternatives to those uses, and on laboratory standards that can be performed without such substances, on the understanding that, should new compelling information become available, including opportunities for significant reductions in production and consumption, that information should be reported in its annual progress report."

Information addressing Decision XXXI/5 is provided in Chapter 7 of the 2022 MCTOC Assessment Report. The reader is also referred to the MCTOC Executive Summary in Annex 1 of this report. MCTOC noted that many laboratory uses of controlled substances, e.g., as a common solvent or cleaning agent, have been phased out using alternative chemicals and/or procedures. Nevertheless, it is challenging to identify alternatives to ODS for some specific laboratory uses within such a wide range of chemical reactions undertaken in laboratories. In its report, MCTOC updated its review of standards from its 2018 Assessment Report. While significant progress has been made by the international standard bodies and non-A5 parties in the development or revision of standards to replace ODS in analytical use, there still exist standards that allow the use of ODS. For some standards, the alternative or alternative procedures may exist, but the ODS method remains as an active standard for these standard bodies, implying some barrier in adopting the alternatives or alternative procedures in standard development or revision. It may be more challenging for A5 parties to adopt the alternatives or alternative procedures due to the difficulties and/or complexities in the use of the alternatives. Parties may wish to consider actions to facilitate the adoption of alternatives in A5 parties, such as international cooperation between different standards organisations and between parties.

1.2.7. XXXI/6: Process agents

Decision XXXI/6, "Process agents," paragraph 3, requests the TEAP "to report in its quadrennial reports on any progress made by parties in reducing their use and emissions of controlled substances as process agents and on any new alternatives to such uses, including new production processes and emissions-reduction techniques, on the understanding that should new compelling information become available, that information should be reported in its annual progress report."

Information addressing Decision XXXI/6, paragraph 3 is provided in Chapter 3 of the 2022 MCTOC Assessment Report. The reader is also referred to the MCTOC Executive Summary in Annex 1 of this report. The process agent uses first defined in Table A of decision X/14 included 25 applications of ODS including CTC, CFC-113, CFC-11, and CFC-12. 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. From 2010 onwards, A5 parties were included in the measures for process agent uses. By 2019, when Tables A and B were last updated by decision XXXI/6, the number of process agent applications had reduced to 10 across 4 parties, and maximum emissions limits were 509 tonnes for 4,327.5 tonnes of make-up or consumption.

MCTOC noted that most 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 can be up to 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.

MCTOC discussed a suite of measures that can be applied to minimise make-up/consumption and emissions and each one to be considered by an operator. These measures include limiting makeup/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.

2 KEY FINDINGS FROM TECHNICAL OPTIONS COMMITTEES

2.1. Flexible and Rigid Foams Technical Options Committee (FTOC)

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

2.1.1. Progress in transitions

- There is no single 'drop-in' FBA replacement for currently used HCFCs or HFCs. There are different technical, economic, safety, and environmental performance properties for each low GWP, zero ozone depletion potential (ODP) alternative and different needs for each market subsector.
- There is a proliferation of blends across the whole of the foam sector which is an indication of the reality that there is no single best solution.
- Overall cost also is a major factor in the consideration of the major emerging technologies. A key factor of alternative selection is the size of the manufacturing plant since the economies of scale have a considerable bearing on the relative importance of capital and operational costs.
- The transition away from ODS foam blowing agents in some regions and market segments (e.g., spray foam and extruded polystyrene) may be delayed because of cost, especially where local codes require higher thermal performance.[3]
- The price of HFC blowing agents has risen substantively during the pandemic and is nearly as high as HFO and hydrochlorofluoroolefin (HCFO) prices were prior to the pandemic in some A5 parties.
- There has been a significant increase in the use of HFC-365mfc/HFC-227ea or HFC-365mfc/HFC-245fa blends in some A5 parties and a reversion to HFC-365mfc blends and HFC-245fa in some non-A5 parties due to shortages of low GWP FBAs.
- There continues to be a trend away from the use of FC FBAs with every transition. As the phase-out of HCFCs and the phase-down of HFCs progress, there will be limited availability and increasing prices of FBAs which will drive the selection of alternative foam blowing agents. It has been estimated that less than 20% of the FBA volume will be comprised of FCs after the transition to low GWP FBAs globally. This is in part due to direct conversions to other FBAs and in part as a result of the use of blends with lower concentrations of FCs.

2.1.2. Availability of Supply

Raw material shortages and limited access to production sites during quarantine periods reduced manufacturing supplies and demand during the early years of the global pandemic, including raw materials for foam manufacture and foams for the end-uses that incorporate them, such as refrigeration equipment. These markets have also been impacted by severe weather. According to *Fortune Business Insights,* the foam market contracted by 1.7% in 2020.[4] However, some economists note that there are continued supply disruptions and labour-market pressures which, coupled with interest rate increases, may contribute to continued slow recovery or even local or global recessions.[5]

- Low-GWP FBA shortages continue in both A5 and non-A5 parties but now to a lesser degree than previously reported. Supply issues are understood to have started in 2020. Logistics issues, raw material shortages, manufacturing issues, severe weather, and increasing demand for low-GWP FBAs have been highlighted as creating shortfall conditions. There have been recent announcements that additional production capacity for HFOs/HCFOs has come on-line.

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

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

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

- There have also been reported shortages of hydrocarbons of sufficient purity for foam use, such as cyclopentane.
- It is worth noting that the availability of high-GWP HFCs, particularly HFC-365mfc/HFC-227ea (which is banned in many non-A5 parties), is slowing the transition to low GWP FBAs. There has been a notice that at least one HFC FBA manufacturing facility will close in 2024.
- There are still reports of continued use of allocation procedures to phase-out supply to customers due to inability to fulfil all supply requests.
- An additional update on planned supply relative to forecasted demand will be provided in 2023 TEAP Reports as additional information becomes available.

2.1.3. Construction Recovery and Growth

- Global population growth drives demand for polymeric foams used in the main end-use industries, including building & construction, cold chain, furniture & bedding, packaging, and transportation industries.
- Polyurethane, polyisocyanurates, polystyrene and phenolic foams contribute to the energy efficiency of heating and cooling systems in buildings, while flexible polyurethane foams provide acoustic insulation, energy absorption for packaging and comfort in applications such as mattresses and furniture.
- Increasing focus on reducing heating and cooling load in buildings and appliances to meet the climate challenge will increase demand for polymeric foams as thermal insulation.
- The main factors influencing thermal insulation requirements are legislative, regulatory, and building standard mandates to reduce heating and cooling loads in both commercial and residential buildings.
- There is likely to be some recovery in all markets negatively impacted by the pandemic, in the near-term, including construction projects halted due to lack of funds, quarantine mandates, and resulting labour shortages.
- According to *The Future of Polymer Foams*, the annual production of polymer foam was estimated to be 29,357 thousand tonnes in 2021 and is projected to grow to 37,254 thousand tonnes in 2026 with an annual growth rate of 4.9% over this period, with a significant portion of this growth projected to occur in Asia. The polyurethane foams market was estimated to have the largest market share of polymer foams with approximately 51% of the market share with extruded polystyrene foams at 37% of the market in 2020.[6]
- According to *Mordor Intelligence*, the extruded polystyrene (XPS) market is projected to grow by over 4% per year from 2022 to 2027, after a significant slowdown in building construction during the pandemic. As construction resumes, increased demand for insulation materials to reduce building heating and cooling load is expected to lead to the growth of insulation markets for XPS, polyurethane (PU) and other insulation in the coming years. Polymer insulation growth is expected to increase at the fastest pace in the residential market due to population growth (new homes) and increased focused on better insulation in existing homes. Growth in the Asia-Pacific region is expected to dominate the market.[7]
- XPS is typically used for its low-moisture permeability and high-compression strength in applications including refrigerated transport, perimeter insulation and cold stores. Polyurethane, polyisocyanurate[8], and phenolic rigid foam are not used as widely as other thermal insulation materials (i.e., mineral wool or fibreglass) in building insulation due to relatively high cost. However, the low thermal conductivity of all three types of foam at wide operating temperatures dominates the insulation demand from the cold chain and district cooling and heating systems, including internal building services usage.

2.1.4. Cold Chain

- According to *Global Newswire*, the global cold chain market is expected to grow from a value of approximately $245 billion in 2021 to $800 billion in 2030, with[9] an annual growth rate of over 14%.
- There is increasing demand from the retail sector to mitigate food waste and degradation. Asia Pacific is expected to grow at the fastest rate due to the presence of major food and healthcare providers. For example, China's cold chain industry has been growing at a remarkable 19% since 2014.

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

[7] It should be noted that it has been estimated by F-TOC members that XPS foam manufacturing capacities in North America and Europe are currently close to capacity to meet current market demand.

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

[9] Global Newswire , Cold Chain Logistics Market Size to Worth Around USD 801.26 Bn by 2030, as viewed September 4, 2022

2.2 FSTOC (Fire Suppression Technical Options Committee)

- The FSTOC continues to express concern with expanded use of alternative refrigerants owing to their potential flammability and yet-to-be-determined effects on firefighting systems (e.g., agent effectiveness, by-products generated, etc.). Flammable refrigerants need additional care in system design, installation, and servicing. This could be a significant issue in A5 parties, where additional training will be required. Parties may wish to consider ensuring support for training / capacity building in A5 parties where flammable refrigerants are being used as part of the HFC phase-down. In addition to industry standard tests for measuring flame propagation, new methods are being developed to address these concerns. These issues are of particular concern to the military sector or other applications that may be subject to extreme environments. Parties may wish to address awareness programmes to re-establish this loss in institutional memory.
- Halon emissions may be higher than the FSTOC models predict. For halon 1301, FSTOC needs further information on emissions from feedstock production and use, and location of emissions. For halon 1211, atmospheric concentration derived emissions are near or above reported global amounts produced. For halon 2402, further information is needed on emissions from decommissioning activities in Asia.
- Many halon applications have transitioned to alternatives, some of which are high-GWP HFCs. Most of the alternatives to high GWP HFCs are considered to be per- and poly-fluoroalkyl substances (PFAS) in some definitions and are being proposed for a complete phase-out in some regulations. Halons are still needed for several enduring uses (e.g., oil & gas, nuclear power plants, military, civil aviation), the last of which is still growing.
- The run-out date of halon 1301 is now estimated to be 2-5 years sooner than in the 2018 Assessment Report (2030 to 2049 as compared to 2032 to 2054) depending on the modelling scenario used. This is mainly due to less halon 1301 being available to support enduring uses.
- HFC phase-down regulations in non-A5 parties are having a bigger impact on the cost and availability of HFC fire suppressants than initially anticipated by the FSTOC. It is the FSTOC's experience that HFCs contained in fire protection equipment have historically enjoyed a relatively high level of recycling and reuse. As the supply of newly produced HFCs for fire protection decreases in response to phase-down regulations, recycling becomes even more important as an alternative source of supply and is likely to increase in the future.
- Some PFAS definitions include most in-kind halon and high-GWP alternatives. Some regulations may therefore curtail or prohibit most of the in-kind alternatives available, leaving the original halons (high ODP and GWP), HFC-23 (extremely high-GWP) and potentially CF3I (toxicity issues and potentially ODP issues) as the only viable alternatives.
- The world's first pilot halon destruction for carbon offset occurred in February 2021 in the US, using internally sourced halon 1301 for the creation of carbon credits which were traded in the voluntary carbon market. The FSTOC is concerned that destroying halon 1301 for carbon credits could contribute to global shortages / regional imbalances of halon 1301 to support long-term enduring uses.
- FSTOC continues to see issues regarding the loss of historical knowledge 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 halon management but not being familiar with the issues surrounding halons, HCFCs, HFCs, and their alternatives use, recycling, and banking. Lack of understanding about long-term needs for halon 1301 has also resulted in halon destruction. FSTOC notes that this lack of experience and historical knowledge is becoming 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 address awareness programmes to re-establish this loss in institutional memory.

2.3. MBTOC (Methyl Bromide Technical Options Committee)

- Phase-out of controlled, non-exempted (i.e., non-QPS) uses of MB is virtually complete. Parties report that greater than 99.8% of the baseline consumption of 66,428 tonnes for these controlled non-QPS uses has been phased out by 1 Jan 2023.
- In 2022, only two remaining non-A5 parties applied for Critical Use Nominations (CUNs) for pre-plant soil fumigation in strawberry nursery industries and one A5 party for use in structural fumigation of houses. In 2021, reported MB consumption for controlled uses was around 40 tonnes. All other non-exempt uses of MB have been replaced by other processes. No CUN was based solely on economic factors.
- Stocks are considered to be used for some other unreported controlled uses of MB, possibly amounting to around 1,000 tonnes. MBTOC notes once again that MB is still offered on the internet for any use, including preplant soil fumigation and treatment of stored products.
- The phasing out of MB under the control measures of the Montreal Protocol (Annex E) has led to over 30% of the present decline in ozone degrading chemical concentration in the atmosphere (i.e., Equivalent Effective Stratospheric Chlorine or EESC). This is the single largest contribution to improvement of the ozone layer from any chemical at this time.

- In the latest report by parties in 2021, 100% of reported MB production was for QPS purposes. Since 2018, despite controlled uses being sought under CUNs, no Party has reported production of MB for these controlled uses (non-QPS).
- Only 55 of 198 parties report use of MB for QPS, with seventeen countries using about 94% of the reported QPS consumption. Annual consumption of MB for QPS purposes, an exempted use, has remained relatively constant over more than 20 years, at around 10,000 tonnes. A5 parties account for ~57% of global MB consumption for QPS purposes (5,922 tonnes) and non-A5 parties ~43% (4,479 tonnes). MBTOC reinforces that alternatives are available for most pre-shipment uses, which if adopted could result in replacing 30-40% (i.e. 3,000-4,000 tonnes) of the total QPS MB.
- Elimination of emissions from QPS use is the largest short-term gain that could be made to restore the ozone layer. Complete elimination of emissions from QPS use of MB, could result in a further significant (i.e. ~10%) and rapid reduction to the present EESC. This is one of the very few measures available to Parties that would result in this magnitude of rapid reduction. Technical alternatives (e.g. ethane dinitrile and hydrogen cyanide) for both Q and PS purposes are becoming increasing available and effective alternatives to MB for commodity treatments and in instances where MB is still needed, recapture technologies are now available.

2.4. MCTOC (Medical and Chemical Technical Options Committee)

2.4.1. Production, including Feedstocks

- The overall increase in ODS feedstock uses through the last decade has been mostly due to the increase in feedstock uses of HCFCs, particularly HCFC-22, while uptake of HFOs is driving a more recent increase in CTC feedstock use.
- Using A7 reported data and MCTOC's *most likely* emission factors, global emissions of controlled substances during production, distribution and feedstock use have been estimated for 2020.
  - ODS feedstock production, distribution and use emissions were 53,100 tonnes (19,948 ODP tonnes);
  - ODS non-feedstock production and distribution emissions were 9,403 tonnes (672 ODP tonnes);
  - HFC production and distribution, including feedstock use, emissions were 25,728 tonnes (42.8 MMTCO2e).
- HCFC-22, the largest ODS feedstock, is mainly used to produce tetrafluoroethylene (TFE) and hexafluoropropylene (HFP) used in fluoropolymer production. The manufacture of HCFC-22 generates HFC-23 by-production and emissions, for which Article 2J of the MP establishes destruction requirements. The manufacture of TFE/HFP from HCFC-22 feedstock generates by-production and emissions of HFC-23 and PFC-c-318 (c-C4F8) with very high GWP. If unabated, these emissions as CO_2e would be higher than the estimated emissions of HFC-23 from HCFC-22 production. Parties may wish to consider the significance of these potential emissions.
- HFC-23 can also be formed as by-product during the production of HFC-32. Production processes of other fluorocarbons, such as for HFC-125, HFC-134a, HFC-143a, and possibly some steps of HFO production processes, can also result in by-production of HFC-23, although preliminary data indicates at much lower rates than for HCFC-22 and HFC-32 production. HFC-125 production can result in by-production of CFC-113, -114, -115.
- An increasing trend in production of carbon tetrachloride (CTC) is likely to continue due to expected increasing demand for HFO/HCFOs. Based on A7 reported CTC production of 289 ktonnes for 2020, global CTC emissions are estimated as 17.8 ktonnes (7.1–28.1 ktonnes), of which 12.8 ktonnes (4.6–20.6 ktonnes) arise directly from CTC production, handling, supply chain, and use. A further 5 ktonnes (2.5–7.5 ktonnes) CTC emissions arise from non-chloromethanes production, e.g., the vinyl chain production process, is identified as a new potential source of unreported CTC emissions.
- Parties may wish to consider any actions that they might want to take concerning those HFCs not listed in Annex F with GWPs above 53 with known commercial use (HFC-245cb, HFC-245eb, HFC-52-13p, HFC-76-13sf, HFC-c447ef, *cis*-1,1,2,2,3,4-hexaflurorocyclobutane). HFEs used as solvent replacements for controlled substances have GWPs (IPCC AR6 values) between 59 and 580. Some fluorinated ethers with GWPs greater than 53 are used as inhalation anaesthetics where emissions are more likely to occur. Parties may wish to consider any actions that they might want to take concerning anaesthetics that are halogenated ethers and other halogenated ethers with known commercial use with GWPs (IPCC AR6) greater than 53.

2.4.2. Process agents

- Most of the removals of process agents from Table A, as updated in decisions, 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.

2.4.3. Solvents

- Solvent uses of controlled substances include metal, electronics, and precision cleaning. Alternatives include not-in-kind technologies, such as aqueous cleaning, semi-aqueous cleaning, hydrocarbon and oxygenated solvents, and in-kind solvents, such as chlorinated solvents and fluorinated solvents, including high-GWP HFCs not listed in Annex F and low-GWP HFOs, HCFOs and HFEs, and their blends.

- n-Propyl bromide continues to appear as a marketed solvent at trade exhibitions with demand in several markets (e.g., China, Japan, and the United States). Relatively low workplace exposure standards indicate that use of n-propyl bromide in solvent applications will likely be limited to applications where worker exposure is controlled and will require significant emission control.

2.4.4. Semiconductor and other electronics manufacturing

- HFCs, including HFC-23 (CHF3), HFC-32 (CH2F2) and HFC-41 (CH3F), are used for etching circuits, chamber cleaning, and as a heat transfer fluid to control temperature in semiconductor and other electronics manufacturing. For etching and chamber cleaning, alternatives include a range of fluorinated chemicals, many with higher GWPs and one with a low GWP. Emissions controls significantly reduce HFC emissions. Some parties appear to treat production and consumption of HFCs in semiconductor manufacturing in the same way as other emissive uses and others as feedstock use, excluding the portion resulting in HFC emissions in the process. Parties may wish to consider how to treat HFC production and consumption for semiconductor uses for the purposes of Article 7 data reporting.

2.4.5. Magnesium production

- HFC-134 is used as a cover gas in magnesium production, casting processes and recycling, to prevent oxidation and combustion of molten magnesium. Sulphur hexafluoride (SF6), with a very high GWP, is the most widely used cover gas. Several gases with lower GWPs are used as alternatives to SF6, including HFC-134a and a fluoroketone. Global demand for HFC-134a as a cover gas, while relatively small, is expected to continue.

2.4.6. Laboratory and analytical uses

- Parties may wish to consider actions to facilitate the adoption of ODS alternatives for laboratory and analytical uses in A5 parties, such as international cooperation between different standards organisations and between parties. Possible actions may include sharing more information on alternatives as well as on the revision of standards that use ODS.

2.4.7. End-of-life management and destruction technologies

- Effective management of banks of ODS and HFCs, by maximising recovery, recycling, reclamation, reuse, and ultimately destruction after all other options have been exhausted, can minimise the global impacts of potential emissions at EOL.
- Banks in non-A5 parties are currently the largest overall and will rapidly reach end-of-life in the next decade. Banks in A5 parties are growing rapidly with the uptake of HFC-containing equipment and will dominate global quantities by the early 2030s. With increasing quantities potentially available for recovery and management in A5 parties, timely efforts to establish effective EOL management capacity would have a significant impact on preventing HFC emissions.
- With improved economies of scale, through the recovery of increased quantities of ODS/HFCs, the anticipated cost per kg of recovered controlled substances for EOL management could be minimised, assuming infrastructure is available and investment in EOL management has been made within a supportive policy framework. Several approaches are possible to finance the required infrastructure/capability and to economically incentivise the servicing and waste management sectors that support the management of EOL ODS/HFCs.
- In many countries, EOL ODS/HFCs are considered as hazardous wastes, with their transboundary movement subject to requirements of the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal and related international shipping standards. This requires informed consent by the governments of the exporting, transit, and importing countries. While effective in restricting illegal trade in waste, the process of informed consent is inevitably bureaucratic and time consuming, resulting in significant transaction costs. This is a significant barrier to EOL ODS/HFC management. Parties may wish to consider how relevant international treaty bodies can work together to facilitate transboundary movement of EOL ODS/HFCs.
- Decision XXX/6 requests TEAP to assess destruction technologies listed (in annex II to the report of the Thirtieth Meeting of the Parties) as not approved or not determined, as well as any other technologies. Parties may wish to consider inclusion of cement kilns as an approved destruction technology for dilute sources of ODS and Annex F, Group 1, HFCs, for which there is already approval for concentrated sources. Parties may also wish to consider removing the category, Portable Plasma Arc, as a separate approved technology to rationalise and consolidate the list of approved destruction technologies.

2.4.8. Aerosols

- A significant proportion of aerosol propellants have migrated to hydrocarbons and dimethyl ether. A smaller proportion migrated to using HFCs or still use HCFCs, where flammability, toxicity, safety in use, and/or VOC content are considerations. Technically and economically feasible alternatives to controlled substances are commercially available for all aerosols, although not all alternatives are suitable across all aerosol applications in all locations. Parties may wish to consider the advantages of reducing the use of HFCs in the aerosol sector, where that is technically and economically feasible. Given that aerosols are totally emissive, any action taken would provide rapid reduction in HFC consumption and emissions.

2.4.9. Pressurised metered dose inhalers

- In response to the Montreal Protocol, pharmaceutical companies replaced CFC propellants in pMDIs with HFC-134a and to a lesser extent HFC-227ea. Under the Kigali Amendment, the production and consumption of Annex F HFCs are scheduled to be phased down.
- Most of the carbon footprint of pMDIs is due to propellant released. All currently available HFC pMDIs have a far greater carbon footprint than DPIs or SMIs.
- Lower GWP HFC-152a and HFO-1234ze(E) are under development as potential replacement propellants for HFC-134a and HFC-227ea in pMDIs.
- Four companies have announced plans to reformulate, with their target to introduce the first new pMDIs containing HFC-152a or HFO-1234ze(E) in 2025.
- In non-A5 parties, it is currently unlikely that transition would be completed before 2030, even for the limited number of products announced to date. For A5 parties, the timetable for HFC phase-down is longer than for non-A5 parties, nevertheless, multinational inhaler manufacturers in A5 parties, with targets to reduce their carbon footprints, seek to maintain and build global market access.
- There are a range of issues and potential challenges that could emerge in the transition away from high GWP propellant pMDIs to inhalers with lower GWPs, which could create risks to inhaler markets and patient health. These include global and national frameworks that address transition challenges; continuity in, and stability of, the supply of pharmaceutical-grade HFCs; rising cost of bulk HFC-134a and HFC-227ea propellants; regulatory approvals; exports of pMDIs; patent protections; manufacturing capacity for pMDIs with the new propellants, DPIs and SMIs; patient and physician information.
- Technical-grade HFC-134a, imported from Japan and/or the United States, is manufactured to pharmaceutical-grade HFC-134a in the United Kingdom by a single company, and then exported globally for pMDI manufacture. For technical reasons at the HFC-134a manufacturing facilities, the Kigali Amendment's 70% reduction in non-A5 parties in 2029 is likely to impact and limit the global supply of technical- and pharmaceutical-grade HFCs for pMDIs, when an adequate supply of lower GWP pMDIs might not yet be available to meet patient demand.
- Parties may wish to consider:
  - The range of technical and economic issues associated with the transition from high GWP HFC pMDIs to ensure adequate supplies of pMDIs and other inhalers during HFC phase-down.
  - The need for global and national coordination in the HFC phase-down and its impact on the transition away from high GWP HFC pMDIs to ensure patient safety.
  - How to ensure that adequate bulk HFC-134a and/or pMDIs are available in their own markets, and in their export markets, to avoid risks to the continuous supply of pMDIs for patients.
  - Measures that facilitate efficient, timely development while assuring the safety and effectiveness of the new pMDIs.

2.4.10. Sterilants

- Sterilization technologies and applications continue to move to deploy environmentally safer processes as best practice, in parallel with meeting the essential needs for patient safety. With alternative technologies available, MCTOC believes that sterilization applications using controlled substances are no longer a relevant risk for the Montreal Protocol. The complete phase-out of HCFCs in sterilization is readily achievable in A5 Parties to meet the Montreal Protocol schedule. Unless circumstances change, MCTOC will not include sterilization in future technical updates.

2.5. RTOC (Refrigeration, Air Conditioning and Heat Pumps TOC)

- The Montreal Protocol has been shown to be successful in phasing out HCFCs with an essentially complete phase-out in non-A5 parties and strong progress in A5 parties.
- The Kigali Amendment to the MP has provided the signal to mobilise the RACHP sector into a transition towards lower GWP refrigerants.
- Ultralow-, low-, and medium-GWP alternative refrigerants are available for all RACHP applications and are being widely applied in some applications and regions.
- Accessibility is still a major hindrance for the widescale adoption of lower GWP refrigerants and the progress towards the Kigali Amendment phase-down schedule.

- Most ultralow-, low-, and medium-GWP refrigerants have different flammability classes (lower flammability, flammable, and higher flammability). As such, the RACHP sector continues to update the relevant safety standards to enable their use. Most recent updates reduced the restrictions on flammable refrigerants and increased the allowable flammable refrigerant charge limits for self-contained commercial refrigeration and air-to-air AC applications.
- Trifluoroacetic acid (TFA), one of the decomposition products of some refrigerants, is a chemical that is included within the Organisation for Economic Co-operation and Development (OECD) definition of per- and poly-fluoroalkyl substances (PFAS). The OECD PFAS definition does not include HFC-32, HFC-152a, HFO-1132 and HFO-1123. Information on PFAS and TFA are provided in the 2022 EEAP Assessment Report. There is a proposal from five European countries to update their own PFAS definition, which may impact RACHP applications in some countries.
- While high-GWP HFC phase-down focuses on the direct GHG emissions from the RACHP sector, the indirect GHG emissions are equally or more impactful to climate change. The indirect GHG emissions are due to energy consumption from the RACHP applications and can be reduced significantly through improved equipment energy efficiency, reduced demand using high-performance buildings and cold-chain, and reduced carbon intensity of the electricity network.

2.5.1. Sustainability in the RACHP sector

- RACHP applications play a key role in sustainable development.
- RACHP equipment contribute to climate change through direct emissions of GWP refrigerants and indirect emissions from energy consumed during lifetime operation.
- Standards and methods are available to perform sustainability assessments for RACHP applications.
- RACHP uses refrigerants with a range of potential adverse effects. Some adverse effects are real and immediate (e.g., flammability and toxicity), some are near term on climate (e.g., high-GWP), and some are uncertain (e.g., TFA).
- It is important to balance the benefits and risks of refrigerant selection, including known safety and environmental impacts, being mindful of areas of scientific uncertainty.
- Sustainability issues should be balanced with technical issues for RACHP applications.
- Readers are encouraged to consult with the 2022 EEAP Assessment Report on TFA and PFAS.

2.5.2. Refrigerants

- Two new single component refrigerants (FIC-13I1 and HFO-1132(E)) and 23 new refrigerant blends have received designations and classifications by ASHRAE Standard 34 and/or ISO 817 since the publication of the 2018 RTOC Assessment Report.
- There is no single "ideal" refrigerant. Refrigerant selection is a balanced result of weighing several factors which include, environmental issues, suitability for the targeted use, availability, cost of the refrigerant and associated equipment and service, energy efficiency rating, safety, and ease of use.
- The HFC phase-down under the Kigali Amendment as well as regional regulations are driving the industry towards the use of low-GWP refrigerants. Ultralow-, low- and medium-GWP alternatives to high-GWP refrigerants exist and have been used in many applications, where new ones are being continuously introduced.
- Many of the alternative refrigerants that are now being used are expected to only play a temporary role in the phase-down process, as their GWP may still be high for future applications.
- Refrigerants with low direct impact on climate change are often flammable (e.g., HCs) and may have higher toxicity (e.g., ammonia). In order to maintain the current safety levels, safety standards are being updated, new technologies are being developed and an increased level of training will be required.
- Refrigerant emissions into the atmosphere can result in decomposition products which could be harmful to the Earth's eco-system. Some of the current and alternative synthetic fluorinated refrigerants, (HCFCs, HFCs, and HFOs) produce varying amounts of trifluoroacetic acid (TFA, formula C2HF3O2) during their atmospheric decomposition. Understanding the TFA budget in the different parts of the environment is key for evaluating future environmental impacts of all anthropogenic TFA (WMO, 2022).
- Article 7 reported data give no sector-specific consumption information on HFCs and are difficult to interpret. One can consider Multilateral Fund and other survey data, but availability of reliable data is limited.
- Five different types of models exist for the calculation of HFC consumption, inventories, and emissions of which three are bottom-up based models. With different ways of calculating refrigerant consumption, banks and emissions, they have become key for the future understanding of the impact of refrigeration, AC and heat pump systems on the environment.

2.5.3. Sealed domestic and commercial refrigeration appliances and heat pump tumble dryers

- Around 2 billion refrigerators are installed worldwide, with 200 million new domestic refrigerators and freezers being sold each year dominated by the HC-600a refrigerant technology.

- Due to Kigali Amendment, stand-alone commercial refrigeration appliances are moving to more efficient HC-290 technologies in both non-A5 and A5 parties following the revision of safety and equipment standards in 2019.
- Domestic heat pump tumble dryers (HPTDs) use 40 to 50 % of energy of conventional dryers, they continue to gain market share. Common refrigerants are HFC-134a, R-407C, and R-410A but transition to HC-290 is seen in Europe.

2.5.4. Food retail and food service refrigeration

- The shift to ultralow- and low-GWP in new systems and retrofit to low- or medium-GWP in existing systems, while also maintaining or improving the energy efficiency, is critical in the expansion of a sustainable cold chain to reduce food loss and waste.
- Food Retail and Food Service refrigeration conversion to ultralow-, low- and medium-GWP refrigerants is progressing well in all regions, but high-GWP refrigerants are still being used in many countries.
- The most common ultralow- and low-GWP refrigerants being applied are R-744, HC-290, and HFO blends such as R-454C, R-454A and R-455A.
- There is a continuing effort to improve energy efficiency while transitioning to ultralow- and low-GWP systems through refrigeration load reduction and improved vapour compression system design and component efficiency.
- Existing high-GWP R-404A and HFC-134a systems are being proactively converted to medium-GWP A1 refrigerants (e.g., HFO blends such as R-448A, R-449A, R-450A, and R-513A).

2.5.5. Transport refrigeration

- Transport refrigeration is an important part of cold chain systems. To ensure safe and reliable operation, the knowledge, competency for safe service, spare parts, as well as relevant safety processes and procedures, must be available all along the transport routes.
- The majority of trucks and trailers still use R-404A but new equipment in Europe and in North America uses R-452A with a significant reduction in GWP. Furthermore, HFC-134a are being converted to R-513A or HFC-1234yf.
- Light commercial vehicles use mainly HFC-134a, while some begin to use HFO-1234yf.
- The majority of marine container refrigeration units still use HFC-134a.
- Air conditioning in cruise liners air conditioning which has used HFC-134a is being replaced by HFC-1234ze(E). R-717 is returning in fishing vessels.
- The GWP of the refrigerants used is expected to come down consistently with present and future legislation. Future systems may be based on HC-290, R-744, A2L or A1 refrigerant blends.
- Progress has been made in the area of design standards, which are becoming available for the subsectors. A scarcity of qualified people to maintain and service systems with various levels of complexity along the transport routes, combined with availability problems of spare parts including refrigerants, can slow down the transition to the ultralow-, low- and medium-GWP alternative refrigerants or new solutions.

2.5.6. Air-to-air air conditioners and heat pumps

- The phase-out of HCFC-22 in non-A5 parties is complete for new equipment.
- The phase-out of HCFC-22 is progressing well in A5 parties where some have already completed HCFC-22 phase-out.
- In addition to HFC-32, there are several medium-GWP HFC/HFO blends being adopted, such as R-454B, R-452B and R-463A.
- In addition to these refrigerants, transition also includes adoption of HC-290 for single split and portable AC units, which is underway in China, South-East Asia, and Latin America.
- Component and system optimisation remain a design challenge over and above those with conventional refrigerants, such as HCFC-22 and R-410A. Availability and accessibility of certain components and technologies and in some regions are a major hindrance to uptake of medium- and particularly low-GWP alternatives. Also, the high price of some low- and medium-GWP blends is a strong deterrent.
- Larger, more complex and distributed systems pose the greatest challenges to adoption of medium- and low-GWP alternatives, although larger ducted and VRF systems with medium-GWP alternatives are becoming available.
- Revised safety standards (e.g., International Electrotechnical Commission (IEC) 60335-2-40) enable more extensive and cost-effective application of low-GWP refrigerants in smaller systems and medium-GWP refrigerant in larger systems. Risk assessment for all stages of the equipment lifetime is important.
- Improving energy efficiency for air-to-air air conditioners is an important challenge linked to the Kigali Amendment. Many countries have ambitious minimum energy performances rules. Although some alternative refrigerants are conducive to improvements in efficiency, availability of certain system components is crucial, such as high efficiency compressors, heat exchangers, advanced controls and energy recovery systems.

2.5.7. Applied building cooling systems

- The phase-out of ozone-depleting refrigerants in chillers, namely CFCs (e.g., CFC-11), is essentially complete. CFCs have been completely phased out for new equipment in non-A5 parties, and the CFC banks are decreasing in existing chillers. Some A5 parties are still using HCFC-22 in new equipment, but global production of such chillers is very small.
- The installed base within buildings will remain in service due to the long equipment lifetime, with continued HFC servicing needs.
- A complete range of new chillers that use refrigerants with lower GWP, compared with the original HCFC or HFC refrigerant, is available in all major markets. The new chillers maintain or improve full and part load performance.
- Even though new products have been introduced, products using refrigerants with high GWP have not be discontinued and are in fact the dominant products being sold today in most market except Europe. Regulations being adopted in other regions will accelerate the changes.
- Non-fluorinated refrigerants, namely R-717 and HC-290, are used in applications of specific sizes
- Life cycle climate performance analyses indicate that the GHG emissions from chillers are dominated by their energy use, not the direct effect caused by leaking refrigerant.

2.5.8. Mobile AC/HP

- Currently, there are still several refrigerants in use. HFC-134a is used globally. Where regulations require low GWP refrigerants, HFO-1234yf and R-744 provide market options. HFO-1234yf is widely adopted, especially for passenger vehicles. It remains unclear when other mobile AC applications, such as buses and heavy-duty trucks, will follow the light-duty vehicle trends.
- Vehicle refrigerant use is shifting from being an optional feature for passenger cooling to a requirement for total vehicle thermal management. The progressive electrification of road transport in Europe, China and North America requires a new generation of refrigerants that can deliver thermal management in addition to passengers' cooling. Hence, electrification is broadening the technical options leading to reconsider the current refrigerant choices to include R-744, HFOs and blends as viable options.
- European regulations investigating PFAS are very broad and not product-specific at this time. This could lead to HFO-1234yf re-evaluation as an option for mobile AC. More details can be found in Chapter 3 of this report.
- R-744 is a market alternative to HFO-1234yf for light duty vehicles and buses. Class A2 and class A3 (e.g., R-152a, hydrocarbons) refrigerants are being investigated, considering that secondary-loop architectures are an option for the electrified vehicle thermal systems.

2.5.9. Industrial refrigeration, heat pumps and heat engines

- Industrial refrigeration, heat pumps, and heat engines are used in a range of industries such as food and beverage, fisheries, pharmaceuticals, petrochemicals, district cooling and heating systems, etc.
- Industrial heat pumps are suitable for use in industrial applications because they provide heat at high temperatures and will be important in decarbonizing the industry.
- Industrial refrigeration and heat pumps traditionally use R-717 but R-744 is also increasingly being used. There is also an emerging trend for the use of HCs and HC mixtures – especially for low temperature applications.

2.5.10. Heating only heat pumps

- Heating only heat pumps have a role in buildings decarbonisation replacing fossil-fuel powered heating systems. Cost effectiveness remains an important consideration with a trade-off between increased capital cost versus lower operating cost when compared with fossil-fuel powered heating systems.
- Water heating heat pumps newly installed today use high-GWP R-410A, HFC-134 and R-407C, medium-GWP HFC-32 and low-GWP R-454C, HC-290, HC-600a, R-744 and R-717. The majority of new equipment installed uses R-410A and HFC-32. In some A5 parties HCFC-22 is still being used.
- At present, the main markets for water heating heat pumps are China, the EU, and Japan, and the market will increase rapidly - several states in the US have decarbonization plans that will increase the adoption of heat pumps.
- Since heat pumps are more material intensive than fossil fuel combustion boilers or direct electric heating, the material resource efficiency has to be considered carefully as this will influence the affordability. The selection of a refrigerant for a certain water heating application will influence both the material resource and energy efficiency as well as the life cycle climate impact.

2.5.11. Not-In-Kind technologies

- Not-In-Kind (NIK) technologies could play an important role in sustainable cooling and heating, especially in niche applications.
- Widely available NIK include absorption technologies, direct/indirect evaporative cooling (IEC), hybrid IEC systems, and desiccant cooling.
- NIK technologies can provide lower operating lifecycle cost compared with mechanical vapour compression in some specific conditions.
- Deep sea, lake, and ocean cooling have been investigated and few installations have been implemented. Studies have shown potential for low lifecycle operating cost.
- Other NIK technologies, including magnetocaloric, are in emerging and research and development phases. Some of these technologies, e.g., solid state cooling, are relatively successful in niche markets.

2.5.12. Servicing and refrigerant conservation

- In most A5 parties especially in LVCs and VLVCs, the majority of refrigerants is used for servicing.
- Proper servicing, described in codes and applied by trained and certified technicians, reduces direct emissions of refrigerants, and minimises the degradation of energy efficiency in RACHP equipment over time.
- Capacity building in A5 parties, comprising LVCs and VLVCs includes training programmes (e.g., training of trainers, infrastructure), the provision of appropriate tools, and improved access to spare parts.
- Refrigerant conservation is an effective part of reducing consumption of virgin refrigerants and limiting emissions. The creation of a market mechanism with financial incentives for recovery and recycling is essential to sustain a circular economy.
- While the Montreal Protocol explicitly encourages parties to minimize emissions, refrigerant banks are currently not explicitly managed or controlled as an obligation for Parties under by the Protocol.
- The potential to change the economic viability/affordability of destruction exists with the strengthening of source based Extended Producer Responsibility (EPR) schemes, the imposition of usage fees, and by directing carbon finance revenues back to the refrigeration servicing sector.

3 STATUS OF BANKS AND STOCKS OF CONTROLLED SUBSTANCES

3.1. Introduction

Decision XXXI/2 requested the TEAP to provide an assessment and evaluation of the "status of banks and stocks of controlled substances and the options available for managing them so as to avoid emissions to the atmosphere." This Chapter provides a summary of information on banks and stocks of ODS and HFCs, and EOL management and destruction options contained in the respective Technical Options Committees reports as part of the 2022 TEAP quadrennial assessment.

There is growing recognition that large banks of controlled substances are continuing to accumulate in equipment and products, and that currently only a limited amount is being recovered at EOL for destruction. Effective management of ODS/HFC banks aims to minimise the global impacts associated with the release of ODS/HFCs, by minimising emissions, and by supporting HFC phase-down through recovering HFCs for recycling, reclamation and reuse. As a consequence, less virgin HFCs would need to be produced.

Historically, controlled substances in banks outside of fire suppression reaching EOL have largely been emitted. Since it is the FSTOC's experience that HFCs contained in fire suppression equipment have historically enjoyed a relatively high level of recycling and reuse, the discussion on banks and emissions within the fire suppression sector will be discussed separately. Higher level of emissions has been the case for EOL CFC refrigerants and foams (except for some long-life applications such as building insulation and chiller refrigerants because of their low leakage rate and/or propensity for recovery). This failure to manage banks (outside of fire suppression) represents a lost opportunity to mitigate significant ozone depletion and climate impacts. Now, HCFCs and HFCs are reaching EOL and they too will be emitted if not responsibly recovered. This will accelerate over the next several decades as phase-out of HCFCs is completed and phase-down of HFCs under the Kigali Amendment gains momentum. It is therefore appropriate to implement technically and economically feasible measures that would enhance and maximise the circular economy through life cycle ODS/HFC management, that is, recovery, consolidation, recycling, reclamation, reuse, and, when no longer viable for reuse, destruction of controlled substances in banks at EOL.

Environmentally sound destruction of surplus or contaminated ODS and HFCs at EOL is generally encouraged by the Montreal Protocol because it avoids unnecessary emissions and protects the stratospheric ozone layer and/or the climate. However, the Montreal Protocol does not mandate the destruction of ODS or Annex F Group I HFCs. The exception, under Article 2J, is emissions of HFC-23 (Annex F, Group II) generated in production facilities that manufacture Annex C, Group I, or Annex F substances, where emissions must be destroyed to the extent practicable using technologies approved by parties.

This Chapter is structured into four subsequent sections:

- 3.2 An overview of non-fire suppression ODS and HFC banks and previous studies
- 3.3 Information on banks and management strategies in the RACHP and foams sectors including:
    - Assessing the current understanding of the quantity of controlled substances available in banks and when those banks might reach their end of life to become potentially available for recovery and eventual destruction.
    - Addressing the destruction of controlled substances under the Montreal Protocol in terms of definitions and formal obligations of parties.
    - Providing currently available data on the actual recovery and destruction of EOL controlled substances both at a global level based on data reported to the Ozone Secretariat, and for several larger non-A5 parties and regions that appear to account for a large portion of available data. This is compared with current bank estimates to provide a general assessment of the estimated proportion of EOL ODS/HFC reaching EOL that is recycled, reclaimed and/or destroyed.
    - Discussing the options available for EOL chemicals management, which encompasses the scope of ODS/HFC management, the various barriers and factors that affect developing an effective system, and current initiatives being pursued to promote EOL management globally.
- 3.4 Estimates of global halon, HCFC, and HFC banking and emission reduction strategies in the fire suppression sector
- 3.5 Emission reduction strategies for methyl bromide

3.2. ODS and HFC banks

This section provides background on ODS/HFC banks definitions and research concerning the amount of common ODS and HFC controlled substances estimated to be contained or banked in equipment and products currently in use and in the future. This includes estimates of amounts of these substances reaching end-of-life and thus being available for management to prevent them from being emitted. The section concludes with the outlook for ODS/HFC banks. Options for EOL management are described in section 3.3.

3.2.1. What are banks?

The IPCC/TEAP Report on Safeguarding the Ozone Layer and the Global Climate System 2005[10] (SROC) defines ODS banks as the total amount of substances contained in existing equipment, chemical stockpiles, foams, and other products not yet released to the atmosphere.

A further useful definition is the "reachable" bank, also referred to as "active"[11] bank, being those substances that are contained in equipment or product in use and thus potentially reachable or accessible for management upon entering the waste stream at its end-of-life. In practice, end-of-life can occur at different stages in the lifetime of equipment or for various reasons. For example, in the case of early retirement programs focused on achieving energy savings, recovery might be done earlier than the end of the expected equipment lifetime. In contrast, the "non-reachable" or "inactive" bank denotes substances that were landfilled or illegally dumped within the equipment or product.[12] ODS/HFC banks management aims to prevent emissions from active banks as far as is technically and economically feasible by monitoring for leaks, installing systems correctly, appropriately maintaining operating systems, and enabling the recovery and management[13] at end-of-life.

3.2.2. History and literature on ODS/HFC banks

Accumulating banks of controlled substances in equipment and products, and the impact of their uncontrolled emissions on ozone depletion and climate, gained increasing attention from approximately 2000 onwards.

The first complete data set on ODS banks was prepared for the SROC in the year 2005.[14] The TEAP supplement[15] to the SROC comprised data sets of ODS banks for 2002 and 2015, providing breakdowns for non-A5 and A5 parties, substance groups (Halons, CFC, HCFC) and sub-sectors. The data are expressed in metric tonnes, ODP tonnes, and GWP-weighted tonnes (metric tonnes CO_2e). Subsequently published studies focussed on refinements of the underlying model assumptions and the global bank estimates initially presented in the SROC, and which are based on the RIEP model (Refrigerant Inventory and Emission Previsions).[16]

A list of published studies on ODS banks is provided in Table 3.1 and provides a chronology and highlights important definitions and contents.

Table 3.1 Overview of studies concerning ODS and HFC banks, modified based on Heubes et al., 2015[17]

Author	Year	Title	Contents
TEAP	2002	Task Force on Destruction Technologies	Material flows of CFC-11, estimated emission of CFC-11 from foams
TEAP	2002	Task Force on Collection, Recovery & Storage	Combined top-down and bottom-up approach to estimate ODS bank in foams and refrigeration equipment for 2002

[10] IPCC/TEAP, 2005, Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons, Authors: Bert Metz, Lambert Kuijpers, Susan Solomon, Stephen O. Andersen, Ogunlade Davidson, José Pons, David de Jager, TahlKestin, Martin Manning, and Leo Meyer (Eds), Cambridge University Press, United Kingdom, pp. 478.

[11] The terms of active and inactive bank are used in the UNEP, 2021, *Report of the Technology and Economic Assessment Panel, Volume 3: Decision XXXI/3 Task Force Report on Unexpected Emissions of Trichlorofluoromethane (CFC-11)*, May 2021.

[12] Executive Committee of the Multilateral Fund, Meeting Document: UNEP/OzL.Pro/ExCom/48/42, *Report of the meeting of experts to assess the extent of current and future requirements for the collection and disposition of non-reusable and unwanted ODS in A5 countries (follow up to decision 47/52)*, 20 March 2006.

[13] The term management covers actions that would encompasses recovery for recycling, reclamation and reuse, storage pending a management activity, direct destruction, and chemical transformation management options.

[14] Ibid., IPCC/TEAP, 2005.

[15] TEAP, 2005, Report of the Technology and Economic Assessment Panel, Supplement to the IPCC/TEAP Report, November 2005.

[16] Clodic, D. and L. Palandre, 2004, Determination of Comparative HCFC and HFC Emission Profiles for the Foam and Refrigeration Sectors Until 2015, Part 1: Refrigerant Emission Profiles, Centre d' Energetique (Ecole des Mines de Paris and Armines), Report for U.S. EPA and ADEME, April 2004.

[17] Heubes, J., Papst, I., Gloel, J., 2015, Management and destruction of existing ozone depleting substances banks, G-S03-2015-en-01, GIZ, Eschborn, August 2015. https://www.giz.de/en/downloads/giz2015-en-study-ods-banks-management.pdf. Accessed December 2022.

Author	Year	Title	Contents
TEAP	2005	Task Force Report on Foam End-of-Life	CFC-11 bank projection to 2100 (cited from IPCC/TEAP 2005)
IPCC, TEAP	2005	Special Report on Safeguarding the Ozone Layer and TEAP Supplement	First comprehensive data set on ODS banks, split in developed and developing countries for 2002 and 2015
TEAP	2006	Report on Expert Meeting to Assess the Extent of Current and Future Requirements for the Collection and Disposition of Non-Reusable and Unwanted ODS in A5 countries	Definition of "reachable banks" and "accessibility"
TEAP Task Force on HCFC issues	2007	Emissions Reduction Benefits arising from earlier HCFC phase-out and other Practical Measures	First global prediction of ODS banks until 2050
TEAP XX/7 Task Force	2009	Environmentally Sound Management of Banks of Ozone-Depleting Substances; Interim and Final report	Assessment of effort to manage ODS banks, split in substance groups (CFC and HCFC) and sectors (refrigeration, air conditioning and foam)
TEAP XX/8 Task Force	2009	Assessment of Alternatives to HCFCs and HFCs and Update of the TEAP 2005 Supplement Report Data	Update of the TEAP 2005 data, by including accelerated HCFC phase-out; calculation of ODS banks until 2020
ICF	2010	Identifying and Assessing Policy Options for Promoting the Recovery and Destruction of Ozone Depleting Substances (ODS) and Certain Fluorinated Greenhouse Gases (F-Gases) Banked in Products and Equipment	First bottom-up approach for European Union member states to estimate ODS banks
SKM Enviros	2012	Further Assessment of Policy Options for the Management and Destruction of Banks of ODS and F-Gases in the European Union	Refined bottom-up approach for European Union member states to estimate ODS banks, integrating a floating point of time for EOL rather than a fixed year, taking the annual equipment fleet out of use over several years rather than all at the same time.
SAP	2014	Scientific Assessment of Ozone Depletion: 2014	Global aggregated emissions from ODS banks (2015–2050)
GIZ Proklima	2015	Management and destruction of existing ozone depleting substances in ODS banks	Overview study
GIZ Proklima	2018	Global banks of ozone depleting substances: A country-level estimate	Top-down estimate per country, using reported consumption data
GIZ Proklima	2020	Banks and Emission of CFC-11 and CFC-12: Country data and possible consequences for global modelling	Investigates country-research data on equipment and product lifetimes and their impact on global modelling
TEAP	2021	Decision XXXI/3 TEAP Task Force Report on Unexpected Emissions of CFC-11	Weibull function for probabilistic distribution of equipment/product lifetime replacing one average lifetime

The GIZ estimate of ODS banks covers CFC-11, CFC-12, HCFC-22, HCFC-141b, HCFC-142b and combines data on HFC banks retrieved from the Green Cooling Initiative Database (country-level RACHP sector data equipment estimates) and was published in 2018 (GIZ 2018).[18] The ODS banks are estimated using a country-based model, taking reported consumption per country up to 2014, attributing

[18] Papst, I., 2018, *Global banks of ozone depleting substances: A country-level estimate*, G-S05-2017-en-01, GIZ, Eschborn, 2018. https://www.green-cooling-initiative.org/

the consumption to instant release uses, RACHP, or foam sector. The applied top-down estimates for emission factors and equipment lifetime were informed by earlier work of TEAP.

Studies covering HFC banks are rare. The Green Cooling Database[19] (GIZ 2016) calculates RACHP sector HFC banks, which is the major bank-building use of HFCs. In addition, there are some national ODS/HFC banks inventories on Tier 2 level[20] that were carried out within GIZ Proklima projects that cover the RACHP sector.[21] Criteria for a potential funding window were developed for consideration by the Executive Committee (ExCom) of the Multilateral Fund (MLF) "t*o provide Article 5 parties with assistance to prepare an inventory of banks of used or unwanted controlled substances and to develop a plan for the collection, transport, and disposal (including consideration of recycling, reclamation, and cost-effective destruction) of such substances*" (ExCom Decision 90/49(c)). Such inventories would support planning, implementation organisations, and the industry stakeholders in directing their efforts.

ExCom document UNEP/OzL.Pro/ExCom/91/66[22] identified that one of the main barriers for the successful implementation of the ODS disposal projects funded by the Multilateral Fund was the absence of a national inventory of the targeted waste substances, resulting in a discrepancy in the amounts of ODS targeted for destruction and the actual amounts destroyed. This demonstrated a lack of understanding on where the waste substances were, and how these could be collected. The paper developed criteria for a funding window to provide A5 parties with assistance in the development of inventories of banks of used or unwanted controlled substances and plans for the collection, transport, and disposal (including consideration of recycling, reclamation, and cost-effective destruction) of such substances (decision 90/49(c)). Decision 91/66 established a funding window for the preparation of national inventories of banks of used or unwanted controlled substances and plans for the collection, transport and disposal of such substances, including consideration of recycling, reclamation and cost-effective destruction; and agreed criteria and funding for the development of those national inventories and plans.[23]

Further guidance material on taking stock of ODS/HFC banks on a national basis and a roadmap for end-of-life banks management was prepared during a GIZ Proklima project that has been ongoing since 2014.[24]

Substantive research has been undertaken on CFC-11 banks in response to the detection of their unexpected emissions. The TEAP Taskforce on Unexpected Emissions of CFC-11 developed banks projection of CFC-11 using a Weibull function for probabilistic distribution of equipment and product lifetimes. This replaces the usual approach of using a single average lifetime per category and results in a more realistic model of when equipment and products are decommissioned. Bank estimates are continuously refined as part of the on-going work of TEAP and its TOCs.

3.2.3. ODS/HFC banks in the RACHP and foams sectors

The data presented below is composed of different data sets applicable to different controlled substances. While TEAP data provide more detail in terms of applications and regional distribution, other available datasets cover more substances. More research and better country data will refine the details of ODS/HFC bank distribution, but is unlikely to change the overall picture, which is described in the following section. An overall summary of presented substances is provided before presenting data per substance.

In total, a combined 6,000 ktonnes of ODS and HFC are contained in the active bank, equalling 16 $GtCO_2e$ (estimate for 2022, combined sources outlined below) (Figs. 3.1 and 3.2).

fileadmin/Publications/2018_Global_banks_of_ozone_depleting_substances.pdf. Accessed December 2022.

19 GIZ, 2016, Green Cooling Database, www.green-cooling-initiative.org.

20 Tier 2 level approach is where banks are calculated by a stock model on appliances in use per application.

21 ODS banks inventories were carried out in Colombia (https://www.international-climate-initiative.com/fileadmin/Dokumente/2018/180820_Bancos_de_SAO_y_HFC.pdf), Dominican Republic, Ghana, Iran (https://www.international-climate-initiative.com/legacy/Dokumente/2019/20190604_IRAN_ODS_Bank_Inventory_-_English_Version.pdf), Tunisia (https://www.international-climate-initiative.com/fileadmin/Dokumente/2018/180820_Results_of_the_national_inventory_of_ozone-depleting_substances_for_the_year_2015.pdf).

22 Executive Committee of the Multilateral Fund, Meeting Document: UNEP/OzL.Pro/ExCom/91/66, *Criteria for a funding window for an inventory of banks of used or unwanted controlled substances and a plan for the collection, transport and disposal of such substances (Decision 90/49(c)*), 8 November 2022.

23 Executive Committee of the Multilateral Fund, Meeting Document: UNEP/OzL.Pro/ExCom/91/72, Report of the Ninety-First Meeting of the Executive Committee, 9 December 2022.

24 GIZ, 2017, Global roadmap on ODS Bank Management, 2017; *Guideline to conduct an ODS bank inventory, 2017; Guideline on policy measures for the management and destruction of ozone depleting substances, 2017; Guideline to establish a collection system for equipment containing ODS*, 2017; *Guideline for the transboundary movement of ODS waste*, 2017. Accessible at https://www.giz.de/en/worldwide/30797.html.

Fig. 3.1 Total estimated ODS and HFC banks, several sources, 2010–2050 (ktonnes)

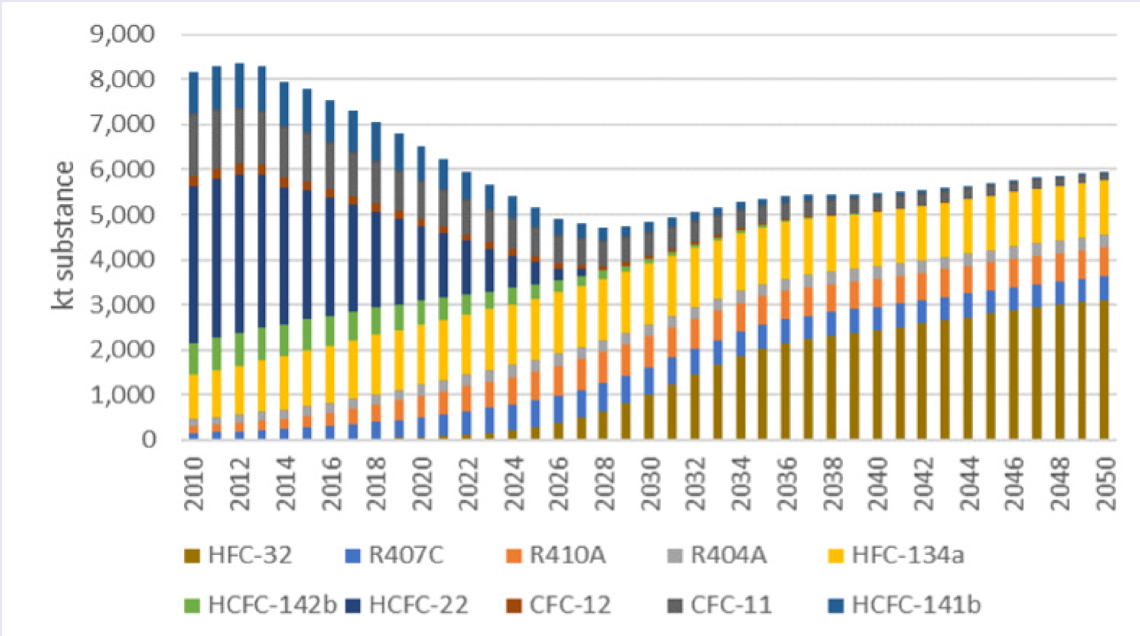
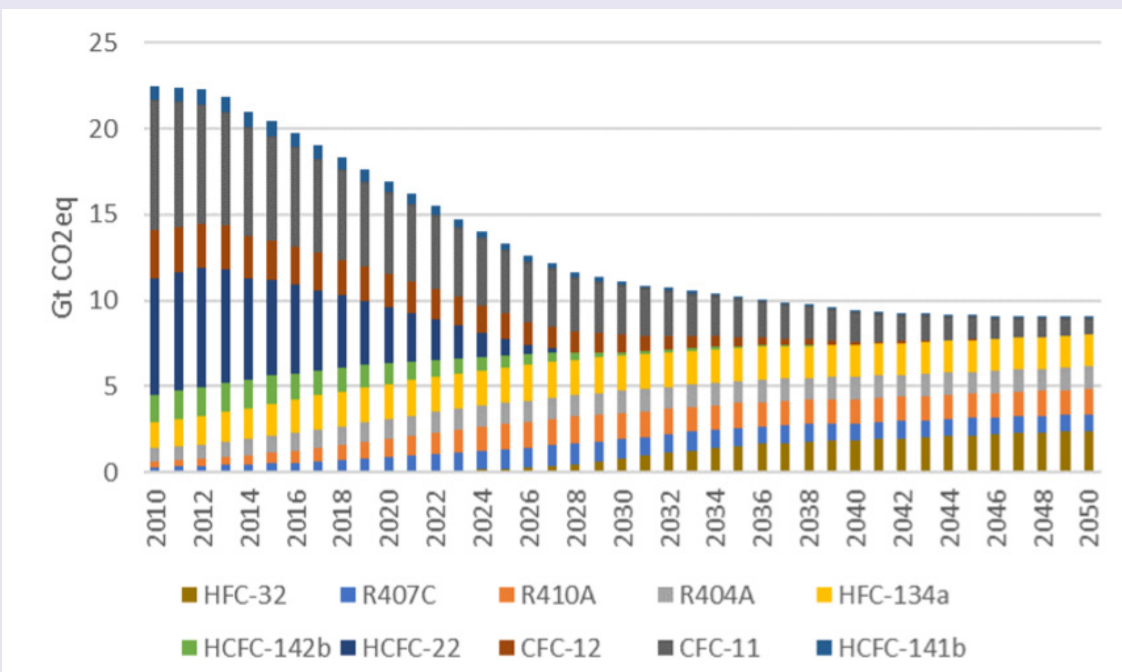


Fig. 3.2 Estimated bank of ODS and HFCs, RACHP and foams sector combined, several sources, 2010–2050 in $GtCO_2e$ (GWP as in IPCC AR6)



Annual quantities of between 250 and 400 ktonnes (about 0.5 to 0.8 $GtCO_2e$) of ODS and HFCs are estimated to arise from decommissioning in the RACHP and foams sectors from 2020 to 2050 (Fig. 3.3). Combined ODS and HFC annual decommissioning is estimated to start to peak in absolute amounts in the mid-2030s onwards, and peak in amounts by $GtCO_2e$ around 2035 (Figs. 3.3 and 3.4).

Fig. 3.3 Estimated ODS and HFC amounts being decommissioned, RACHP and foams sectors combined, several sources, 2010–2050 (ktonnes)

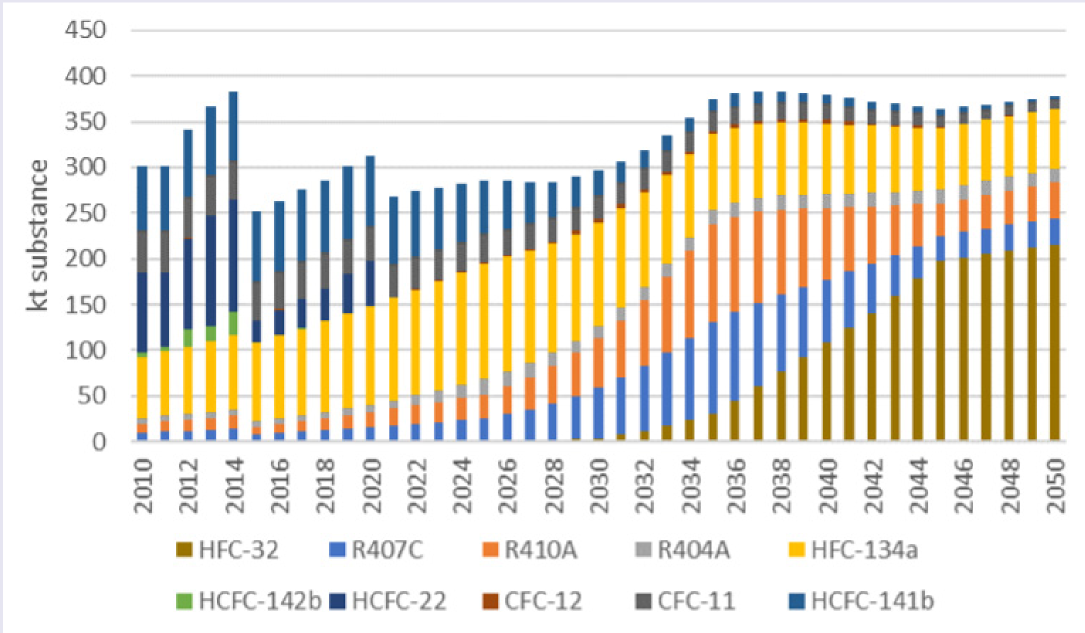
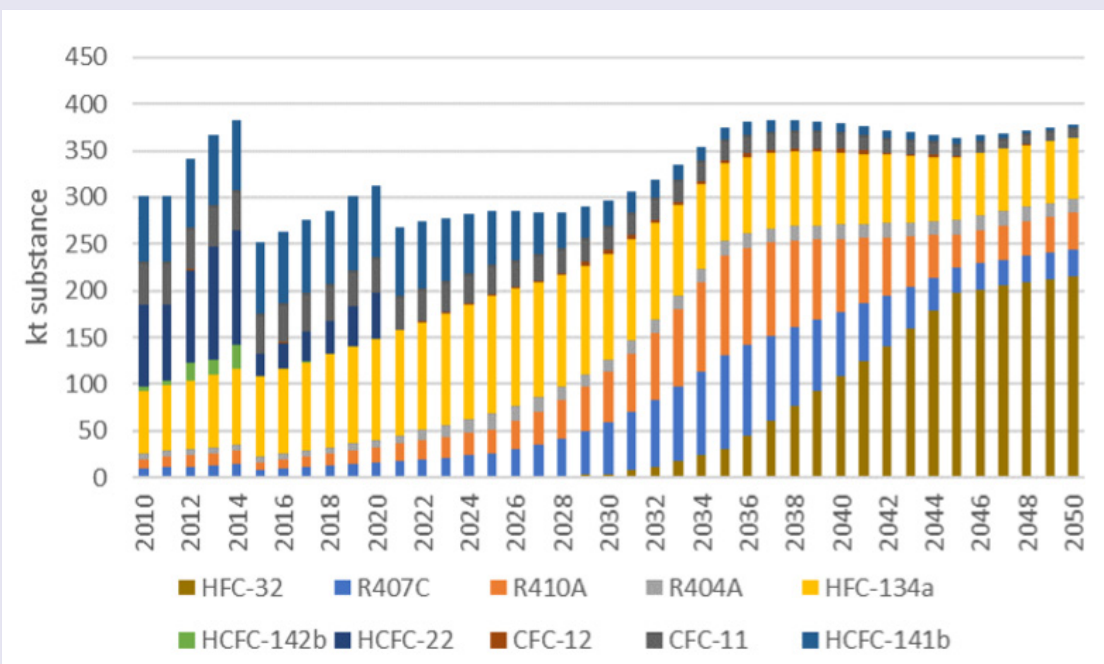


Fig. 3.4 Estimated ODS and HFC amounts being decommissioned, RACHP and foams sector combined, several sources, 2010–2050 in $GtCO_2e$ (GWP as in IPCC AR6)



Active global ODS banks of the 5 most common ODS (CFC-11, CFC-12, HCFC-22, HCFC-141b, HCFC-142b) amount to 3,200 ktonnes substance, equivalent to 9.9 $GtCO_2e$ in 2022 (see Figure 3.1 and 3.2). There is a rapid decrease as ODS-containing equipment and products are reaching their end-of-life each year. The 5 most common ODS being decommissioned are estimated at 110 ktonnes (0.27 $GtCO_2e$) in 2022.

Active HFC banks in the RACHP sector, which is the predominant usage of HFCs, are estimated at 2,800 ktonnes (5.5 $GtCO_2e$) in 2022 and 3,900 ktonnes (6.8 $GtCO_2e$) in 2030 (Green Cooling Database, GIZ 2016[25]).

While ODS banks have been more concentrated in non-A5 parties, HFC banks are currently more evenly distributed between non-A and A5 parties and are expected to become concentrated in A5 parties.

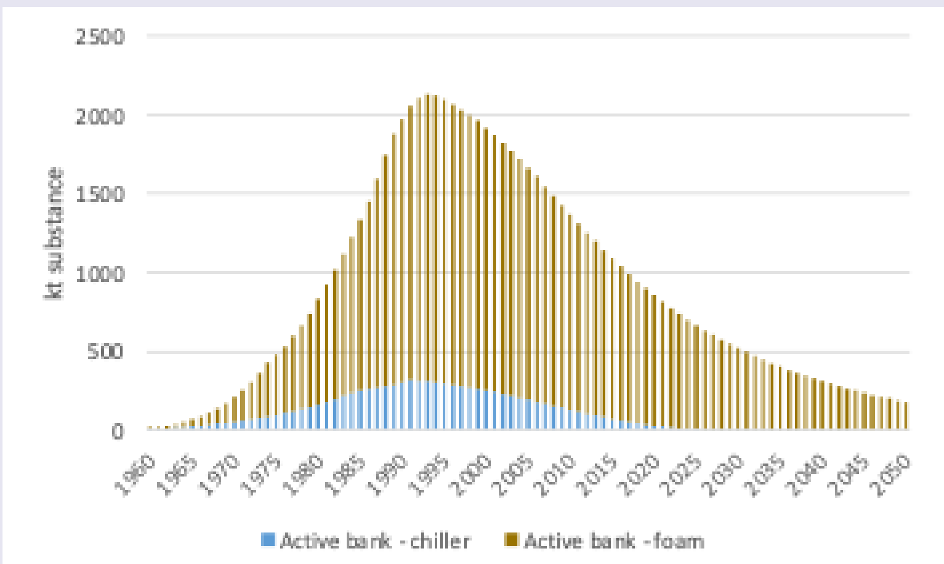
Given the long period since the CFC phase-out in non-A5 parties, where most of the CFCs were used, CFC banks are largely emitted except for in-service building insulation foam and unreachable foam waste disposed in landfill. Several countries require by regulation that building foam is removed from the building prior to demolition and is then destroyed, including the blowing agent.[26] The largest current ODS bank in foam is constituted of HCFCs, particularly HCFC-22 (mostly within RACHP equipment), but also HCFC-141b and HCFC-142b mostly contained in foam products.

Sensitivity analysis shows that assumptions on equipment lifetime have a strong impact on the decline rate of banks; if equipment lifetimes are longer – and country-specific studies imply that – the decline rate of banks is lower, resulting in more time until the opportunity to have capacity in place to recover ODS at end-of-life and prevent emissions.[27] On the other hand, as equipment lifetime is a distribution rather than a single value, some equipment will reach EOL earlier, requiring capacity at earlier stages. With HFC banks building up, the challenge of dealing with active banks responsibly persists, even as HCFCs are phased out.

3.2.3.1. CFC-11 banks and amounts reaching end-of-life

The total active and inactive CFC-11 banks (foams, refrigerants, and storage) are estimated to be 1,500 ±100 kilotonnes in 2021. The total active CFC-11 bank is estimated to be 800 ±50 kilotonnes, 3.8 $GtCO_2e$, in 2021.[28] As illustrated in Figure 3.5, the majority of remaining active CFC-11 bank is within construction foam, mostly located in non-A5 parties.

Fig. 3.5 Estimated active CFC-11 bank, 1960–2050 (ktonnes) (TEAP 2022[29])



The global peak of the CFC-11 decommissioned from the largest portion of active banks, i.e., all foams in products at end-of-life, is estimated to have occurred around the year 2010, at about 45 ktonnes/year, and then subsequently decreases slowly over time to currently approximately 35 ktonnes/year and projected to reach under 10 ktonnes/year by 2050 (Fig. 3.6).

25 GIZ, 2016, Green Cooling Database, www.green-cooling-initiative.org.

26 Papst, I., 2020, Banks and Emissions of CFC-11 and CFC-12: Country data and possible consequences for global modelling, GIZ, Eschborn, 2020. https://www.green-cooling-initiative.org/fileadmin/Publications/2020_ODS_CFC11_CFC12-banks.pdf. Accessed December 2022.

27 UNEP, 2021, *Report of the Technology and Economic Assessment Panel, Volume 3: Decision XXXI/3 Task Force Report on Unexpected Emissions of Trichlorofluoromethane (CFC-11)*, May 2021.

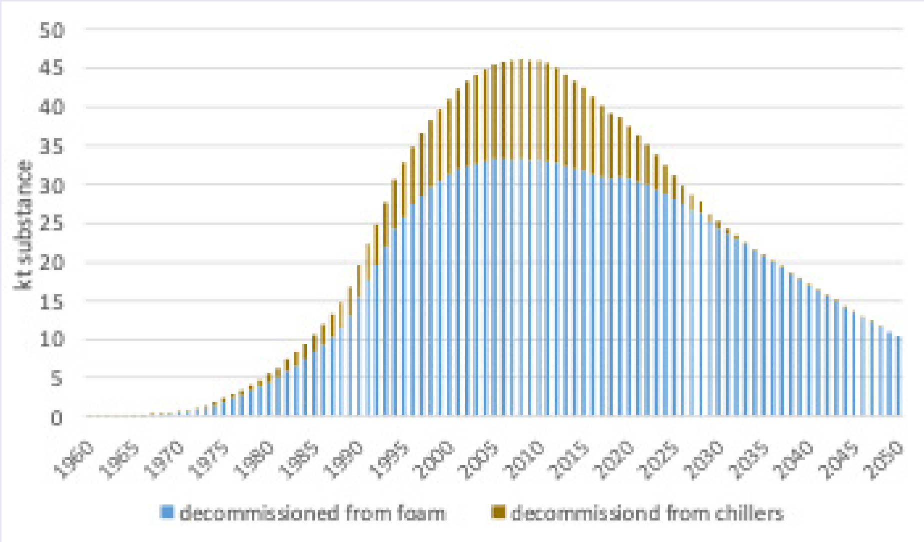
Papst, I., 2020, Banks and Emissions of CFC-11 and CFC-12: Country data and possible consequences for global modelling, GIZ, Eschborn, 2020. https://www.green-cooling-initiative.org/fileadmin/Publications/2020_ODS_CFC11_CFC12-banks.pdf. Accessed December 2022.

28 UNEP, 2021, *Report of the Technology and Economic Assessment Panel, Volume 3: Decision XXXI/3 Task Force Report on Unexpected Emissions of Trichlorofluoromethane (CFC-11)*, May 2021.

29 TEAP, 2022, Personal communications with Helen Walter-Terrinoni, FTOC co-chair.

These global peaks are dominated by the foam banks, foam products, and decommissioning patterns in the United States and Europe, owing to their overwhelming size.

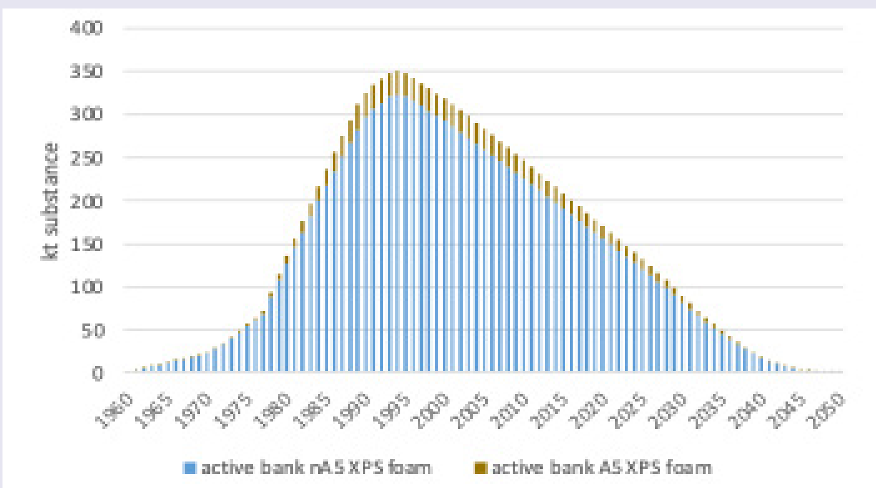
Fig. 3.6 Estimated CFC-11 being decommissioned, 1960–2050 (ktonnes) (TEAP 2022)



3.2.3.2. CFC-12 banks and amounts reaching end-of-life

Historically, CFC-12 banks were composed of refrigerants and foam-blowing agents. While CFC-12 refrigerant banks are believed to have reached their end-of-life, the remaining bank is in foams. The CFC-12 foam bank is much smaller than the CFC-11 foam bank and mainly found in XPS-foams used for construction in non-A5 parties (Fig. 3.7).

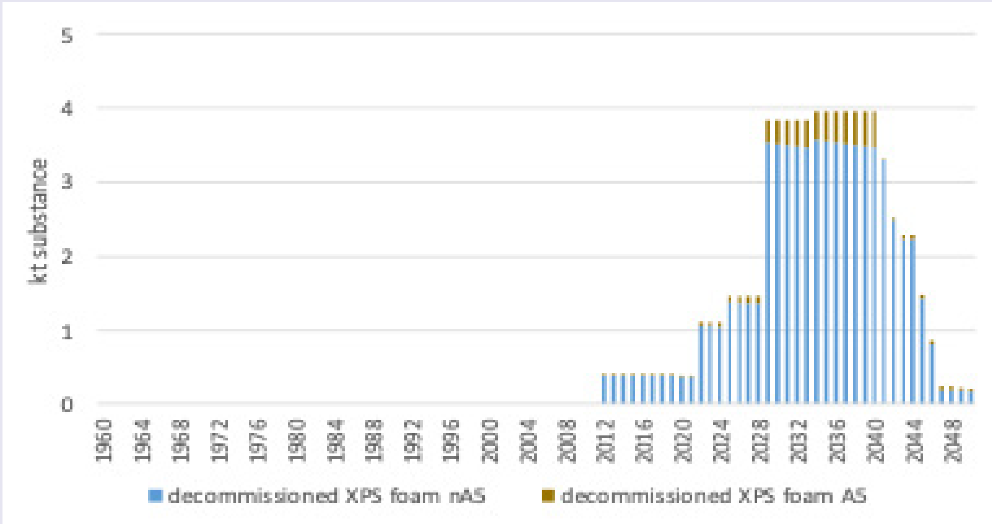
Fig. 3.7 Estimated active CFC-12 bank in XPS Foam, 1960–2050 (ktonnes) (GIZ 2020[30])



Due to the long lifetimes of buildings, the majority of CFC-12 containing foams are expected to be decommissioned in the 2030s (Fig. 3.8).

[30] Papst, I., 2020, Banks and Emissions of CFC-11 and CFC-12: Country data and possible consequences for global modelling, GIZ, Eschborn, 2020. https://www.green-cooling-initiative.org/fileadmin/Publications/2020_ODS_CFC11_CFC12-banks.pdf. Accessed December 2022.

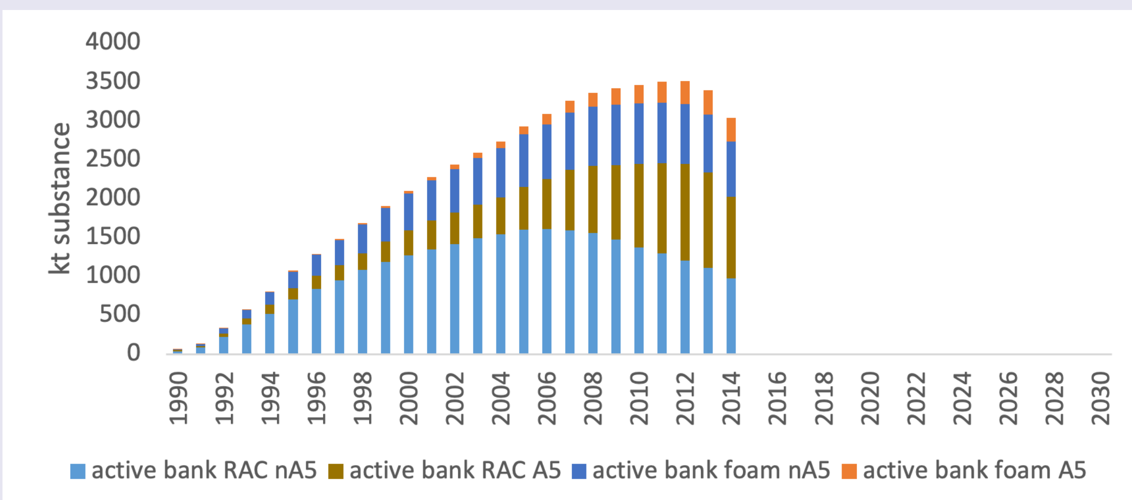
Fig. 3.8 Estimated CFC-12 being decommissioned from XPS foam, 1960–2050 (ktonnes) (GIZ 2020[31])



3.2.3.3. HCFC-22 banks and amounts reaching end-of-life

HCFC-22 is mainly used as refrigerant, which constitutes the main bank of HCFC-22. An analysis made in 2018 uses consumption data up to 2014 and shorter equipment lifetimes than were used in more recent models (GIZ 2018[32] and GIZ 2020[33]). The longer equipment lifetimes used in the later study means that the steep downward trend after 2012 that is shown in Fig. 3.9 might not be as steep as indicated, resulting in a longer prevalence of active banks after 2030.

Fig. 3.9 Estimated active HCFC-22 bank, 1990–2014 (ktonnes) (GIZ 2018)



HCFC-22 being decommissioned was not modelled for a time series after 2020, when amounts in A5 parties were estimated to be around 40 ktonnes, with a rising tendency.

[31] Ibid., Papst, I., 2020. GIZ.

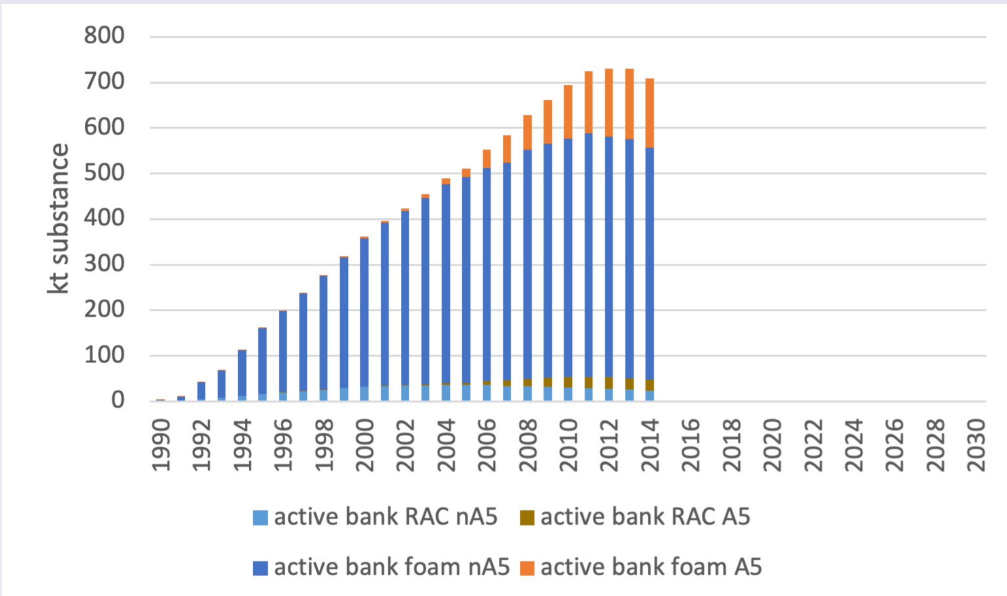
[32] Papst, I., 2018, *Global banks of ozone depleting substances: A country-level estimate*, G-S05-2017-en-01, GIZ, Eschborn, 2018. https://www.green-cooling-initiative.org/fileadmin/Publications/2018_Global_banks_of_ozone_depleting_substances.pdf. Accessed December 2022.

[33] Papst, I., 2020, Banks and Emissions of CFC-11 and CFC-12: Country data and possible consequences for global modelling, GIZ, Eschborn, 2020. https://www.green-cooling-initiative.org/fileadmin/Publications/2020_ODS_CFC11_CFC12-banks.pdf. Accessed December 2022.

3.2.3.4. HCFC-142b banks and amounts reaching end-of-life

HCFC-142b is mainly used as a foam blowing agent, which constitutes the main bank of HCFC-142b. Most of the HCFC-142b bank is in non-A5 parties. Analysis dates from 2018, using consumption data up to 2014, with a tendency to use shorter product lifetimes than is used in more recent models (GIZ 2018) (Fig. 3.10).[34] With longer lifetimes, this means that foams containing HCFC-142b might be expected to reach decommissioning also well after 2050.

Fig. 3.10 Estimated active HCFC-142b bank, 1990–2014 (ktonnes) (GIZ, 2018)



HCFC-142b being decommissioned was not modelled for a time series after 2020, when amounts in A5 parties were estimated to be around 26 ktonnes, with a rising tendency.

3.2.3.5. HCFC-141b banks and amounts reaching end-of-life

Most of the active bank of HCFC-141b is in construction foams. This has recently shifted, as foams in refrigeration equipment containing HCFC-141b are decommissioned and the blowing agent is either released or added to the inactive bank. The global active bank peak is now estimated to have occurred, with continued decommissioning of appliances and buildings that contain HCFC-141b being greater than new HCFC-141b usage to create new foams (Fig. 3.11). The timing of the global peak quantities from decommissioning of foams containing HCFC-141b is estimated to occur over the next 5 years (Fig. 3.12).[35]

[34] Ibid., Papst, I., 2018. GIZ.

[35] UNEP, 2022, Report of the Technology and Economic Assessment Panel, Volume 1, Progress Report, May 2022.

Fig. 3.11 Estimated active bank of HCFC-141b, 1990–2050 (ktonnes) (TEAP, 2022)

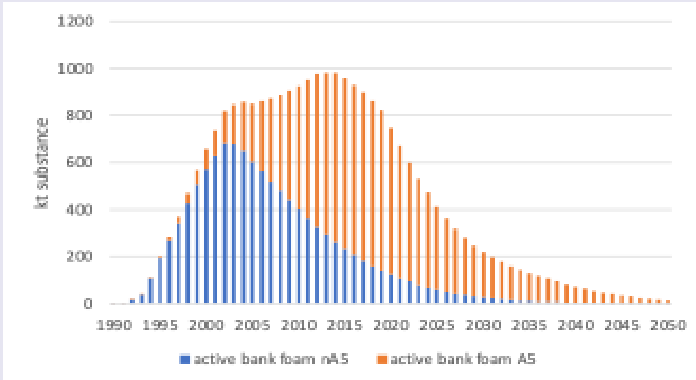
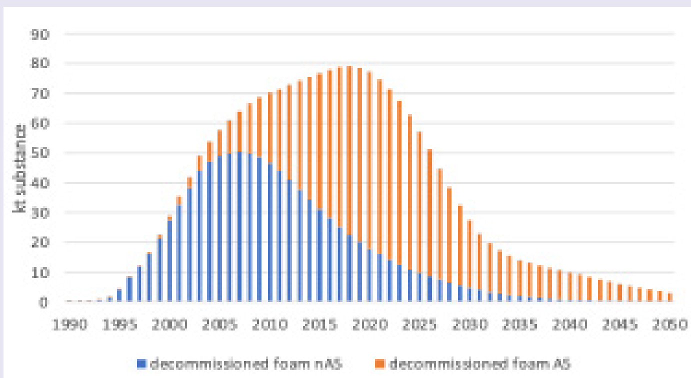


Fig. 3.12 Estimated HCFC-141b being decommissioned, 1989–2050 (ktonnes) (TEAP, 2022)



3.2.3.6. HFC bank

Bank estimates for HFC-134a, HFC-32, R-404A, R-407C, and R-410A within the RACHP sector were estimated previously using the database of the Green Cooling Initiative (GIZ 2016); the results of this study are presented in the sections below.[36]

The database employs a top-down Tier 2 approach, where banks are calculated by a stock model on appliances in use per application (19 applications of RACHP equipment in total), projecting RACHP equipment sales and stock up to 2050, deducting banks and emissions using country group specific (non-A5 and A5) assumptions. As the database and its projections date from 2016, the provisions of the Kigali Amendment were not taken into consideration. However, the effect of the European F-gas Regulation (515/2014) was considered. Nevertheless, the 2016 analysis remains pertinent because the Kigali Amendment is unlikely to significantly change the estimated absolute amounts (in metric tonnes) of refrigerants of any sort that are banked; the Kigali Amendment will have a long-term effect in lowering the GWP (in CO_2e) of the substances that are banked.

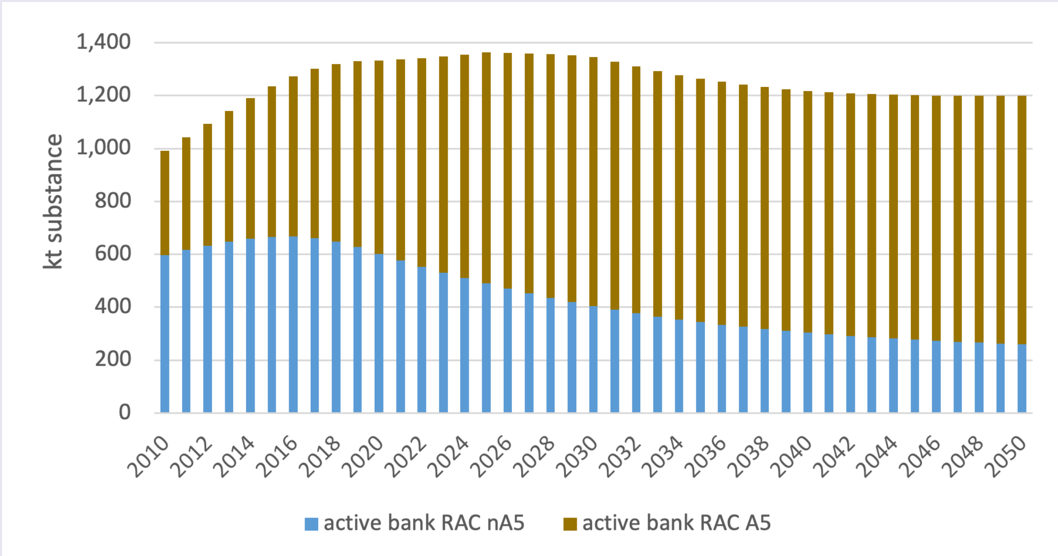
Bank estimates of HFCs in foam banks are not currently available.

3.2.3.7. HFC-134a banks and amounts reaching end-of-life

Since HFC-134a is used in several RACHP applications and was introduced during the CFC phase-out, the bank was estimated to be comparably large at approximately 1,300 ktonnes (2 $GtCO_2e$) and almost equally distributed between non-A5 and A5 parties in 2022 (Fig. 3.13).

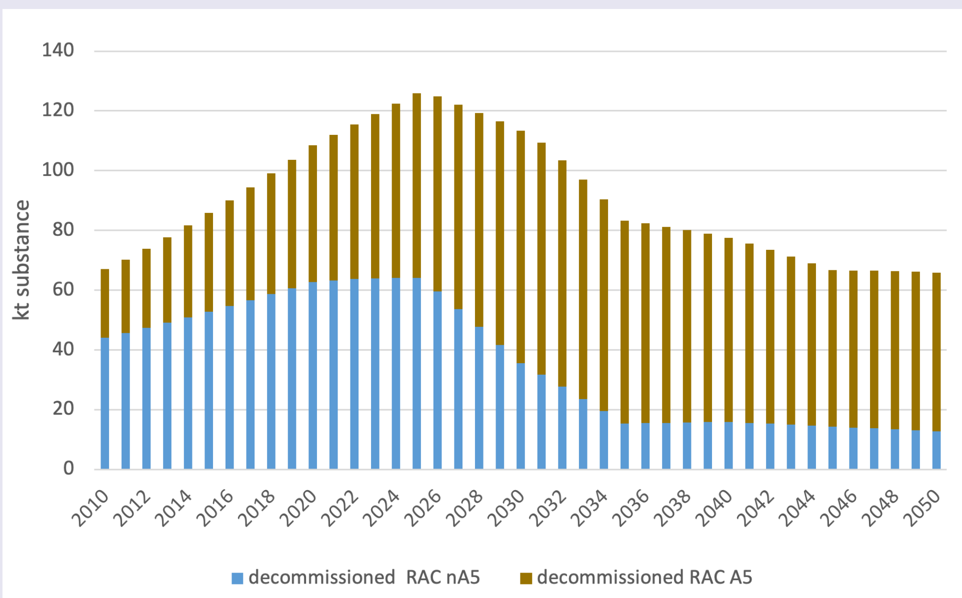
[36] GIZ, 2016, Green Cooling Database, www.green-cooling-initiative.org.

Fig. 3.13 Estimated active bank of HFC-134a, 2010–2050 (ktonnes) (GIZ, 2016)



Annual amounts reaching the end-of-life are currently larger in non-A5 parties (ca. 64 ktonnes), with A5 parties catching up and exceeding the amounts reaching end-of-life in non-A5 parties in the coming decade (ca. 78 ktonnes in 2030) (Fig. 3.14).

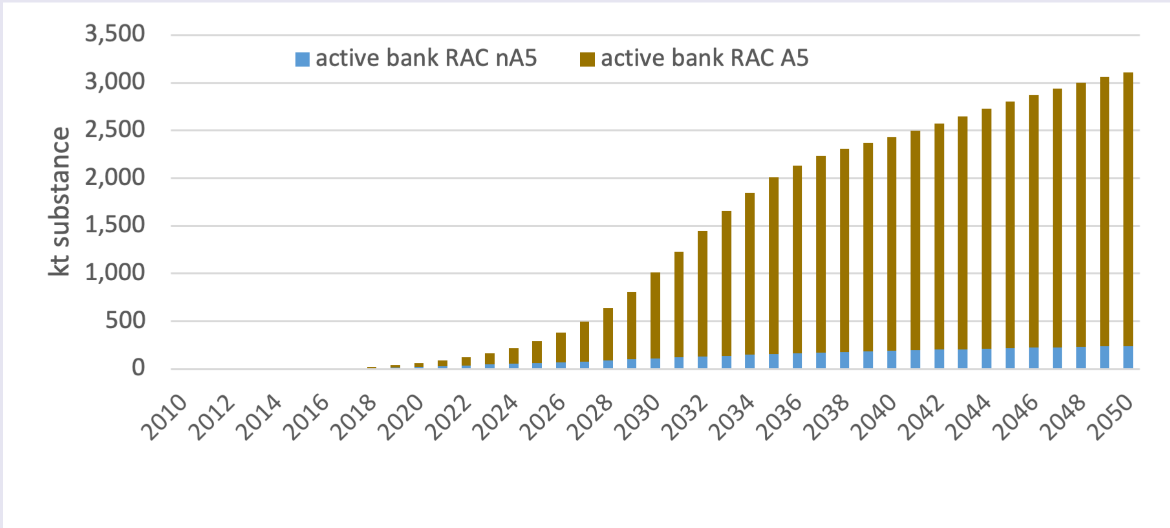
Fig. 3.14 Estimated HFC-134a being decommissioned, 2010–2050 (ktonnes) (GIZ, 2016)



3.2.3.8. HFC-32 banks and amounts reaching end-of-life

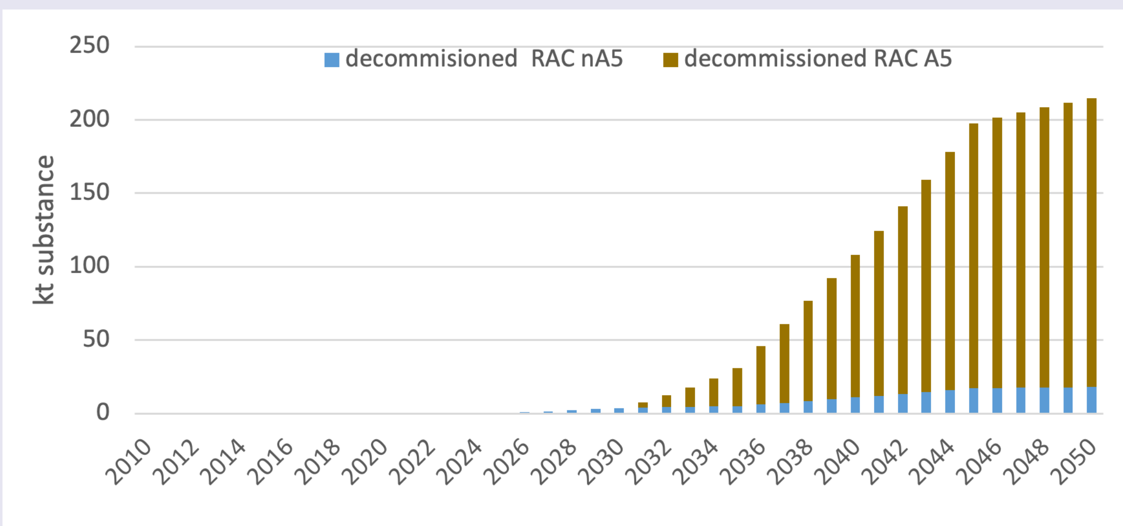
The use of pure HFC-32 as refrigerant is a comparatively recent development, which is reflected in the bank projections, showing a steep increase beyond 2030 in this study, especially in A5 parties. The total global active bank of HFC-32 was estimated to be 1,000 ktonnes (780 $MMTCO_2e$) in 2030 (Fig. 3.15) (GIZ 2016). With the effect of the Kigali Amendment taken into consideration, trends for HFC-32 are now likely to differ from those projected in this study. Due to the HFC phase-down, HFC-32 is increasingly replacing the R-410A in the same RACHP applications. This trend was not apparent when the original study was undertaken. Nevertheless, the Kigali Amendment is unlikely to significantly change the estimated absolute amounts (in metric tonnes) of banked refrigerants.

Fig. 3.15 Estimated active bank of HFC-32, 2010–2050 (ktonnes) (GIZ, 2016)



Tangible amounts of HFC-32 from decommissioned equipment are expected to be available for management from 2030 onwards (Fig. 3.16).

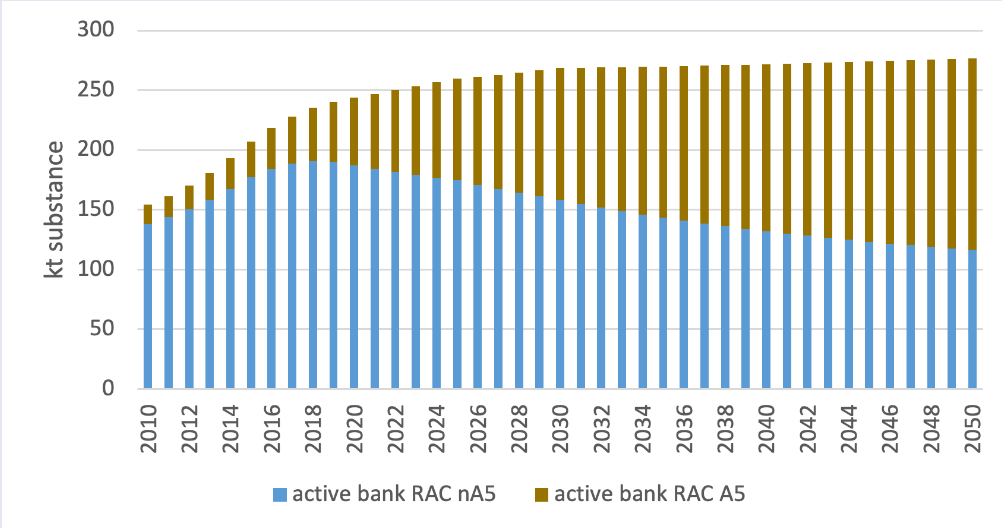
Fig. 3.16 Estimated HFC-32 being decommissioned, 2010–2050 (ktonnes) (GIZ, 2016)



3.2.3.9. R-404A (HFC blend) banks and amounts reaching end-of-life

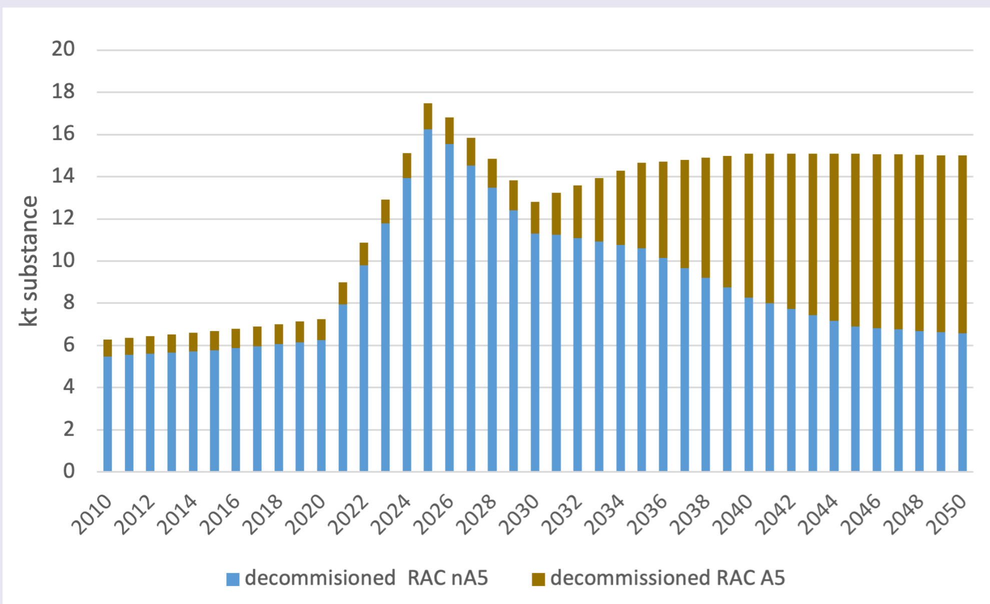
R-404A, an HFC blend of HFC-125, HFC-134a, and HFC-143a, was primarily used to replace R-502 (a blend of HCFC-22 and CFC-115) and HCFC-22 in low and medium temperature refrigeration applications and has been predominantly in banks in non-A5 parties, with a trend to increasing banks in A5 parties. The total global active bank of R-404A was estimated to be 250 ktonnes (1.2 GtCO_2e) in 2022 (Fig. 3.17) (GIZ 2016). With the effect of the Kigali Amendment taken into consideration, trends for R-404A are now likely to differ from those projected in this study. Due to the HFC phase-down, R-404A is now being replaced by lower GWP refrigerants. Nevertheless, the Kigali Amendment is unlikely to significantly change the estimated absolute amounts (in metric tonnes) of banked refrigerants.

Fig. 3.17 Estimated active bank of R-404A, 2010–2050 (ktonnes) (GIZ, 2016)



The projected amounts available at decommissioning show some dynamic resulting from the transition to other refrigerants in non-A5 parties. Due to this transition, available amounts from decommissioning are expected to peak before 2030 (Fig. 3.18).

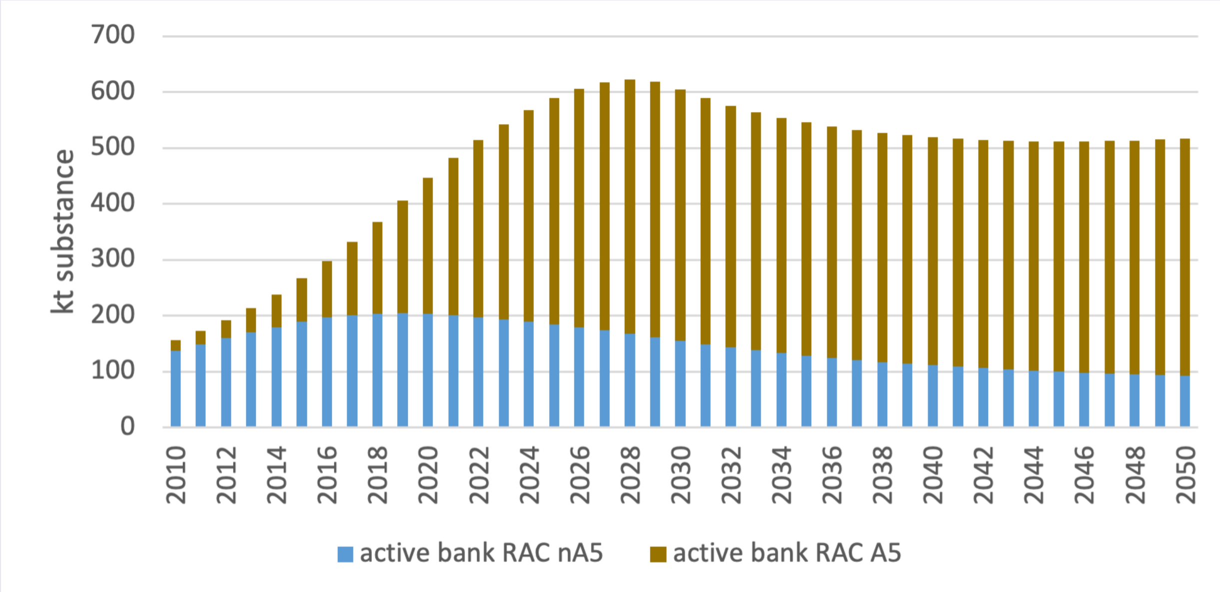
Fig. 3.18 Estimated R-404A being decommissioned, 2010–2050 (ktonnes) (GIZ, 2016)



3.2.3.10. R-407C (HFC blend) banks and amounts reaching end-of-life

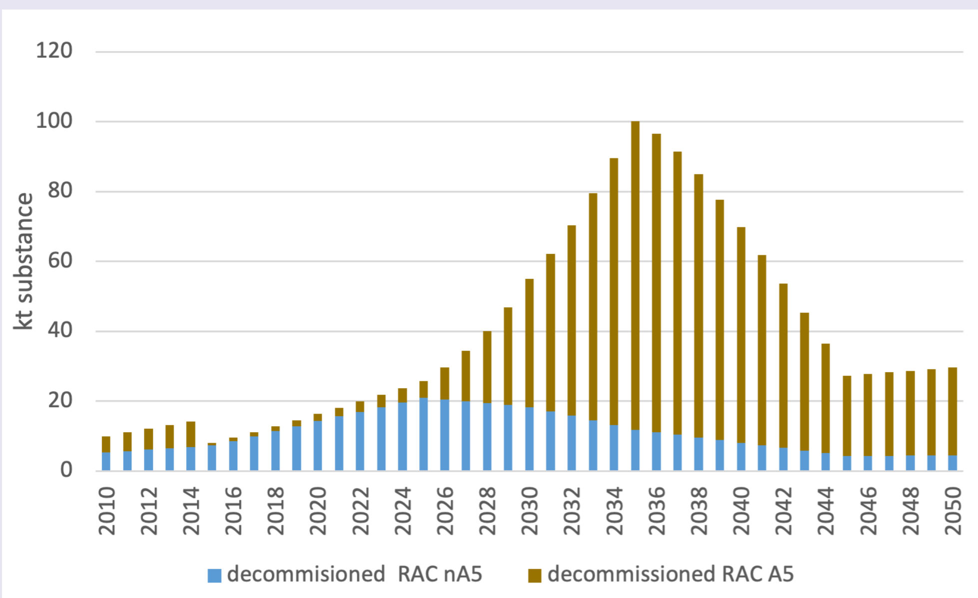
R-407C, an HFC blend of HFC-32, HFC-125 and HFC-134a, is used in air conditioning applications. Similar to R-410A, R-407C banks exhibit a similar trend, with almost equal bank distribution estimated in non-A5 and A5 parties in 2022, with a trend towards an increasing bank in A5 parties. The total global active bank of R-407C was estimated to be 510 ktonnes (980 $MMTCO_2e$) in 2022 (Fig. 3.19) (GIZ, 2016). With the effect of the Kigali Amendment taken into consideration, trends for R-407C are now likely to differ from those projected in this study. Due to the HFC phase-down, R-407C is now being replaced by lower GWP refrigerants. Nevertheless, the Kigali Amendment is unlikely to significantly change the estimated absolute amounts (in metric tonnes) of banked refrigerants.

Fig. 3.19 Estimated active bank of R-407C, 2010–2050 (ktonnes) (GIZ, 2016)



Expected amounts of substance from decommissioned equipment are projected to increase in the 2030s, predominantly in A5 parties (Fig. 3.20).

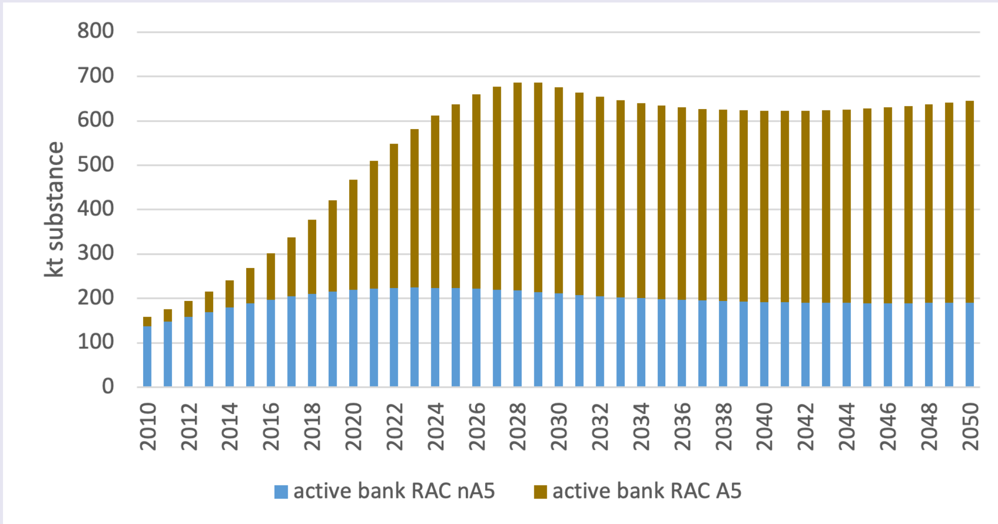
Fig. 3.20 Estimated R-407C being decommissioned, 2010–2050 (ktonnes) (GIZ, 2016)



3.2.3.11. R-410A (HFC blend) banks and amounts reaching end-of-life

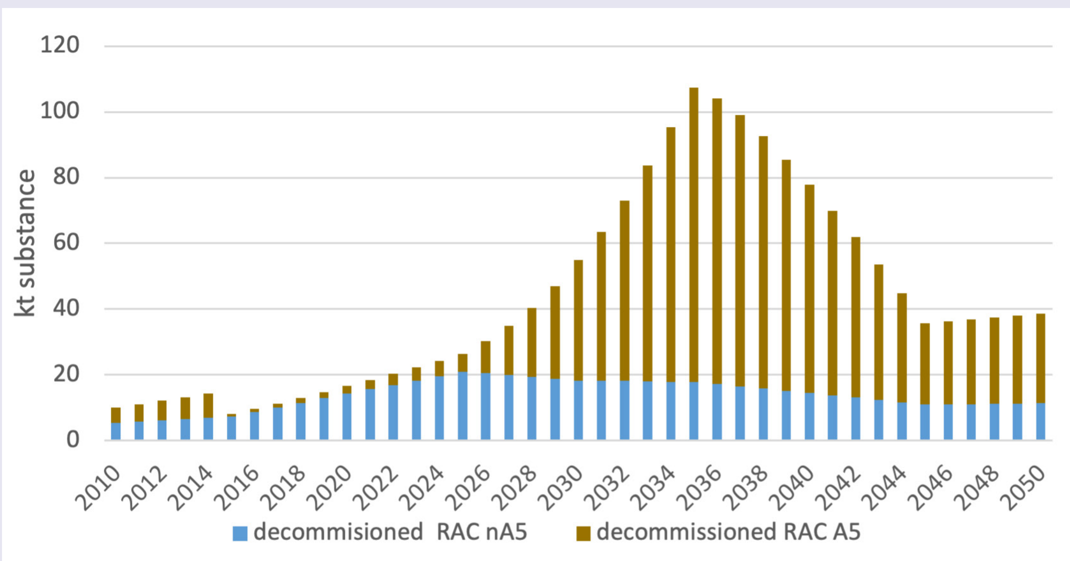
R-410A, an HFC blend of HFC-32 and HFC-125, is used increasingly in non-A5 parties, as air conditioning equipment transitions away from HCFC-22. The total global bank was estimated to be 550 ktonnes (1.2 $GtCO_2e$) in 2022 (Fig. 3.21) (GIZ, 2016). With the effect of the Kigali Amendment taken into consideration, trends for R-410A are now likely to differ from those projected in this study. Due to the HFC phase-down, R-410A is now being replaced by lower GWP refrigerants, in particular HFC-32. Nevertheless, the Kigali Amendment is unlikely to significantly change the estimated absolute amounts (in metric tonnes) of banked refrigerants.

Fig. 3.21 Estimated active bank of R-410A, 2010–2050 (ktonnes) (GIZ, 2016)



The estimated amounts of R-410A from decommissioned equipment follow the increasing trend of the bank, peaking in the 2030s (Fig. 3.22).

Fig. 3.22 Estimated R-410A being decommissioned, 2010–2050 (ktonnes) (GIZ, 2016)



3.2.4. ODS/HFC banks outlook

With the ongoing transition in A5 parties from HCFCs to HFCs and other alternatives, the (refrigerant) amounts of HCFCs available for end-of-life treatment are expected to increase. Non-A5 parties are confronted with both HCFCs and HFCs reaching end-of-life. The shift from HCFCs to high GWP HFCs marks a transition from ozone depletion to climate change issues because HFC emissions are reported under national greenhouse gases and are potentially part of nationally determined contributions (NDCs).

The largest banks overall are currently in non-A5 parties and will rapidly reach end-of-life in the next decade. If not recovered and responsibly managed as a priority, they will likely be emitted, as happened with CFC banks before them. Accelerated action on the management of EOL ODS/HFCs might increasingly be considered a priority under national greenhouse gas emissions mitigation objectives, especially where there might be currently low rates of recovery and destruction.

Banks in A5 parties are currently smaller but growing rapidly and will dominate global banks volumes by the early 2030s. This will be the result of declining banks in non-A5 parties and the rapid uptake of HFC-containing equipment in A5 parties, occurring with the completion of HCFC phase-out.

Quantities potentially available for recovery and management are expected to increase in A5 parties due to the ongoing HCFC phase-out and the later HFC phase-down. Timely efforts to establish effective EOL management capacity to prevent HFC emissions would have a significant impact, given the predicted size and growth of these banks in larger industrialised A5 parties.

With improved economies of scale, through the recovery of increased quantities of ODS/HFCs, the anticipated cost per kg of recovered controlled substances for EOL management could be reduced, or minimised, assuming infrastructure is available and investment in EOL management has been made within a supportive policy framework.

Country-specific studies may be needed to investigate and understand local capabilities, organisational arrangements, structures and relationships of refrigerant importers and distributors, and national refrigeration service providers, who usually carry out recovery and collection irrespective of the source of financing.

3.3. Implementation of EOL ODS/HFC management in the RACHP and foams sectors

3.3.1. EOL ODS/HFC banks management

Effective management of accumulated ODS and HFC active banks, by maximising recovery, recycling, reclamation, reuse, and ultimately destruction after all other options have been exhausted, can minimise the global impacts associated with the potential release of emissions at EOL. By maximising recovery, recycling, reclamation and reuse, effective banks management can limit the amounts of controlled substances that would otherwise require destruction and minimise associated costs. Furthermore, for the RACHP sector, effective HFC bank management can also minimise the amounts of controlled substances (virgin refrigerant) that is newly manufactured, minimising overall HFC emissions, and can also aid parties in managing their HFC phase-down targets.

Effective banks management need not be limited to ODS and HFCs. The phase-down of HFCs, and/or the leapfrogging of HFC technologies, will result in increasing banks of other alternative refrigerants and foam blowing agents. HFOs and HCFOs are being used to replace HFCs in some applications, although they are not controlled substances under the Montreal Protocol. Leap-frogging HFC-based equipment into these and other low GWP alternatives contributes to active HFC bank prevention, reducing the quantity of HFCs and the GWP of the bank requiring future EOL management. Nevertheless, resource efficiency and circular economy requirements suggest that effective bank management may also be appropriate for these low GWP alternatives. The breakdown of some HFOs/HCFOs results in the formation of different yields of trifluoroacetic acid (TFA) (see section 2.7.4). In addition, there may be a significant bank of equipment containing hydrocarbons by 2050.

Banks management discussed here is directed towards two main sectors[37], the RACHP and the foams sectors. The RACHP sector deals with refrigerant recovery from concentrated sources. The foams sector deals with recovery of blowing agent from foams, which are dilute sources, where the controlled substance is embedded in the foam product in relatively low mass concentrations relative to the overall product mass. Different approaches to EOL ODS/HFC management are required depending on the concentrated or dilute form in which it appears at end of life, with consequential differences in regulatory requirements, infrastructure, economic factors, and destruction technology requirements.

3.3.2. Management of concentrated EOL ODS/HFC

For the RACHP sector, there are basic measures that can be taken at the source:

1. Promoting on-site recovery and recycling, where technically feasible, meaning, to fill the refrigerant back into the same system after servicing or repairing the system. This can involve a basic cleaning of the refrigerant that can be done on-site to remove water, oil, and particles. On-site recycling is critical to the maintenance and service of RACHP equipment during its lifetime to avoid emissions. The technical skills, equipment, and infrastructure are the same as those required for EOL recovery and recycling.
2. Promoting on-site recovery of controlled substances for subsequent off-site reclamation utilising specialised equipment. Similar to recycling, reclamation allows the reuse of the used controlled substance for servicing existing equipment and in new equipment (where permissible).
3. Transitioning as rapidly as practical away from controlled substances where suitable lower GWP alternatives exist. This could limit the amount of EOL ODS/HFCs requiring management.

From a general resource utilisation efficiency perspective, recycling and/or reclamation are preferable in comparison with destruction, as recycling and/or reclamation reduces the amount of virgin refrigerant required (unless the destruction process can recover basic

[37] Banks and EOL Halons management is described in detail in the UNEP, 2022, *2022 Report of the Fire Suppression Technical Options Committee, 2022 Assessment Report*.

chemicals such as hydrogen fluoride for further reuse in a beneficial way). However, destruction is the ultimate end-of-life phase for refrigerants, thereby minimising emissions.

Reclamation is the reprocessing and upgrading of recovered controlled substance through such mechanisms as filtering, drying, distillation, and chemical treatment, to restore the substance to a specified standard of performance. It often involves processing "off-site" at a central facility.

Reclamation requires a managed returnable cylinder/container infrastructure to return recovered refrigerant to a central facility. Such a system is typically integrated into refrigerant supply infrastructure and is most effective when returnable containers are mandated, and non-refillable (disposable) containers are prohibited. However, in some settings, such as very low refrigerant use or widely dispersed low density of equipment, the banning of disposable cylinders can be more challenging than in densely populated areas.

In some countries, there is developing capability to separate mixtures of refrigerants for reuse, for example by distillation, lower GWP refrigerant components from higher GWP HFCs, with the option of destroying the high GWP HFCs if no longer required.

Where recovered refrigerants are not suitable for reclamation then destruction becomes the only option to avoid emissions. To achieve sufficient quantities for economic destruction, the overall infrastructure for supply and return of refrigerants needs to be readily adaptable and expandable to collect and securely store EOL ODS/HFCs for refrigerant destruction. The 2022 RTOC Assessment Report includes Chapter 13, which discusses servicing and refrigerant conservation.

3.3.3. Management of dilute EOL ODS/HFC

For dilute EOL ODS/HFC, primarily insulating foams from refrigeration appliance and building construction, but also packaging and automotive foam applications, different sets of challenges exist in EOL management. With the transition away from ODS and HFC as blowing agents in many applications, the issue concerns a large existing bank that is reaching its EOL, although this is projected to decline in the future due to effective global transition to low GWP blowing agents.

Historically these foam product waste streams have mostly been part of the general solid waste stream that has utilised land disposal or open burning in some cases. In general, recovery and EOL treatment, largely through some form of thermal destruction, requires several steps starting with separation from the general solid waste stream, either at source or prior to conventional solid waste disposal. This results in a higher solid waste unit cost relative to current land disposal. Given the relatively low proportion of controlled substances within the overall foam product waste volume, low returns are realised in terms of amount recovered for EOL ODS/HFCs per volume handled. The net overall cost/kg of ODS/HFC recovery and destruction is consequently much higher than for concentrated EOL ODS/HFCs. This is compounded by high emission rates of blowing agents during handling and size reduction inherent in the largely manual process required to transport and prepare it for destruction. Alternatively, the extraction of blowing agent can be done in a closed environment but this is also not necessarily cost effective. The net result is poor cost and operational efficiency compared with concentrated ODS/HFC in EOL management in terms of mitigating emissions. This also makes management of dilute waste streams a less attractive target for carbon finance mechanisms.

Refrigeration appliance foam and its treatment can be part of regulations dealing with waste electric and electronic equipment (WEEE), particularly in non-A5 parties, often organised under extended producer responsibility (EPR) arrangements. Refrigerators and freezers are collected at source, or segregated from solid waste after collection, as one category of WEEE for which special requirements for recycling apply. In addition to the recovery of refrigerants, the separation of foam and potentially extraction of the blowing agents also occurs after which the foam/blowing agent is destroyed by a qualified technology. Ideally, this is done in a closed environment, where the insulation foam is shredded and, through thermal treatment, the liberated blowing agent is collected in concentrated form for destruction. More commonly, the foam is manually separated from the refrigeration equipment cabinets and doors and then destroyed using available facilities, such as waste to energy facilities, cement kilns, electric arc steel furnaces, or commercial hazardous waste facilities noting that all these options come with considerable losses of blowing agent and inherently poor accuracy of actual quantities destroyed.[38]

To ensure sound treatment of construction insulating foams containing ODS or HFCs, they need to be separated at source from the building prior to its demolition and then destroyed. Some countries have regulations in place making this process mandatory. It is noted that the amounts generated are low compared to overall national waste streams. Research on additional costs for such a procedure has shown them to be less than 1% of total renovation or demolition costs (Obernosterer *et al.*, 2007[39]). Therefore, separation and destruction of insulating materials containing controlled substances should not substantially impact demolition costs.

A similar regulatory approach to WEEE could potentially be applied to ODS/HFC containing foams in packaging and automotive waste streams, something that would require source or pre-disposal separation from the general solid waste stream, if practical. An additional complication with these foam wastes at EOL, at least in the short-term, may be the potential for them to contain flame retardants now banned under the Stockholm Convention. Options for their destruction are generally currently limited to existing thermal oxidation processes, noting the potential inherent losses involved, although technically similar extraction of blowing agent could be accomplished by shredding and extraction within an enclosed environment with recovered substance being managed as a

[38] In the absence of analysis of elements of foam waste, which is not practical, the overall waste stream recovered for management will contain a mixture of controlled substance as well as other blowing agents that will also change over time.

[39] Obernosterer R., Smutny R., Jäger E., 2007, *Nachhaltige FCKW Bewirtschaftung Österreich*, RMA Austria, Villach, November 2007.

concentrated EOL ODS/HFC waste stream.

The above approaches for dilute EOL ODS/HFC waste streams are generally implemented within national initiatives for a circular economy approach to the separation of priority solid waste streams. Within a broader policy framework that internalises the associated costs, these policies are anticipated to increasingly break down the barriers and limitations faced by individual waste streams.

3.3.4. Financing EOL ODS/HFC management

Sound and sustainable financing mechanisms for EOL management that cover recovery, collection, recycling, reclamation, destruction and storage (pending any one of the activities mentioned) of controlled substances are required. Several approaches are possible to finance the required infrastructure/capability and to economically incentivise the servicing and waste management sectors.

- Experience shows reclamation can be effective and financially sustainable when an enforced quota system restricts the quantities of new substances available in a market, creating demand for and commodifying reclaimed material.
- Carbon finance mechanisms can be applied within countries or on an international basis. For example, in the United States, the carbon offset registries, like the American Carbon Registry and the Climate Action Reserve Registry, provide carbon credits for the destruction of ODS sourced from United States' territories and other international sources. Verra is another registry promoting and incentivising the creation of offset credits from the destruction of internationally sourced ODS. Regardless of Registry, strict eligibility and additionality criteria apply to the creation of offset credits under the various methodologies. Other "cap and trade" arrangements or applications of carbon taxation can be applied to EOL ODS/HFCs, with appropriate policies and regulatory measures.
- Financing can also be linked to extended producer responsibility schemes, as is done with electrical and electronic appliances including refrigerators and freezers, where importers are expected to cover the cost for recycling of the equipment. This is often organised by an authorised entity that is supported by importers and producers of equipment, depending on their market shares. Such schemes may be mandated or adopted as voluntary initiatives by individual, or groups of, importers and producers.
- Regulatory approaches, such as levy or tax systems, on the import of controlled substances and/or advance disposal charges applied on new equipment purchase, whose revenues are administered by an authorised authority for EOL management. They can be combined with a refund system for returned substances, providing a financial incentive for recovery, recycling and return for reclamation.
- Early replacement programs, focussed on acquiring new equipment with energy savings, using corporate environmental and sustainability goals, sustainability programs, can also contribute to a sustainable financing scheme.

To date, MLF support for EOL ODS management for A5 parties has been limited to a demonstration destruction program completed in 2018.[40] From this, ExCom has followed up with an examination of further action in the area.[41] Furthermore, ExCom decision 90/49[42] allows the inclusion of measures for environmentally sound management of used or unwanted controlled substances in new stages of HPMPs and Stage I Kigali HFC Implementation Plans. This could potentially provide direct grant funding to assist A5 parties in expanding refrigeration servicing sector infrastructure to better address EOL ODS/HFC management, as well as capacity strengthening resources to support development of other financing mechanisms.

There has been increasing recognition that management of EOL ODS/HFC and associated banks has yet to be prioritised by either the Montreal Protocol or the Convention on Climate Change. Consequently, collective international action is developing that would raise awareness of this issue and promote independent policy action and financial support for addressing it. An example is the recent establishment of the Climate and Ozone Protection Alliance (COPA)[43], which is an initiative initially funded by Germany and managed by GIZ, with UNDP and UNIDO as implementing partners jointly with GIZ. Its objective is to fill the gap that exists on international action related to EOL ODS/HFC banks management. This would be accomplished through a network of public and private sector partners that would be able to mobilize funding to address the issue both globally and at a country level.

Regardless of the overall financing scheme, recovery needs to be incentivised for the service company/technician who performs the recovery, and logistics need to be integrated into existing structures to optimize handling and transport activities for both concentrated and dilute waste streams. Within regulatory systems, this can mean that the operator is obliged to ensure recovery and thus pay the extra cost for recovery (e.g., in several European countries). Additional incentives can be provided through refunds upon delivery of collected substances. In the case of the RACHP sector, distributors further up the logistics chain would be obliged to take back the recovered refrigerant and either recycle, reclaim, or destroy it. As destruction is expensive and uneconomic, except potentially where a mature carbon finance or other mechanism that creates a viable waste market is operating, it needs to be mandated by regulation.

Collection systems for EOL ODS/HFCs may use the existing infrastructure for refrigerant distribution using the same channels as for

[40] Executive Committee of the Multilateral Fund, Meeting Document: UNEP/OzL.Pro.ExCom/84/11, *Final Report on the Evaluation of Pilot Demonstration Projects on ODS Disposal and Destruction*, November 2019.

[41] Executive Committee of the Multilateral Fund, Meeting Document: UNEP/OzL.Pro/ExCom/89/9, *Synthesis Report Describing Best Practices and Ways for the Executive Committee to Consider Operationalizing Para 24 of Decision XXXVIII/2 (Decision 84/87(b))*, February 2022.

[42] Executive Committee of the Multilateral Fund, Meeting Document: UNEP/OzLPro.ExCom/90/40, *Report of the 90th Meeting of the Executive Committee*, June 2022, p. 43.

[43] https://www.copalliance.org/

new/reclaimed refrigerant in the reverse direction. Some companies have invested in rapid-recovery systems, which are equipped with powerful pumps that speed up and optimise the recovery process, reducing labour cost as well as the downtime of the system and thus improve the economics of the process. Larger refrigerant distributors operating internationally are increasingly moving toward a business model involving full integration of both the supply of refrigerants and its recovery/reclamation/recycling and EOL management through to destruction.

3.3.5. Transboundary movement barriers to EOL ODS/HFC management

The ability to smoothly undertake the transboundary movement of EOL ODS/HFCs is necessary to achieve global access to environmentally sound destruction of EOL ODS/HFC. In many countries, EOL ODS/HFCs are considered as hazardous wastes, based on their global ozone depleting and climate impacts and their potential for unsuitable disposal. As such their transboundary movement will be subject to the requirements of the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal and related international shipping standards. The basis of the Basel Convention is that there must be informed consent by the governments of the exporting country, transit countries, and the importing country, as well as standards for environmentally sound management of environmentally sensitive waste streams. The Convention's objective is to prevent the transfer of hazardous and other waste environmental legacies that originated in developed countries to developing countries, which might not have the capacity or resources to manage such legacies. While generally associated with traditional hazardous chemical wastes, the issue of transferring such environmental liabilities from developed to developing countries has included dilute EOL ODS/HFC wastes contained in exported, used and inoperable refrigeration equipment thereby transferring waste insulation foam for disposal to countries without the capacity to handle it.

While effective in restricting illegal trade in waste, the process of informed consent is inevitably bureaucratic and time consuming given the approvals required by multiple jurisdictions sequentially, resulting in significant transaction costs associated with the process. This is a significant barrier to EOL ODS/HFC management, including reclamation, and/or destruction, particularly for parties that lack national capability for local reclamation and/or destruction, or the resources to undertake export transactions involving the relatively small quantities low-volume consuming countries might generate.

Some of the key complexities relate to:

- Inconsistencies with classification of the material
- Increased administrative efforts
- Increased shipping costs
- Increased time to process Basel paperwork at each port, adding time to the journey
- Difficulties locating a carrier that is prepared to carry material when classified as 'hazardous waste'
- The possibility of venting as a means of responding to challenges of the transboundary movement.

Several approaches, likely in combination, could be adopted to address this issue. These include:

- **Accumulating quantities at source**— An important prerequisite for cost effective EOL management is to accumulate enough controlled substances to be destroyed to make land and/or sea transport viable and justify the individual shipment transaction costs. This requires the collection, consolidation, and secure storage of the controlled substances in appropriately sized and qualified tankage, until a viable quantity is available for shipping. This would typically be an amount that might fill a standard shipping container. For EOL refrigerant, this would involve investment in incremental infrastructure that is developed and operated collectively by refrigeration servicing providers.
- **Development of a regional EOL ODS/HFC management approach**— Recognising the potential for development of smaller scale EOL ODS/HFC destruction facilities (see section 8.6.4) and the potential availability of existing industrial based destruction capacity, such as cement kilns, there could be opportunities for regional cooperation to develop an economically sustainable regional approach using this destruction capacity. A regional approach could serve several countries in reasonable proximity that are willing to cooperate efficiently on Basel Convention approvals.
- **Involvement of refrigerant distribution companies and carbon trading enterprises in facilitating export transactions**— The participation of international refrigerant distribution firms, individually or collectively, could facilitate the consolidation, handling, and export/import transactions of EOL ODS/HFCs requiring destruction. This fits the developing business model of several international companies and is consistent with product stewardship/extended producer responsibility policies. This could also facilitate greater use of carbon trading mechanisms, including participation of entities specialising in brokering such transactions, noting that an equitable distribution of revenues would need to be maintained.
- **International cooperation to facilitate transboundary movement of EOL ODS/HFCs**— International measures might need to be considered to facilitate movement of EOL ODS/HFCs under the Basel Convention, including, e.g., UN Secretariat level dialogue of technical and economic issues relevant to the Montreal Protocol and barriers to the transboundary movement of EOL ODS/HFCs. EOL ODS/HFC management is also relevant to international efforts to curb greenhouse gas emissions, e.g., under the United Nations Framework Convention on Climate Change (UNFCCC). Parties may wish to consider how the Montreal Protocol, the UNFCCC, and the Basel Convention could work together to facilitate transboundary movement of EOL ODS/HFCs to encourage preferential recovery/recycling and environmentally sound destruction of EOL ODS/HFCs, thereby minimising their emissions.

3.4. Global Emissions and Banking in the Fire Suppression Sector

Since the earliest days of the Montreal Protocol, the FSTOC has maintained that recovered/recycled/reclaimed fire suppressants represent a viable alternative to newly produced agents which would serve to greatly reduce emissions and production. With the support of the parties of the Montreal Protocol, the fire suppression industry developed internal policies and procedures through specifications, standards and codes that would make this vision technically and economically feasible. This resulted in greatly reducing the amount of halons produced and ultimately emitted, and allowed for halons to be the first ODS to be completely phased out in non-A5 parties. This practice has been naturally expanded to include HCFCs and high GWP HFCs and to all of their in-kind alternatives.

The FSTOC has been estimating banks and emissions of halons since the earliest days of the Montreal Protocol. There are two independent methods to estimate emissions of halons: 1) the FSTOC model which takes account of the total amount of recorded production, allows for production losses, destruction, and emissions from the bank and 2) emissions estimates derived from atmospheric concentration measurements, in this case measured by the Advanced Global Atmospheric Gases Experiment (AGAGE) network. Historically the agreement between these completely independent methods has been remarkably good for halons 1301 and 1211. However, since 2010, the emissions derived from atmospheric measurements have been consistently higher for halons 1301 and 1211 than those estimated by the FSTOC model.

3.4.1. Halon 1301

The FSTOC halon 1301 model emissions compare well with the annual mean emissions derived from mixing ratios (atmospheric concentrations) from the latest data using the methodology of Vollmer *et al*. (2016) (hereafter referred to Vollmer) until about 1998 where the FSTOC model emissions are generally lower than the mean FSTOC estimates generally fall within +/-1 sigma uncertainty of the mean except for 2011 – 2012, where the FSTOC model estimates are slightly lower than the -1 sigma value.

Differences are seen during the periods of increasing and decreasing emissions from 1999-2000, 2010-2016 and 2018-2021, instead of the decay pattern expected from emissions from a finite global bank. A potential source could have been from fire protection systems from shipbreaking activities, but that is not anticipated in recent years as recovered halon 1301 has a significant market value and it is reported that halon is currently handled carefully during shipbreaking. Another possible source for these emissions could be from halon 1301 production and use as a feedstock for the pesticide Fipronil and several other chemicals, whose emissions would not be accounted for in the FSTOC model but would be included in the Vollmer estimates. However, the amount of halon 1301 that is from feedstock production and use would need to be at the higher end of the Medical and Chemicals (MC)TOC-estimated emissions of 7.5%. The FSTOC is seeking additional information on halon 1301 feedstock production, use, and emissions to better understand if the higher levels of emissions can be attributed primarily to feedstock use versus from the fire protection bank.

Using mean emission estimates from Vollmer provides a global bank estimate range of 26,250 – 27,500 metric tonnes compared to 35,000 metric tonnes for the FSTOC model. This difference is becoming significant as the amount of halon that is available to support enduring fire protection uses becomes smaller over time. The Vollmer data also provide a much higher mean annual emission rate for 2021 of nearly 5.5% of a 26,500 metric tonne bank. This is more than double the approximately 2.25% composite rate from the FSTOC model and much higher than the 2%+/-1% rate developed by Verdonik and Robin (2004). The combination of a potential higher emission rate than generated by the FSTOC model and a smaller bank of halon 1301 could also imply that there is going to be a significant reduction in available halon 1301 to support ongoing needs in civil aviation, oil and gas, militaries, etc., which could result in a much earlier run-out date.

3.4.2. Halon 1211

The FSTOC projected regional distribution of the global bank of halon 1211 shows that at the end of 2022, almost 80% of the estimated 20,500 metric tonnes is equally divided between the North America region and the Western Europe and Australia region with about 20% estimated to remain in A5 parties. The estimate for A5 parties is significantly lower than projected in the 2010 Assessment, which reflects FSTOC concerns with halon 1211 bank management. This trend continues with lower emissions rates expected in the North America region and the Western Europe and Australia region resulting in these regions containing over 90% of the global bank in the next 20 years.

Both the mean and +1 sigma uncertainty emissions from Vollmer are higher than the cumulative production reported to the FSTOC meaning that the bank would be completely exhausted. However, the bank cannot be exhausted as there are still emissions in Northwest Europe being measured and halon 1211 is still widely used on civil aircraft. This suggests that either more halon 1211 has been produced than reported to the FSTOC (and thus more emissions) and/or the emissions are at the lower end of the Vollmer estimates.

3.4.3. Halon 2402

The FSTOC model emission rates as a function of the size of the bank have been updated for this assessment. The current model aligns the emission rates for 2402 with those currently used for halon 1301, with the exception of Japan, which uses the same emission factors as for North America. The FSTOC estimates that the majority of halon 2402 remains in the former Countries with Economies in Transition (CEITs), but also with significant quantities remaining in Europe.

The FSTOC model estimate of emissions is generally higher than the mean estimate of emissions from the updated Vollmer data from about 1980 until 2020 and near or above the +1 sigma uncertainty until 2018. The Vollmer data show increasing emissions from 2016 – 2021, with the FSTOC estimate going below the mean but staying within +/-1 sigma uncertainty. This increase would not be expected from an average emission rate of the bank unless something has changed. It has been reported to the FSTOC that there is a major decommissioning programme underway in Vladivostok, Russia that could account for an increase in emissions. As emissions would be expected to be kept to a minimum, but not totally avoidable, the level of increase in emissions suggests that this effort involves a sizeable amount of decommissioning. It is presumed that this recovered halon 2402 will remain in the global bank to support enduring uses of halon 2402.

Vollmer emissions estimates provide a mean bank range of 15,500— 19,500 metric tonnes. This is compared with the FSTOC model estimate of a remaining bank of 13,000 metric tonnes. It should be noted that the FSTOC model does not include emissions from the reported use of halon 2402 as a process agent which would place the FSTOC model emissions and bank estimate within the range of uncertainty of the estimates using the Vollmer data.

3.4.4. HFCs

Unlike halons, the majority of which were exclusively used for fire protection, HFC-227ea is also used in metered dose inhalers (MDIs) and in foam blowing. Therefore, to estimate the global emissions from fire protection, it was necessary to create a model that can separate the annual emissions into those three categories of use. The model was initially developed in 2018 in coordination with a MCTOC co-chair and a FTOC co-chair and has been updated in 2022. The model uses best estimates of annual global production capacity of HFC 227ea beginning in 1993 and carried out until 2021.

The annual emission rate from the fire protection bank was updated to be 3% from 2011 – 2021. Emissions from production were updated ranging from 0.1% to 1.25% per the latest MCTOC estimates.

The HFC-227ea model emissions and the emissions derived from atmospheric measurements are in excellent agreement, with the HTOC model results generally between the +/-1 sigma uncertainly in the atmospheric derived estimates.

The model estimates the global fire protection bank of HFC-227ea to be 178,000 metric tonnes. Based on emission estimates from the US and Northwest Europe, the FSTOC estimates that more HFC-227ea is in A5 parties than in non-A5 parties.

There are several known applications of HFC-125 in fire protection including some military uses but these are estimated to be quite small. Since the largest use of HFC-125 is as a blend in several refrigerants, it is not possible to estimate the amount of HFC-125 used in or emitted from fire protection systems using atmospheric measurements alone.

Unlike HFC-227ea and HFC-125, which are purposely produced, HFC-23 is a by-product of HCFC 22 manufacturing. As a result, it is not possible to estimate the amount of HFC-23 used in fire protection from atmospheric measurements. HFC-23 is typically limited to use in cold temperature applications. Its use is expected to be small compared to HFC-227ea.

As was the case for HFC-227ea and HFC-125, there are other non-fire protection uses of HFC 236fa. However, unlike HFC-227ea, there is little information available on the relative take up of HFC-236fa in the fire protection market. At this time, there is not sufficient information to estimate HFC-236fa installed quantities or emissions in the fire protection sector.

3.4.5. Global Halon, HCFC, and HFC Banking (Agent Management)

A bank is defined as all agents contained in fire extinguishing cylinders and storage cylinders within any organization, country, or region. Likewise, the ‘global bank’ is all agent presently contained in fire equipment plus all agent stored at recycling centres, at fire equipment companies, at users’ premises, etc., i.e., it is all agent that has been produced but has yet to be emitted or destroyed. The collection, reclamation, storage, and redistribution of fire extinguishing agents is referred to as “Banking”. These concepts and terminologies apply to all fire suppression gases including halons, HCFCs, HFCs, and their alternatives.

FSTOC continues to see issues regarding the loss of historical knowledge 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 halon management but not being familiar with the issues surrounding halons, HCFCs, HFCs, and their alternatives use, recycling, and banking. Lack of understanding about long-term needs for halon 1301 has also resulted in halon destruction. FSTOC notes that this lack of experience and historical knowledge is becoming 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 address awareness programmes to re-establish this loss in institutional memory.

3.4.6. Emission Reduction Strategies and Banking

Avoidable halon and other halogenated gaseous fire extinguishing agent releases account for greater emissions than those needed for fire protection and explosion prevention. Clearly such releases can be minimized.

- Do not use halons in new fire protection applications or new designs of equipment where alternatives exist.
- Take advantage of opportunities to re-evaluate the need for existing halon systems or extinguishers and replace them with suitable alternatives where it is technically and economically feasible to do so.

- Do not use HCFCs and high-GWP HFCs in fixed systems unless approved by the facility owner and a full risk analysis has been performed by a fire professional with expertise in their use and specifications, and the agent was deemed the only viable option taking into consideration safety, efficacy, economics, and environmental effects.
- Encourage the application of risk management strategies and good engineering design to take advantage of alternative fire protection schemes.
- Educate and train personnel on system characteristics.
- Manage storage of halon and other halogenated gaseous fire extinguishant reserves and perform routine leak detection.
- Implement national Awareness Campaigns on all environmental concerns (ODS, GWP, Climate Change).
- Develop or adopt Technical Standards and Codes of Conduct.
- Develop databases and implement record keeping on halon, HCFC and HFC installed base quantities, transfers, and emissions.
- Develop halon, HCFC, and HFC fire extinguishing agent management plans including end of useful life considerations.
- Ensure "Responsible Use" of halons and other halogenated gaseous fire extinguishing agents.

3.4.7. Destruction

The FSTOC maintains the position that destruction should only be employed as the final disposition option when halons, HCFCs, HFCs, and their alternatives are too contaminated and cannot be reclaimed to an acceptable purity.

The world's first pilot halon destruction for carbon offset occurred in February 2021 in the US, using internally sourced halon 1301 for the creation of carbon credits which were traded in the voluntary carbon market. The FSTOC is concerned that destroying halon 1301 for carbon credits could contribute to global shortages / regional imbalances of halon 1301 to support long-term enduring uses.

When local access to reclamation or destruction services is not available, the classification of halons as hazardous waste by some parties results in the application of the Basel Convention for "The Control of Transboundary Movements of Hazardous Wastes and their Disposal". This continues to obstruct the international movement of halons and in future could also affect other fire extinguishing agents.

The FSTOC is not aware of any new information, such as test data, relating to already approved destruction technologies.

3.5. Banks and Stocks of Methyl Bromide

MBTOC provides the following comments in response to the requirement of Decision XXXI/21 to report on the status of banks and stocks of controlled ODS and the options available for managing them so as to avoid emissions to the atmosphere:

- Whilst banks of other ODS are held in equipment, foams, etc., banks of MB are only held as chemical in cylinders (i.e. stocks) either ready for use for QPS or for non-QPS applications. Additionally, unused MB has been reported to exist in waste cylinders at various locations (e.g. growers' properties, warehouses) throughout countries after phase-out of MB for preplant soil, structural and commodity uses. Known examples include the Philippines and Ethiopia;
- MBTOC considers that the amount of stocks left over in countries after phase-out may be quite substantial, but has no way of obtaining information of these stocks;
- Globally there are stocks from recent production of MB held at numerous sites ready for future consumption for legitimate QPS uses. This should only be in countries requiring use of MB for treatment of commodities for international and national trade. Unfortunately, it is impossible to calculate the size of these stocks/banks of MB;
- Additionally, now that phase-out of controlled, non-exempted (i.e., non-QPS) uses of MB is virtually complete, there should be no stocks held for controlled uses. Parties have reported that 40 tonnes from the original baseline consumption of 66,428 tonnes were being consumed for controlled uses in 2021. All other non-exempt uses of MB have reportedly been replaced. However, the lack of any formal requirement by parties to report stocks of MB left over (or still needed) after the phase-out deadline for controlled uses is considered a problem. This is because it is potentially leading to a relatively small, but significant amount of stock being used for unreported controlled uses of MB;
- Also, as QPS uses of MB, presently at approximately 10,000 tonnes, are exempted from phase-out under the Montreal Protocol, there is a possibility that some of this stock is used for controlled uses. MBTOC is continually being made aware of MB uses in various sectors that do not appear to fit within the definitions of QPS under the Montreal Protocol. MBTOC notes that MB is still offered on the internet for any use.

3.5.1. Options available for managing MB stocks and banks to avoid emissions to the atmosphere

Elimination of emissions of MB from QPS use (~8,000 tonnes) and any remaining emissions from stocks/banks of MB is the single largest short-term gain that could be made to further reduction of EESC and improvement in the ozone layer. Complete elimination of emissions from these uses of MB, could result in a further significant (i.e. ~10%) and rapid reduction to the present EESC. Technical alternatives to both Q and PS purposes are becoming increasingly available and this is the best means to reduce emissions to the atmosphere of MB and reduce the level of stocks for this use. There are only 55 parties who presently report use of MB for QPS and hence are justified in holding stocks.

To reduce emissions from any excess stocks from decaying cylinders and cannisters (0.5 kg in size) i.e. where MB is no longer required, the MB could be resold if practical or destroyed by approved destruction technologies rather than vented off directly to the atmosphere (e.g. high temperature treatment and hydrolysis).

MBTOC notes that a number of Decisions urge Parties to minimise emissions of MB and to use MB recovery and recycling technology where technically or economically feasible for QPS treatments until alternatives to MB are available e.g. (Decisions VII/5, XI/13). Information is also available on the internet to show how to recover MB safely from old cylinders for later destruction of the MB and allowing for recycling of the cylinders (GIZ, https://www.youtube.com/watch?v=55NRBo-Zrp8). Even a cylinder after use will contain approximately 1% of the original MB amount. And if not returned to be reused will slowly leak emissions of MB into the atmosphere.

Reduction in emissions 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 (0.7 years), adoption of any suitable alternatives and in some cases adoption of recapture/destruction would have an immediate benefit in reducing atmospheric MB levels. It is an important opportunity available to Parties to rapidly enhance ozone layer recovery, with effects of reducing emissions from QPS and better management of stocks observable in the stratosphere within 2 years.

In order for MBTOC to report accurately on the status of stocks and banks in the future and provide accurate information on methods to reduce emissions, parties may wish to:

- Continue to consider a formal mechanism under the Montreal Protocol collect accurate data and to report annually on stocks of MB from all relevant parties;
- Ensure all production is accurately reported against MB consumption to avoid controlled QPS production being used for controlled uses. This will ensure that an appropriate level of stocks is retained only for QPS needs;
- Clearly identify the techniques being used for fumigation (e.g. under tarp, within shipping containers, warehouse, ship holds, etc) and the sector/pest combinations for all remaining uses of MB, to determine the potential for reducing emissions. Recapturing MB to avoid emissions to the atmosphere is presently more suited to shipping containers.

4 THE IMPACT OF THE PHASE-OUT OF OZONE-DEPLETING SUBSTANCES ON SUSTAINABLE DEVELOPMENT

4.1. Introduction

Paragraph 8 of Decision XXXI/2 requested the TEAP, in its 2022 Assessment Report, to consider the "*impact of the phase-out of ozone-depleting substances (ODS) and the phase-down of HFCs on sustainable development*." This same request was made previously, for the 2018 Assessment Report.

Defined as "*the development that meets the needs of the present without compromising the ability of future generations to meet their own needs*"[44], sustainable development has since been addressed at numerous UN meetings and various commitments have been made. There is an increasingly urgent, global call for action to improve human lives and protect the environment. Currently, sustainability is addressed through three pillars: economic viability, environmental protection, and social equity.

The approach taken by the TEAP to respond to Decision XXXI/2 and previously to Decision XXVII/6 has been to consider key United Nations decisions, agreements and reports related to sustainable development, and relating these to the impact of the global transition away from ozone-depleting substances in the various sectors of use, as assessed in the quadrennial assessments of the TOCs.

4.2. Montreal Protocol: Progress in ODS phase-out

Elimination of the production and consumption of 99% of ODS, and the projected recovery of the stratospheric ozone layer, are among 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 (SAP 2022). By 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 combined impacts of the Protocol on climate and on the ozone layer not only saved the world from a catastrophe, but also contributed to sustainable development.

The Kigali Amendment has confronted parties – especially developing countries - with the challenge of preparing for and achieving the HFC phase-down, sometimes whilst implementing the final stages of their HCFC phase-out Management Plans (HPMPs). The main sectors impacted are refrigeration and air conditioning, where most of these substances are used, but the wide range of activities where refrigeration is a matter of interest extends this impact much further.

4.3. Montreal Protocol: Impact on Sustainable Development Goals

The current environmental governance framework is based on the Sustainable Development Goals (SDGs), which resulted from decades of work of the UN system and its member countries. The process of implementing SDGs started on 1 January 2016 and envisions achieving most goals and targets by the end of 2030 (some earlier). The Division for Sustainable Development Goals of the UN Department of Economic and Social Affairs (ECOSOC) supports SDG knowledge, builds capacity to address them and in general, deals with all issues related to the SDGs. There are 17 goals each with its own specific targets, some of which have already passed preliminary deadlines.

Recently (2022), on occasion of UNEP's 50th anniversary, the Stockholm+ 50 conference was held, focussing on accelerating actions towards environmental protection and improved livelihoods. These actions are framed around three main issues: achieving a healthy planet, recovery from the COVID-19 pandemic, and sustainable and inclusive development.

For 35 years, the MP has contributed in many ways to the achievement of most SDGs. Its contributions are particularly significant in protecting human health, improving livelihoods, protecting the environment, fostering sustainable production practices, and improving food security. Contributions to industry and innovation, clean and efficient energy and economic growth are also important.

[44] United Nations 1987. The Brundtland report "Our Common Future"

The Kigali Amendment has established direct linkages between ozone layer protection and climate change, thus strengthening the impact of the Protocol on SDG achievement.

TEAP has considered the impact of the phase-out of ODS under the Montreal Protocol on sustainable development by analysing how the transitions taking place in each sector relate to relevant SDGs, as presented on Table 4.1.

Table 4.1 Key contributions of the Montreal Protocol to the SDGs

Goal	Description	Examples of contributions from the Montreal Protocol
1	*No poverty.*	• Adoption of alternatives to methyl bromide in some countries increased net income of families by gaining access to some markets not previously available with use of MB.
	End poverty in all its forms everywhere	• Refrigerant enabled cold chains are a required element of the economies of the world, enabling chemical processing, manufacturing, food preservation and building environmental conditioning.
		• Today, fire protection in all forms is an important enabler of a functioning society but in particular for global and local communications (e.g., telephones, internet) and energy production and storage, including green energy storage and thereby contributes to economic growth. This is helping lift people out of poverty.
2	*Zero hunger.*	• Protection of the ozone layer has prevented an excessive increase of ultraviolet (UV) radiation which is harmful to plant growth as well as animal health leading to adverse impacts on agricultural production.
	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	• The MB phase-out generated a large amount of information and experience on plant production, particularly in intensive agriculture, where MB was primarily used. Non-chemical alternatives and sustainable practices were implemented, and large numbers of growers, technical staff and others were trained. MB phase-out led to the implementation of production practices that are sustainable in the long term by protecting non-renewable resources, increasing the productivity and resilience of different crops, enhancing food security, economic development, and positively impacting human health.
		• Inadequate food preservation leads to tragic consequences: 600 million people, almost 1 in 10 worldwide, fall ill after eating contaminated food. Of these, 420 000 people die each year, including 125 000 children under the age of five years. The use of a cold chain increases food safety and the food availability. Fresh meat or fish for example has a shelf life of 1 day or less at ambient storage temperatures (20-30°C). The shelf life can reach 10 days with cooling
		• Refrigeration helps fight food loss and waste and improves food security. Overall, losses due to a deficient cold chain account for around 13-14% of food production[45]. If all these losses were eliminated, one billion people could be fed, thus significantly meeting the future needs of humanity.
		• CFC-free alternatives for refrigeration combined with foam providing better insulation contributes to more efficient cold chains.
		• The use of information and data sharing through the internet and increasingly through AI, are being used to increase agriculture sustainability. Fire suppression systems in server farms and internet infrastructure support maintaining these capabilities, particularly during times of disaster.

[45] (Opinion| Insufficient cold chains lead to food loss that could feed 950 million people - Dailynewsegypt) had it at 13%. UNEP/FAO Sustainable Food Cold Chains: Opportunities, Challenges and the Way Forward | UNEP - UN Environment Programme

3	**Ensure healthy lives and promote well-being for all at all ages**	• With 99% of ODS phased out, the ozone layer is on the path to recovery, preventing a dangerous increase in UV radiation and millions of cases of skin cancers and cataracts per year. • The remaining uses of MB for QPS purposes are highly emissive as MB is directly vented into the atmosphere, with very negative impacts on human health and the environment. • Alternatives to MB are generally safer for human health, by reducing use of chemical pest and disease control agents and thus improving worker safety by avoiding exposure to a substance which is hazardous for human health. Industrial exposure to MB has been linked to prostate cancer. • The transition away from CFC-containing pressurised metered dose inhalers (pMDIs) for asthma and COPD (Chronic Obstructive Pulmonary Disease) led to the development of a range of inhalers, allowing patients to have wider choices and better disease control. • A more efficient cold chain has also made the storage of medicines and vaccines safer and improved their accessibility in developing countries. This fact has become particularly relevant with the COVID-19 pandemic. • Higher efficiency cold appliances with smaller and affordable sizes of fridges have provided better conservation and safer food for A5 parties in a clear demonstration that zero ODS implementation is promoting well-being for all ages. • Higher energy efficiency in refrigeration and air conditioning (RAC) leads to lower energy consumption and generation requirements and lower air pollution.
4	*Quality education.* **Ensure inclusive and equitable quality education and promote lifelong opportunities for all**	• The MB phase-out generated a large amount of information and experience on plant production, particularly in intensive agriculture, where MB was primarily used. Non-chemical alternatives and sustainable practices were implemented, and large numbers of growers, technical staff and others were trained. • The Montreal Protocol, through funding provided by the multilateral Fund, is providing capacity building and training to technicians in A-5 countries contributing to the application of servicing best practices, and safe working environment both for technicians and end users. • Many educational resources are online; fire suppression systems that protect servers and other IT resources continue to ensure access to educational material around the world.
5	**Gender equality**	• In December 2019, the Executive Committee to the Montreal Protocol approved an Operational Policy on Gender Mainstreaming for all Projects Funded by the Multilateral Fund, with the purpose of contributing to the achievement of gender equality and women's empowerment. The implementing agencies have adopted gender mainstreaming guidelines, which need to be incorporated in all projects. • The MB phase-out has benefited women by creating jobs and providing training and access to sustainable production methods in many regions. A good example is Mexican horticulture where MB use was avoided by introducing grafted plants, which require intensive hand labour. • Gender mainstreaming activities in encouraging women to join the RACHP sector and removing barriers to their participation in the workforce will provide opportunities to women in A5 countries and enable their social and economic independence.
6	*Clean water and sanitation.* **Ensure availability and sustainable management of water and sanitation for all**	• MB phase-out as a pre-plant soil fumigant has eliminated MB residues leaching into water and soils. Multiple long-term use of methyl bromide on soils can lead to accumulation of excessive bromide ion resulting from decomposition of the applied methyl bromide. • Water is used for various cooling processes in RACHP systems. On the one hand for separate re-cooling systems (evaporative cooling systems, cooling towers) as well as for cooling condensers and as a heat sink at heat pumps. Water temperatures and keeping the water body biologically clean are key factors. • In addition to the pure use of water for heating or cooling purposes, the problem of keeping drinking and ground water clean due to foreseeable contamination from the breakdown products of refrigerants is becoming increasingly important. • Many water treatment plants utilise fire suppression systems that protect their control rooms and other IT resources, thus continuing to ensure access to clean drinking water in cities in both A5 and non-A5 countries.

7	**Ensure access to affordable, reliable, sustainable and modern energy for all**	• The Montreal Protocol and its Kigali Amendment have been instrumental for developing RACHP systems which are ozone-friendly and energy efficient. Manufacturers and research institutes have worked on designs and manufacturing practices that produce energy efficient products which in turn mean lower energy bills for consumers. • With the adoption of zero ODP refrigerants and better foam insulation, refrigerators became twice as efficient between 1994 and 2015. 8Annual refrigerator production was estimated at 100 million units and energy consumption at 375 kilowatt hour (kWh) per year in 2018. As a result, 10 new power plants with 500 MW capacity were avoided each year, just by using energy efficient domestic refrigerators or, in absence of this effort, energy consumption would have been 750 kWh. • Improvements first introduced during the CFC and HCFC phase-out stages are now continuing with the HFC phase-down under the Kigali Amendment. Along with zero ODP refrigerants the RACHP industry is improving the energy efficiency of associated components and systems. TEAP still estimates that the sector accounts for 7.8% of total greenhouse gas emissions globally, of which 20 – 37% are direct, and 63-80% indirect (IIR 2017, data for 2014)[46]. • New generations of zero ODS and low GWP of blowing agents and advances in foam processing together with cooling envelope (system, compressors, etc.) have substantially improved energy efficiency in storage, transportation and conservation of products. The savings in energy and reduction of annual electricity bills and better food conservation, which are beneficial for each individual. • Refrigeration technology (Organic Rankine Cycle-ORC) is increasingly being used to produce power. Heat pumps are considered a key technology in order to decarbonize heating demands in residential and industrial applications, by replacing fossil fuels. Renewable energies can also provide cooling such as solar cooling and evaporative cooling. • Fire protection systems are vital for the safe operation of power generating facilities in both A5 and non-A5 countries. Additionally, the increased use of interconnected power suppliers (e.g., smart grid) are increasingly being used to increase the use of affordable, reliable, sustainable and modern energy, with fire suppression systems an integral part of their resilience.
8	**Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all**	• The ODS phase-out has positively impacted the global economy "by an estimated half a trillion USD between 1987 and 2060" (TEAP 2018). This can be estimated in terms of avoided damage to agriculture systems, avoided negative impacts to fisheries and avoided damage to materials like plastic and wood caused by excessive UV radiation. The benefits associated to the diseases prevented and the human lives saved are difficult to calculate, but no doubt very large. • Alternative technologies in the RACHP sector have required investments in new, modified and retrofitted production lines, with associated economic reductions mainly achieved through energy efficiency especially for A5 parties. • In regions with high temperature and air humidity (HAT) where large economic development has taken place, air-conditioning has improved the indoor air quality as well as worker comfort and productivity. • The Protocol has provided very large opportunities for job training in many sectors all over the world: sustainable agriculture production practices when phasing out MB and recycling and reclaiming plus servicing of the alternative chemicals and technologies in the RACHP sector are two examples of this. • Funds provided by Montreal Protocol via Multilateral Fund have enabled enterprises in developing countries to get updated in new foam technologies (zero ODS, sustainable materials and more energy efficient) with higher quality, more reliable processing, and modern equipment, as well. This new scenario in the enterprises have contributed to generate and provide better jobs for operators and engineers linked to chemistry, mechanical, electrical/electronic and computer areas. • Air conditioning also affects the well-being and productiveness. Research suggests productivity decreases on hot and humid days. Higher temperatures decrease humans' physical and cognitive performance, making it harder for people to complete basic tasks. Evidence indicates that in countries with already high average temperatures, such as Thailand, India, or Nigeria, individual productivity reduces by as much as 4% for each one-degree Celsius increase in average temperature. Refrigeration is also increasingly used in surgery (cryosurgery), for diagnoses (scanners), for transplants and analyses (tissue, gamete banks, etc.). • Today, fire protection in all forms is an important enabler of a functioning society and contributes to economic growth.

[46] Data from: https://ourworldindata.org/emissions-by-sector confirm the percentages shown.

9	**Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation**	• An enormous number of new patents associated with the development of alternative products and technologies have been filed since the signature of the MP in 1987. They have been aimed at developing alternatives to ODS that enable their phase-out (and more recently the HFC phase down) and reflect the amount of innovation and initiatives occurring around the world, led by industries and research institutes. • The Montreal Protocol has encouraged the adoption of climate-friendly, safer alternatives, which frequently are not-in-kind technologies that are not direct replacements for controlled substances. Good examples are soil-less plant production, bio-fumigation or grafting, in agriculture; architecture that reduces cooling needs; refrigeration based on absorption and adsorption, natural refrigerants, non-solvent cleaning methods. The wide range of options together with a large degree of innovation, adaptation and training has made these alternatives more affordable. • The Montreal Protocol has been a driver for recycling and reclaiming the refrigerants, for implementing more efficient production practices, thus improving competitiveness and facilitating market access in many sectors. • In the fire protection sector, there was quick development of effective alternatives to halons, which leave no residues, reduce damage to a minimum, and are compatible with energised electrical systems. They are especially useful in telecommunications, cloud applications, server and data centres for digital technologies (internet). • Using solar energy and waste heat from refrigeration and air conditioning have replaced some refrigerants and the need of vapor compression. This has not only contributed to phase-out but has helped avoid 'technology disruption'. • Directing ODS phase-out via exemptions rather than sanctions has helped incentivise Research & Development around the world. Clear examples are seen in the replacement of MB, pMDIs, laboratory and process agents, and others. • Foam insulation have been using to seal building envelopes from air infiltration further reducing heating and cooling loads. New generation of foams that are environmentally friendly are applied with lower densities contributing to provide better internal space with good cost balance and high insulation performance. • Building science trends toward efforts to reduce cooling and heating loads increase the amount of foam and its associated FBA usage and selection. It should be noted that a careful balance of air infiltration and ventilation has been identified as a key aspect of "healthy buildings" as a result of the pandemic, and it is anticipated that more information will become available in the coming years that better balance these needs. • Research and development in the field of not-in-kind technologies is contributing to a refrigerant-free environment. Innovative technologies for ultra-low temperature refrigeration are enabling new applications including vaccine storage. • Today, fire protection in all forms is an important enabler of a resilient infrastructure. This contributes to a well-functioning society and contributes to economic growth, promoting sustainable industrialization and fostering innovation.
10	*Reduced inequalities.* **Reduce inequality within and among countries**	• Implementation of projects funded by Montreal Protocol via Multilateral Fund have enabled enterprises in developing countries to get updated technologies using zero ODS and low GWP. These projects enable enterprises of A5 parties to get updated in terms of technology, be more competitive to supply locally and also to export, which is a way to reduce inequality among countries. • In 2020[47], less than 3% of almost three billion people living in the hottest parts of the world own an air conditioner. Advancement in technology and manufacturing processes can make cooling affordable to a larger percentage of people in the low-income bracket without compromising the efficiency of the units or the quality of performance.

[47] Share of population living in a hot climate and air conditioner ownership by selected region, 2020 – Charts – Data & Statistics - IEA

11	**Make cities and human settlements inclusive, safe, resilient and sustainable**	• Cities around the world located in high temperature regions need RACHP to function and develop properly. Efficient RACHP equipment mitigates high pollution associated with coal-fired power stations through reduced energy consumption and requirements. • Food and jobs are required for 80 million new people every year due to population growth. The population growth drives an increase in demand for food, housing, energy, and the associated waste products. Food security in cities is critical and relies on a functioning cold chain. Newly installed refrigerant-based products that support this demand provide improved energy efficiency, food storage efficiency and productivity. • Today, fire protection in all forms is an important enabler of a resilient infrastructure including where flammable refrigerants are being used as part of the HFC phase-down. This contributes to a well-functioning society and contributes to economic growth.
12	**Ensure sustainable consumption and production patterns**	• Food waste and spoilage of perishable products in general has been substantially reduced, particularly in tropical developing countries. • Phase-out of MB has promoted the use of non-chemical alternatives, such as the use of solar energy to kill soil borne pests and adoption of resistant varieties and rootstocks. Use of alternatives has also meant less added bromine ion resulting from MB treatment in stored products. • The use of information and data sharing through the internet and increasingly through AI, are being used to understand food supply issues and constraints and can lead to more efficient use of food (i.e., reduce current levels of food loss). Fire suppression systems in server farms and internet infrastructure support maintaining these capabilities, particularly during times of disaster. • Sustainable management systems, rationalizing production, avoiding unnecessary emissions, and creating recycling banks where possible, have provided a way to use some environmentally damaging but essential chemicals. Halon 1301 - a potent ODS and GHG - which is critical to fire protection, particularly in civil aviation, is a good example of this. By carefully managing stockpiles and minimising emissions, fresh production of Halon 1301 has been avoided for 20 years. • Food waste occurs in early levels of the food supply chain. It is estimated that about 30% of all food produced globally is lost or goes to waste (FAO 2012). The importance of functioning cold chains has been further highlighted in the context of the COVID-19 pandemic. A functioning cold chain is essential for the distribution of most COVID-19 vaccines. Food and vaccine loss are reduced through proper access to refrigeration and cold chains.
13	**Take urgent action to combat climate change and its impacts**	• The MP has had a major impact on mitigating climate change. By phasing out CFCs, Halons, HCFCs, and now phasing down HFCs – gases with very high GWP, about 135 billion tonnes of CO2 equivalent emissions were averted between 1990 and 2010. Without the Protocol, ODS would have increased exponentially in the atmosphere, and the Earth could have experienced a temperature increase of up to 4 degrees. • This whole process has stimulated technological developments including improved foam insulation and energy efficiency of RACHP equipment, with benefits for mitigating climate change. • With the Kigali Amendment, the phase down of HFCs is taking place along with improvements in energy efficiency, which is expected to particularly benefit A5 parties. • Buildings account for 17.5% of the global energy-related emissions from the generation of electricity used to run RACHP systems among others. RACHP accounts for 7.8% of global greenhouse gas emissions, of which 37% are due to direct emissions (leakage) of fluorocarbons (CFCs, HCFCs and HFCs) used as refrigerants, and 63% to the production of electrical energy required to operate the installations. Energy efficient products and use of ultralow-GWP refrigerants in the systems will further reduce the direct impact on global warming. The use of renewable energy (e.g., solar, wind, hydro, and geothermal) will reduce the indirect emissions. Heat pumps will also play an important role in replacing fossil fuels for heating purposes both residentially and in industry. • The use of information and data sharing through the internet and increasingly through AI, are being used to report on refrigerant leakage, EE loss, etc. Fire suppression systems in server farms and internet infrastructure support maintaining these capabilities, particularly during times of disaster.

14, 15	**Conserve and sustainably use the oceans, seas and marine resources for sustainable development;** **Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and biodiversity loss**	• Catastrophic effects of excessive UV-radiation on land and marine ecosystems, which results from ozone layer depletion, have been averted because of the Montreal Protocol. Elimination of all ODS has reduced the effect of UVB on all living marine and terrestrial organisms. • Marine organisms like phytoplankton, fish larvae and small fish are very sensitive to UV rays and are the basis of economies in many countries and the sectors that depend on the oceans' resources. Phytoplankton is the essential element and basis of sea ecosystems. • MB phase-out has a positive effect on preserving biodiversity as its toxicity to soil organisms is extremely high • The use of information and data sharing through the internet and increasingly through AI, are being used to enhance capabilities to conserve and sustainably use the oceans, seas and marine resources for sustainable development Fire suppression systems in server farms and internet infrastructure support maintaining these capabilities, particularly during times of disaster.
16	*Peace, justice and strong institutions.* **Promote peace and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels**	• The Montreal Protocol sets a strong example of collaborative consensus decision-making for the benefit of all countries. It is also the only universally ratified UN environment protocol. By protecting the ozone layer and reducing climate change it has enabled hot developing countries to maintain healthier populations through enhanced accessibility of refrigeration and air-conditioning, sustainable agriculture, safe air travel, reliable and resilient IT innfrastructure and many other stabilising impacts.
17	*Partnerships for the goals.* **Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development**	• The Protocol is a great example of how engaging relevant stakeholders can lead to effective actions both globally and locally. • The MLF provides financial support for developing (A5) parties to comply with the control measures of the Montreal Protocol. Partnering with the Global Environment Facility (GEF) has been critical for funding countries with economies in transition, which were not eligible for MLF funding. The funding support through MLF and GEF has assisted countries worldwide in converting to more environmentally friendly technologies. • In some regions, MB phase-out has led to adoption of alternatives that have facilitated and promoted trade and partnership between countries in many areas such as research, training, academic exchange, etc.

5 TEAP ORGANISATIONAL MATTERS

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.

TEAP is successfully implementing the TOR including: a review of membership and reappointment process throughout all the TOCS; developed guidelines for nominations to the TOCs; developed standardised disclosure of interest/conflict of interest online forms and guidance; standardised the practice of reviewing TOR requirements with members at the opening of each TEAP, TOC and TSB meetings.

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.

TEAP and its TOCs continue to review membership and work to identify the needed expertise to meet current and new demands relevant to decisions, including HFC phase-down with the implementation of the Kigali Amendment. TEAP continues its efforts in achieving A5 and non-A5 balance, considering geographical and gender balance.. TEAP looks to the continuing support of parties to identify the needed experts based on its matrix of needed expertise and to ensure that those experts are able to fully participate in the activities and work of the TEAP and its TOCs for parties.

During the COVID pandemic TEAP and TOC activities continued through virtual meetings, with all reports published on time. Since 2018 TEAP has prepared and published 33 reports responding to ongoing as well as new decisions from parties (see Table 6.1). However, the lack of face-to-face meetings may have some longer-term impacts on TEAP/TOC activities, and especially to its consensus-based process in preparing its reports. In the future TEAP/TOCs will likely function in part through a greater number of on-line meetings, which will necessarily be shorter to enable participation by members in different time-zones. However, we envisage that face to face or hybrid meetings will remain an essential part of TEAP/TOC function and consensus.

The challenge for TEAP and for the parties, is both to maintain the needed expertise and to recruit new volunteers with needed technical expertise, ability to work independently, confidentially, and to reach consensus, and the necessary time, energy, and ability to write clearly. Some TOCs have experienced attrition, through the retirement of members or the lack of support for their participation, with increasing loss of expertise. Some members have been unable to travel to face-to-face meetings for diverse administrative reasons, including COVID controls, and longer timelines with visas.

Some non-A5 experts find it increasingly difficult to obtain funding support for travel from their organisations and/or parties. Companies that previously supported non-A5 meeting attendance have transitioned to using virtual meetings to conduct their business and find it increasingly difficult to justify travel to TOC meetings.

TEAP and its TOCs are making efforts to recruit active new members to meet gaps in expertise with some success. Several new members have been identified through their work on task forces. This has enabled the new experts to familiarise themselves with the process, and allows TEAP to consider their capability and suitability for TEAP/TOC membership.

5.1. TEAP Reports 2019-2022

In the 4 years since its 2018 Assessment Report, TEAP has prepared 33 reports in response to ongoing as well as new requests in Decisions issued by the parties to the Montreal Protocol.

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

Table 5.1 below provides a full list of reports prepared by TEAP since 2018.

Table 5.1 Technology and Economic Assessment Panel reports produced in response to parties' requests during the period 2019–2022

Year	*Issue*	*Request by parties to TEAP*	*Reports produced addressing decisions*
	Progress update		
2019	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 **Decision XI/17** – Report on any important new developments	TEAP May 2019 progress report
	Thematic		
2019	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 2019 interim report September 2019 final report
2019	Energy Efficiency	**Decision XXX/5**– task force report on cost and availability of low-GWP technologies/equipment that maintain/enhance energy efficiency	May 2019 Task Force report September 2019 Task Force report
2019	Unexpected CFC-11 emissions	**Decision XXX/3** – TEAP task force report on unexpected emissions of trichlorofluoromethane (CFC-11) Final report	May 2019 Task Force Report September 2019 Task Force report
2019	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
2019	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
2019	Laboratory and analytical uses of controlled substances	**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
2019	Laboratory and analytical uses of controlled substances	**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
2019	n-Propyl Bromide	**Decision XIII/7** – Report on use and emissions of n-propyl bromide	Considered. No new information available, no report prepared
2019	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		
2019	Quadrennial assessment	**Decision XXVII/6** – Prepare and present the assessment panels' synthesis report	TEAP 2018 Assessment Report (submitted in 2019) 2018 Synthesis report of the 3 Panels*.
		Number of reports produced in 2019:	9

* The three Panels of the Montreal Protocol – EEAP, SAP and TEAP prepared their joint 2018 Synthesis Report (submitted in 2019)

Year	*Issue*	*Request by parties to TEAP*	*Reports produced addressing decisions*
	Progress update		
2020	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 **Decision XI/17** – Report on any important new developments	May 2020 progress report
	Thematic		
	Critical-use nominatio	**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)	2020 interim report 2020 final 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 report to the parties when appropriate	Considered. No new information available, no report prepared
	Laboratory and analytical uses of controlled substances	**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
	Energy Efficiency	**Decision XXXI/7** – Continued provision of information on energy-efficient and low-global-warming-potential technologies	September 2020 Task Force 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		
	Replenishment	Decision XXXI/1 -Assessment of the funding requirement for the replenishment of the Multilateral Fund for the period 2021-2023	May 2020 Task Force report October 2020 Task Force Responses to Comments and Questions Submitted by the Parties
		Number of reports produced in 2020:	6

Year	*Issue*	*Request by parties to TEAP*	*Reports produced addressing decisions*
	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 **Decision XI/17** – Report on any important new developments	September 2021 progress report and addendum (RTOC Report – Vaccines cold chain subcommittee)
	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)	June 2021 interim report September 2021 final report
	Unexpected emissions of CFC-11	**Decision XXXI/3** – Unexpected emissions of tricholofluoromethane (CFC-11)	June 2021 Task Force report
	Energy efficiency	**Decision XXXI/7** – Continued provision of information on energy-efficient and low-global-warming-potential technologies	June 2021 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	September 2021 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 report to the parties when appropriate	Considered. No new information available, no report prepared
2021	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	September 2021 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
	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 2021–2023	Decision XXXI/1 – Prepare a report on the appropriate level of the 2021–2023 replenishment of the Multilateral Fund	September 2021 Replenishment Task Force report (2021–2023)
		Number of reports produced in 2021:	8

Year	*Issue*	*Request by parties to TEAP*	*Reports produced addressing decisions*
	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 **Decision XI/17** – Report on any important new developments	May 2022 progress report
	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 2022 interim report September 2022 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, considering parties' submissions, and recommend any reductions to the make-up and maximum emissions	May 2022 progress report
	Energy Efficiency	**Decision XXXIII/5** – Continued provision of information on energy-efficient and low-global-warming potential technologies	May 2022 Task Force report
	Alternatives to HFCs	**Decision XXVIII/2** – Information on alternatives to HFCs	September 2022 Working Group report
2022	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 **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 **Decision XXVI/5** – Report on the development and availability of laboratory and analytical procedures that can be performed without using controlled substances	May 2022 progress report
	n-Propyl Bromide	**Decision XIII/7** – Report on use and emissions of n-propyl bromide	May 2022 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 XXXI/2** – Prepare the TEAP 2022 quadrennial assessment	TEAP and TOCs 2022 quadrennial assessment reports (5)
		Number of reports produced in 2022:	10

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.

ANNEX 1. TEAP AND TOC MEMBERSHIP INFORMATION

TEAP and TOC Membership Lists - Status on 31 December 2022

The following lists include members who participated in the preparation of the 2022 TEAP quadrennial assessment.

Table 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**
Suely Carvalho	Independent Expert	Brazil
Marco Gonzalez	Independent Expert	Costa Rica
Rajendra Shende*	Terre Policy Centre	India
Ray Gluckman	Gluckman Consulting	UK
Shiqiu Zhang	College of Environmental Sciences and Engineering, Peking University	China
TOC Chairs	**Affiliation**	**Country**
Omar Abdelaziz	The American University in Cairo	Egypt
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	Consultant to AGC Inc	Japan
Ian Porter	La Trobe University	Australia
Helen Tope	Planet Futures	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, 2022

Table 2. FTOC – Flexible and Rigid Foams Technical Options Committee at 31st December 2022

Co-chairs	Affiliation	Country	Appointed through
Helen Walter-Terrinoni	The Air Conditioning, Heating and Refrigeration Institute	US	2025
Paulo Altoé	Independent Expert	Brazil	2024

Members	Affiliation	Country	Appointed through
Paul Ashford	Anthesis	UK	2023
Kultida Charoensawad	Covestro	Thailand	2024
Roy Chowdhury	Foam Supplies	Australia	2025
Joseph Costa	Arkema	US	2026
Gwyn Davis	Kingspan	UK	2024
Gabrielle Dreyfus	Climate Works	US	2025
Rick Duncan	Spray Polyurethane Association	US	2023
Ilhan Karaağaç	Kingspan	Turkey	2024
Shpresa Kotaji	Huntsman	Belgium	2023
Simon Lee	Independent Expert	US	2023
Yehia Lotfi	Technocom	Egypt	2024
Smita Mohanty	CIPET : School for Advanced Research in Polymers	India	2024
Miguel Quintero	Independent Expert	Colombia	2025
Sascha Rulhoff	Haltermann	Germany	2026
Enshan Sheng	Huntsman	China	2026
Koichi Wada	Japan Urethane Industry Institute	Japan	2024
Dave Williams	Honeywell	US	2023
Ernest Wysong	Natural Polymers	US	2024

Table 3. HTOC - Halons Technical Options Committee at 31st December 2022 (Now FSTOC)

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**
Mohammed Jane Alam	Jahanabad Trading	Bangladesh
Jamal Alfuzaie	Independent Expert	Kuwait
Johan Åqvist	FMV (Swedish Defence Materiel Administration)	Sweden
Youri Auroque	European Aviation Safety Agency	France
Michelle M. Collins	Consultant – EECO International	USA
Khaled Effat A. Mohamed	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
Dr. R.P. Singh	Institute of Defence Scientists and Technologists	India
Donald Thomson	MOPIA	Canada
Mitsuru Yagi	Nohmi Bosai Ltd & Fire and Environment Prot. Network	Japan

Consulting Experts	Affiliation	Country
Clare Bowens	The Gas Xchange	UK
Sidney de Brito	Embraer	Brazil
Carl Chappell	Hilcorp	USA
Thomas Cortina	Halon Alternatives Research Corporation	USA
Joshua Fritsch	US Army Ground Vehicles Systems Center	
Matsuo Ishiyama	Nohmi Bosai Ltd & Fire and Environment Prot. Network	Japan
Nikolai Kopylov	All Russian Research Institute for Fire Protection	Russian Federation
Steve McCormick	US Army Ground Vehicles Systems Center	USA
	Huntingdon Ingalls Industries	
John G. Owens	3M Company	USA
John J. O'Sullivan	Bureau Veritas	UK
Mark L. Robin	Chemours	USA
Joseph A. Senecal	FireMetrics LLC	USA

Table 4. MBTOC – Methyl Bromide Technical Options Committee at 31st December 2022

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	EcO_2, Netherlands	Netherlands
Mohamed Besri	Institut Agronomique et Vétérinaire Hassan II	Morocco
Ken Glassey	Senior Advisor Operational Standards Biosecurity, MAF	New Zealand
Alfredo Gonzalez	Independent Expert/ Fumigator	Philippines
Takashi Misumi	MAFF	Japan
Aysze Ozdem	Turkish Ministry of Agriculture	Turkey
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
Tim Widmer	United States Department of Agriculture	USA

Table 5. MCTOC - Medical and Chemicals Technical Options Committee at 31st December 2022

Co-chairs	Affiliation	Country
Kei-ichi Ohnishi	Consultant to AGC Inc.	Japan
Helen Tope	Independent Consultant, Planet Futures	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	Inhaled Delivery Solutions	USA
Bill Auriemma	Diversified CPC International	USA
Olga Blinova	St. Petersburg Pasteur Institute	Russia
Stephanie Bogle	U.S. Environmental Protection Agency	USA
Steve Burns	AstraZeneca	UK
Nick Campbell	Arkema	France
Andrea Casazza	Chiesi Farmaceutici	Italy
Nee Sun (Robert) Choong Kwet Yive	University of Mauritius	Mauritius
Rick Cooke	Man-West Environmental Group Ltd.	Canada
Takeshi Eriguchi	AGC Inc.	Japan
Maureen George	Columbia University School of Nursing	USA
Kathleen Hoffmann	Sotera Health Company	USA
Jianxin Hu	College of Environmental Sciences & Engineering, Peking University	China
Ryan Hulse	Honeywell	USA
Fang Jin	Guangzhou Medical University	China
Rabinder Kaul	SRF Limited	India
Javaid Khan	The Aga Khan University	Pakistan
Andrew Lindley	Independent consultant to Koura and European Fluorocarbon Technical Committee (EFCTC)	UK
Gerald McDonnell	DePuy Synthes, Johnson & Johnson	Ireland
Robert Meyer	Consultant, Greenleaf Health	USA
B. Narsaiah	CSIR-Indian Institute of Chemical Technology (Retired)	India
Timothy J. Noakes	Koura	UK
John G. Owens	3M	USA
Irene Papst	HEAT GmbH, Germany	Austria
Jose Pons Pons	Spray Quimica	Venezuela
John Pritchard	Independent Consultant, Inspiring Strategies	UK
Rabbur Reza	Beximco Pharmaceuticals	Bangladesh
Christian Sekomo	University of Rwanda	Rwanda
David Sherry	Nolan Sherry & Associates Ltd.	UK
Peter Sleigh	Koura	UK

Members	Affiliation	Country
Jørgen Vestbo	Manchester University NHS Foundation Trust and Allergi-og Lungeklinikken, Vanløse	Denmark
Kristine Whorlow	Non-Executive Director	Australia
Alex Wilkinson	East and North Hertfordshire NHS Trust	UK
Gerallt Williams	Aptar Pharma	UK
Ashley Woodcock	Manchester University NHS Foundation Trust	UK
Arzu Yorgancıoğlu	Celal Bayar University Medical Faculty	Turkey
Lifei Zhang	National Research Center for Environmental Analysis and Measurement	China
Consulting Experts	**Affiliation**	**Country**
Hideo Mori	Tokushima Regional Energy	Japan
Yizhong You	Journal of Aerosol Communication	China

Table 6. RTOC – Refrigerants Technical Options Committee at 31st December 2022

Co-chairs	Affiliation	Country
Omar Abdelaziz	American University, Cairo	Egypt
Roberto Peixoto	Maua Institute, IMT, Sao Paulo	Brazil
Fabio Polonara	Università Politecnica delle Marche, Ancona	Italy
Members	**Affiliation**	**Country**
Maria C. Britto Bacellar	Johnson Controls, JCI	Brazil
Jitendra Bhambure	Independent Expert	India
James M. Calm	J. M. Calm Engineering Consultancy	USA
Radim Cermák	Ingersoll Rand	Czech Republic
Guangming Chen	Zhejiang University, Hangzhou	PR China
Daniel Colbourne	Re-phridge Consultancy	UK
Richard De Vos	Independent Expert	USA
Sukumar Devotta	Independent Expert	India
Martin Dieryckx	Daikin Europe N.V,	Belgium
Dennis Dorman	Trane Co.	USA
Bassam Elassaad	Independent Expert	Lebanon
Ray Gluckman	Gluckman Consulting	UK
Dave Godwin	U.S. EPA	USA
Marino Grozdek	University of Zagreb	Croatia
Samir Hamed	Petra Industries	Jordan
Herlianika Herlin	PTAWH	Indonesia
Martien Janssen	Re/genT B.V.	Netherlands
Michael Kauffeld	Karlsruhe University of Applied Sciences	Germany
Mary E. Koban	AHRI	USA
Jürgen Köhler	University of Braunschweig	Germany
Holger König	Ref-tech Consultancy	Germany
Lambert Kuijpers	Agent Consultancy	Netherlands
Richard Lawton	Cambridge Refrigeration Technology CRT	UK
Tingxun Li	Guangzhou San Yat Sen University	PR China

Members	Affiliation	Country
Carloandrea Malvicino	Stellantis (FCA)	Italy
D. Mohan Lal	Anna University, Chennai	India
Mousa Maher	NHM Consultancy	Saudi Arabia
Petter Nekså	SINTEF Energy Research	Norway
Horace Nelson	Independent Expert	Jamaica
Tetsuji Okada	JRAIA	Japan
Alaa M. Olama	Independent Expert	Egypt
Alexander C. Pachai	Johnson Controls, JCI	Denmark
Per Henrik Pedersen	DTI, Consultant	Denmark
Rajan Rajendran	Emerson	USA
Giorgio Rusignuolo	UTC Carrier	USA
Asbjorn Vonsild	Vonsild Consulting	Denmark
Hiroichi Yamaguchi	Toshiba Carrier Co	Japan
Samuel Yana Motta	Oak Ridge national laboratories	Peru
Consulting Experts	**Affiliation**	**Country**
Brian Fiegen	Trane Co.	USA
Kenneth Hickman	Johnson Controls, JCI	USA
Kenneth Hoffman	GEA	England

ANNEX 2. EXECUTIVE SUMMARIES 2022 TOCS ASSESSMENT REPORTS

1 FLEXIBLE AND RIGID FOAMS TOC (FTOC)

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

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

The transition away from ODS foam blowing agents in some regions and market segments (e.g., spray foam and extruded polystyrene) may be delayed because of cost, especially where local codes require higher thermal performance[48]. It should be noted that the price of HFC blowing agents has risen substantively during the pandemic and is nearly as high as hydrofluoroolefin (HFO) and hydrochlorofluoroolefin (HCFO) prices were prior to the pandemic in some A5 parties.

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

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

There have been recent announcements that additional production capacity for HFOs/HCFOs has come on-line. This has eased the supply constraints to some degree; although, there are still reports of continued use of allocation procedures to parse out supply to customers due to inability to fulfil all supply requests.

An additional update on planned supply relative to forecasted demand will be provided in 2023 TEAP Reports as additional information becomes available.

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

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

1.2. Overview of Foam Market

1.2.1. Global Foams Market

Raw material shortages and limited access to production sites during quarantine periods reduced manufacturing supplies and demand during the early years of the global pandemic, including raw materials for foam manufacture and foams for the end-uses that incorporate them, such as refrigeration equipment. These markets have also been impacted by severe weather. According to *Fortune Business Insights*, the foam market contracted by 1.7% in 2020.[49] However, some economists note that there are continued supply disruptions and labour-market pressures which, coupled with interest rate increases, may contribute to continued slow recovery or even local or global recessions.[50]

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

According to *Mordor Intelligence*, the extruded polystyrene (XPS) market is projected to grow by over 4% per year from 2022 to 2027, after a significant slowdown in building construction during the pandemic. As construction resumes, increased demand for insulation materials to reduce building heating and cooling load is expected to lead to the growth of insulation markets for XPS, polyurethane (PU) and other insulation in the coming years. Polymer insulation growth is expected to increase at the fastest pace in the residential market due to population growth (new homes) and increased focused on better insulation in existing homes. Growth in the Asia-Pacific region is expected to dominate the market.[52]

1.2.2. Major Issues Influencing the Global Foams Market

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

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

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

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

According to *Global Newswire*, the global cold chain market is expected to grow from a value of approximately $245 billion in 2021 to $800 billion in 2030, with[53] a growth rate of over 14%. There is increasing demand from the retail sector to mitigate food waste and degradation. Asia Pacific is expected to grow at the fastest rate due to the presence of major food and healthcare providers. For example, China's cold chain industry has been growing at a remarkable 19% since 2014.

Extruded Polystyrene (XPS) is typically used for its low-moisture permeability and high-compression strength in applications including refrigerated transport, perimeter insulation and cold stores. Polyurethane, polyisocyanurate[54], and phenolic rigid foam are not used as

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

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

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

[52] It should be noted that it has been estimated by F-TOC members that XPS foam manufacturing capacities in North America and Europe are currently close to capacity to meet current market demand.

[53] Global Newswire , Cold Chain Logistics Market Size to Worth Around USD 801.26 Bn by 2030, as viewed September 4, 2022.

[54] For simplicity, any reference to rigid polyurethane foam in this report is understood to include foams referred to as polyisocyanurate foams. These foams have similar

widely as other thermal insulation materials (i.e., mineral wool or fibreglass) in building insulation due to relatively high cost. However, the low thermal conductivity of all three types of foam at wide operating temperatures dominates the insulation demand from the cold chain and district cooling and heating systems, including internal building services usage.

In Europe, the volume of XPS foam insulation is generally increasing at a rate corresponding to gross domestic product (GDP) growth with variation in individual countries. There is increased demand for thick (>200mm) XPS panels to meet specific construction requirements[55].

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

chemistries and use similar starting materials. Most foams sold a polyisocyanurate are usually mixture of polyurethane and polyisocyanurate polymers.

55 Thicker XPS is used decoratively and for roofs where they can be cut around protruding features. Thicker foams also do not allow for moisture intrusion between layers which reduces thermal performance and provide more weight for ballast to prevent wind uplift and may have implications for building structure.

Multiple layer XPS foam manufacturing techniques usually require the use of bonding chemicals which may increase thermal conductivity or water transfer. Additionally, those

2 FIRE SUPPRESSION TECHNICAL OPTIONS COMMITTEE (FSTOC)

2.1. Renaming of the Halons Technical Options Committee as the Fire Suppression Technical Options Committee

The Halons Technical Options Committee (HTOC) role has broadened over the years. Its initial focus was solely on halons and their alternatives. Over time, the HTOC also focused on hydrochlorofluorocarbon (HCFC) agents and their alternatives and more recently on hydrofluorocarbons (HFCs) and their alternatives. As a result, the expertise of the HTOC was much wider than just considering alternatives to halons.

Another aspect of this broader role is that of safety aspects beyond general agent toxicity and fire protection systems, both in terms of the high pressures of fire protections system cylinders and the increasing use of flammable refrigerants, as HFCs are phased down in the refrigeration, air-conditioning, and heat pump sector, as outlined in section 2.3.

In the light of this, in November 2022, the parties to the Montreal Protocol adopted Decision XXXIV/11, which inter alia, renamed the Halons Technical Options Committee as the Fire Suppression Technical Options Committee (FSTOC). This change was welcomed by the committee.

For this report, all references to the committee's current and past work, actions, and opinions are referred to as the FSTOC. All references to the previous reports are referred to as the HTOC.

2.2. Alternate Refrigerants and their Potential Flammability

The FSTOC continues to express concern with expanded use of alternative refrigerants owing to their potential flammability and yet-to-be-determined effects on firefighting systems (e.g., agent effectiveness, by-products generated, etc.). In addition to industry standard tests for measuring flame propagation (e.g., the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 34 and the International Organization for Standardization (ISO) Standard 817), new methods are being developed to address these concerns. These issues are of particular concern to the military sector or other applications that may be subject to extreme environments.

2.3. Impact of Existing and Possible Future Regulations on the Fire Protection Sector

HFC phase-down regulations in non-A5 parties are having a bigger impact on the cost and availability of HFC fire suppressants than initially anticipated by the FSTOC. It is the FSTOC's experience that HFCs contained in fire protection equipment have historically enjoyed a relatively high level of recycling and reuse. As the supply of newly produced HFCs for fire protection decreases in response to phase-down regulations, recycling becomes even more important as an alternative source of supply and is likely to increase in the future.

Commercially used fire suppression agents such as HFCs, fluoroketone (FK)-5-1-12, and 3,3,3 trifluoro-2-bromo-propene (2-BTP) are now classified as perfluoroalkyl and polyfluoroalkyl substances (PFAS) under the Organization for Economic Cooperation and Development (OECD) and European Union (EU) definitions. Five European countries are preparing a proposal for a Registration, Evaluation, Authorization and restriction of CHemicals (REACH) restriction that could prohibit the manufacture, import, sale and use of PFAS and products containing PFAS at some future date. Restricting or prohibiting the sale or use of these agents could have significant impacts on the ability of users to effectively protect a range of hazards from fire and explosion.

On December 20, 2022, 3M Corporation announced that it will cease manufacture of all PFAS by the end of 2025, **3M (2022**). This includes the fire suppressant FK 5-1-12. The FSTOC will continue to monitor this situation.

chemicals are likely to make the recycling process of XPS either much more complicated or impossible which is economically undesirable. There are very few manufacturers that can produce this as a monolithic board, leading to the use of multiple layers, which has some disadvantages, or the need by producers to invest in new thermal bonding technology.

The misapplication of the Basel Convention continues to provide a significant challenge in relation to accessing facilities capable of reclaiming or destroying Ozone Depleting Substances (ODS) and HFCs from an international movement perspective, especially for countries without reclamation facilities.

In the 2018 Assessment report, the FSTOC was of the opinion that the initial 10% reduction in HFC production would not have a significant impact on the fire protection sector. In contrast, for example, what we have seen in the United States of America (US) is that there has already been significant impact on the cost of HFCs. The FSTOC believes this is for the following reasons:

- HFCs used for fire extinguishing are high-GWP,
- the allocation mechanism in the US is GWP-weighted,
- market factors mean that producers and importers have to decide which HFCs to manufacture or import, based on their GWP and future market needs.

The combined effect of these factors means that the HFC phase-down in the US is having a large effect on the production and consumption of HFC fire extinguishants. The US HFC phase-down began on January 1, 2022, and it has already had a significant impact on the pricing of HFCs for fire protection.

In the EU, the European F gas Regulation has a much greater level of quota reduction and for the period 2021-2023, the reduction is 55% of the 2015 baseline. A 2020 report by the European Environment Agency (EEA) estimates the total supply of newly-produced HFCs (production and consumption) for fire protection in the EU has decreased by over 90% since the phase-down began in 2015, **EEA (2020)**. It appears that the use of HFCs in the EU has been replaced in part by FK 5 1-12 and inert gases.

In Japan, the use of HFCs for fire protection has been gradually decreasing in response to adoption of the Kigali Amendment and other efforts to prevent global warming. The amount of HFCs newly installed for fire protection in 2021 in Japan is about 30% of the most installed year, 2012.

The FSTOC anticipates additional impacts to the fire protection sector as the Kigali amendment phase-down continues and begins to impact additional regions and parties. This could reduce commercial viability of production of some HFC fire extinguishing agents in the future. This has implications for HFC banking to support enduring uses.

2.4.Alternatives to Halons, HCFCs, and HFCs

A new agent, Halocarbon Blend 55 (A50/50 weight% blend of FK-5-1-12 and hydrochlorofluoro-olefin (HCFO)-1233zd(E)), was added to the US Environmental Protection Agency (EPA) Significant New Alternatives Policy (SNAP) list. It was adopted into National Fire Protection Association (NFPA) 2001, **NFPA (2022)** as “HB-55,” and in the International Standard ISO 14520-17, **ISO (2022)** designated as “Halocarbon Blend 55.”

As a result of the HFC phase-down, the market share of both inert gas (IG) and FK systems is growing at the expense of HFC systems in total flooding fire extinguishing systems.

For portable extinguishers, no new agents have been developed to commercialization since 2018. There are still two in-kind alternatives to halons, HCFCs, and HFCs, namely FK-5-1-12, and 2 BTP. In some circumstances carbon dioxide (CO_2) can be used.

In the US only, 2-BTP is currently approved for use by the US EPA only in handheld extinguishers, and engine nacelle and APUs on aircraft, **EPA (2016)**. In July 2022, the EPA published a Notice of Proposed Rulemaking (NPRM) which would widen allowable non-residential uses, **EPA (2022)**. There were no adverse comments to the NPRM related to 2-BTP.

On December 20, 2022, 3M corporation announced that it will cease manufacture of all PFAS by the end of 2025, **3M (2022)**. The FSTOC has been informed that this includes the fire suppressant FK-5-1-12. The FSTOC will continue to monitor this situation.

2.5.Enduring Uses of Halons, HCFCs and HFCs

2.5.1.Civil Aviation

Civil aviation emissions of halon 1301 are thought to be a significant part of global emissions. Owing to the COVID-19 Pandemic there was a 60% decrease in civil aviation flight hours in 2020. However, emissions of halon 1301 did not go down at all, suggesting most aviation emissions are not occurring during flight operations. The FSTOC continues to liaise with the International Civil Aviation Organization (ICAO) and other aviation stakeholders to better understand the sources of emissions and identify opportunities to reduce them. As part of this, the Halon Recycling Corporation has produced a best practice guidance document on reducing emissions and ensuring quality during servicing of aviation fire extinguishers, **HRC (2022)**.

The FSTOC has identified several issues affecting the availability and quality of recovered halons from all fire protection sectors, but especially from the civil aviation sector. This has been reported in the last two HTOC progress reports and the situation may be getting worse.

As a response to Decision XXX/7, the run-out date for halon 1301 has been re-evaluated, using the latest estimated size of the halon 1301 bank.

Depending on the modelling scenario, the run-out dates are estimated to be in the range of 2030 to 2049, compared with 2032 to 2054, as detailed in the 2018 Assessment Report.

2.5.2. Military Uses

Many commercially available extinguishing agents have been assessed against the range of unique military fire protection requirements. In summary:

- Alternatives to halons have been adopted in military applications where they have been found to be technically and economically feasible.
- For new designs, there are many instances where the original halon or high-Global Warming Potential (GWP) HFC is the only solution that will meet stringent design requirements associated with military applications and will continue to be for the foreseeable future.
- The military sector does not represent a large enough market segment to influence chemical manufacturers to continue production of required HFCs or investigate new alternatives.
- It is not believed that any new chemicals, beyond that noted in section 1.3 above, will be commercially available for the military to evaluate as viable replacements in the foreseeable future.

2.5.3. Hydrocarbon Production and Transportation Pipeline

Enduring uses of halon 1301 and halon 2402 systems in the hydrocarbon production and transportation pipeline sector are mainly associated with existing facilities with explosion prevention (inerting) and fire protection (suppression) requirements in inhospitable locations with harsh climatic conditions such as the Alaskan North Slope in the US, the North Sea in Europe, Eastern Europe, and the Russian Federation.

- Alternatives to halons and HFC have been adopted where they have been found to be technically and economically feasible.
- There are instances where the original halon or high-GWP HFCs are the only solutions that will meet hazard management requirements and will continue to be so for the foreseeable future.
- This sector does not represent a large enough market segment to influence chemical manufacturers to continue production of required HFCs or to investigate new alternatives.
- It is not believed that any new chemicals, beyond that noted in section 3 above, will be commercially available for evaluation in the foreseeable future.

Therefore, existing facilities will likely remain protected by halon or HFCs resulting in enduring uses of halons, HFC-23 and HFC-227ea throughout the facility lifetime.

2.6. Global Emissions and Banking

There are two independent methods to estimate emissions of halon 1301: 1) the FSTOC model which takes account of the total amount of recorded production, allows for production losses, destruction, and emissions from the bank and 2) emissions estimates derived from atmospheric concentration measurements, in this case measured by the Advanced Global Atmospheric Gases Experiment (AGAGE) network. Historically the agreement between these completely independent methods has been remarkably good for halons 1301 and 1211. However, since 2010, the emissions derived from atmospheric measurements have been consistently higher for halons 1301 and 1211 than those estimated by the FSTOC model.

2.6.1. Halon 1301

The FSTOC halon 1301 model emissions compare well with the annual mean emissions derived from mixing ratios (atmospheric concentrations) from the latest data using the methodology of **Vollmer et al. (2016)** (hereafter referred to Vollmer) until about 1998 where the FSTOC model emissions are generally lower than the mean. FSTOC estimates generally fall within +/-1 sigma uncertainty of the mean except for 2011 – 2012, where the FSTOC model estimates are slightly lower than the -1 sigma value.

Differences are seen during the periods of increasing and decreasing emissions from 1999-2000, 2010-2016 and 2018-2021, instead of the decay pattern expected from emissions from a finite global bank. A potential source could have been from fire protection systems from shipbreaking activities, but that is not anticipated in recent years as recovered halon 1301 has a significant market value and it is reported that halon is currently handled carefully during shipbreaking. Another possible source for these emissions could be from halon 1301 production and use as a feedstock for the pesticide Fipronil and several other chemicals, whose emissions would not be accounted for in the FSTOC model but would be included in the Vollmer estimates. However, the amount of halon 1301 that is from feedstock production and use would need to be at the higher end of the Medical and Chemicals (MC)TOC-estimated emissions of 7.5%. The FSTOC is seeking additional information on halon 1301 feedstock production, use, and emissions to better understand if the higher levels of emissions can be attributed primarily to feedstock use versus from the fire protection bank.

Using mean emission estimates from Vollmer provides a global bank estimate range of 26,250 – 27,500 metric tonnes compared to 35,000 metric tonnes for the FSTOC model. This difference is becoming significant as the amount of halon that is available to support enduring fire protection uses becomes smaller over time. The Vollmer data also provide a much higher mean annual emission rate for 2021 of nearly 5.5% of a 26,500 metric tonne bank. This is more than double the approximately 2.25% composite rate from the FSTOC model and much higher than the 2%+/-1% rate developed by **Verdonik and Robin (2004**). The combination of a potential higher emission rate than generated by the FSTOC model and a smaller bank of halon 1301 could also imply that there is going to be a significant reduction in available halon 1301 to support ongoing needs in civil aviation, oil and gas, militaries, etc., which could result in a much earlier run-out date.

2.6.2. Halon 1211

The FSTOC projected regional distribution of the global bank of halon 1211 shows that at the end of 2022, almost 80% of the estimated 20,500 metric tonnes is equally divided between the North America region and the Western Europe and Australia region with about 20% estimated to remain in A5 parties. The estimate for A5 parties is significantly lower than projected in the 2010 Assessment, which reflects FSTOC concerns with halon 1211 bank management. This trend continues with lower emissions rates expected in the North America region and the Western Europe and Australia region resulting in these regions containing over 90% of the global bank in the next 20 years.

Both the mean and +1 sigma uncertainty emissions from Vollmer are higher than the cumulative production reported to the FSTOC meaning that the bank would be completely exhausted. However, the bank cannot be exhausted as there are still emissions in Northwest Europe being measured and halon 1211 is still widely used on civil aircraft. This suggests that either more halon 1211 has been produced than reported to the FSTOC (and thus more emissions) and/or the emissions are at the lower end of the Vollmer estimates.

2.6.3. Halon 2402

The FSTOC model emission rates as a function of the size of the bank have been updated for this assessment. The current model aligns the emission rates for 2402 with those currently used for halon 1301, with the exception of Japan, which uses the same emission factors as for North America. The FSTOC estimates that the majority of halon 2402 remains in the former Countries with Economies in Transition (CEITs), but also with significant quantities remaining in Europe.

The FSTOC model estimate of emissions is generally higher than the mean estimate of emissions from the updated Vollmer data from about 1980 until 2020 and near or above the +1 sigma uncertainty until 2018. The Vollmer data show increasing emissions from 2016 – 2021, with the FSTOC estimate going below the mean but staying within +/-1 sigma uncertainty. This increase would not be expected from an average emission rate of the bank unless something has changed. It has been reported to the FSTOC that there is a major decommissioning program underway in Vladivostok, Russia that could account for an increase in emissions. As emissions would be expected to be kept to a minimum, but not totally avoidable, the level of increase in emissions suggests that this effort involves a sizeable amount of decommissioning. It is presumed that this recovered halon 2402 will remain in the global bank to support enduring uses of halon 2402.

Vollmer emissions estimates provide a mean bank range of 15,500–- 19,500 metric tonnes. This is compared with the FSTOC model estimate of a remaining bank of 13,000 metric tonnes. It should be noted that the FSTOC model does not include emissions from the reported use of halon 2402 as a process agent which would place the FSTOC model emissions and bank estimate within the range of uncertainty of the estimates using the Vollmer data.

2.6.4. HFCs

Unlike halons, the majority of which were exclusively used for fire protection, HFC-227ea is also used in metered dose inhalers (MDIs) and in foam blowing. Therefore, to estimate the global emissions from fire protection, it was necessary to create a model that can separate the annual emissions into those three categories of use. The model was initially developed in 2018 in coordination with a Medical and Chemicals (MC)TOC co-chair and a Rigid and Flexible Foams (F)TOC co-chair and has been updated in 2022. The model uses best estimates of annual global production capacity of HFC 227ea beginning in 1993 and carried out until 2021.

The annual emission rate from the fire protection bank was updated to be 3% from 2011 – 2021. Emissions from production were updated ranging from 0.1% to 1.25% per the latest MCTOC estimates.

The HFC-227ea model emissions and the emissions derived from atmospheric measurements are in excellent agreement, with the HTOC model results generally between the +/-1 sigma uncertainly in the atmospheric derived estimates.

The model estimates the global fire protection bank of HFC-227ea to be 178,000 metric tonnes. Based on emission estimates from the US and Northwest Europe, the FSTOC estimates that more HFC-227ea is in A5 parties than in non-A5 parties.

There are several known applications of HFC-125 in fire protection including some military uses but these are estimated to be quite small. Since the largest use of HFC-125 is as a blend in several refrigerants, it is not possible to estimate the amount of HFC-125 used in or emitted from fire protection systems using atmospheric measurements alone.

Unlike HFC-227ea and HFC-125, which are purposely produced, HFC-23 is a by-product of HCFC 22 manufacturing.

As a result, it is not possible to estimate the amount of HFC-23 used in fire protection from atmospheric measurements. HFC-23 is typically limited to use in cold temperature applications. Its use is expected to be small compared to HFC-227ea.

As was the case for HFC-227ea and HFC-125, there are other non-fire protection uses of HFC 236fa. However, unlike HFC-227ea, there is little information available on the relative take-up of HFC-236fa in the fire protection market. At this time, there is not sufficient information to estimate HFC-236fa installed quantities or emissions in the fire protection sector.

2.6.5. Global Halon, HCFC, and HFC Banking (Agent Management)

A bank is defined as all agent contained in fire extinguishing cylinders and storage cylinders within any organization, country, or region. Likewise, the 'global bank' is all agent presently contained in fire equipment plus all agent stored at recycling centres, at fire equipment companies, at users' premises, etc., i.e., it is all agent that has been produced but has yet to be emitted or destroyed. The collection, reclamation, storage, and redistribution of fire extinguishing agents is referred to as "Banking". These concepts and terminologies apply to all fire suppression gases including halons, HCFCs, HFCs, and their alternatives.

FSTOC continues to see issues regarding the loss of historical knowledge 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 halon management but not being familiar with the issues surrounding halons, HCFCs, HFCs, and their alternatives use, recycling, and banking. Lack of understanding about long-term needs for halon 1301 has also resulted in halon destruction. FSTOC notes that this lack of experience and historical knowledge is becoming 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 address awareness programmes to re-establish this loss in institutional memory.

2.7. Emission Reduction Strategies and Banking

Avoidable halon and other halogenated gaseous fire extinguishing agent releases account for greater emissions than those needed for fire protection and explosion prevention. Clearly such releases can be minimized.

- Do not use halons in new fire protection applications or new designs of equipment where alternatives exist.
- Take advantage of opportunities to re-evaluate the need for existing halon systems or extinguishers and replace with suitable alternatives where it is technically and economically feasible to do so.
- Do not use HCFCs and high-GWP HFCs in fixed systems unless approved by the facility owner and a full risk analysis has been performed by a fire professional with expertise in their use and specifications, and the agent was deemed the only viable option taking into consideration safety, efficacy, economics, and environmental effects.
- Encourage the application of risk management strategies and good engineering design to take advantage of alternative fire protection schemes.
- Educate and train personnel on system characteristics.
- Manage storage of halon and other halogenated gaseous fire extinguishant reserves and perform routine leak detection.
- Implement national Awareness Campaigns on all environmental concerns (ODS, GWP, Climate Change).
- Develop or adopt Technical Standards and Codes of Conduct.
- Develop databases and implement record keeping on halon, HCFC and HFC installed base quantities, transfers, and emissions.
- Develop halon, HCFC, and HFC fire extinguishing agent management plans including end of useful life considerations.
- Ensure "Responsible Use" of halons and other halogenated gaseous fire extinguishing agents.

2.8. Destruction

The FSTOC maintains the position that destruction should only be employed as the final disposition option when halons, HCFCs, HFCs, and their alternatives are too contaminated and cannot be reclaimed to an acceptable purity.

The world's first pilot halon destruction for carbon offset occurred in February 2021 in the US, using internally sourced halon 1301 for the creation of carbon credits which were traded in the voluntary carbon market. The FSTOC is concerned that destroying halon 1301 for carbon credits could contribute to global shortages / regional imbalances of halon 1301 to support long-term enduring uses.

When local access to reclamation or destruction services is not available, the classification of halons as hazardous waste by some the parties results in applying the Basel Convention, The Control of Transboundary Movements of Hazardous Wastes and their Disposal, which continues to obstruct the international movement of halons. In the future this could also affect other fire extinguishing agents.

The FSTOC is not aware of any new information, such as test data, relating to already approved destruction technologies.

2.9. Alternatives to HFCs

The fire protection industry has worked on developing alternatives to halons, HCFCs, and now HFCs for over four decades as environmental concerns have evolved. Extensive research was conducted initially to identify alternatives to halons, while simultaneously implementing improvements to maintenance, servicing, and storage of halons, user awareness and training, replacement of halon systems where practical, as well as highly improved risk management. The evolution of alternatives has proceeded along the path of selection of chemicals with the most similar characteristics followed by research and development including testing, certification, toxicity and safety analyses, standards development, and commercialization. In that process, several HFCs were developed through to commercialization (note: both the agent and hardware must successfully pass all testing and certifications). Following the commercialization of HFCs, development of further alternatives continues, and other chemicals were developed including FK 5 1 12, 2-BTP, CF3I, and some combinations with inert gases, water mist, or solid particulates. This evolution has been fairly linear, as makes sense, in that the most likely candidates would be the most commercially viable due to the extensive cost of research and development.

For fire protection applications, information where alternatives to HFCs are available are provided for applications in the following subsectors of use: civil aviation; military ground vehicles, naval, and aviation applications; oil and gas, general industrial fire protection, and merchant shipping. For an alternative to be acceptable, it must have passed all six Decision XXVI/9 criteria, 1) it is commercially available, 2) technically proven, 3) environmentally sound, 4) economically viable and cost effective, 5) safe to use, and 6) easy to service, according to FSTOC's interpretation of these criteria. FSTOC notes that some alternatives are actually halon alternatives rather than HFC alternatives. Furthermore, in some sectors or applications, HFCs were not used and there are no alternatives to the halons available, e.g., in aircraft cargo compartments. In these cases, it seems appropriate to state that, currently, alternatives to HFCs are not applicable (N/A).

On December 20, 2022, the 3M corporation announced that it will cease manufacture of all PFAS by the end of 2025, 3M (2022), including the fire suppressant FK-5-1-12. The FSTOC understands that there are other manufacturers of this agent. Clearly, this is an evolving situation, and the FSTOC expects to understand more fully the potential impacts to HFCs and their alternatives in the future.

2.10. References

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3 METHYL BROMIDE TECHNICAL OPTIONS COMMITTEE (MBTOC)

3.1. Concise Summary

Phase-out of controlled, non-exempted (i.e. non-Quarantine and Pre-shipment) uses of methyl bromide (MB) is virtually complete. Parties report that greater than 99.8% of the baseline consumption of 66,428 tonnes for these controlled non-QPS uses has been phased out by 1 Jan 2023. There are only two remaining uses which are still applying for CUNs in 2022 in non- A5 parties for preplant soil fumigation in strawberry nursery industries and one reported use for structural fumigation of houses in A5 countries.. In 2021, reported MB consumption for controlled uses was around 40 tonnes. All other non-exempt uses of MB have been replaced by other processes. A relatively small, but significant amount of stocks may be being used for some other unreported controlled uses of MB, possibly amounting to around 1000 tonnes.

The phasing out of MB under the control measures of the Montreal Protocol (Annex E) has led to over 30% of the present decline in ozone degrading chemical concentration in the atmosphere (i.e. Effective Equivalent Stratospheric Chlorine- EESC). This is the single largest contribution to improvement of the ozone layer from any chemical at this time.

In 2021, 100% of reported MB production was for QPS purposes, and production for controlled uses was zero. Since 2018, no Party has reported production of MB for controlled uses (non-QPS). However, MBTOC notes once again that MB is still offered on the internet for any use, including preplant soil fumigation and treatment of stored products.

Annual consumption of MB for QPS purposes, an exempted use, has remained relatively constant over more than 20 years, at around 10,000 tonnes. Seventeen countries use about 94% of the reported QPS consumption and only 55 of 198 parties report use of MB for QPS. Data also shows that in 2021 A5 Parties accounted for 57% of global MB consumption for QPS purposes (5922 tonnes), down from 67% in 2017; non-A5 Party consumption, at 4,479 tonnes was 43%, up from 31% in 2017. MBTOC reinforces that alternatives are available for most pre-shipment uses and if adopted could result in replacing 30-40% (i.e. 3000-4000 tonnes) of the total QPS MB.

Elimination of emissions from QPS use is the single largest short-term gain that could be made to further reduction of EESC and improvement in the ozone layer. Complete elimination of emissions from QPS use of MB, could result in a further significant (i.e. ~10%) and rapid reduction to the present EESC. This is one of the very few measures available to Parties that would result in this magnitude of rapid reduction. Technical alternatives to both Q and PS purposes are becoming increasing available, with new chemicals such as ethane dinitrile and hydrogen cyanide showing good efficacy against pests. Emissions can also be managed through use of recapture technologies.

3.2. Mandate and report structure

Under Decision XXXI/2 taken at the Thirty-First Meeting of the Parties to the Protocol in 2019, the Parties requested the Assessment Panels to update their 2018 reports in 2022 and submit them to the Secretariat by 31 December 2022 for consideration by the Open-ended Working Group and by the Thirty Fifth Meeting of the Parties to the Montreal Protocol, in 2022.

The MBTOC 2022 Assessment reports on advances since 2018 to replace MB), now exclusively used under Critical Use by both A5 and non-A5 Parties. It also reports on QPS uses, which are presently exempt from controls under the Montreal Protocol. It covers 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 MB production and consumption in both A5 and non-A5 Parties, estimated levels of emissions of MB to the atmosphere, and strategies to reduce those emissions.

3.3. The Methyl Bromide Technical Options Committee (MBTOC)

On December 2022, MBTOC had 16 members; nine (56%) from non-A5 and seven (44%) from A5 parties. These members come from seven A5 and eight non- A5 parties.

3.4. 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 MB 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 MB 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 MB by 1 January 2005 in non-A5 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-A5 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 2022 the number had declined to two applications for approximately 20 tonnes for use in 2023 and 2024.

Use of MB 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. In 2022, only one party requested 20 tonnes of MB under the CUE provisions for use in 2023.

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

Recently, during its 18th meeting, the Chemical Review Committee (CRC) of the Rotterdam Convention held in September 2022 recommended that MB be listed under Annex III of the Rotterdam Convention, which includes pesticides and industrial chemicals that have been banned or severely restricted for health or environmental reasons. If the Conference of the Parties to this convention accepts this recommendation, then MB will be subjected to the Prior Informed Consent procedure enabling its 165 parties to share information and responsibility and take decisions on potential future imports. MBTOC will continue to watch this issue closely and assess its impacts on MB use and availability.

3.5. Production and consumption trends

At the time of writing this report, all Parties had submitted data to the Ozone Secretariat for controlled uses in 2021 except Israel. 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 2021, global *production* for the MB uses controlled under the Protocol was reported at a negative value of -38.66 tonnes, indicating that quantities exported or destroyed exceeded production for that year and that such quantities were taken from stockpiles. Production was thus considered zero compared to the 1991 reported production of 66,430 tonnes. Since 2018, no party has reported production of MB for controlled uses.

Global *consumption* of MB 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. In 2021 reported consumption fell to negative values, implying that quantities exported exceeded consumption for that year. Consumption for controlled uses was around 40 tonnes, for CUNs.

The official aggregate baseline for non-A5 countries was 56,083 tonnes in 1991. In 2005 (the first year of critical use provisions), non-A5 consumption had been reduced to 11,470 tonnes, representing 21% of the baseline. Many A5 parties achieved complete phase-out of MB before their 2015 deadline.

In 2021, reported MB consumption for controlled uses was around 40 tonnes (under the critical use exemption), although stocks substantially higher than this may be used in some sectors in various countries. Total stocks are unknown, as only parties requesting CUNs are required to report them. After nearly 20 years of applications for critical uses, the amount of methyl bromide requested has fallen from 18,700 tonnes for 2005 to 40 tonnes submitted for either 2023 or 2024. Non-A5 parties requested CUEs from 2003 and in 2022 only two – Australia and Canada - remain (over 99% of the controlled baseline has been replaced). Only four A-5 parties requested CUNs since 2014, and currently only South Africa remains with a CUE for 2023.

3.6. 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 40 tonnes of the original 62,000 tonnes of MB used in 1994 by non-A5 and A5 Parties for controlled reportedly remained in 2021, although there are some uses not reported as an unknown level of stocks of methyl bromide are used. MBTOC considers these stocks may be around 1200 tonnes. 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.

3.6.1. Alternatives for soil treatments

The reduction in consumption of MB for soil fumigation has been the major contributor to the overall reduction in global consumption of MB for controlled uses with amounts used in 2022 falling 99.9% from about 57,400 tonnes in 1992 to about 20 tonnes, in non-A5 Parties. Substantial stocks of up to 1200 tonnes, MB may still be used in some A5 countries although presently these are not required to be reported.

MB is presently used in non-A5 countries for strawberry runner production only. Some preplant soil uses, a portion of which was previously considered under the CUN process, are classified as QPS in one country under national legislation outside of the Montreal Protocol (e.g., forest nurseries, strawberry runners). Since 2018, A5 Parties submitted CUNs for strawberry fruit and runners, ginger and tomatoes. In 2022, no CUN was requested for any A5 soil use of MB.

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 disulphide (DMDS) and others) are widely used around the world and have successfully replaced MB. The registration of methyl iodide has just been granted for one party to use in the strawberry runner industry. 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; bio fumigation and organic amendments; solarisation and bio solarisation; trap cropping; hot water; biological control; and microwaves. A combination of treatments within an IPM programme 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 35 t for 2023 use (four CUNs from 3 Parties, two A5 and two non-A5).

This chapter of the 2022 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 runner production in Australia and Canada. In the past, many, strawberry runner industries around the world relied on MB soil fumigation to produce fruit and disease-free strawberry transplants, but most of them have phased-out MB and successfully implemented alternatives.

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

In 2022, only one remaining use for 20 t was submitted as a CUN and granted a CUE for structures by the Republic of South Africa. This CUN is the last sector to nominate from A5 parties after only a small number of nominations received from A5 parties after the scheduled phase-out in 2015. 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 since attributable directly to the application of the Montreal Protocol measures.

In this sector and in those countries where MB has been phased out, mainly phosphine and sulfuryl fluoride have taken its place with phosphine mainly 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 recent registration of ethanedinitrile (EDN) has provided another useful alternative for many products but particularly wood and wooden product exports, which is the largest use of MB for quarantine (est. approx. 4,500 tonnes). The MB phase-out has in general been associated with changes in application technology, logistics and the 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 dependent.

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 MB. 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 programs over the recent decade, 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 MB itself) are under increasing regulation with potential to making their use infeasible in particular situations.

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

Article 2H exempts MB used for QPS treatments. MB 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 (e.g., observing appropriate dosages, avoiding duplicate treatments, ensuring gas-tightness of fumigation chambers). MBTOC continues to identify the for replacing between 30 and 45% of QPS uses with immediately available alternatives and considers that Parties may wish to step up efforts to reduce and replace QPS uses, particularly those for pre-shipment uses.

Pre-shipment uses are against endemic pests, and thus do not have the same need for the same level of pests control as quarantine treatments. This means alternatives are more readily available and that the risk from survival of a pathogen is much less. If also means that the importing country is not as concerned about the risk, otherwise they would set up a bilateral quarantine regulation for official control of the pest. In this case the treatment is no longer a pre-shipment treatment and MB would be allowable under the quarantine exemption.

Since the MBTOC 2018 Assessment Report (MBTOC, 2019), 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. New Zealand has recently revised its policy of requiring recapture for all QPS uses of MB and has approved EDN, a fumigant with excellent potential to replace a MB used to treat logs.

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. Replacing MB for quarantine treatments can be complex, as often it has long been a proven, well recognized, cost effective and readily available treatment. Many non-MB treatments are, however, published in countries quarantine regulations, and research results are encouraging users to accept and adopt alternative QPS treatments.

Since the 2018 Assessment report acceptance under domestic quarantine (biosecurity) protocols, bilateral arrangements and IPPC regulations of a number of technical alternatives as effective as MB for specific commodities has increased. These include irradiation, cold and heat treatments, modified atmospheres, phosphine, systems approaches, SF, EDN and ethyl formate.

Global production of MB reported for QPS purposes in 2021 was 10,143 tonnes, a similar amount to the level used over the previous 4 years. Although there is some variation in reported QPS production and consumption on a year-to-year basis, there is no obvious long term increase or decrease.

Production of MB for QPS was only reported by five parties in 2021: 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 and by 2021 over 250 times greater.

In the period between 2015 and 2021, 55 parties reported consumption of MB for QPS purposes, however 17 of these parties account for over 90% of the global reported QPS consumption. The remaining 38 countries report consumption below 50 tonnes, often much lower amounts and often not every year. MB users for QPS can be classified in four groups as follows: Big consumers with a reduction trend (Japan and China); medium consumers with an increasing trend (Australia, Egypt, India, México, New Zealand, Vietnam); small consumers on a downward trend (Brazil, Chile, Indonesia and Thailand); And small consumers with a stable or slightly upward trend (El Salvador, Malaysia, Korea).

Research programs globally are continuing to find alternatives to replace MB. The successful application of these alternatives for QPS uses would accelerate the decline in stratospheric MB levels with a near-term impact on the stratospheric ozone layer recovery. MBTOC considers Q and PS to have different priority for use of MB with PS uses having greater potential for adoption of alternatives.

In 2021, global consumption was reported at 10,401 tonnes, with A5 Parties accounted for 57% (down from 67% in 2017) and non-A5 Party consumption to 43%, (up from 31% in 2017). Nevertheless, global QPS consumption remains relatively stable around 10,000 t.

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 (including both A5 and non-A5 parties accounted for 48% of global QPS consumption, down from 55% in 2017; Australia and New Zealand for 15% North America (US + Canada) increased from 26% in 2017 to 37.5% in 2021.

While there remain some data gaps and uncertainties, information supplied by the Parties in 2018 and 2022 allowed MBTOC to estimate that five uses consumed more than 80% of the MB used for QPS in 2021: 1) Logs; 2) Pre-plant soils use; 3) Sawn timber and wood packaging material (ISPM-15); 4) Grains and similar foodstuffs; and 5) Fresh fruit and vegetables. These are the same categories as in 2018, but proportions have changed. On the basis of these estimates and currently available technologies to replace MB for QPS, MBTOC has estimated that between 30 and 45% of the MB used for QPS purposes could be replaced with immediately available alternatives.

Ethane dinitrile has recently been registered as an MB alternative for export logs in New Zealand and can potentially reduce MB use substantially. Sulfuryl fluoride, a common timber and structural fumigant for termites is also effective, however, environmental issues (very high GWP) and the difficulty with efficacy against insect eggs cannot be overlooked.

For pre-plant soil quarantine treatments of various types of nursery materials, alternative fumigants are available, which can 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.

In the absence of regulatory or economic incentives to adopt alternatives, MB 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 or more economic market cost.

With the aid of the Ozone Secretariat, MBTOC has taken steps to reactivate the Memorandum of Understanding (MOU) between the Ozone Secretariat and the International Plant Protection Convention (IPPC), which was drawn in 2012. The IPPC has now approved and published 26 international approved non-MB treatments in recent years for use on a combination of fresh produce, wood or pest specific treatments through the work of the TPPT.

MBTOC keeps track of efforts made by IPPC and its subsidiary bodies to replace MB use for quarantine purposes as far as possible without losing the high degree of control in the various fields of application.

3.8. Emissions from methyl bromide use and their reduction

The large reduction (99%) in the reported consumption of MB (MB) since 1999 for controlled non-QPS uses has resulted in a significant decline in atmospheric emissions of MB. Since the peak in emissions of MB of around 50,000 tonnes in 1998, anthropogenic emissions of MB have declined by approximately 71% with stratospheric MB concentrations as measured in the southern hemisphere falling from a peak of 8.5 ppt to present 2021 levels of around 6.0 ppt. The reduced consumption and the related emissions of MB to date, has been responsible for the present fall of approximately 30% in Effective Equivalent Stratospheric Chlorine (EESC), thus contributing to a similar gain to the present recovery of the ozone layer. Annual (2021) emissions from remaining uses are c. 8505 t MB, being about 8455 t from QPS uses and 73 tonnes from CUEs with minor amounts, probably less than 100 t, from the 4,000 t used for feedstock. There is a potential further gain of 10% to the present ozone layer recovery if these emissions were to be eliminated.

MB emissions to the atmosphere from known usage of MB have remained relatively stable since the last Assessment in 2017. MBTOC estimates that a large proportion of the MB used for QPS applications is emitted (83% on average, with wide variation between different applications) and this is released directly to the atmosphere. The remainder of applied MB is converted to non-volatile reaction products and retained in the treated materials and associated packing and structures.

The reduction of emissions of MB to the atmosphere to date has been due mostly to adherence in most cases to phase-out schedules under the Montreal Protocol under Annex E for non A5 Parties by 2005 and A5 parties by 2015, and almost complete reductions for MB use presently being requested under the Critical Use exemption process.

There has been an unexplained rise in MB mole fraction in the atmosphere to 6.0 ppt in mid-2020, one of three small fluctuations observed since 1998. These small fluctuations do not correspond fully with variation in the reported annual global MB production and consumption and the resultant emissions. Some studies report that the unexplained part of the gap in the top down to bottom up estimate of emissions may be due to climate impacts and La Nina events, others suggesting that production and consumption not be being fully reported or sources fully known from some regions globally. A recent review of the global budget of sources and sinks of MB (both natural and anthropogenic) concluded that the fact that the budget gap declined during phase-out as anthropogenic emissions decline, suggests that at least part of the gap results from underestimation of past anthropogenic emissions.

As nearly all uses of MB for fumigation are now nearly all from QPS uses there is opportunity on a technical basis, to control the remaining emissions of MB from fumigations either by adopting recapture/destruction technologies for current QPS structural and commodity fumigations or by adopting non-ODS alternatives. MBTOC estimates that in 2021, 7955 tonnes of MB were emitted from QPS commodity treatments, with about 4296 t available in practice for recapture/destruction. The balance of applied MB that is unavailable for recapture is either lost through reaction to non-ODS degradation products (c.15%) or inadvertently leaked to the atmosphere during and after the fumigation treatment.

Emissions of MB from remaining CUE and QPS soil treatments are considered to be around 500 t. However, these treatments are not suitable to recapture/destruction technologies. MBTOC considers that barrier films are the best way to reduce emissions and should be mandatory. MBTOC also notes that emissions from these applications could be avoided by adoption of alternative non-MB treatments.

MBTOC notes that a number of Decisions urge Parties to minimise emissions of MB and to use MB recovery and recycling technology where technically or economically feasible for QPS treatments until alternatives to MB are available e.g. (Decisions VII/5, XI/13). Some countries and local jurisdictions have regulations in place, or proposed, to minimise MB emissions from fumigation operations through use of recapture and/or destruction technologies, but these have mainly been issued in relation to local air quality, not ozone layer protection.

A variety of recapture/destruction systems for space fumigations (commodity and structures) are available commercially or at an advanced stage of development. In 2021, total recapture of MB from fumigations is considered to unlikely to have exceeded 100 t annually. MBTOC notes that quantities of MB recaptured or destroyed are not routinely reportable unless by an Approved Destruction Process.

Reduction in emissions 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 (0.7 years), adoption of any suitable alternatives and in some cases adoption of recapture/destruction would have an immediate benefit in reducing atmospheric MB levels. It is an important opportunity available to Parties to rapidly enhance ozone layer recovery, with effects of reducing emissions from QPS observable in the stratosphere within 2 years.

3.9. Economic issues

No CUN has to date relied solely on an argument of economic infeasibility to argue for an exemption. Nevertheless, MBTOC analyses any arguments and calculations about the economics of the use of MB alternatives put forward by a Party because it is always possible that MBTOC may recommend against an exemption on technical grounds but find that economic factors mitigate against the use of alternatives. This is in addition to the conventional notion that the use of an alternative to MB may be technically feasible, but that it may turn out to be economically infeasible.

As noted in previous Assessment Reports, it is sufficient in most cases to use **partial budgets** to assess economic feasibility.

4 MEDICAL AND CHEMICAL TECHNICAL OPTIONS COMMITTEE (MCTOC)

4.1. Executive Summary

4.1.1. Production, including Feedstocks

This chapter describes the production of controlled substances, including for feedstock uses, and a range of related issues, including by-production, production intermediates, estimated emissions for production, distribution and use of feedstocks, stocks, illegal trade, patents, regulatory issues, precursor substances to per- and polyfluoroalkyl substances (PFAS) and trifluoroacetic acid and its salts (TFA), carbon tetrachloride (CTC), ODS that are not controlled substances such as dichloromethane, chloroform, ethylene dichloride, trichloroethylene, perchloroethylene, and methyl chloride, and HFCs that are not listed in Annex F.

4.1.2. Feedstocks

Total reported production of ODS since 2002 has increased, due to production for feedstock offsetting the decrease in calculated production for emissive uses. The proportion of HCFC-22 as a percentage of total reported ODS production increased significantly in the period 2002 to 2007, and is now over 50% of total ODS production, due to the increasing use of HCFC-22 as a feedstock.

Feedstocks are chemical building blocks that allow the cost-effective commercial synthesis of other chemicals. As raw materials, feedstocks are converted to other products, except for de minimise residues and emissions of unconverted raw material. Emissions from the use of 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 and HFC feedstocks in a responsible, environmentally sensitive manner and, in most countries, are regulated through national pollution control measures.

There is no Montreal Protocol definition for production for use as feedstock. However, there is the definition of "controlled substances produced" in Article 1, paragraph 5, "Controlled substances produced" as used in Article 1, paragraph 5 is the calculated level of controlled substances manufactured by a party. This excludes the calculated level of controlled substances entirely used as a feedstock in the manufacture of other chemicals…". The term "manufactured" is not defined; although a common-sense definition would be "to make or process (a raw material) into a finished product".

As revised in decision XXX/10 and Annex III to MOP-30, Article 7 data reporting instructions and guidelines require the reporting of feedstock uses for all controlled substances and, when calculating production, the Montreal Protocol allows countries to deduct amounts of controlled substances used for feedstock and amounts destroyed. When reporting production data, parties are not expected to deduct these figures from their data. The Secretariat makes the necessary deductions. All feedstock produced during a calendar year is reportable for that year, even if it has not been used.

In 2020, total ODS production and import reported for feedstock uses was 1,475,007 tonnes (554,116 ODP tonnes), a small decrease compared to 2019 (1,486,288 tonnes). The overall increase in ODS feedstock uses through the last decade has been mostly due to the increase in feedstock uses of Annex C1 HCFCs, particularly HCFC-22, while uptake of HFOs is driving a more recent increase in CTC feedstock use. It is highly likely that the COVID pandemic had an impact on feedstock production and consumption in 2020.

In 2020, the proportions of the largest ODS feedstocks were HCFC-22 (48% of the total mass quantity), CTC (20%), and HCFC-142b (11%). HCFC-22 is by a considerable margin the largest feedstock used, with 713,536 metric tonnes reported in 2020. HCFC-22 is mainly used to produce tetrafluoroethylene (TFE) and hexafluoropropylene (HFP), which can be used to make fluoropolymers, such as polytetrafluoroethylene, and some HFCs and HFOs. HCFC-142b is used to make polyvinylidene fluoride. The feedstock use of CTC has increased in recent years, due to growing demand for lower GWP HCFO/HFOs and perchloroethylene (PCE).

Following the entry into force of the Kigali Amendment, reporting of HFCs, including production and import for feedstock uses, is required for all parties that have ratified the amendment. The HFC feedstock data reported for 2020 and 2021 is incomplete due to the timing of reporting obligations, e.g., depending on when some parties ratified. The largest reported HFC feedstock is HFC-152a (thousands of tonnes).

Some HFC-23 generated as a by-product during the manufacture of HCFC-22 is recovered and used as a feedstock to produce Halon 1301 (bromotrifluoromethane), used as a feedstock for the manufacture of the pesticide fipronil and other chemicals. Further uses of HFC-23 as feedstock have recently been investigated. One particularly attractive process is the reaction of HFC-23 with chloroform, producing HCFC-22 and HCFC-21, using HFC-23 as a valuable feedstock, reducing waste, and improving the efficiency of the HCFC-22 manufacturing process.

4.1.3. By-production of controlled substances, including of HFC-23

By-production of controlled substances in other production processes occurs through over or under reaction enroute to the intended product (e.g., HFC-23 is an over fluorination of HCFC-22), the presence of impurities that undergo reaction, and unintended side reactions. Plants are designed to minimise by-production of controlled substances.

Several production pathways use HCFC-22, tetrafluoroethylene (TFE) or hexafluoropropene (HFP) (both made from HCFC-22 feedstock) as feedstocks, including HFO-1234yf, HFC-125, HFC-227ea, HFC-32. The manufacture of HCFC-22 generates HFC-23 by-production and emissions.

HCFC-22 is by a considerable margin the largest feedstock used, with 713,536 tonnes reported production in 2020. About 97% of this is used to produce TFE and HFP, both used primarily to manufacture fluoropolymers. Article 2J of the MP, sets out destruction requirements for HFC-23 from HCFC-22 production. However, there are also significant high GWP by-products associated with production of TFE/HFP from HCFC-22, that if emitted contribute to global warming. The manufacture of TFE/HFP from HCFC-22 used as feedstock generates by-production and emissions of HFC-23 and very high GWP PFC-c-318 (c-C4F8). If unabated, these emissions as CO_2e are higher than the estimated emissions of HFC-23 from HCFC-22 production when applying the Executive Committee indicated maximum emission rate for HFC-23 from HCFC-22 production. Parties may wish to consider the significance of these potential emissions.

HFC-23 can also be formed as by-product during the production of HFC-32. Production processes of other fluorocarbons, such as for HFC-125, HFC-134a, HFC-143a, and possibly some steps of HFO production processes, can also result in by-production of HFC-23, among a range of other fluorochemical by-products, although preliminary data indicates at much lower rates than for HCFC-22 (2–4 % HFC-23 by weight) and HFC-32 (< 0.1 % HFC-23 by weight) production. Depending on process conditions, electrochemical fluorination of alkanes can also generate fluorinated by-products, including HFC-23. HFC-125 production can also result in by-production of CFC-113, -114, -115.

4.1.4. Production of intermediates that are substances listed in Annexes A to F

In chemical production, intermediates are the chemical building blocks that raw materials go through when being chemically transformed into products. Intermediates are either isolated or not isolated within the same process prior to consumption to make the final product. A non-isolated intermediate formed in a chemical process is not considered as a finished product while it remains within the chemical process. As such, a non-isolated intermediate is not commonly reported under Article 7. For example, the formation of the intermediate HCFC-21 is not commonly reported as a feedstock in the process of manufacturing HCFC-22. Substances that are produced, isolated and stored prior to being transferred to a separate process plant (even if within the same establishment) would be considered as a finished product, subject to reporting as production for feedstock use, and are not considered intermediates.

There will be a wide range of emission factors for intermediates from these processes. Intermediates that are formed and consumed almost immediately within a single vessel will have a much lower potential for emission, tending to insignificant, with an emission factor of near zero. An intermediate formed, processed, and potentially held between different reaction loops within the same process will have a higher potential for emission, although the emission rate could still be expected to be considerably lower, by one or more orders of magnitude, than emissions of the final product.

4.1.5. Production emissions and their mitigation

An emission is usually considered to be the release of a substance into the environment; although often used to describe gas releases to the atmosphere, they can also include substances released in solids or liquids that later transition to the atmosphere. In some processes, substances can be dissolved or entrained in some of the co-products and can then be released to the environment in the location where these co-products are subsequently stored and used, which is often remote from the plant that produced them. Most processes will employ a range of elements of good practice for minimising emissions.

Emissions during chemical manufacturing can result from products, co-products[56], intermediates, feedstock, or by-products; which of these are being emitted will have an important bearing on how the operation mitigates those emissions.

Emissions of products, co-products, intermediates, and feedstocks from processes are economically undesirable and the process operators will seek to minimise them, employing a range of good practices.

Emissions of unwanted by-products, and to a lesser extent low value co-product, is a different consideration. For financial reasons, a process will typically seek to minimise the formation of unwanted by-products. Nevertheless, in some cases an increase in the rate of production of the desired product at the expense of a higher production rate of by-product may be economically attractive. There would usually be a need to include additional equipment (such as destruction or separation and chemical transformation technologies), with further operating and maintenance costs to the process to mitigate these unwanted by-product emissions. However, the lack of a clear environmental, safety or economic drivers has often meant that, once produced, these unwanted by-products are emitted unabated. If there are no financial incentives, regulatory controls may be needed to ensure that the emissions of unwanted by-products

[56] Associated products that have a commercial value but are not the main product of the process, e.g., in the case of controlled substances, hydrochloric acid (HCl aq.) is a common co-product with a low sales value relative to the cost of chlorine.

produced by the process are minimised. Various techniques are possible to treat unwanted by-products to minimise their emission, typically end-of-pipe processes.

4.1.6. Estimated emissions of controlled substances from production, distribution, and feedstock use

Emissions of controlled substances during their production, distribution, and feedstock use contribute to overall global emissions.

MCTOC has reviewed and revised emission factors for production, distribution, and feedstock use of controlled substances in chemical manufacturing processes and outlined variables that can influence the applicability of these emission factors.

Global emissions of controlled substances during production, distribution and feedstock use are estimated using MCTOC's most likely emission factors. Distribution emissions depend on specific the supply chains and containers used, such as disposable cylinders. Distribution emissions from disposable cylinders are not considered in these estimates.

Table ES.1 Estimated emissions of controlled substances from production, distribution, and feedstock use

Reported Production 2020	Production Tonnes	Emission Factor (EF)				Emissions		
		Production	Distribution	Feedstock use	Total EF	Metric Tonnes	ODP Tonnes	MMT CO_2e
ODS feedstock use	1,475,007	2.50%	0.50%	0.60%	3.60%	53,100	19,948	
ODS non-feedstock	284,942	2.50%	0.80%		3.30%	9,403	672	
HFCs total production incl. feedstock use	779,644	2.50%	0.80%		3.30%	25,728		42.8

Notes: ODS non-feedstock production is the calculated production [calcProd = Production - Feedstock uses - Destruction - QPS uses for MB], negative reports were excluded. HFC reported production in 2020 probably accounts for about 80% of total HFC production (due to the timing of reporting obligations). Excludes emissions due to the use of disposable cylinders.

4.1.7. Patents

With the global implementation of Kigali amendment, the production and application of HFCs alternatives become crucial for successful phase-down of HFCs. Patents are increasingly becoming a cause for concern for both the chemical manufactures and equipment manufacturers related to those HFCs alternatives. The restriction of free access to patents has raised great concerns about the technology ability, as well as the availability of the alternatives, especially by A5 parties. Parties may wish to consider mechanisms to facilitate technology transfer to enable the most rapid global fulfilment of the Kigali Amendment.

4.1.8. Carbon tetrachloride

Production of carbon tetrachloride (CTC) has increased in recent years (to a recent peak of 318 ktonnes in 2019), due mainly to growing demand for CTC use as feedstock to HFCs and HFOs/HCFOs and to perchloroethylene. This trend is likely to continue due to expected increasing demand for HFO/HCFOs.

Based on Article 7 reported CTC production of 289 ktonnes for 2020, global CTC emissions are estimated as 17.8 ktonnes (7.1–28.1 ktonnes), of which 12.8 ktonnes (4.6–20.6 ktonnes) arise directly from CTC production, handling, supply chain, and use, and a further 5 ktonnes (2.5–7.5 ktonnes) from anthropogenic non-chloromethanes production, such as the vinyl chain production process. The production process of the vinyl chain (production of ethylene dichloride to vinyl chloride monomer to polyvinyl chloride) occurring on chlorine producing sites is identified as a new potential source of unreported CTC emissions.

4.1.9. Very short-lived substances

Many ozone-depleting substances not controlled under the Montreal Protocol that are being evaluated by atmospheric scientists are chlorinated hydrocarbons with a very low ODP, known as very short-lived substances (VSLS) because of their short atmospheric lifetimes. Chlorinated VSLS have a relatively small, but growing, contribution to total tropospheric chlorine, assessed at 4% in 2020.

Dichloromethane (DCM) production in 2020 is estimated at over 1,800 ktonnes. Feedstock use for HFC-32 manufacture exceeded 400 ktonnes in 2020. Solvent use and emissions in non-A5 parties peaked in the early 2000s and have now stabilised at around 200 ktonnes/year; solvent growth in A5 parties has led to calculated global emissions of greater than 1,400 ktonnes in 2020.

New regulations in China will ban the use of DCM in foam blowing agent and public paint stripping applications by 2025, resulting in a possible usage reduction of about 300 ktonnes/year.

Chloroform (CFM) production exceeded 1,500 ktonnes in 2020, mostly used as feedstock for HCFC-22. HCFC-22 production for emissive uses is expected to decline sharply in 2025. However, growth of CFM as a feedstock for TFE/HFP production will likely result in maintenance of a similar level of global CFM production. Solvent uses are expected to account for some of the unexpectedly highemissions of chloroform.

Ethylene dichloride (EDC) production in 2020 was more than 62,000 ktonnes, with a great deal of global trade. EDC is used to make vinyl chloride monomer (VCM), which is then polymerised to make PVC. Emissions from production and feedstock use are estimated to be 60–105 ktonnes. Consumption for solvent use could amount to an additional 3–20 ktonnes of emissions globally.

Trichloroethylene (TCE) production and use in non-A5 parties are in decline; however, TCE production for feedstock is expected to continue at close to current global levels until the impact of the Kigali Amendment leads to declining production of HFC-134a. The use of TCE as feedstock to HFC-134a has continued to grow and was an estimated 360–380 ktonnes in 2020. TCE consumption as an emissive solvent has dropped by 40% globally since 2000 to around 110 ktonnes/year in 2020. TCE emissions are widespread from its main solvents markets in South and East Asia.

Perchloroethylene (PCE)— The largest use of PCE, currently close to 400 ktonnes/year, is as feedstock to several fluorocarbons, including CFC-113 and CFC-113a, used as feedstock for other fluorocarbons. Some of this PCE feedstock usage is expected to decline with implementation of the Kigali Amendment. Solvent use, for dry-cleaning and metal cleaning, has declined to around 175 ktonnes/year in recent years. Absent regulations, it is expected that perchloroethylene consumption as solvent will remain close to present levels. Solvent emissions of 160–170 ktonnes/year dwarf emissions from feedstock production and use, which are expected to be in the range of 8–16 ktonnes.

Methyl chloride (MeCl) is produced and used almost exclusively as feedstock for two main families of products: chloromethanes and organic silicone compounds. From the limited available data, production is estimated to be in the range 4,500–5,000 ktonnes/year. Emissions from production and feedstock uses are estimated to be in the range 5–8 ktonnes. Global emissions originate largely from natural sources.

4.1.10. Response to decision XXIX/12: HFCs not listed in Annex F

Decision XXIX/12 requests “the assessment panels…to provide…information on the consumption and production of hydrofluorocarbons not listed in Annex F of the Protocol which have global warming potential no less than the lowest global warming potential of the hydrofluorocarbons listed in Annex F…”. Annex F references 100-year GWP values from IPCC Assessment Report 4 (AR4), which is interpreted here as the basis for the GWP threshold mentioned in decision XXIX/12 as the lowest GWP of Annex F HFCs, i.e., GWP 53 for HFC-152 listed in Annex F.

Some of the HFCs listed in Annex F have not had significant commercial use (to date), including HFC-134, HFC-143, HFC-236cb, HFC-245ca, and HFC-152.

There is no definition for “hydrofluorocarbons” in the Montreal Protocol. SAP 2018[57], Appendix A, separates saturated HFCs (i.e., those included in Annex F) from unsaturated HFCs (generally known commercially as HFOs). The Montreal Protocol’s Annex F references 100-year GWP values from AR4 (Table 2.14 (errata))[58]. IPCC AR6[59] (AR6) provides 100-year GWPs for a greater number of HFCs (HFCs and HFOs) compared to AR4, which did not include any HFOs. AR6 groups saturated HFCs and unsaturated HFCs together as hydrofluorocarbons. Even if unsaturated HFCs (the HFOs) are included within the scope of hydrofluorocarbons, most would have GWPs that are lower than the GWP threshold of 53 defined through decision XXIX/12.

The AR6 list of HFC substances has been used to identify additional HFCs that have 100-year GWPs exceeding the defined threshold of 53 and available information about their commercial use. 100-year GWP values are not listed in AR4 Table 2.14 (errata) for these substances, which therefore requires AR6 GWP values to be used to determine if they exceed the defined threshold of GWP 53 (HFC-152). The comparison of AR4 and AR6 GWPs shows significant differences for some HFCs, including for existing Annex F HFCs, in part due to changes in how GWPs are calculated. AR6 GWP for HFC-152 is 21.5 compared with AR4 GWP for HFC-152 of 53, which is the GWP threshold defined in the decision. Those HFCs that are not included in Annex F and that have GWPs above the threshold of 53 are included in Table 2.19.

Parties may wish to consider any actions that they might want to take concerning those HFCs not listed in Annex F with GWPs above 53 with known commercial use (HFC-245cb, HFC-245eb, HFC-52-13p, HFC-76-13sf, HFC-c447ef, cis-1,1,2,2,3,4-hexaflurorocyclobutane).

HFEs used as solvent replacements for controlled substances have GWPs (AR6 values) between 59 and 580. HFE solvents are most likely used in equipment where emissions are minimised to avoid losses. Some fluorinated ethers with GWPs greater than 53 are used as inhalation anaesthetics where emissions are more likely to occur. Reported production and consumption could be a valuable data set

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[57] WMO (World Meteorological Organization), 2018, *Scientific Assessment of Ozone Depletion: 2018*, Global Ozone Research and Monitoring Project–Report No. 58, 588 pp., Geneva, Switzerland, 2018.

[58] IPCC, 2012, *AR4 Climate Change 2007, The Physical Science Basis, The Working Group I Contribution to the IPCC Fourth Assessment Report Summary for Policymakers,* Technical Summary and Frequently Asked Questions, Table 2.14 (Errata), 15 June 2012.

[59] IPCC, 2021, *Climate Change 2021, The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Chapter 7 Supplementary Material, Table 7.SM.7, contains metrics for substances including greenhouse gas lifetimes, radiative efficiencies and Global Warming Potentials (GWPs).

for anaesthetics that could be correlated with related emissions of substances, either from their production, use, or with the expected impact of emission abatement measures. Several halogenated ethers with GWPs greater than 53 are in commercial use, including as solvent replacements for controlled substances. The primary use is as anaesthetic gases, which are not historically related to controlled substances under the Montreal Protocol, some are also ozone-depleting substances. Anaesthetic gases are estimated to contribute up to 0.1 % of total greenhouse gas emissions and account for around 5 % of total healthcare emissions.

Parties may wish to consider any actions that they might want to take concerning anaesthetics that are halogenated ethers and other halogenated ethers with known commercial use with GWPs (IPCC AR6) greater than 53.

4.2. 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 of decision X/14 included 25 applications of ODS including CTC, CFC-113, CFC-11, and CFC-12. 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. From 2010 onwards, A5 parties were included in the measures for process agent uses. By 2019, when Tables A and B were last updated by decision XXXI/6, the number of process agent applications had reduced to 10 across 4 parties, and maximum emissions limits were 509 tonnes for 4,327.5 tonnes of make-up or consumption.

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.

Most 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 up to 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.

A suite of measures exist that can be applied to minimise 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.

4.3.Solvents

The main applications of HCFC and HFC solvents are metal cleaning, where metal working oil, grease, pitch wax, etc., are cleaned from metals, electronics cleaning, where flux is cleaned, precision cleaning, where particulate or dust is cleaned from precision parts (e.g., military equipment and aerospace components), and coating deposition, where coatings are dissolved in solvent to deposit onto surfaces e.g., medical devices such as syringe needles.

Solvents using HCFCs and HFCs 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 coating deposition.

HFCs are commonly used as azeotropic mixtures, which are mixtures of two or more liquids that have the same mixture concentration in liquid and vapour phases. Fluorinated solvents, like HFC-43-10-mee, HFC-365mfc, and HFC-245fa (a solvent used in aerosols), have poorer solvency than chlorinated solvents because of the lower dipole of the fluorine-carbon covalent bond compared with the chlorine-carbon bond. As a result, HFCs are often mixed with chlorinated chemicals to boost the solvency.

Many alternative solvents and technologies developed as ODS alternatives are also the candidates for alternatives to HCFCs and high-GWP HFCs. These include not-in-kind technologies, such as aqueous cleaning, semi-aqueous cleaning, hydrocarbon and oxygenated solvents, and in-kind solvents, such as chlorinated solvents and fluorinated solvents, including high-GWP HFCs not listed in Annex F and low-GWP HFOs, HCFOs and HFEs, with various levels of acceptance. Alternatives are being used for electronics defluxing/cleaning and precision cleaning in several industries automotive, aerospace, medical device, and optical components where high levels of cleanliness are required. Industries have their own set of specific solvent requirements and associated test procedures, e.g., to ensure cleaned parts are acceptable for use.

Several blends of HFEs, HCFOs and HFOs are available as HFC and HCFC alternatives. These blends take advantage of key properties of the solvent alternatives, for example, blending a non-flammable solvent with one that has high solvency while also reducing the cost. The major trend in the development of solvents is the introduction of substances with unsaturated molecules, and thus short atmospheric lifetimes, near zero-ODP and low-GWP, such as HFOs, HCFOs, CFOs and hydrobromofluoroolefins (HBFOs).

Medical grade HFC-134a is used in relatively minor quantities in sub-critical liquid solvent extraction (under pressure) of bio-organics from biomass in the production of food flavours, fragrances, cannabinoids, and other bio-organics. Alternative solvent extractants include super-critical carbon dioxide, ethanol, hexane, and butane, which, compared with HFC-134a, are considered disadvantageous.

Solvent end users work to control emissions to every extent possible since this directly affects their operating costs. Solvent cleaning systems (often referred to as vapor degreasers) will contain primary cooling coils for condensation of the boiling solvent and secondary coils operated at much lower temperature to reduce solvent vapor concentrations and emissions. Many users will also recycle solvent for reuse. Only the largest solvent equipment installations would typically find the use of additional solvent capture and recovery equipment, such as carbon adsorption, to mitigate fugitive emissions to be cost effective.

4.3.1. n-Propyl bromide

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 for building and construction material, and as a refrigerant flushing agent. Consumer uses include degreasers, cleaners, adhesives, sealants, and automotive care products. n-Propyl bromide is also used in consumer aerosol products for electronics cleaning and degreasing, dusters, adhesives, textile spot removers, and paintable mould release agents. Alternatives to n-propyl bromide are the same as, or similar to, other solvent alternatives to controlled substances.

n-Propyl bromide is not a controlled substance under the Montreal Protocol. There are concerns regarding its use based both on its potential for ozone depletion and its toxicity. n-Propyl bromide may also contribute to photochemical smog and is regulated as a volatile organic compound.

Primarily due to health and safety risk characterisations for n-propyl bromide, several countries regulate its use. 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 several markets (e.g., China, Japan, and the United States).

4.3.2. Semiconductor and other electronics manufacturing

In semiconductor and other electronics manufacturing, fluorinated gases/liquids such as HFCs are used for dry etching (to form circuit patterns on wafers), chamber cleaning (to remove deposited silicon materials from chamber walls), and as a heat transfer fluid (to control etching performance).

Dry etching utilises plasma-generated fluorine radicals and other reactive fluorine-containing ions that react with the substrate or thin-film to be etched. The fluorinated gases used in dry etching include PFCs, HFCs, sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3). PFCs such as PFC-14 (CF4), PFC-c318 (cyclic C4F8) are used. The most commonly used HFCs for dry etching are HFC-23 (CHF3), HFC-32 (CH_2F2) and HFC-41 (CH3F).

HFC-23 is commonly used for selective etching of silicon dioxide (SiO2) and silicon nitride (SiN). PFC-c318, HFC-32, HFC-41 and C4F6 (perfluoro-1,3-butadiene) are utilised in high aspect hole etching. PFC-c318, perfluorobuta-1,3-diene, and HFC-32 are also used to form polymer films (CFx) to protect the sidewalls during high aspect hole etching.

Not all the fluorinated gas breaks down, or is consumed, in the plasma. Radicals and molecules can also recombine in the plasma. Unreacted gas (or recombined molecules) accounts for most emissions of fluorinated gases from electronics manufacturing. A small fraction of the gas will also be converted into fluorinated by-products.

The walls of the chemical vapour deposition chamber, electrodes, and chamber hardware are cleaned using fluorinated chemicals. Plasma-generated fluorine radicals and other reactive fluorine-containing ions are used to remove the build-up of silicon materials on the chamber walls and tools. PFC-116 (C2F6), SF6 and NF3 are the most commonly used gases for chamber cleaning. HFCs are only minimally used for chamber cleaning.

Fluorinated heat transfer fluids are used for thermal management. PFCs, perfluoroalkyl amine, hydrofluoroether, and perfluoropolyether are commonly used fluorinated chemicals used as heat transfer fluids. Fluorinated heat transfer fluids are used for thermal management. PFCs, perfluoroalkyl amine, hydrofluoroether, and perfluoropolyether are commonly used fluorinated chemicals used as heat transfer fluids. HFCs are not commonly used as heat transfer fluids.

Global consumption of HFCs (HFC-23, HFC-32, HFC-41) for electronics manufacturing has increased significantly over the last decade. With an average annual growth rate of 15% since 2013, total global consumption of HFC-23 for semiconductor manufacturing (etching and chamber cleaning) is estimated at 720 tonnes in 2020. Historically, HFC-41 and HFC-32 have been consumed in much smaller quantities, although consumption is growing. While disaggregated data was not available, HFC-32 is expected to be about 300 to 500 tonnes, and likely more, in 2020. Consumption of all three HFCs are expected to increase with increasing semiconductor production and the increasing complexity of semiconductor devices. The global consumption of HFC-32 and HFC-41 are also expected to continue to increase at a high rate due to their use in high aspect hole etching.

Future demand for HFCs used as heat transfer fluids is expected to remain limited or decrease, as countries move to phase-out non-essential uses of HFCs.

Like semiconductor manufacturing, etching and chamber cleaning are the key processes that use fluorinated chemicals in other electronics manufacturing, i.e., flat panel display (includes use of HFC-23), photovoltaics (HFCs not commonly used) and microelectromechanical systems (includes use of HFC-23).

HFC emissions from electronics manufacturing consist of the unutilised portion of the process gas and gases formed as a by-product during the process from other process gases. Some facilities have implemented emissions control technologies that significantly reduce emissions of HFCs and other fluorinated gases during semiconductor manufacturing. Abatement and scrubbing of process emissions is considered best practice. Pollutant emissions are required to meet local regulatory standards.

For etching and chamber cleaning, alternatives to HFC use in semiconductor manufacturing include other fluorinated gases, such as saturated PFCs, SF6 and NF3, many of which have higher GWPs and lower utilization rates than HFCs, such as HFC-32 and HFC-41.

Some parties appear to treat production and consumption of HFCs in semiconductor manufacturing in the same way as other emissive uses; while other parties appear to treat the production and consumption of HFCs for semiconductors as feedstock use, excluding the portion that results in emissions of HFCs in the process.

Parties may wish to consider how to treat HFC production and consumption for semiconductor uses for the purposes of Article 7 data reporting.

4.4. Magnesium production

Cover gases are used in magnesium production, casting processes, and recycling to prevent oxidation and combustion of molten magnesium. Without protection, molten magnesium will oxidise and ignite in the presence of air and form magnesium oxide (MgO) deposits that greatly reduce the quality and strength of the final product.

Sulphur hexafluoride (SF6), with a very high GWP of 22,800, is the most widely used cover gas. Several gases with lower GWPs are used as alternatives to SF6, including HFC-134a (GWP of 1,430) and a fluoroketone (GWP of 0.1). Consumption of HFCs as a cover gas in magnesium production is relatively small, possibly 100s tonnes or less. It is expected that there will continue to be a demand for HFC-134a, especially is locations that are phasing out higher GWP SF6 and are not yet phasing out HFCs.

4.5. Laboratory and analytical uses

Laboratory and analytical uses (LAUs) 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.

Parties authorised an essential use exemption for LAUs for the first time in decision VI/9, according to conditions set out in Annex II of the report for the 6th Meeting. Annex II authorises essential use production for LAUs 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 LAUs exemption under these specified conditions, excluded additional specific uses from the global exemption, and/or requested the TEAP to report on developments in alternatives to the use of controlled substances. Decision XXXI/5 extended the global LAU exemption indefinitely beyond 2021, without prejudice to the parties deciding to review the exemption at a future meeting.

In 2020, the global production of ODS produced for LAUs was 123.61 tonnes, when CTC and methyl bromide were the only two controlled substances produced for LAUs. CTC remains the predominant ODS during the years, with production of 123.59 tonnes in 2020. In 2020, production of ODS for LAUs was 11 tonnes in non-A5 parties and 113 tonnes in A5 parties.

Many laboratory uses of controlled substances, e.g., as a common solvent or cleaning agent, have been phased out using alternative chemicals and/or procedures. In 2018, MCTOC reviewed the use of ODS in laboratory and analytical, including CTC used as a solvent in bromination reactions using N-bromosuccinimide (NBS). MCTOC identified several procedures where ODS can be replaced by non-ODS solvents and are no longer required for those procedures. Nevertheless, it is challenging to identify alternatives to ODS for some specific laboratory uses within such a wide range of chemical reactions undertaken in laboratories.

International bodies, such as ASTM International and ISO, have been working on the development of new standard methods to replace ODS in laboratory and analytical uses. In this report, MCTOC has updated its review of standards, based on its 2018 Assessment Report. The websites of major global standard organizations were scrutinised, and the results indicated that some bodies seemed to have eliminated the use of some ODS for their standards, e.g., CTC on the European Committee for Standardisation (CEN) database.

Significant progress has been made by the international standard bodies and non-A5 parties in the development or revision of standards to replace ODS in analytical use. However, there still exist standards that allow the use of ODS. For some standards, the alternative or alternative procedures may exist, but the ODS method remains as an active standard for these standard bodies, implying some barrier in adopting the alternatives or alternative procedures in standard development or revision. It may be more challenging for A5 parties to adopt the alternatives or alternative procedures due to the difficulties and/or complexities in the use of the alternatives.

The reasons that non-ODS methods are not adopted in A5 parties are adherence to standard methods that use ODS, and the cost of implementing new methods including training. It takes a lot of time and skilled resources to implement new methods; however, in many cases, non-ODS alternatives are available and may have been adopted by international standards bodies or in non-A5 parties.

Therefore, international cooperation between different standards organisations and between parties should be encouraged to facilitate and accelerate the development or revision of standards for the replacement of ODS in analytical uses. Possible actions may include sharing more information on alternatives as well as on the revision of standards that use ODS.

Parties may wish to consider actions to facilitate the adoption of alternatives in A5 parties, such as international cooperation between different standards organisations and between parties.

4.6. End-of-life management and destruction technologies

This Chapter supplements information on EOL management of ODS/HFC and destruction contained in the 2022 Assessment Reports of the respective Technical Options Committees for Flexible and Rigid Foams, Halons, and Refrigeration, Air Conditioning and Heat Pumps.

Effective management of accumulated active banks of ODS and HFCs, by maximising recovery, recycling, reclamation, reuse, and ultimately destruction after all other options have been exhausted, can minimise the global impacts associated with the potential release of emissions at EOL. By maximising recovery, recycling, reclamation and reuse, effective banks management can limit the amounts of controlled substances that would otherwise require destruction and minimise associated costs. Furthermore, for the RACHP sector, effective HFC bank management can also minimise the amounts of controlled substances that is newly manufactured, minimising overall HFC emissions, and can also aid parties in managing their HFC phase-down targets.

Based on information available from several sources, a combined 6,000 ktonnes of ODS and HFC are estimated to be contained in the active bank in 2022, equalling 16 $GtCO_2e$.

Annual quantities of between 250 and 400 ktonnes (between 0.5 to 0.8 $GtCO_2e$) of ODS and HFCs are estimated to arise from decommissioning in the refrigeration, air-conditioning, and heat pumps (RACHP) and foams sectors from 2020 to 2050. Combined ODS and HFC annual decommissioning is estimated to start to peak in absolute amounts in the mid-2030s onwards, and peak in amounts by $GtCO_2e$ around 2035.

Active global ODS banks of the 5 most common ODS (CFC-11, CFC-12, HCFC-22, HCFC-141b, HCFC-142b) amount to 3,200 ktonnes substance, equivalent to 9.9 $GtCO_2e$, in 2022. There is a rapid decrease as ODS-containing equipment and products are reaching their end-of-life each year. ODS being decommissioned are estimated at 110 ktonnes (0.27 $GtCO_2e$) in 2022.

Active HFC banks in the RACHP sector, which is the predominant usage of HFCs, are estimated at 2,800 ktonnes (5.5 $GtCO_2e$) in 2022 and 3,900 ktonnes (6.8 $GtCO_2e$) in 2030.

The largest banks overall are currently in non-A5 parties and will rapidly reach end-of-life in the next decade. While ODS banks have been more concentrated in non-A5 parties, HFC banks are currently more evenly distributed between non-A and A5 parties. Banks in A5 parties are growing rapidly and will dominate global banks volumes by the early 2030s, resulting from declining banks in non-A5 parties and the rapid uptake of HFC-containing equipment in A5 parties.

The shift from HCFCs to HFCs EOL management marks a transition from ozone depletion to climate change issues, with HFC emissions reported under national greenhouse gases and potentially part of nationally determined contributions. Accelerated action on the management of EOL ODS/HFCs might increasingly be considered a priority under national greenhouse gas emissions mitigation objectives.

With quantities potentially available for recovery and management expected to increase in A5 parties, timely efforts to establish effective EOL management capacity to prevent HFC emissions would have a significant impact, given the predicted size and growth of these banks in larger industrialised 5 parties. With improved economies of scale, through the recovery of increased quantities of ODS/HFCs, the anticipated cost per kg of recovered controlled substances for EOL management could be reduced, or minimised, assuming infrastructure is available and investment in EOL management has been made within a supportive policy framework.

Effective banks management need not be limited to ODS and HFCs. The phase-down of HFCs, and/or the leapfrogging of HFC technologies, will result in increasing banks of other alternative refrigerants and foam blowing agents. HFOs and HCFOs are being used to replace HFCs in some applications, although they are not controlled substances under the Montreal Protocol. Leap-frogging HFC-based equipment into these and other low GWP alternatives contributes to active HFC bank prevention, reducing the quantity of HFCs and the GWP of the bank requiring future EOL management. Nevertheless, resource efficiency and circular economy requirements suggest that effective bank management may also be appropriate for these low GWP alternatives.

For the management of concentrated EOL ODS/HFCs from the RACHP sector, recycling and reclamation are preferable in comparison with destruction because recycling and reclamation reduces the amount of virgin refrigerant required. Where recovered refrigerants are not suitable for reclamation then destruction becomes the only option to avoid emissions.

To achieve sufficient quantities for economic destruction, the overall infrastructure needs to be readily adaptable and expandable to collect and securely store EOL ODS/HFCs for refrigerant destruction.

For the management of dilute EOL ODS/HFCs from the foams sector, historically, these waste streams have been mostly part of the general solid waste stream destined for land disposal or open burning. Capture and EOL treatment, largely through thermal destruction, requires several steps starting with separation from the general solid waste stream, either at source or prior to conventional solid waste disposal, resulting in a higher solid waste unit cost relative to land disposal. Given the relatively low proportion of ODS/HFCs as a proportion of the foam product waste volume, low returns are realized in terms of amount captured for EOL ODS/HFCs per volume handled. The net overall cost/kg of ODS/HFC destruction is consequently much higher than for concentrated EOL ODS/HFCs. Several programs to manage EOL ODS/HFCs are implemented through regulatory, circular economy, and extended producer responsibility initiatives.

Several approaches are possible to finance the required infrastructure/capability and to economically incentivise the servicing and waste management sectors that support the management of EOL ODS/HFCs, including regulatory approaches (such as market quotas for new refrigerant, levies), carbon finance mechanisms, extended producer responsibility, early replacement programs for equipment with associated energy savings, MLF support for A5 parties, and international cooperation through public and private sector partners.

The ability to smoothly undertake the transboundary movement of EOL ODS/HFCs is necessary to achieve global access to environmentally sound destruction of EOL ODS/HFC. In many countries, EOL ODS/HFCs are considered as hazardous wastes. As such their transboundary movement will be subject to the requirements of the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal and related international shipping standards. This requires informed consent by the governments of the exporting, transit, and importing countries, as well as standards for environmentally sound management of environmentally sensitive waste streams.

While effective in restricting illegal trade in waste, the process of informed consent is inevitably bureaucratic and time consuming, resulting in significant transaction costs. This is a significant barrier to EOL ODS/HFC management, including reclamation, and/or destruction, particularly for parties that lack national capability for local reclamation and/or destruction, or the resources to undertake export transactions involving the relatively small quantities low-volume consuming countries might generate.

Parties may wish to consider how the Montreal Protocol, the UNFCCC, and the Basel Convention can work together to facilitate transboundary movement of EOL ODS/HFCs to encourage preferential recovery/recycling and environmentally sound destruction of EOL ODS/HFCs, thereby minimising their emissions.

Environmentally sound destruction of surplus or contaminated ODS and HFCs at end-of-life is encouraged by the Montreal Protocol because it avoids unnecessary emissions and helps protect the stratospheric ozone layer and/or the climate. However, the Montreal Protocol does not mandate the destruction of ODS or Annex F Group I HFCs. The exception is HFC-23 (Annex F, Group II) generated in facilities manufacturing Annex C, Group I or Annex F substances, from which emissions must be destroyed to the extent practicable using technologies approved by parties.

The Protocol's definition of 'production' of controlled substances subtracts the amounts destroyed from the amounts produced. The use of destruction technologies approved by parties applies to the amounts of controlled substances destroyed and accounted for within the Protocol's definition of 'production'. The Protocol's destruction technology approval process sets a benchmark for technologies to achieve a level of efficiency for destruction of controlled substances (destruction and removal efficiency of 99.99% for concentrated sources), which aids in the process of accounting for destroyed amounts.

The Ozone Secretariat provides data reported to the Montreal Protocol under Article 7 on the destruction of controlled substances. Cumulatively, 382,574 tonnes of ODS have been reported as destroyed since 1996; reported CTC destruction accounts for 71% of the total. Global Article 7 reported destruction of ODS other than CTC indicates that annual destruction has been in the range of 4,475 to 6,355 tonnes and may be trending downward. Non-A5 parties have accounted for over 99% of the reported destruction of ODS other than CTC since 1996.

There can be purposes for destroying controlled substances other than those within Montreal Protocol requirements. Many countries that destroy controlled substances might not report that destruction under Article 7, which is for the purposes of calculating production under the Montreal Protocol. Moreover, some destruction, like the destruction of dilute sources of waste foams, are rarely reported to the Montreal Protocol. These activities are motivated by other factors, ranging from direct regulatory mandates, integration with broader circular economy policies applied to solid waste streams, and a direct need to conserve scarce landfill capacity by targeting high volume waste streams. Destruction of controlled substances is an activity that can also be undertaken within national waste management, circular economy requirements, or extended producer responsibility.

Despite a few reported effective examples, global recovery and destruction rates of EOL ODS/HFCs from decommissioned equipment and products are likely to fall well below a level where a significant impact is being achieved in mitigating ozone depletion or greenhouse gas emissions.

Parties have taken several decisions to approve destruction technologies that are used for the destruction of controlled substances for the purposes of Montreal Protocol production data reporting requirements under Article 7 and destruction of HFC-23 under Article 2J. Over time, the list of destruction technologies approved by parties has been updated, with the most recent list of approved destruction processes contained in Annex II to the 30th MOP under decision XXX/6. It should be made clear that, in meeting any broader needs for environmentally sound destruction, parties are free to apply technologies, whether on the Montreal Protocol approved list or not, that satisfy national regulatory standards.

Decision XXX/6 on destruction technologies for controlled substances requests TEAP to assess destruction technologies listed (in annex

II to the report of the Thirtieth Meeting of the Parties) as not approved or not determined, as well as any other technologies, and to report to parties. A summary of recommendations follow that are elaborated in the chapter.

MCTOC has considered the development of smaller scale variants of currently approved technologies, in particular plasma arc. There is no reason to consider down-sized versions of this technology to be any different on a technical basis, or in terms of performance, to the higher capacity, higher powered torch versions already approved by parties. As a general category these technologies (large and small) are ostensibly the same. As such, MCTOC does not consider there to be a need for parties to approve smaller scale versions as a separate category of technology. Portable Plasma Arc, which employs a small-scale nitrogen plasma arc process, was added to the list as a separate approved technology from Nitrogen Plasma Arc, which is listed as a separate class.

Parties may wish to consider removing the category, Portable Plasma Arc, as a separate approved technology to rationalise and consolidate the list of approved destruction technologies.

Cement kilns are not an approved technology for the destruction of dilute waste, even though it is an approved technology for the destruction of concentrated EOL ODS/HFCs, except for Halons, methyl bromide and HFC-23. In terms of DRE and the technical performance advisory criteria for other pollutants, cement kilns have already demonstrated that they meet DRE for concentrated sources of a range of ODS and Annex F, Group 1, HFCs (99.99% versus 95% for dilute sources), which would qualify them for destruction of dilute sources.

Parties may wish to consider inclusion of cement kilns as an approved destruction technology for dilute sources of ODS and Annex F, Group 1, HFCs, for which there is already approval for concentrated sources.

National and/or local governments require their own performance standards to meet emissions limits, and it is expected that any technology is required to meet local emissions standards on an installation specific basis.

4.7. Aerosols

Aerosols are used in a wide range of different applications. The term aerosol product describes a product pressurised with a propellant that expels its contents from a canister through a nozzle. 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 hydrochlorofluorocarbons (HCFCs e.g., HCFC-22), hydrofluorocarbons (HFCs) (e.g., HFC-134a, HFC-152a), hydrofluoroolefins (HFOs, e.g., HFO-1234ze(E)), hydrocarbons (HCs), and dimethyl ether (DME).

Some aerosol products contain solvents, including HCFCs, HFCs, hydrofluoroethers (HFEs), aliphatic and aromatic solvents, chlorinated solvents, water, esters, ethers, alcohols, ketones, and hydrochlorofluoroolefins (HCFO, e.g., HCFO-1233zd(E)).

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. They are also used in technical aerosols where flammable propellants can be used safely. Hydrocarbons and oxygenated hydrocarbons (such as DME) are volatile organic compounds (VOCs) that contribute to photochemical smog generation. Strict VOC controls can have an impact on the choice of propellant, where hydrocarbons are avoided. The use of compressed gases (nitrogen, nitrous oxide, carbon dioxide) as propellants has increased because of these regulations and the availability of better cans.

A smaller proportion of aerosols migrated to using HFCs. Non-flammable and non-toxic HFCs have been used where flammability, toxicity, safety in use, and/or VOC content are considerations. HFCs, including HFC-152a, are often used where emissions of VOCs are controlled. HFCs and HFO-1234ze(E) are more expensive than hydrocarbons and mostly used when their properties are needed.

While the European Union's aerosol market is the largest overall globally, its HFC consumption for aerosols has been phased out. This compares with North America, as the second largest regional producer of aerosols with the largest HFC consumption in aerosols.

For 2021, global HFC demand is estimated to be around 44,000 tonnes (~3,000 tonnes HFC-134a; ~41,000 tonnes HFC-152a), corresponding to a warming impact from direct emissions of about 9.4 $MMTCO_2e$. This represents an overall reduction in the global warming impact of HFC-containing aerosols of more than 50% since 2015. These reductions are due to the decrease in global consumption of HFC-134a in aerosols, especially in North America. Meanwhile, there has been an increase in the global consumption of HFC-152a in aerosols since 2015. Overall HFC demand in aerosols continues to be dominated by the North American market, with probable growth in HFC aerosol consumption in the Asia and Asia-Pacific region.

HCFC production and consumption (as defined) in non-A5 parties was required to be phased out by 1 January 2020, with allowance for essential use exemptions if authorised by the Montreal Protocol. Between 1 January 2020 and 1 January 2030, for any non-A5 party, Article 2F, paragraph 6, allows HCFC consumption and production in any year up to 0.5% of the baseline consumption allowance, for restricted applications including topical medical aerosol applications for the specialised treatment of burns. Otherwise, aerosol use of HCFCs can continue in non-A5 parties from recycled or stockpiled sources, for as long as those sources remain. In the Russian Federation, topical medical aerosol applications use HCFC-22 (as a propellant) and HCFC-141b (as a solvent), which are now being sourced from stockpiles. HCFC-22 and HCFC-141b are used in China for aerosols, including for Traditional Chinese Medicines, by several large pharmaceutical companies and some smaller companies.

Technically and economically feasible alternatives to controlled substances are commercially available for all aerosols, although not all alternatives are suitable across all aerosol applications in all locations. Many factors affect the selection of a given propellant or alternative, including regulatory approval of products, industry codes of conduct, VOC controls, supplier, regulatory controls on HCFCs and HFCs, ease of use, and propellant properties, such as flammability or safety for certain uses.

Parties may wish to consider the advantages of reducing the use of HFCs in the aerosol sector, where that is technically and economically feasible. Given that aerosols are totally emissive, any action taken in this area would provide rapid reduction in HFC consumption and emissions. Accounting by a country, including their aerosol production and their import of finished aerosols containing HFCs, might help it determine the implications of any phase-down policies, including financial implications.

4.8. Pressurised 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. Inhalers offer effective symptomatic benefit and control of disease, by delivering drugs directly to the airways, whilst minimising systemic side effects. Oral drugs are also prescribed for asthma and COPD; some of these can have serious side effects.

There are two common types of highly portable inhalation devices for the delivery of respiratory drugs: (pressurised) metered dose inhaler (pMDI) and the dry powder inhaler (DPI) in single- or multi-dose. Other methods of delivering drugs to the lung include soft mist inhalers (SMIs) and nebulisers.

Under the Montreal Protocol, the use of CFCs as propellants for pMDIs was successfully phased out worldwide without significant adverse impact to medical care. Pharmaceutical companies replaced CFCs with HFCs propellants in pMDIs; HFC-134a and to a lesser extent HFC-227ea. With the Kigali Amendment, the production and consumption of HFCs listed in Annex F is scheduled to be phased down. Annex F HFCs include HFC-134a, HFC-227ea and HFC-152a.

For both asthma and COPD, there are two main categories of inhaled treatment, bronchodilators (“relievers”) and anti-inflammatory medications (“preventers”). Inhaled salbutamol (a short-acting reliever) remains by far the most used treatment worldwide, mainly as inexpensive HFC pMDIs. Some estimates put the total global use of salbutamol pMDIs at greater than 60% of total pMDI use.

Following reformulation, the pMDI remains popular, especially because it is relatively affordable for the short-acting bronchodilator salbutamol, which is the predominant short-term relief or “rescue” treatment for acute symptoms in asthma/COPD worldwide. DPIs are suitable for many patients and are widely prescribed for the treatment of asthma and COPD.

Complex considerations are necessary when patients and healthcare professionals make an informed choice about a patient’s inhaled therapy, considering 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. 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 to take environmental impact into account in their choice of inhaler.

Based on available industry data on the proportion of pMDI, DPI and SMI units sold, while dynamics vary in different markets, pMDIs remain the dominant option sold in most markets for the delivery of all inhaled therapy, except for the European Union and India where DPIs are more dominant. For preventer (or maintenance) therapy only, DPIs are the dominant option sold for the delivery of inhaled maintenance therapy in most markets.

Access to affordable inhaled medicines for chronic respiratory diseases is severely limited in low- and middle-income countries, which causes avoidable morbidity and mortality. Generally, multi-dose DPIs (mDPIs) are less affordable than single-dose DPIs and pMDIs; single-dose DPIs can be more affordable than pMDIs. In A5 parties, locally made pMDIs are more affordable than some imported brands. SMIs (are usually more expensive than pMDIs for short-acting reliever medication, but they can be as equally cost-effective as DPIs or pMDIs for some drugs, particularly long-acting bronchodilators. SMIs are generally likely to be unaffordable in A5 parties for most patients. In all parties, the cost of some or any treatments can be unaffordable for a portion of patients.

Based on HFC manufacturing industry estimates, approximately 800–825 million HFC MDIs (assuming a global weighted average fill weight: 14.61 g/HFC-134a MDI and 11.38 g/HFC-227ea MDI) are currently manufactured annually worldwide, using approximately 10,700 tonnes HFC-134a and HFC-227ea in 2021. One industry estimate puts the number of DPIs manufactured worldwide at 450 million annually.

All currently available HFC pMDIs have a far greater carbon footprint than DPIs or SMIs. Life cycle assessments consistently demonstrate that the large majority (88–98%) of the carbon footprint of pMDIs is due to propellant release during use or end of life. DPIs and SMIs are propellant-free inhalers and consequently have far smaller carbon footprints. The smallest carbon footprints are seen in reusable SMIs or single-dose DPIs. Re-usable single-dose devices are the most popular devices in some regions due to their affordability.

Two low-GWP (global warming potential) chemicals are under development as potential propellants for pMDIs (HFC-152a and HFO-1234ze(E)) as replacements for HFC-134a and HFC-227ea. Limited carbon footprint information is available for potential new pMDIs in development using lower GWP propellants, though it is clear they will have far smaller carbon footprints.

Three pharmaceutical companies and one major contract development and manufacturing organization (CDMO) have announced plans to reformulate their pMDI products with lower GWP propellants, with their target to begin introducing new pMDIs containing HFC-152a or HFO-1234ze(E) into the market in 2025. Together, these companies account for over 70% of the pMDI market revenues from the United States and Europe.

However, to reformulate is a lengthy and costly process, and for many companies it is unclear whether this would be financially justified.

The projected timescale for the introduction of the lower GWP pMDIs from the 4 companies active in the field may be at risk if health authorities require full clinical development programmes to be completed for switches of the propellant when there are no other substantial changes in the formulation. Health authorities have not yet announced specific guidelines; some general guidance on the clinical data requirements is urgently needed, especially given the possibility of accelerated HFC phase-down.

Given the differences in regulatory expectations and the pace of approval in different countries, together with the time it takes to convert both patients and the supply chain, it is currently unlikely that transition in non-A5 parties would be completed before 2030, even for the limited number of products announced to date. There is only one company that has publicly announced reformulation of a reliever pMDI, yet salbutamol pMDIs account for well over half of all inhaled doses of medication. Based only on company announcements, a significant proportion of global production of salbutamol pMDI could potentially be in the earlier stages of development of replacements.

For 5 parties, the timetable for HFC phase-down is longer than for non-A5 parties. Nevertheless, there are multinational inhaler manufacturers based in these countries that have corporate targets to reduce their carbon footprints and that wish to maintain and build global market access. Some are investigating prototype formulations with low-GWP propellants, although none have yet announced plans to launch products. The patent landscape may also play a role in their decision-making because the current suppliers of pharmaceutical grade HFC-152a and HFO-1234ze(E) have several patents pending or granted in this field.

It is likely that the cost of bulk HFC-134a and HFC-227ea propellants will rise substantially over the next few years as other industrial uses decline, and quota mechanisms impact on their availability.

There are a range of issues and potential challenges that could emerge in the transition away from high GWP propellant pMDIs to inhalers with lower GWPs, including pMDIs using lower GWP propellants, DPIs and SMIs, which could create risks and disruptions to inhaler markets and patient health. These include global and national frameworks that establish clear market signals and address transition challenges; continuity in, and stability of, the supply of pharmaceutical-grade HFCs; regulatory approvals; exports of pMDIs; patent protections; manufacturing capacity for pMDIs with the new propellants, DPIs and SMIs; patient and physician information.

The transition of high GWP HFC pMDIs to lower GWP pMDIs within the global HFC phase-down is a complex manufacturing and marketing transition that requires careful forward planning of the supply chain to avoid patient harm. Market authorisation of the new lower GWP pMDIs by health authorities is another critical factor in a successful transition and could benefit from a coordinated approach.

Bulk pharmaceutical-grade HFC-134a manufactured in the United Kingdom is exported around the world, where pMDIs are then manufactured locally. India, and potentially China, also have the capacity to manufacture pharmaceutical-grade HFC-134a; however, certification by pMDI manufacturers of new supply chains for pharmaceutical-grade HFC-134a is difficult to achieve. Several major pharmaceutical companies manufacture pMDIs in Europe from bulk HFC import allocations, for subsequent export of HFC pMDIs around the world.

To guarantee adequate pharmaceutical-grade HFC-134a during transition, adequate amounts of technical-grade HFC-134a from Japan and/or the United States would need to continue to be supplied to the single purifier of bulk pharmaceutical-grade HFC-134a located in the United Kingdom. Technical-grade HFC-134a plants operate at a minimum capacity below which it becomes technically challenging or impractical to continue to manufacture HFC-134a (below 60–70% of normal running rate).

The Kigali Amendment's 70% reduction of production and consumption from baseline for Annex F HFCs in non-A5 parties in 2029 is likely to impact and limit the global supply of pharmaceutical-grade HFCs for pMDIs, at which time it is also possible that an adequate supply of lower GWP pMDIs might not yet be available to meet patient demand.

How different regions manage their HFC phase-down within the global HFC phase-down will be important in ensuring global, regional, and local management of the supply chains during the transition away from high GWP HFC pMDIs. National implementation of HFC phase-down requirements may have implications for the global HFC and pMDI supply chains, including export markets. Flexibility within global and national HFC phase-down frameworks may need to be considered during the transition from high GWP to lower GWP pMDIs.

Regulatory approvals of the new pMDI products may benefit from a coordinated approach, taking into careful consideration the HFC phase-down and the stability in supply of pharmaceutical-grade HFCs, to ensure continued patient access to essential treatments. Timely transition and access to new technology could avoid large price increases with the loss of generic salbutamol HFC-134a pMDIs if or when HFC-134a supplies are shut down for technical and economic reasons.

Parties may wish to consider the range of technical and economic issues associated with the transition from high GWP HFC pMDIs to ensure adequate supplies of pMDIs and other inhalers during HFC phase-down.

Parties may wish to consider the need for global and national coordination in the HFC phase-down and its impact on the transition away from high GWP HFC pMDIs to ensure patient safety.

Parties may wish to consider how to ensure that adequate bulk HFC-134a and/or pMDIs are available in their own markets, and in their export markets, to avoid risks to the continuous supply of pMDIs. This necessity may persist for up to 10 years, until full ranges of affordable low GWP pMDIs are available worldwide.

Parties may wish to consider measures that facilitate efficient, timely development while assuring the safety and effectiveness of the new pMDIs.

4.9. Sterilants

Sterilization is an important process in the provision of good quality healthcare services. It is defined as validated processes used to render products free from viable microorganisms. Sterilization requires strict application of the principles of quality management to ensure validation of the selected process and implementation of effective routine control; reliable equipment; and knowledge of materials compatibility and biocompatibility.

Sterilization of materials, including medical devices and pharmaceutical products and packaging, can be performed in facilities ranging from industrial settings with large outputs of similar items (e.g., by manufacturers of sterile medical devices such as single-use syringes, or specialist contractors offering a sterilization service to medical device manufacturers) and dissimilar items (such as procedure packs and kits), to smaller facilities including hospitals and dental clinics with much smaller outputs but great diversity of items. Process requirements for these settings are essentially similar but the types of sterilization processes used, and the challenges presented to assuring sterility, differ.

EO can be used as a sterilant either alone or diluted with other gases to make non-flammable mixtures. A mixture of 12% by weight EO and 88% dichlorodifluoromethane (CFC-12) (12/88) was once widely used for this purpose. CFC-12 use for sterilization has been successfully phased out in non-A5 Parties, and in most, if not all, A5 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% by weight EO in a mix of HCFC-124 and HCFC-22) were virtual drop-in replacements for the 12/88 mixture using CFC at that time. Estimated global use of HCFCs in sterilization is now considered to be significantly less than 50 metric tonnes over 10 years ago, which amounts to less than 2 ODP tonnes worldwide. EO/HCFC use has subsequently been significantly reduced or eliminated by converting to 100% ethylene oxide or conversion to other sterilization technologies.

The complete phase-out of HCFCs in sterilization is readily achievable in A5 Parties to meet the Montreal Protocol schedule. The useful lifetime of existing EO/HCFC sterilizers is about 20 years when well maintained. Therefore, by 2030, at the latest, any remaining sterilizers in A5 parties should be ready for replacement with available alternative technologies that do not use ozone-depleting substances. Industrial and healthcare facility procurement should take into consideration the HCFC phase-out, redundancy of EO/HCFC sterilization equipment, and lack of availability of HCFC-containing blends, in making future investment decisions.

HFC mixtures (10.4% by weight EO in a mix of HFC-125 and HFC-227) used in existing sterilization equipment with modified process controls were initially tested in the United States. Technical problems were identified that would require re-engineering, and potentially new equipment, in addition to validation of the new process. HFC blends have not been broadly adopted or used worldwide, although initially some sterilization service providers in Asia continued to explore the potential application.

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 ethylene oxide (EO), formaldehyde) and oxidative processes (including hydrogen peroxide gas, gas plasma systems, liquid or gaseous peracetic acid, and ozone). Further sterilization methods based on these and other chemical agents are under continuing investigation for commercialisation.

No single sterilant or sterilization process is compatible with the range of potential products or materials, be they designed for single-use or designed to be processed in healthcare facilities and used multiple times. The nature and complexity of items and loads to be sterilized will vary according to the user requirements. Some items are more robust than others regarding pressure, temperature, moisture, and radiation dose. Therefore, several different processes are available for use, and each will offer specific advantages depending on the need.

Technologies that can be considered to avoid processes using ozone-depleting EO/HCFC blends include use of heat-sterilisable devices, use of single-use devices sterilized by alternative heat, radiation or other chemical technologies, use of 100% EO sterilization processes, and a range of other methods that will sterilize most of the heat sensitive medical devices used in healthcare or industrial settings. Alternative low temperature processes for sterilization that have been commercialised include hydrogen peroxide gas (used with or without the generation of plasma during the process), humidified ozone gas, nitrogen dioxide gas, liquid phase peracetic acid formulation and low temperature steam-formaldehyde processes. Other low temperature methods have routinely reported but have yet to be widely deployed.

Any alternative to the use of any remaining ozone-depleting substances 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.

Many of these alternative technologies provide significant advances, such as better safety profiles and turn-around times, and reduced cost per cycle.

MCTOC believes that sterilization applications using controlled substances are no longer a relevant risk for the Montreal Protocol. Unless circumstances change, MCTOC proposes not to include sterilization in its technical updates in the next quadrennial assessment. Sterilization technologies and applications continue to move to deploy environmentally safer processes as best practice, in parallel with meeting the essential needs for patient safety.

5 REFRIGERATION, AIR CONDITIONING AND HEAT PUMPS TECHNICAL OPTIONS COMMITTEE (RTOC)

5.1. Sustainability in the RACHP sector

The RACHP sector will continue to play an important role into the sustainable future of mankind, with a focus on efficient cold chains and comfort applications. There is a wealth of information about the impact of refrigerants on the environment. For different RACHP applications, it is important to balance the benefits and risks of refrigerant selection, including known safety and environmental impacts, being mindful of areas of scientific uncertainty. Based on these considerations, standards have been developed as listed in Table 2-1 of Chapter 2 of the RTOC 2022 Assessment Report.

CO_2 equivalent emissions include direct and indirect emissions. Direct emissions relate to the emissions of the GWP refrigerant into the atmosphere. They may be reduced through leak minimisation and technician training. Indirect emissions relate to the energy consumed over the lifetime of the equipment and may be reduced through energy efficiency improvement and renewable energy integration.

5.2. Refrigerants

Since publication of the RTOC 2018 Assessment Report, two new single component refrigerants (FIC-13I1 and HFO-1132(E)) and 23 new refrigerant blends have received designations and classifications by ASHRAE Standard 34 and/or ISO 817. These include mixtures of HFCs, HFOs, CO_2 (R-744), HCs and two mixtures that include new single component refrigerants, R-466A and R-474A. R-466A (a mixture containing FIC-13I1, ODP < 0.04, GWP100 = 733, is a non-flammable replacement of R 410A with approximately a third of its GWP. However, the use of FIC-13I1 (ODP < 0.09) raises the question of the acceptability of short-lived ozone depleting substances. R-474A is a A2L refrigerant mixture of HFO-1132(E) and HFO-1234yf which largely matches R-407C.

Alternatives to high-GWP refrigerants are available for all RACHP applications. However, there is no single "ideal" refrigerant. As result of the implementation of the Kigali Amendment, ultralow-, low- and medium-GWP refrigerants are being introduced for all applications, sometimes as blends of these refrigerants even with traditional HFC refrigerants. The large number of new refrigerants being proposed creates a challenge to identify the optimal refrigerant for each application. Many of the proposed alternatives are seen as intermediate solutions for the HFC phase-down.

Selection of the optimal refrigerant for a specific application is a balance between environmental issues, suitability for the targeted use, availability, cost of the refrigerant and associated equipment and service, energy efficiency rating, safety, and ease of use.

Using new refrigerants often requires a system redesign or an update to the system architecture. This can be as simple as changing the lubricant or more complex. For example, the earlier transition from CFC-12 primarily to HFC-134a only required changes of the lubricants and some elastomeric seals. However, the shift from HCFC-22 to R 410A required those changes along with additional and extensive modifications of compressor, heat exchangers, controls, and other items.

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 the current safety levels, new technologies are being developed and an increased level of training will be needed. System and appliance safety standards are being continually updated to enable the use of alternative new refrigerants.

Refrigerant emissions into the atmosphere may result in decomposition products which could be harmful to the Earth's eco-system. Some of the current and alternative synthetic refrigerants, (HCFCs, HFCs, and HFOs) produce varying amounts of trifluoroacetic acid (TFA, formula C2HF3O2) during their atmospheric decomposition (see the EEAP 2022 report (Madronich et al., 2022) and (WMO, 2022) for further detailed information).

Data on the production of ODS substances and HFCs are reported by parties under Article 7 of the Montreal Protocol and made available by the Ozone Secretariat in aggregated form. Consumption data are not directly reported by Parties. Article 7 reported data give no sector-specific consumption information on HFCs and are difficult to interpret.

For a better understanding of comprehensive and sector specific HCFC and HFC consumption data, the best approach is the use of "bottom-up stock models". Details and accuracy of these models are described. Bottom-up stock models can be validated by comparing the modelled estimates of refrigerant consumption with "top-down" data such as the Article 7 data reported to the Ozone Secretariat or with specific atmospheric data.

Refrigerant designations or identifiers, as well as physical, safety, and environmental data are tabulated in the Annex to Chapter 3 of the RTOC 2022 Assessment Report.

5.3. Sealed domestic and commercial refrigeration appliances and heat pump tumble dryers

Compact and factory sealed equipment includes domestic refrigerators, a wide variety of self-contained commercial refrigeration applications (e.g., beverage coolers, ice cream cabinets, vending machines, water coolers, ice machines, professional refrigerated under counter storage cabinets or freezers, stand-alone plug-in display cases (horizontal and vertical), and refrigerated drug cabinet), and heat pump tumble dryers (HPTD).

Approximately 200 million domestic refrigerators and freezers were sold with a market value of about US$ 35 to 50 billion annually. In 2019, the global installed domestic refrigerators was estimated to be 2.0 billion and consuming almost 4% of global electricity. The entire global new production of domestic refrigeration appliances is based on non-ODS refrigerants, predominantly HC-600a and to a small extent HFC-134a. Migration from HFC-134a to HC-600a is continuing, driven by the Kigali Amendment schedule or local regulations on HFCs. In the USA, migration to HC-600a is expected to be complete by 2023. Many A5 parties including China and India have migrated to HC-600a. The energy efficiency of refrigerators continues to improve worldwide driven by MEPS and increasing consumer awareness.

Self-contained commercial refrigeration (SCCR) appliances mainly use HFC-134a, R-404A, and HCs. With the successful revision of safety and equipment standards in 2019, SCCR appliances are migrating to more efficient HC-290 technologies, and this trend is spreading to some A5 parties. In larger charge systems, migration from R-404A to R-744 is occurring but will eventually move to HCs.

Domestic heat pump tumble dryers (HPTD) are more efficient than conventional electrically heated dryers using 40 to 50 % less energy. Some EU manufacturers have ceased production of conventional electrical dryers due to energy label requirements. HPTDs continue to gain market share supported by reduced cost from the economy of scale. The most commonly used refrigerants in HPTDs are HFC-134a, R-407C, and R-410A. Some transition to HC-290 has happened in European countries. HPTDs have yet to make significant penetration into North American or A5 markets.

MEPS drive manufacturers to innovate for better energy efficiency with reduced costs. Many countries with low market volumes are yet to initiate MEPS, possibly due to the risk of short-term rise in cost.

Regulations for mandatory end-of-life refrigerant handling are established in many non-A5 parties. They are being introduced in some A5 parties, but the small unit charge, the relatively low number of appliances, and their geographical dispersal reduces the commercial opportunities for recovery and recycling.

5.4. Food retail and food service refrigeration

Refrigeration applications in food retail and food service are critical to reduce food waste. They have received a lot of attention due to the associated societal and environmental benefits they bring, and the relatively large electricity consumption of operating such systems. The commonly used HFCs in existing food retail and food service are R-404A and HFC-134a and in many A5 parties HCFC-22 continues to be used. Globally, several countries and regions are adopting controls on the use of high-GWP HFC refrigerants in food retail and food service applications. These actions by governments have accelerated the development of new lower GWP refrigerants and systems and are being aided by new safety standards for flammable and high-pressure refrigerants. The net effect is that the transition to ultralow- and low-GWP refrigerants is moving at a faster pace in food retail and food service compared to most other RACHP applications.

R-744 are increasingly being used in food retail systems worldwide – both in cascaded systems (R-744 for low temperature cascaded with a second refrigerant such as HFC-134a, R-450A, R513A, HFO-1234ze, or similar, and R-717 or HC-290 in limited cases) and in trans critical all-R744 systems. Trans critical systems are being modified extensively to reduce their energy penalty at high ambient conditions with component and system technologies. R-744 is introduced in food service applications with condensing units.

Meanwhile, several high-, medium- and low-GWP HFC/HFO blends (both A1 and A2L) are being approved for use worldwide in various equipment types with A2L refrigerants in smaller charge systems such as distributed systems and condensing units. High- and medium-GWP A1 blends are important for retrofitting existing R-404A and HFC-134a equipment as transition refrigerants to reduce the CO_2 equivalents of existing equipment. Retrofits are a growing trend in Europe and North America, where the recovered and recycled or reclaimed R-404A and HFC-134a is used for servicing existing equipment. As a result, reclaimed and recycled refrigerant and refrigerant banks within the fleet of equipment are viewed as an asset requiring proper management. This can be achieved using existing leak sensing and mitigation technology that are used primarily for flammable refrigerants.

Energy efficiency increasingly influence the choice of refrigerants that retailers make when selecting new equipment. Equipment in food service and food retail last for 10 to 20 years and as such the life cycle cost of operating and maintaining the equipment is an important factor in the decision making. Reducing the refrigeration load is the first place to start for reducing energy consumption, which is followed by various other efficiency improvement options like the choice of refrigerant, compressors, heat exchangers, etc. The conversion to low-GWP refrigerants in food retail and food service applications is taking place while maintaining or improving energy efficiency.

5.5. Transport refrigeration

Transport refrigeration deals with preservation of food, pharmaceutical products, and other temperature-sensitive goods in transit, and is very important for the food and medicine cold chains. It includes refrigeration units for trucks, trailers, light commercial vehicles, marine containers, rail, and air transport. This chapter also covers refrigeration onboard ships, and comfort cooling for passenger railcars and aircraft.

In order to ensure safe and reliable operation, the knowledge, competence for safe service and spare parts, as well as relevant safety processes and procedures, must be available along the transport routes. The latest low-GWP refrigerants are not easily available everywhere and this is slowing the transition for example with transcontinental transport.

The majority of trucks and trailers employ R-404A. New equipment in Europe and in North America uses R-452A offering a significant reduction in GWP. Light commercial vehicles use mainly HFC-134a, while some use HFO-1234yf. The majority of marine container refrigeration units operate on HFC-134a. The latest of these units are being offered as being retrofittable to R-513A. A marine container operating on R-744 is available with limited market penetration.

Legislation is driving lower GWP in transport refrigeration, although the pace and refrigerant options are uncertain. A2L or A1 blends, with GWP levels below 500 such as R-454A and R-454C, present options for the transition. HC-290 or R-744 systems may prevail in the longer term – but still present significant challenges.

Direct emissions are being reduced by design by eliminating leak points, and indirect emissions through alternative ways of powering the refrigeration system, by eliminating diesel engine operation, for example using hybrid or fully electric power trains.

Different types of ships use different refrigerants. HFCs are currently being replaced by alternative systems which are finding their way from other market segments, such as R-744 for food storage systems. For cruise liners air conditioning, HFC-134a is being replaced by HFC-1234ze(E). R-717 was common before 1970 and today is experiencing a revival in many ships and in particular fishing vessels.

5.6. Air-to-air air conditioners and heat pumps

Air conditioners, including air-heating heat pumps (sometimes referred to as reversible air conditioners), range in size from 1 kW to 750 kW although the majority are less than 70 kW. The most popular are non-ducted single splits, which are produced in excess of 80 million units per year. All products sold within non-A5 countries use non-ODS refrigerants. Around 10% of new systems in A5 countries use HCFC-22, with a substantial proportion of the installed equipment still using HCFC-22. In addition to the widespread use of R-410A, the extensive introduction of HFC-32 in residential split air conditioners continues in many countries around the world, accounting for nearly half of the total production of split room air conditioners in 2021.

Manufacturers and research organisations within all regions continue to evaluate and develop products with various HFC/HFO blends, such as those comprising HFC-32, HFC-125, HFC-134a, HFO-1234yf and HFO-1234ze. Products are being introduced with medium-GWP alternatives, R-454A, R- 454B, R-452B and R-463A. Some enterprises within the Middle East still see R-407C and HFC-134a and in some applications R-410A as favourable alternatives to HCFC-22. In addition, transition towards to HC-290 in China, Southeast Asia, and South America is underway, but except for small split and portable units, there is limited market introduction so far because of perceived safety and liability risks.

The adoption of revised international safety standards (e.g., IEC 60335-2-40) with improved requirements particularly and less stringent charge limitations for class A2L, A2, and A3 refrigerants enables greater application of low-GWP refrigerants for this category of products. Numerous research activities are continuing to investigate a variety of aspects related to the application of flammable refrigerants in air conditioning equipment.

5.7. Applied building cooling systems

Applied building cooling systems are used in commercial buildings of all types and require engineering services to design and install. The dominant products used in these systems are chillers (that provide comfort through water networks) or packaged commercial unitary product (that provide comfort through air distribution networks).

Existing products using HFC refrigerants have not been discontinued and remain the dominant products sold in most markets. The installed base of these products will remain in service due to the long equipment lifetime. HFC alternatives are currently limited by safety regulations. One of the remaining challenges to their widespread adoption is the standards and codes variations between regions.

Nevertheless, there is a complete range of chillers in all major markets that use refrigerants with lower GWP, while maintaining or improving full and part load performance. Non-fluorinated refrigerants, namely R-717 and HC-290, are used in applications of specific sizes. Absorption chillers, which do not use a vapour compression cycle, are also available but are less efficient in the absence of waste heat.

Life Cycle Climate Performance (LCCP) calculations show that global warming effects from chillers are dominated by energy use over their lifetimes, rather than the direct emissions. Full and part load or seasonal energy consumption is therefore an important factor to consider during the development of new products.

5.8. Mobile AC/HP

Currently, there are still several refrigerants in use. HFC-134a is used globally. Where regulations require low GWP refrigerants, HFO-1234yf and R-744 provide market options. HFO-1234yf is widely adopted, especially for passenger vehicles. It remains unclear when other mobile AC applications, such as buses and heavy-duty trucks, will follow the light-duty vehicle trends.

Vehicle refrigerant use is shifting from being an optional feature for passenger cooling to a requirement for total vehicle thermal management. The progressive electrification of road transport in Europe, China and North America requires a new generation of refrigerants that can deliver thermal management in addition to passengers' cooling. Hence, electrification is broadening the technical options leading to reconsider the current refrigerant choices to include R-744, HFOs and blends s as viable options.

European regulations investigating PFAS are very broad and not product-specific at this time. This could lead to HFO-1234yf re-evaluation as an option for mobile AC. More details can be found in Chapter 3 of this report.

R-744 is a market alternative to HFO-1234yf for light duty vehicles and buses. Class A2 and class A3 (e.g., R-152a, hydrocarbons) refrigerants are being investigated, considering that secondary-loop architectures are an option for the electrified vehicle thermal systems.

5.9. Industrial refrigeration, heat pumps and heat engines

Industrial refrigeration, heat pumps, and heat engines are ubiquitous. They are used in a range industries such as food and beverage, fisheries, pharmaceuticals, petrochemicals, district cooling and heating systems, etc. Industrial refrigeration and heat pumps traditionally use R-717 but R-744 is also increasingly being used. R-717/R-744 cascade systems are also being widely adopted to mitigate risks associated with ammonia. There is also an emerging trend for the use of HCs and HC mixtures – especially for low temperature applications.

Heat recovery power-producing-systems, using Organic Rankine Cycles (ORC), may be useful where industrial waste heat is available. However, while the technology is still developing, systems are coming to the market using low-GWP refrigerants, but HFC-245fa is still being used.

5.10. Heating only heat pumps

Heating only heat pumps comprise heat pump water heaters, space heating heat pumps, and combined space and hot water heat pumps. They are sought for their potential role in buildings decarbonisation. Cost effectiveness remains an important consideration with a trade-off between capital and operating cost when compared with fossil-fuel powered heating systems. One of the recent innovations is the use of locally installed heat pumps in district heating and cooling systems to reduce typical grid losses.

Refrigerant selection depends greatly on the service water temperature. Heat pumps commercialised today employ a wide variety of refrigerants. The majority of new equipment uses R-410A and HFC-32. R-454B is currently being considered as a replacement for R-410A. In some A5 parties, HCFC-22 may still be used; although, there are no technical barriers to its phase-out. The European F-Gas regulations are driving the market towards low- and medium-GWP alternatives such as HC-290 and HFC-32. These refrigerants result in improved performance over R-410A and are cost-effective in small- to medium-sized systems.

Heat pumps are more material intensive than fossil fuel combustion boilers or direct electric heating. Therefore, the trade-off between energy efficiency improvements and material utilization has to be considered carefully.

At present, the main markets for water heating heat pumps are China, the EU, and Japan. China accounted for approximately 60% of the global demand of roughly 3.4 million units in 2019. This market is substantially smaller than the 100 million annual global air conditioner market. This suggests that heat pump market has the potential for rapid expansion. It is important to note that several states in the US have decarbonization plans that will increase the adoption of heat pumps.

5.11. Not-In-Kind technologies

Not-In-Kind (NIK) technologies could play an important role in sustainable cooling and heating. Absorption technologies operated using waste heat, direct/indirect evaporative cooling (IEC), hybrid IEC systems, desiccant cooling, and fossil-fired absorption systems are widely available. NIK technologies can provide lower operating lifecycle cost compared with mechanical vapour compression in some specific conditions. Typically, NIK technologies have higher capital cost than traditional systems.

Deep sea, lake, and ocean cooling have been investigated and few installations have been implemented. Studies have shown potential for low lifecycle operating cost, but at capital costs are higher than traditional IK systems. It has also been implemented in limited installations.

Other NIK technologies, including magnetocaloric, are in emerging and research and development phases. Some of these technologies, e.g., solid state cooling, are relatively successful in niche markets.

5.12. Servicing and refrigerant conservation

Refrigerants used in the servicing sector constitute the majority of consumption in many A5 parties, especially low- and very low- volume consuming countries (LVCs and VLVCs). Servicing and refrigerant conservation have an important role in the global efforts to reduce direct and indirect emissions. It is important to address the responsible use of refrigerants during the lifetime of products. Furthermore, proper servicing minimises the gradual degradation of energy efficiency in RACHP equipment over time.

The application of proper servicing techniques by trained and certified technicians, using proper tools, is crucial for the conservation of refrigerants as well as for the safety of the technicians and end users. Proper servicing techniques are described in codes. Capacity building activities in LVCs and VLVCs include training programmes, e.g., training of trainers, infrastructure, tools, and improved access to spare parts. The continuity of training, along with the application of the principals learned in daily work environments, is a major pillar for the introduction and the proliferation of low-GWP, energy-efficient refrigerants.

Refrigerant conservation is based on reducing leakages and emissions during the lifetime of equipment as well as the recovery and recycling of refrigerants during servicing and at the end-of-life. Predictive and preventive maintenance contribute to the reduction of emissions, while awareness on recovery and the provision of the tools to perform recycling and reclamation ensure the success of the programmes related to these efforts.

UN environment programme | ozone secretariat