

**MONTREAL PROTOCOL
ON SUBSTANCES THAT DEPLETE
THE OZONE LAYER**

**REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL**

SEPTEMBER 2019

**VOLUME 1: DECISION XXX/3 TEAP TASK FORCE REPORT ON
UNEXPECTED EMISSIONS OF TRICHLOROFLUOROMETHANE
(CFC-11)**

FINAL REPORT



Montreal Protocol on Substances that Deplete the Ozone Layer
United Nations Environment Programme (UNEP)
Report of the Technology and Economic Assessment Panel

September 2019

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ON UNEXPECTED EMISSIONS OF
TRICHLOROFLUOROMETHANE (CFC-11)**

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Foreword

The 2019 TEAP Report, September 2019

The 2019 TEAP Report, September 2019, consists of 3 volumes:

Volume 1: Decision XXX/3 Task Force Report on Unexpected Emissions of Trichlorofluoromethane (CFC-11), Final Report

Volume 2: Evaluation of 2019 Critical Use Nominations for Methyl Bromide, Final Report

Volume 3: Decision XXX/5 Task Force Report on Cost And Availability of Low-GWP Technologies/Equipment that Maintain/Enhance Energy Efficiency (Volume 3)

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REPORT OF THE TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL, SEPTEMBER 2019: VOLUME 1

DECISION XXX/3 TEAP TASK FORCE REPORT ON UNEXPECTED EMISSIONS OF TRICHLOROFLUOROMETHANE (CFC-11)

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Key Messages

- In response to scientific findings of an unexpected increase in global emissions of CFC-11 after 2012, parties requested the Technology and Economic Assessment Panel (TEAP) to provide them with relevant information on potential sources of emissions of CFC-11 and related controlled substances.
- Based on modelling of CFC-11 production, usage, emissions and comparison against atmospheric-derived emissions, it is unlikely that past production and historic usage can account for the unexpected CFC-11 emissions, including from existing foam banks.
- It is unlikely that there has been a resumption of newly produced CFC-11 usage in refrigeration and air-conditioning uses, flexible foams, aerosols, solvents, feedstock uses, tobacco expansion and other miscellaneous applications.
- It is likely that there has been a resumption of newly produced CFC-11 usage in closed-cell foams.
- There are a number of economic drivers that might have encouraged the reversion to CFC-11 in closed-cell or rigid foam, including price increases and reduced availability of HCFC-141b due to the global phase-out. Reversion from HCFC-141b to CFC-11 can be made with technical ease.
- Based on modelling using reported CFC-11 production data, it seems that the expected emissions from the CFC-11 foam banks in Northeast Asia are insufficient to account for the atmospheric-derived emissions from eastern mainland China in Rigby *et al.*
- Various parties imported up to 7,500 tonnes per year HCFC-141b in foam systems. Foam systems could be mislabeled and used by a recipient without knowing what blowing agent is in the system.
- The “most likely” modelling scenario predicts 40,000 to 70,000 tonnes per year CFC-11 production would have been required from 2012 onwards to account for the increased CFC-11 emissions.
- The most likely production routes are CTC to CFC-11 on micro-scale plants using minimal equipment (to make low grade CFC-11 for foam blowing use); and CTC to CFC-11/12 on a large-scale in an existing liquid phase plant (HCFC-22 and/or HFC-32 plant).
- Between 45,000 to 120,000 tonnes of CTC would be required to supply between 40,000 to 70,000 tonnes of CFC-11 production, depending on the proportion of co-produced CFC-12. The CTC quantity required for CFC-11 production is expected to be at the lower end of the range if, as predicted, the objective is higher CFC-11 selectivity.
- The quantity of CFC-12 co-produced as a result of any CFC-11 production is dependent on the exact production option chosen, and how the plant is set up and operated. With CFC-11 as the target chemical, for the most likely production routes, the range of CFC-12 co-production is between 0-30% of total CFC-11/12 production.

Executive Summary

The Montreal Protocol was established to protect the stratospheric ozone layer by reducing ozone-depleting substances (ODS), such as chlorofluorocarbons (CFCs), in the atmosphere. Successful measures were taken, with the abundance of ODS peaking in the late 1990s and continuously decreasing thereafter. CFC-11 (trichlorofluoromethane, CFC_3) was used primarily as a foam-blowing agent (for flexible and polyurethane (closed cell) insulating foams), as an aerosol propellant, as a refrigerant (for centrifugal chillers used in large buildings and industrial plants), and in a range of other smaller uses, including asthma inhalers, and tobacco expansion. There are alternative chemicals or products available as replacements for CFC-11. A bank of CFC-11 remains in closed cell foams and centrifugal chillers, from which CFC-11 is released slowly into the atmosphere over time.

CFC-11 production peaked between 350,000 and 400,000 tonnes per year, and peak emissions were about 350 gigagrams (or 350,000 tonnes) per year, in the late 1980s.¹ Under the Montreal Protocol, production of CFC-11 in non-Article 5 parties was phased out in 1996; production of CFC-11 in Article 5 parties was phased out in 2010, with some limited exceptions authorised by parties.

Montzka *et al.*, in a letter to *Nature* in 2018, reported an unexpected, global increase in CFC-11 emissions of $13,000 \pm 5,000$ tonnes per year after 2012. The study strongly suggests a concurrent increase in CFC-11 emissions from eastern Asia although the contribution of this region to the global increase was not quantified. The study also suggests that the CFC-11 emissions increase arises from new production that has not been reported to the Ozone Secretariat, which is inconsistent with the agreed phase-out of CFC production by 2010. Rigby *et al.*², in a letter to *Nature* in 2019, reported increased emissions of CFC-11 from eastern mainland China, with emissions shown to be 7.0 ± 3.0 (± 1 standard deviation) gigagrams per year higher in 2014–2017 than in 2008–2012, arising primarily from the northeastern provinces of Shandong and Hebei. These regional emissions were found to account for at least 40–60% of the global increase in CFC-11 emissions, with no evidence for any significant increase in CFC-11 emissions from any other eastern Asian countries or other regions of the world that were adequately monitored by atmospheric measurements.

In response to these scientific findings of an unexpected increase in global emissions of CFC-11 after 2012, at their 30th Meeting, parties requested the Technology and Economic Assessment Panel (TEAP) to provide them with relevant information on potential sources of emissions of CFC-11 and related controlled substances, as given in decision XXX/3. In response, TEAP formed a temporary subsidiary body, in the form of a Task Force, which combines expertise from TEAP and its Technical Options Committees (TOCs), and also outside expertise, to address the requirements of this decision.

Decision XXX/3 requests TEAP to prepare a preliminary report, to be provided in time for the Open-ended Working Group at its forty-first meeting and a final report, to be provided in time for the Thirty-First Meeting of the Parties. This report is the ~~preliminary~~ final report. A submission in response to decision XXX/3, paragraph 3, was received from China, which the Task Force has considered in its assessment. As noted in the report of the contact group on

¹ Montzka, S. *et al.*, An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, 2018, **557**, 413–417. <https://doi.org/10.1038/s41586-018-0106-2>.

² Rigby, M. *et al.*, Increase in CFC-11 emissions from eastern China based on atmospheric observations, *Nature*, 2019, **569**, 546–550. <https://doi.org/10.1038/s41586-019-1193-4>.

unexpected emissions of trichlorofluoromethane (CFC-11) at the 41st meeting of the OEWG, parties were invited to provide any relevant information that they may have on these issues to the Ozone Secretariat by 31 July 2019, in order to give the Task Force time to review it and finalize their report for submission to the Thirty-First Meeting of the Parties. Detailed additional information was provided by China, the European Union, Japan, Mexico, Russia, and the United States. The Task Force utilised information in the analysis and findings of this final report, to confirm or correct its assumptions used in the preliminary report. The Task Force also took into consideration feedback and questions raised at the 41st meeting of the OEWG, as documented in the meeting report.

The ~~preliminary~~ final report is structured to address the different elements in responding to the decision: production of CFC-11 and related controlled substances; foams uses; refrigerant uses; aerosols, solvents and miscellaneous uses; emissions modelling and analysis. It analyses the likelihood of potential sources of emissions. ~~and also identifies additional areas for consideration, as well as additional information needed to further determine the likelihood of some potential sources.~~ The final report adds directly to the preliminary report, with new text shown in grey highlights, and deleted text in strikeout. Headings have been renumbered where needed, and some material moved to appendices, to make way for new, updated analysis and information.

Production options for CFC-11 and related controlled substances

The possible production plant options for the manufacture of CFC-11 have been considered.

The main process routes to CFC-11 production use carbon tetrachloride (CTC) as feedstock; the possible availability of CTC has been considered to meet a range of potential CFC-11 production quantities annually from small-scale (\leq 10,000 tonnes per year) to large-scale (\geq 50,000 tonnes per year).

The Task Force considered 22 potential alternative CFC-11 production routes. The most likely production routes are CTC to CFC-11 on micro-scale plants using minimal equipment (to make low grade CFC-11 for foam blowing use); and CTC to CFC-11/12 on a large-scale in an existing liquid phase plant (HCFC-22³ and/or HFC-32 plant). Less likely but possible is CTC to CFC-11/12 on a large-scale in an existing vapour phase plant (dedicated CFC plant). If new CFC-11 production is occurring, emissions related solely to the production stage may occur but at relatively low rates, which are dependent on the production process used.

Based on modelling of CFC-11 production, usage and emissions and comparison against atmospheric observations, the “most likely” modelling scenario predicts 40,000 to 70,000 tonnes per year CFC-11 production would have been required from 2012 onwards to account for the increased CFC-11 emissions. This places CFC-11 production at the large-scale end of the production ranges considered.

If, ~~as predicted~~, larger scale CFC-11 production (\geq 50,000 tonnes per year) were required to account for the increased emissions, then it seems less likely that a large number of micro-scale

³ Overall likelihood of production route being a significant cause has been revised in light of information received from the parties. CTC to CFC-11/12 on large-scale existing HCFC- 22 liquid phase plant remains technically possible but is also considered unlikely due to compliance monitoring. Owing to the technical feasibility of this route, it remains as one of the most likely potential production routes.

plants would be solely responsible, although this does not preclude some micro-scale plants from contributing to the production.

The production of CFC-11 (and CFC-12) is possible in HCFC-22 plants. Spare annual capacity to produce CFC-11 in a HCFC-22 plant is estimated to be available in: Argentina, Mexico, Russia, and Venezuela for small-scale CFC-11 production (\leq 10,000 tonnes); ~~the European Union and the United States~~⁴ for medium-scale CFC-11 production (between 10,000 and 50,000 tonnes); and China and the European Union, for large-scale CFC-11 production (\geq 50,000 tonnes)⁵.

Similarly, the production of CFC-11 (and CFC-12) is possible in liquid phase HFC-32 plants. The production of 50,000 tonnes per year CFC-11 would require at least 20,000 tonnes per year spare HFC-32 capacity. An estimated 50,000 tonnes per year of spare HFC-32 capacity is estimated to have been available in 2012-2016 and is likely to remain available.

It is possible to produce almost 100% CFC-11 in a detuned CFC-11/12 or adapted modern HCFC-22 or HFC-32 plant. Near 100% CFC-11 production is also considered possible in a micro-production plant that is purposefully designed and operated on a batch basis to produce CFC-11 using similar feedstock and catalyst. The quantity of CFC-12 co-produced as a result of any CFC-11 production is dependent on the exact production option chosen, and how the plant is set up and operated. With CFC-11 as the target chemical, for the most likely production routes, the range of CFC-12 co-production is between 0-30% of total CFC-11/12 production.

CTC is produced in chloromethanes plants as an unavoidable part of the production of dichloromethane and chloroform. China, the European Union, and the United States have the largest chloromethanes capacities, and therefore also the largest potential availability of CTC. In 2016, the global maximum amount of potential CTC available from chloromethanes production, after existing local supply commitments had been met, was 305,000 tonnes. A number of regions have the spare annual capacity that might allow CTC production in the amounts required for small-scale CFC-11 production. Only China has the spare annual capacity that might allow CTC production to supply the larger amounts of CTC required for large-scale CFC-11 production.

CTC is also produced in perchloroethylene/CTC (PCE/CTC) plants, which have the flexibility to produce either substance according to demand. Five PCE/CTC plants are operative in Europe and the United States. Spare global capacity to produce CTC by this process is estimated to be between 50,000-100,000 tonnes per year, existing mainly in the European Union.

Between 45,000 to 120,000 tonnes of CTC would be required to supply between 40,000 to 70,000 tonnes of CFC-11 production, as predicted to account for the increased CFC-11 emissions, depending on the proportion of co-produced CFC-12. The CTC quantity required for CFC-11 production is expected to be at the lower end of the range if, as predicted, the objective is higher CFC-11 selectivity.

⁴ It is considered possible that maximising the CFC -11 production capabilities when adapting the HCFC -22 lines could increase the theoretically available CFC -11 production capacity of the United States to above $>$ 50,000 tonnes of CFC -11 per year.

⁵ For the year 2017, China and the European Union had spare capacity for HCFC-22 production of less than 50,000 tonnes. For the years 2013-2016, China and the European Union had estimated spare capacity greater than 50,000 tonnes per year.

There does not appear to be evidence through customs or other agency activities, including seizures or interceptions, that illicit international trade in significant quantities of CFC-11 or CTC has occurred in recent years. However, there have been indications of recent marketing of CFC-11 for use in foams.

Foams

Based on its current assessment, the Task Force finds that the production of certain foam products using CFC-11 may be a potential source of the sudden and increased emissions of CFC-11. It is likely that there has been a resumption of newly produced CFC-11 usage in closed-cell foams.

It seems unlikely that the unexpected emissions have resulted from the traditional handling of foams at end-of-life alone unless there has been a significant change in those processes from appliances and construction for a very large volume of foams. This has been further validated in the final report by more closely examining the expected timing of increased emissions associated with the dismantling of foams.

There are indications of CFC-11 marketing into foams use. The Foams Technical Options Committee was provided with a copy of an offer for sale of CFC-11 for 2,200 USD/tonne through distribution, has seen offers for sale on internet websites, and has learned more through industry discussions.

Although technically feasible, the Task Force questions the economic incentive for open-cell flexible foams of broadly replacing methylene chloride, given its very low cost, with CFC-11. Nevertheless, the Task Force continues to explore the possibility of use of CFC-11 to reduce volatile organic compound emissions from flexible foams as limited in some parties or limitations in the use of methylene chloride due to toxicity concerns. After reviewing low-cost alternatives available to produce flexible foams, the Task Force has concluded that it is very unlikely that there has been renewed use of CFC-11 in flexible foams.

Further investigation is warranted was completed into the use of CFC-11 for polyurethane (PU) foams and polyol systems for PU rigid foams as it is technically feasible and more economically advantageous than reverting to use CFC-11 in flexible foams. However, it seems unlikely that multi-national or other large system houses would risk their reputations by knowingly using CFC-11.⁶ The increased CFC-11 emissions imply volumes of CFC-11 usage that seem to go beyond that of smaller or local system houses. It is likely that there has been a resumption of newly produced CFC-11 usage in closed-cell foams.

The conversion of enterprises in the spray foam sector and small and medium enterprises (SMEs) has created technical and economic challenges that might drive the use of CFC-11. Whether or not this has resulted in the actual usage of CFC-11 blowing agents, or to any significant degree, has not been confirmed.

There is a difference between the projected estimated CFC-11 emissions from foams in banks (including landfills), based on emission rates found in the literature, and the derived atmospheric emissions, including in regions where CFC-11 has not likely been used in foams in decades (< 1.5% and 3-4%, respectively). It is possible that further processing of foams before

⁶ This comment has been removed as a number of examples of large companies risking their reputations by knowingly violating laws and regulations (e.g., Volkswagen, Enron, etc.)

disposal, through shredding and crushing of foams, accounts for at least some of that difference. Further investigation into emission rates from foams banks is warranted. Parties have provided information in their submissions that has helped to address the gap in the emissions rates when foams are dismantled.

Any scenario where significant CFC-11 is used in rigid or closed cell polyurethane foams would require significant CFC-11 production and would also result in an increase of the foam banks (e.g., emissions of 1,000 tonnes of CFC-11 from the manufacture of closed-cell foams would imply an increase in the foam bank of 3,000 tonnes or more). Further analysis of the potential use of CFC-11 in rigid or closed-cell polyurethane foams was completed for the final report. Even the most extreme bank emissions scenarios do not account for the unexpected emissions of CFC-11. Additional information regarding banks and emissions is included in the emissions chapter.

It is considered economically attractive and technically straight-forward to revert to using CFC-11 from HCFC-141b, or another fluorocarbon, as the other raw materials and equipment used to produce foams are compatible with only slight modifications to ingredient ratios. In addition, there are a number of regulatory, cost and technical drivers that might further encourage the transitions backward to the use of CFC-11, including a shortage in HCFC-141b resulting from the phase-out commencing in 2013.

The MLF Secretariat provided data indicating that up to 7,500 tonnes per year blowing agent had been reported as being incorporated into foam systems and imported by various parties. Foam systems could be mislabeled and used by a recipient without knowing what blowing agent is in the system.

The higher pricing and lack of availability of HCFC-141b related to the ODS phase-out combined with the technical ease of conversion to CFC-11 could be a driver for reverting to use of CFC-11 as a blowing agent. CFC-11 as a blowing agent could also be of interest to companies who erroneously believe that it may reduce foam flammability without using expensive fire retardants.

Refrigeration and air conditioning

Centrifugal chillers using CFC-11 (some used CFC-12) have always been a relatively small part of the total CFC refrigerant inventory and emissions of all refrigeration and air-conditioning (R/AC) sub-sectors. While CFC-12 centrifugal chillers have been virtually phased out, a small number of CFC-11 chillers are still in operation and expected to reach their end of life in the next 1 to 5 years, at the latest. Based on estimates of CFC-11 banks and emissions, emissions from CFC-11 chillers do not constitute a major portion of the global CFC-11 emissions calculated from atmospheric observations in 2002-2012, and similarly emissions from chillers cannot be a cause for the sudden increase of global CFC-11 emissions since 2013, as derived from atmospheric calculations. It is unlikely that CFC-11 production would be employed to maintain a very small number of centrifugal CFC-11 chillers in operation.

It is also unlikely that there is a significant resumption of CFC-12 usage in any R/AC sub-sector in both non-Article 5 and Article 5 parties. This implies that no significant new CFC-12 production would be needed for all R/AC sub-sector uses, and that this would not be the reason for possible CFC-11 co-production. There might be a continuing small CFC-12 demand for a limited number of CFC-12 mobile ACs in certain vehicles, namely some luxury or special vehicles built before 2002 in Article 5 parties. However, this small demand is likely to be supplied from the recycling of refrigerant from aged CFC-12 equipment.

Aerosols, solvents, and other applications

The main use of CFCs was as a pressurized liquid in aerosols, which is an emissive use. While CFC-11 worked very well in combination with CFC-12 to obtain variations in propellant pressure, CFC-11 could not be used alone as a propellant. It is technically feasible to use mixtures of hydrocarbon propellants and CFC-11 in aerosols. If CFC-11 were readily available, it would be technically feasible to use it in aerosol products. However, it seems unlikely that CFC-11 would be produced or used nowadays for aerosols; the main reason is that hydrocarbons are much cheaper than CFCs. While it would be technically possible to make an MDI mixing CFC-11 and HFC-134a or HFC-227a, it seems highly unlikely that any MDI producer would choose this route.

Production of synthetic fibre sheet with CFC-11 is listed in decision XXIX/7 Table A as a process agent and is permitted for use only in the United States, for which emissions are very low. It is extremely unlikely that CFC-11 would be used in a newly established (illicit) plant to manufacture synthetic fibre sheet and that this would be highly emissive. Similarly, it seems extremely unlikely that CFC-11 might be used as a solvent. With the alternatives available, there are also no technical or economic reasons to believe that the recent increase in CFC-11 emissions would be due to tobacco expansion or the processing of uranium.

Emissions and banks modelling

Based on updated modelling and analysis of CFC-11 emissions and banks, it is unlikely that past production, historic usage, and the resulting bank can account for the unexpected CFC-11 emissions, unless there has been a significant change in the treatment of large quantities of banked CFC-11. The final report confirms no evidence of a significant change in the treatment of large quantities of CFC-11 at the end-of-life.

Atmospheric-measurement derived emissions from banks in Western Europe, where CFC-11 has not been used for several decades, continue to generally decline (2-4% per year). If it is assumed that CFC-11 emissions from banks in other regions generally decline in a similar fashion, it appears that the unexpected increases in global CFC-11 emissions cannot be explained by bank emissions. Unless banks are treated very differently in other regions where CFC-11 has been used more recently, or where there is no atmospheric data collected, it seems unlikely that the source of the increased CFC-11 emissions is from CFC-11 banks. Further analysis of regional banks was completed for the final report, incorporating the duration of foam use and the subsequent timing for emissions from dismantling foams. The Task Force concluded that in no region are the unexpected emissions likely to have originated from the existing foam banks.

Scenarios were evaluated combining estimated sales of newly produced CFC-11 into multiple markets (combinations of foams, emissive uses, and chillers). Although technically feasible, the Task Force believes that widespread use of newly produced CFC-11 in sectors other than closed-cell foam is unlikely.

Most of the closed-cell foam as of 2006 was produced in Europe and North America with smaller quantities produced regions in the Southern Hemisphere. It is anticipated that most of the global emissions of CFC-11 would have occurred in those regions during foam manufacturing and installation and during the lifetime of products containing those foams. Destruction of foams is increasing in these regions and there are significant quantities of CFC-11 blown foams still in use in building.

Based on modelling using reported CFC-11 production data, it seems that the expected emissions from the CFC-11 foam banks in Northeast Asia are insufficient to account for the atmospheric-derived emissions from eastern mainland China in Rigby *et al.*

Estimated bottom-up CFC-12 emissions are consistently lower than the atmospheric-measurement derived emissions, indicating high underlying uncertainty in the bottom-up model's assumptions. As a result, estimates of bottom-up CFC-12 emissions are inconclusive.

~~None of the analyses of the available data eliminates the possibility that newly produced CFC 11 might have resumed use in closed cell foams. There are scenarios modelling the potential use of CFC 11 in closed cell foams that align with the derived emissions of CFC 11. Based on this overall evaluation, the Task Force recommends continued exploration into the potential use of CFC 11 in closed cell foams to explain the unexpected increased emissions of CFC 11.~~

Advance

1 Introduction

1.1 Decision XXX/3: Unexpected emissions of trichlorofluoromethane (CFC-11)

In response to recent scientific findings of an unexpected increase in global emissions of CFC-11 after 2012, at their 30th Meeting parties requested the Technology and Economic Assessment Panel (TEAP) to provide them with relevant information on potential sources of emissions of CFC-11 and related controlled substances, as instructed in decision XXX/3.

Decision XXX/3: Unexpected emissions of trichlorofluoromethane (CFC-11)

Noting the recent scientific findings showing that there has been an unexpected increase in global emissions of trichlorofluoromethane (CFC-11) since 2012, after the consumption and production phase-out date established under the Montreal Protocol,

Appreciating the efforts of the scientific community in providing that information,

Expressing serious concern about the substantial volume of unexpected emissions of CFC-11 in recent years,

1. To request the Scientific Assessment Panel to provide to the parties a summary report on the unexpected increase of CFC-11 emissions, which would supplement the information in the quadrennial assessment, including additional information regarding atmospheric monitoring and modelling, including underlying assumptions, with respect to such emissions; a preliminary summary report should be provided to the Open-ended Working Group at its forty-first meeting, a further update to the Thirty-First Meeting of the Parties and a final report to the Thirty-Second Meeting of the Parties;
2. To request the Technology and Economic Assessment Panel to provide the parties with information on potential sources of emissions of CFC-11 and related controlled substances from potential production and uses, as well as from banks, that may have resulted in emissions of CFC-11 in unexpected quantities in the relevant regions; a preliminary report should be provided to the Open-ended Working Group at its forty-first meeting and a final report to the Thirty-First Meeting of the Parties;
3. To request parties with any relevant scientific and technical information that may help inform the Scientific Assessment Panel and Technology and Economic Assessment Panel reports described in paragraphs 1 and 2 above to provide that information to the Secretariat by 1 March 2019;
4. To encourage parties, as appropriate and as feasible, to support scientific efforts, including for atmospheric measurements, to further study the unexpected emissions of CFC-11 in recent years;
5. To encourage relevant scientific and atmospheric organizations and institutions to further study and elaborate the current findings related to CFC-11 emissions as relevant and appropriate to their mandate, with a view to contributing to the assessment described in paragraph 1 above;
6. To request the Secretariat, in consultation with the secretariat of the Multilateral Fund for the Implementation of the Montreal Protocol, to provide the parties with an overview outlining the procedures under the Protocol and the Fund with reference to

controlled substances by which the parties review and ensure continuing compliance with Protocol obligations and with the terms of agreements under the Fund, including with regard to monitoring, reporting, and verification; to provide a report to the Open-ended Working Group at its forty-first meeting and a final report to the Thirty-First Meeting of the Parties;

7. To request all parties:

(a) To take appropriate measures to ensure that the phase-out of CFC-11 is effectively sustained and enforced in accordance with obligations under the Protocol;

(b) To inform the Secretariat about any potential deviations from compliance that could contribute to the unexpected increase in CFC-11 emissions;

1.2 Composition of the Task Force

In response to decision XXX/3, TEAP formed a temporary subsidiary body, in the form of a Task Force, which combines expertise from TEAP and its Technical Options Committee (TOCs), and also outside expertise, to address the requirements of this decision. Membership of the TEAP Task Force on Unexpected CFC-11 Emissions (the Task Force) is listed below. The Task Force includes a number of consulting experts, who have provided an invaluable resource. Disclosures of interests are posted on the Ozone Secretariat's website.

The Task Force worked via teleconference and email and met on 28-29th March in Vienna.

Members	Relevant Expertise to the Task Force	Affiliation	Party
Jose Pons (co-chair)	Production, aerosols, solvents	MCTOC member	Venezuela
Helen Tope (co-chair)	Production, aerosols, solvents	MCTOC co-chair	Australia
Helen Walter-Terrinoni (co-chair)	Foams, banks, emissions modelling	FTOC co-chair	USA
Paulo Altoé	Foams	FTOC co-chair	Brazil
Paul Ashford	Foams, banks, emissions modelling	FTOC member	UK
Nick Campbell	Production, supply chain	MCTOC member	France
Marco Gonzalez	Montreal Protocol and institutions	TEAP Senior Expert	Costa Rica
Dave Godwin	Emissions modelling	RTOC member	USA
Jianxin Hu	Production, phase-out	MCTOC member	PRC
Rabinder Kaul	Production, supply chain	SRF Limited	India
Lambert Kuijpers	Refrigeration and air conditioning, banks, emissions modelling	RTOC member	Netherlands
Richard Lord	Refrigeration and air conditioning, life cycle	Carrier	USA
Bella Maranion	Montreal Protocol and institutions	TEAP co-chair	USA
Keiichi Ohnishi	Production, supply chain, solvents	MCTOC co-chair	Japan
Fabio Polonara	Refrigeration and air conditioning	RTOC co-chair	Italy
Miguel Quintero	Foams	FTOC member	Colombia
Enshan Sheng	Foams	Huntsman	Singapore
David Sherry	Production, supply chain	Nolan Sherry & Associates Ltd.	UK
Sidi Menad Si-Ahmed	Climatology, Montreal Protocol and institutions	TEAP Senior Expert	Algeria
Peter Sleigh	Production, supply chain	Mexichem UK Ltd.	UK
Christina Theodoridi	Catalyst, emissions modelling	NRDC	Greece
Shiqiu Zhang	Environmental economics	TEAP Senior Expert	PRC
Consulting Experts	Relevant Expertise to the Task Force	Affiliation	Party
Angela Austin	Foams	FTOC member	UK
Andy Lindley	Production, supply chain	MCTOC member	UK
Archie McCulloch	Production, supply chain, emissions modelling	Retired private consultant	UK
Steve Montzka	Atmospheric science	NOAA	USA
Matt Rigby	Atmospheric science	University of Bristol	UK
Susan Solomon	Atmospheric science	MIT	USA
Guus Velders	Atmospheric science and emissions modelling	Utrecht University	Netherlands
Dan Verdonik	Fire protection	HTOC co-chair	USA

1.3 Vienna Symposium and Beijing Workshop

A number of TEAP and Task Force members participated in the International Symposium on The Unexpected Increase in Emissions of Ozone-Depleting CFC-11, 25th-27th March 2019, in Vienna, Austria, <https://www.sparc-climate.org/meetings/meetingscfc-11-workshop-march-2019-in-vienna/>. The purpose of the Symposium was to provide a forum for scientists and technologists to explore and present information on the potential causes of the increased CFC-11 emissions. The Task Force presented initial findings of its preliminary report and benefitted from the discussion of relevant science. A report⁷ on the Symposium was included in the July Newsletter of SPARC.

⁷ SPARC, 2019: SPARC Newsletter No. 53, July 2019, 44 pp., available at www.sparc-climate.org/publications/newsletter

China held a Workshop on Capacity Building for the Implementation of the Montreal Protocol in China, March 18-19, 2019, in Beijing, China. The purpose of the workshop was to consider China's implementation mechanism, including how to strengthen monitoring and law enforcement. A number of TEAP and Task Force members were invited as experts in their individual capacities to attend the workshop to participate and share information. A number were unable to attend due to other commitments; those that attended and/or gave presentations, did so in their individual capacities.

1.4 Summary background

CFC-11 (trichlorofluoromethane, CFCl_3) was used primarily as a foam-blown agent (for flexible and polyurethane (closed cell) insulating foams), as an aerosol propellant, as a refrigerant (for centrifugal chillers used in large commercial buildings), and in a range of other smaller uses, including asthma inhalers, and tobacco expansion. There are alternative chemicals or products available as replacements for CFC-11. A bank of CFC-11 remains in closed cell foams and centrifugal chillers, from which CFC-11 is released slowly into the atmosphere over time.

CFC-11 production peaked between 350,000 and 400,000 tonnes per year in the 1980s. Peak emissions were about 350 gigagrams (or 350,000 tonnes) per year in the late 1980s.⁸ Under the Montreal Protocol, production of CFC-11 in non-Article 5 parties was phased out in 1996; production of CFC-11 in Article 5 parties was phased out in 2010. Exceptions were made for small amounts of CFC-11 production for essential uses (i.e., metered dose inhalers for the treatment of asthma and chronic obstructive pulmonary disease), as authorised by parties, and for non-Article 5 parties to produce CFC-11 for the basic domestic needs of Article 5 parties.

The Montreal Protocol was established to protect the stratospheric ozone layer by reducing ozone-depleting substances (ODS), such as chlorofluorocarbons (CFCs), in the atmosphere. Successful measures were taken, with the abundance of ODS peaking in the late 1990s and continuously decreasing thereafter. However, Montzka *et al.*⁹, in a letter to Nature in 2018, reported an unexpected, global increase in CFC-11 emissions of $13,000 \pm 5,000$ tonnes per year after 2012. The study strongly suggests a concurrent increase in CFC-11 emissions from eastern Asia although the contribution of this region to the global increase was not quantified. The study also suggests that the CFC-11 emissions increase arises from new production that has not been reported to the Ozone Secretariat, which is inconsistent with the agreed phase-out of CFC production by 2010.

Subsequently, in July and November 2018, the Environmental Investigation Agency published findings of its investigations into potential sources of the increased CFC-11 emissions from eastern Asia.¹⁰ The international media¹¹ also investigated and reported on potential sources of these emissions.

⁸ Ibid., Montzka, S. *et al.*, 2018.

⁹ Ibid., Montzka, S. *et al.*, 2018.

¹⁰ Environmental Investigation Agency, *Blowing It: Illegal Production and Use of Banned CFC-11 in China's Foam Blowing Industry*, July 2018, <https://eia-international.org/report/blowing-it/>. *Tip of the Iceberg: Implications of Illegal CFC Production and Use*, November 2018, <https://eia-international.org/report/tip-iceberg-implications-illegal-cfc-production-use/>. Both accessed May 2019.

¹¹ *Inter alia*, The New York Times, *In a High-Stakes Environmental Whodunit, Many Clues Point to China*, By Chris Buckley and Henry Fountain, June 24, 2018.

In a letter to Nature in 2019 that updated and expanded upon the original study, Rigby *et al.*¹² reported increased emissions of CFC-11 from eastern mainland China, with emissions shown to be 7.0 ± 3.0 (± 1 standard deviation) gigagrams per year higher in 2014–2017 than in 2008–2012, arising primarily from the northeastern provinces of Shandong and Hebei. These regional emissions were found to account for at least 40–60% of the global increase in CFC-11 emissions, with no evidence for any significant increase in CFC-11 emissions from any other eastern Asian countries or other regions of the world that were adequately monitored by atmospheric measurements¹³. Between 2008 and 2012, annual global emissions of CFC-11 were $64,000 \pm 2,000$ tonnes per year or $63,000 \pm 2,000$ tonnes per year, based on observations from AGAGE or NOAA, respectively.¹⁴ Based on several considerations, Rigby *et al.* suggested that the increase in CFC-11 emissions from eastern mainland China was likely to result from new production and use of CFC-11.

1.5 Relevant findings from the Science Assessment Panel: 2018 Assessment and preliminary summary report to the meeting of the 41st OEWG

The following are excerpts taken from the WMO, Scientific Assessment of Ozone Depletion, 2018¹⁵, relevant to the unexpected increase in emissions of CFC-11.

“There has been an unexpected increase in global total emissions of CFC-11. Global CFC-11 emissions derived from measurements by two independent networks increased after 2012, thereby slowing the steady decrease in atmospheric concentrations reported in previous Assessments. The global concentration decline over 2014 to 2016 was only two- thirds as fast as it was from 2002 to 2012. While the emissions of CFC-11 from eastern Asia have increased since 2012, the contribution of this region to the global emission rise is not well known. The country or countries in which emissions have increased have not been identified.” [Executive Summary, ES.3]

“Observations of the persistent slowdown in the decline of CFC-11 concentrations have only recently allowed the robust conclusion that emissions of CFC-11 have increased in recent

¹² Rigby, M. *et al.*, Increase in CFC-11 emissions from eastern China based on atmospheric observations, *Nature*, 2019, **569**, 546–550. <https://doi.org/10.1038/s41586-019-1193-4>.

¹³ While measurements from many global sites were considered in Rigby *et al.*, the atmospheric measurements that point to increases in emissions from eastern China were taken from the Gosan station in South Korea and the Hateruma station in Japan. These stations are sensitive to, and enable, quantification of emissions from western Japan, the Korean Peninsula, and eastern mainland China, which includes the provinces of Anhui, Beijing, Hebei, Jiangsu, Liaoning, Shandong, Shanghai, Tianjin and Zhejiang. The measurements from these stations suggested that emissions from eastern mainland China are substantially larger than those from western Japan and the Korean Peninsula, and that emissions from two Chinese provinces in particular increased after 2012. No significant emission increase was derived for other eastern Asian countries or regions where atmospheric data enables the quantification of regional emissions, although this existing measurement network does not provide regional emission estimates for many populated regions of the world. The region contributing the remaining fraction of the global CFC-11 emission increase is not identifiable at this time, given the limited regional emission information supplied by the existing measurement network. It is possible that variations in atmospheric circulation may have contributed in part to the slow-down of the global atmospheric concentration decline of CFC-11, but the available evidence compiled in Montzka *et al.* and Rigby *et al.* clearly point to a global emission increase in CFC-11 emissions that is explained in large part by increased emissions from two provinces in eastern China.

¹⁴ Using a two-dimensional model of atmospheric transport and chemistry, and assuming a lifetime of 52 years.

¹⁵ WMO (World Meteorological Organization), *Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58*, 588 pp., Geneva, Switzerland, 2018.

years, as opposed to other possible causes for the slowdown such as changing atmospheric circulation.

- Global CFC-11 emissions, derived from measurements by two independent networks, increased after 2012 contrary to projections from previous Assessments, which showed decreasing emissions (Figure ES-2). This conclusion is supported by the observed rise in the CFC-11 hemispheric concentration difference. Global CFC-11 emissions for 2014 to 2016 were approximately 10 Gg yr⁻¹ (about 15%) higher than the fairly constant emissions derived for 2002 to 2012; the excess emissions relative to projected emissions for recent years is even larger. The increase in global emissions above the 2002–2012 average resulted in a global concentration decline in CFC-11 over 2014 to 2016 that was only two-thirds as fast as from 2002 to 2012.
- The CFC-11 emission increase suggests new production not reported to UN Environment because the increase is inconsistent with likely changes in the release of CFC-11 from banks associated with pre-phase-out production. Depending on how this newly produced CFC-11 is being used, substantial increases in the bank and future emissions are possible.
- Emissions of CFC-11 from eastern Asia have increased since 2012; the contribution of this region to the global emission rise is not well known. The country or countries in which emissions have increased have not yet been identified.” [Executive Summary, ES.18]

In response to decision XXX/3, paragraph 2, the SAP provided a preliminary summary report to the 41st meeting of the Open-ended Working Group. The preliminary report presented a summary of: CFC-11 observations and global network; findings from WMO/UNEP [2018] and the CFC-11 Symposium in Vienna in March; findings from the May 2019 paper by Rigby *et al.* showing regional emissions changes over time estimated from atmospheric measurements made in eastern Asia; and plans for research and reporting on CFC-11 emissions.¹⁶

1.6 Submissions received

A submission in response to decision XXX/3, paragraph 3, was received from China, which is reproduced in Annex 1. The Task Force has considered and incorporated relevant information into its assessment in the preliminary report.

As noted in the report of the contact group on unexpected emissions of trichlorofluoromethane (CFC-11) at the 41st meeting of the OEWG, the Task Force identified a range of topics (see section 1.8) on which it would benefit from additional information from the parties for its final report. Parties were invited to provide any relevant information that they may have on these issues to the Ozone Secretariat by 31 July 2019, in order to give the Task Force time to review it and finalize their report for submission to the Thirty-First Meeting of the Parties.

¹⁶ Scientific Assessment Panel, SAP co-chairs: Bonfils Safari, John Pyle, David Fahey, Paul A. Newman, *SAP interim report on increased emissions of CFC-11*, 41st Open-ended Working Group, Bangkok, Thailand, July 1-5, 2019. http://conf.montreal-protocol.org/meeting/oewg/oewg-41/presentations/English/SAP_CFC-11_presentation_OEWG41_Bangkok_v3.pdf.

Detailed additional information was provided by China, the European Union, Japan, Mexico, Russia, and the United States, on topics including: CFC-11 and related chemicals production, usage and disposal; CFC-11 inventory and recycling; foams usage, end-of-life practices, and related CFC-11 emissions rates; and results of enforcement activities. With appreciation, the Task Force utilised information in the analysis and findings of this final report, to confirm or correct its assumptions used in the preliminary report.

1.7 Preliminary report

Decision XXX/3 requests TEAP to prepare a preliminary report, to be provided in time for the Open-ended Working Group at its forty-first meeting and a final report, to be provided in time for the Thirty-First Meeting of the Parties. The preliminary report was published in May and presented to the 41st meeting of the OEWG.

The preliminary report addressed the decision XXX/3 request to TEAP to “*provide information on potential sources of emissions of CFC-11 and related controlled substances from potential production and uses, as well as from banks, that may have resulted in emissions of CFC-11 in unexpected quantities in the relevant regions.*” The preliminary report was structured to address the different elements in responding to the decision:

- Production of CFC-11, including consideration of production models, implications associated with dichlorodifluoromethane (CFC-12) and carbon tetrachloride, and potential other pathways for producing CFC-11 (Chapter 2);
- Foams, including the history of CFC-11 usage in foam applications, recent indications of marketing of CFC-11 into foams, and the technical feasibility and implications of reverting to CFC-11 in foam use (Chapter 3);
- Refrigerant uses, including the history of CFC-11 and CFC-12 usage in refrigeration and air conditioning (R/AC); a summary of a recent study estimating the numbers of CFC-11 chillers, their CFC-11 banks, and emissions; an analysis of CFC-12 R/AC banks and emissions; and the potential for any resumption of CFC usage in R/AC (Chapter 4);
- Aerosols, solvents and miscellaneous uses, such as tobacco expansion and uranium processing, including the history of CFC-11 usage as a propellant in combination with CFC-12, as a process agent, for tobacco expansion, and as a feedstock in uranium processing (Chapter 5);
- Emissions modelling and analysis, including of CFC-11 emissions and banks, to consider the impact of different usage scenarios on CFC-11 emissions for comparison with derived CFC-11 emissions from atmospheric observations (Chapter 6).
- Conclusions that summarise the findings of the Task Force and elaborate additional considerations including areas for further assessment and additional information needs (Chapter 7).

1.8 Final report

Decision XXX/3 requests TEAP to prepare a preliminary report, to be provided in time for the Open-ended Working Group at its forty-first meeting and a final report, to be provided in time for the Thirty-First Meeting of the Parties. This report is the final report.

This final report completes TEAP's response to decision XXX/3 to "provide information on potential sources of emissions of CFC-11 and related controlled substances from potential production and uses, as well as from banks, that may have resulted in emissions of CFC-11 in unexpected quantities in the relevant regions."

The final report adds directly to the preliminary report, with new text shown in grey highlights, and deleted text as strikeouts. Headings have been renumbered where needed, and some material moved to appendices, to make way for new, updated analysis and information to appear in the main text.

As noted in the Annex II report of the contact group on unexpected emissions of trichlorofluoromethane (CFC-11), the Task Force identified the following topics on which it would benefit from additional information from the parties for its final report:

- a) CTC production quantities and the uses to which CTC was put, by quantity, including export amounts and locations;
- b) CTC and HCFC-22 plant capacities;
- c) Validation of shutdowns and dismantling of plants producing ozone-depleting substances;
- d) Quantities of CFC-11 inventory in stockpiles at the cessation of production, and the fate of such inventory thereafter;
- e) Any evidence of illegal CFC-11 or CTC shipments;
- f) The capacities and production quantities for CFC-11 and CFC-12 and CTC plants in parties regarding which less is known about historical production of ozone-depleting substances;
- g) CFC-11 emission sources related to recycling and destruction of equipment and foams;
- h) Foam blowing agent emissions rates that may be used for any purpose (i.e., to determine insulating capability or exposure from a public health perspective);
- i) Specific end-of-life practices especially for foams; and
- j) Regulations affecting the use of dichloromethane.

The Task Force utilised information received in parties' submissions, and from other sources, in completing the analysis and findings in this final report, and to confirm or correct its assumptions in the preliminary report. The Task Force has also taken into consideration feedback and questions raised at the 41st meeting of the OEWG, as documented in the meeting report, where this was considered within the scope of the decision.

2 Production of CFC-11 and related controlled substances

2.1 Summary

- The possible production plant options for the manufacture of CFC-11 have been considered. These options depend on the desired annual quantity of CFC-11 to be produced and cover a range of plant types that have different capacities, economics, and times to achieve production (for example, whether the plant is rebuilt or converted).
- The main process routes to CFC-11 production use carbon tetrachloride (CTC) as feedstock; the possible availability of CTC has been considered to meet a range of CFC-11 production annually from small-scale ($\leq 10,000$ tonnes per year) to large-scale ($\geq 50,000$ tonnes per year).
- The selected CFC-11 production output range allowed for different CFC-11 production routes to be reviewed by the Task Force to provide an overall assessment of the likelihood of each production route as a contributor to the incremental increase in CFC-11 emissions.
- Historically CFC-11 was most commonly produced from hydrogen fluoride (HF) and CTC mainly in a liquid phase process in the presence of an antimony catalyst. A mix of CFC-11 and CFC-12 is produced, with the proportion of CFC-12 and CFC-11 controlled by varying the operating conditions. 100% CFC-12 is achieved relatively easily; 100% CFC-11 is more difficult to achieve but not impossible in well-operated facilities. An operating range of 30:70, either way¹⁷, can be comfortably achieved. In well-operated facilities, emissions from production processes are low (average 0.5%).
- Of the 22 potential alternative CFC-11 production routes considered by the Task Force, the most likely production routes are: CTC to CFC-11 on micro-scale plants using minimal equipment¹⁸ (to make low grade CFC-11 for foam blowing use); and CTC to CFC-11/12 on a large-scale in an existing liquid phase plant (HCFC-22¹⁹ and/or HFC-32 plant). Less likely but possible is CTC to CFC-11/12 on a large-scale in an existing vapour phase plant (dedicated CFC plant). If new CFC-11 production is occurring, emissions related solely to the production stage may occur but at relatively low rates, which are dependent on the production process used.
- Based on modelling of CFC-11 production, usage and emissions and comparison against atmospheric observations, the “most likely” modelling scenario predicts 40,000 to 70,000 tonnes per year CFC-11 production would have been required from 2012 onwards to account for the increased CFC-11 emissions. This places CFC-11 production at the large-scale end of the production ranges considered.

¹⁷ A range from 30% CFC-12 and 70% CFC-11 to 70% CFC-12 and 30% CFC-11.

¹⁸ A number of plants within this category have been reportedly shutdown in the last few years.

¹⁹ Overall likelihood of production route being a significant cause has been revised in light of information received from the parties. CTC to CFC-11/12 on large-scale existing HCFC- 22 liquid phase plant remains technically possible but is also considered unlikely due to compliance monitoring. Owing to the technical feasibility of this route, it remains as one of the most likely potential production routes.

- If, as predicted, large-scale CFC-11 production ($\geq 50,000$ tonnes per year) were required to account for the increased emissions, then it seems less likely that a large number of micro-scale plants would be solely responsible, although does not preclude some micro-scale plants from contributing to the production.
- The production of CFC-11 (and CFC-12) is possible in HCFC-22 plants. Spare annual capacity to produce CFC-11 in a HCFC-22 plant is estimated to be available in: Argentina, Mexico, Russia, and Venezuela for small-scale CFC-11 production ($\leq 10,000$ tonnes); the European Union and the United States²⁰ for medium scale CFC-11 production (between 10,000 and 50,000 tonnes); and China and the European Union, for large-scale CFC-11 production ($\geq 50,000$ tonnes)²¹.
- Similarly, the production of CFC-11 (and CFC-12) is possible in liquid phase HFC-32 plants. The production of 50,000 tonnes per year CFC-11 would require at least 20,000 tonnes per year spare HFC-32 capacity. An estimated 50,000 tonnes per year of spare HFC-32 capacity is estimated to have been available in 2012-2016 and is likely to remain available.
- It is possible to produce almost 100% CFC-11 in a detuned²² CFC-11/12 or adapted modern HCFC-22 or HFC-32 plant. Near 100% CFC-11 production is also considered possible in a micro-production plant that is purposefully designed and operated on a batch basis to produce CFC-11 using similar feedstock and catalyst. Emissions from this type of illicit and unregulated plant, with inadequate controls, could be up to 10% of CFC-11 production.
- The quantity of CFC-12 co-produced as a result of any CFC-11 production is dependent on the exact production option chosen, and how the plant is set up and operated. With CFC-11 as the target chemical, for the most likely production routes, the range of CFC-12 co-production is between 0-30% of total CFC-11/12 production. Excluding emissions from any CFC-12 usage, it seems plausible that economic factors could limit average CFC-12 emissions to less than say 5% of the CFC-11 production rates, i.e., less than 3,500 tonnes per year of CFC-12 emissions (based on the upper range of predicted CFC-11 production of 70,000 tonnes that could account for the increased CFC-11 emissions).
- Most of the global production (80%) of CTC is from chloromethanes plants, with 20% from perchloroethylene/CTC (PCE/CTC) plants.
- CTC is produced in chloromethanes plants as an unavoidable part of the production of dichloromethane and chloroform. China, the European Union, and the United States have the largest chloromethanes capacities, and therefore also the largest potential availability of CTC. In 2016, the global maximum amount of potential CTC

²⁰ It is considered possible that maximising the CFC -11 production capabilities when adapting the HCFC -22 lines could increase the theoretically available CFC -11 production capacity of the United States to above $> 50,000$ tonnes of CFC -11 per year.

²¹ For the year 2017, China and the European Union had spare capacity for HCFC-22 production of less than 50,000 tonnes. For the years 2013-2016, China and the European Union had estimated spare capacity greater than 50,000 tonnes per year.

²² Detuned by adjusting the production process, which results in reduced performance and efficiency, but allows 100% CFC-11 production.

available from chloromethanes production, after existing local supply commitments had been met, was 305,000 tonnes. A number of regions have the spare annual capacity that might allow CTC production in the amounts required for small-scale CFC-11 production. Only China has the spare annual capacity that might allow CTC production to supply the larger amounts of CTC required for large-scale CFC-11 production.

- CTC is also produced in PCE/CTC plants, which have the flexibility to produce from 0% to 100% of either substance according to demand. Five PCE/CTC plants are operative in Europe and the United States. Spare global capacity to produce CTC by this process is estimated to be 50,000-100,000 tonnes per year, existing mainly in the European Union. At least nine similar plants exist in China, but these exist solely for the purpose of transforming excess chloromethanes/CTC into PCE.
- CFC-11 production of between 40,000 to 70,000 tonnes, predicted to account for the increased CFC-11 emissions, would require supply of between 45,000 to 70,000 tonnes CTC in the lower range and 80,000 to 120,000 tonnes of CTC in the upper range. The CTC quantity required for CFC-11 production is expected to be at the lower end of the range if, as predicted, the objective is higher CFC-11 selectivity. For near 100% CFC-11 production, and almost nil CFC-12 co-production, the range is closer to 45,000 to 80,000 tonnes CTC.
- There does not appear to be evidence through customs or other agency activities, including seizures or interceptions, that illicit international trade in significant quantities of CFC-11 or CTC has occurred in recent years. However, there have been indications of recent marketing of CFC-11 for use in foams.

2.2 Montreal Protocol: History of global CFC-11 production phase-out

2.2.1 Overview

The goal of the Montreal Protocol is to protect the Earth's ozone layer by phasing out the chemicals that deplete it. This phase-out plan includes both the production and consumption of ozone-depleting substances (ODS).

Under the Montreal Protocol, production of CFC-11 in non-Article 5 parties was phased out in 1996; production of CFC-11 in Article 5 parties was phased out in 2010. Exceptions were made for small amounts of CFC-11 production for essential uses, such as for metered dose inhalers and for laboratory and analytical uses, as authorised by the parties. Exceptions were also made for non-Article 5 parties after their mandated phase-out in order to produce CFC-11 for the basic domestic needs of Article 5 parties.

In 1986, 24 countries of the Organisation for Economic Co-operation and Development (OECD) produced 90% (908,000 tonnes) of the global production of CFCs (1.07 million tonnes). The Montreal Protocol and its Amendments mandated a production and consumption freeze for non-Article 5 parties in 1989, a 75% reduction by 1994, and complete phase-out by 1996. By 1994, actual CFC production was about 184,000 tonnes, exceeding the 75% reduction target. In 1996, CFC production by non-Article 5 parties was limited to 34,000 tonnes to satisfy essential uses and to meet the basic domestic needs of Article 5 parties. Of

this, about half was CFC-11 production (16,400 tonnes). CFC-11 production gradually reduced to zero by 2010.^{23,24}

The phase-down and phase-out of CFC production in non-Article 5 parties was guided through regulatory and reporting requirements. For example, in Europe, phase-down and reporting requirements were stipulated in Regulation 3093/94.²⁵ Production for basic domestic needs and essential uses was also permitted through regulation. As a result, most European plants had stopped production by 2000, with one plant remaining in operation until 2009 to supply production authorised by parties after the 1996 phase-out. Similar regulatory approaches were implemented elsewhere.

Reported CFC production in Article 5 parties reached an annual average of 108,000 tonnes between 1995-1997. Reported CFC-11 production in Article 5 parties peaked in 1997 at 46,000 tonnes. The freeze of total CFC production and consumption in Article 5 parties was in 1999, after which the phase-down started. By 2003, CFC-11 production had reduced by half from its peak quantity. In the phase-out year of 2010, CFC-11 production in Article 5 parties was limited to 360 tonnes to satisfy demand for essential uses.

The Multilateral Fund (MLF) was established to assist Article 5 parties meet their Montreal Protocol commitments, including the phase-out of total CFC production and consumption by 2010, including that of CFC-11. Since 1991, the MLF has funded activities including industrial conversion, technical assistance, training and capacity building. The Executive Committee of the MLF (ExCom) approved agreements for the production sector phase-out for the following Article 5 parties: Argentina, China, India, Democratic People's Republic of Korea, Mexico, Romania, and Venezuela.

Typically, the terms of the agreements for production sector phase-out included, *inter alia*, the following:

- A specified ODS production phase-out schedule;
- A specified annual funding level provided for meeting the target reductions;
- Independent technical audits, administered by the relevant Implementing Agency or Agencies,
- Verification of annual ODS production levels and plant dismantling and/or destruction;
- Funds provided for the complete closure of the ODS production capacity that was the total funding to fully comply with production phase-out requirements, and that no additional MLF resources would be requested/provided for related activities;

²³ Andersen, S.O., Sarma, K.M., Ed. Sinclair, L., *Protecting the Ozone Layer: The United Nations History*, 2002, Earthscan on behalf of the United Nations Environment Programme.

²⁴ UNEP Article 7 data reporting.

²⁵ Council Regulation (EC) No 3093/94, 15 December 1994, as published in the Official Journal of the European Communities, No. L 333/1, 22.12.94.

- Withholding of and/or reduction of funds for not meeting the required reduction or required dismantling.

The role of three of the four Implementing Agencies (UNIDO, UNDP, World Bank) was critical to the implementation of the production sector phase-out projects. Responsibilities were specified in the agreements, and included, *inter alia*, the following:

- Ensuring/providing independent verification to the Executive Committee that the phase-out targets and associated activities were met;
- Ensuring technical reviews were undertaken by the appropriate independent technical experts;
- Carrying out supervision missions as required;
- Ensuring the presence of an effective operating mechanism to enable effective, transparent implementation of the programme and accurate, verified reporting of data;
- Independently verifying for the Executive Committee that dismantling of ODS production lines was done appropriately by ensuring that the reactor, distillation towers, receiver tanks for finished products, and control and monitoring equipment are dismantled, rendered unusable for future ODS production and disposed of.

Production sector phase-out under the MLF is summarised in Table 2.1. Specific Article 5 party production sector phase-out agreements are discussed in Appendix 1.

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Table 2.1 Production sector phase-out under the Multilateral Fund

Party	ODS production phased out	Implementing agency	Phase-out date agreed
Argentina	CFC-11 and CFC-12	World Bank	2008
China	CFC	World Bank	2010
	CTC manufactured and used as feedstock for CFC production as per the agreement for the Process Agent/CTC sector plan (phase I)*		2010
	Halon 1301		2010
	Halon 1211		2006
India	CFC	World Bank, UNDP	2009
Korea, DPR	CFC-113	UNIDO	2001
	1,1,1-trichloroethane		2001
	CFC-11, CFC-12		2003
	CTC		2005
Mexico	CFC	UNIDO	2006
Romania	CFC, 1,1,1-trichloroethane	UNIDO	2005
	CTC*		2008
Venezuela	CFC	World Bank	2007

* Except as feedstock for CFC production for essential uses

2.3 CFC-11 production data and their application

The production of CFCs started in the United States (US) in the 1930s. CFC-11 was one of the two most important CFCs, with the other being CFC-12. Global production of CFC-11 was only 1,300 tonnes in 1947. Annual production increased to an initial peak of 390,000 tonnes in 1974, then decreased (as a result of aerosol bans) and increased again to more than 400,000 tonnes in 1987-88. Subsequently, as a result of the Montreal Protocol controls, production steadily decreased.²⁶ Global CFC-11 production was reported as 359, 79, 299, 0, and 142 tonnes for the years between 2010 and 2014 inclusive, after which no production has been reported.²⁷

Several fluorocarbon producers reported the production and sales of controlled ozone-depleting substances (ODS) to a third-party auditor from the 1930s through to 2003. The data was summarized under the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS)²⁸, established in 1989, following on from earlier studies conducted by the Chemical Manufacturers' Association, which recorded audited production of CFCs in developed countries and some developing countries. Similar production data were not available for China, Czech Republic, India, North Korea, South Korea, Taiwan, Romania and Russia. In 1990, the amount reported to AFEAS was estimated to represent about 90% of global production. This had fallen to 50% by 1993 and reduced further as production shifted to Article 5 parties. The production data for 1969-1985, used in this final report, include estimates of additional CFC-11 production from the countries not originally reporting to AFEAS, based on literature sources.^{29,30}

Various methods have been used previously to estimate the gaps in reported CFC production data. For this report, a methodology has been developed to extrapolate and account for CFC-11 production in Russia. According to McCulloch *et al.*, production in Russia commenced around 1968.³¹ However, the exact capacity and production was not reported to AFEAS. Literature indicates that CFC production capacity had reached 80,000 tonnes per year in the early 1980s (including CFC-11, CFC-12 and CFC-113).³² McCulloch *et al.* provide a revised estimate of CFC production in Russia between 1986-2000, broken down by CFC species. Between 1986-1992, CFC-11 production covered on average 41% of the total CFC production in Russia.

²⁶ Source: AFEAS chemical reporting and UNEP Article 7 data reporting. AFEAS - Alternative Fluorocarbon Environmental Acceptability Study.

²⁷ UNEP Article 7 data reporting.

²⁸ AFEAS data is digitally available only on third party websites, including the following:
<https://agage.mit.edu/data/afeas-data>. Accessed May 2019.

²⁹ Gamlen, P.H., *et al.*, The production and release to the atmosphere of CCl_3F and CCl_2F_2 (Chlorofluorocarbons CFC-11 and CFC-12), *Atmospheric Environment*, 1986, **20** (6), 1077–1085.

³⁰ McCulloch, A., *et al.* "Historic Emissions of Fluorotrichloromethane (CFC-11) Based on a Market Survey." *Atmospheric Environment*, vol. 35, no. 26, 2001, pp. 4387–4397., doi:10.1016/s1352-2310(01)00249-7.

³¹ McCulloch, A., *et al.*, Releases of Refrigerant Gases (CFC-12, HCFC-22 and HFC-134a) to the Atmosphere, *Atmospheric Environment*, 2003, **37** (7), 889–902.
www.sciencedirect.com/science/article/pii/S1352231002009755.

³² Gamlen, P.H., *et al.*, The production and release to the atmosphere of CCl_3F and CCl_2F_2 (Chlorofluorocarbons CFC-11 and CFC-12), *Atmospheric Environment*, 1986, **20** (6), 1077–1085.

In the preliminary report (May 2019), an assumption is made that in 1980 CFC-11 production was also 41% of the total CFC production, yielding 32,658 tonnes of CFC-11 for that year. CFC-11 production data for the period 1968-1979 production capacity has been interpolated using a linear regression and the boundary values of 0 tonnes of production in 1967 and 32,658 tonnes in 1980. Alperowicz *et al.* claim that there were two CFC production plants built in Russia in 1980 and 1983 in Volgograd and Yavan respectively, with a capacity of 30,000 tonnes per year.³³ McCulloch *et al.* point out that in order to reconcile what is historically known regarding production in Russia these two plants are likely to have replaced older technologies.³⁴ However, the newly-constructed plants encountered operational difficulties and in 1984 were reported to operate at 25% of their capacity. For this information to be reflected in the data, an assumption has been made that total production was 25% of the plants' capacity on top of the existent CFC production in 1980 and 1983 (when the plants were commissioned). The Volgograd and Yavan plants produced both CFC-11 and CFC-12 – it has been assumed that the production ratio was 70% CFC-11 and 30% CFC-12. For the period 1986-2000, the production estimates provided by McCulloch *et al.* are used in the analysis.³⁵

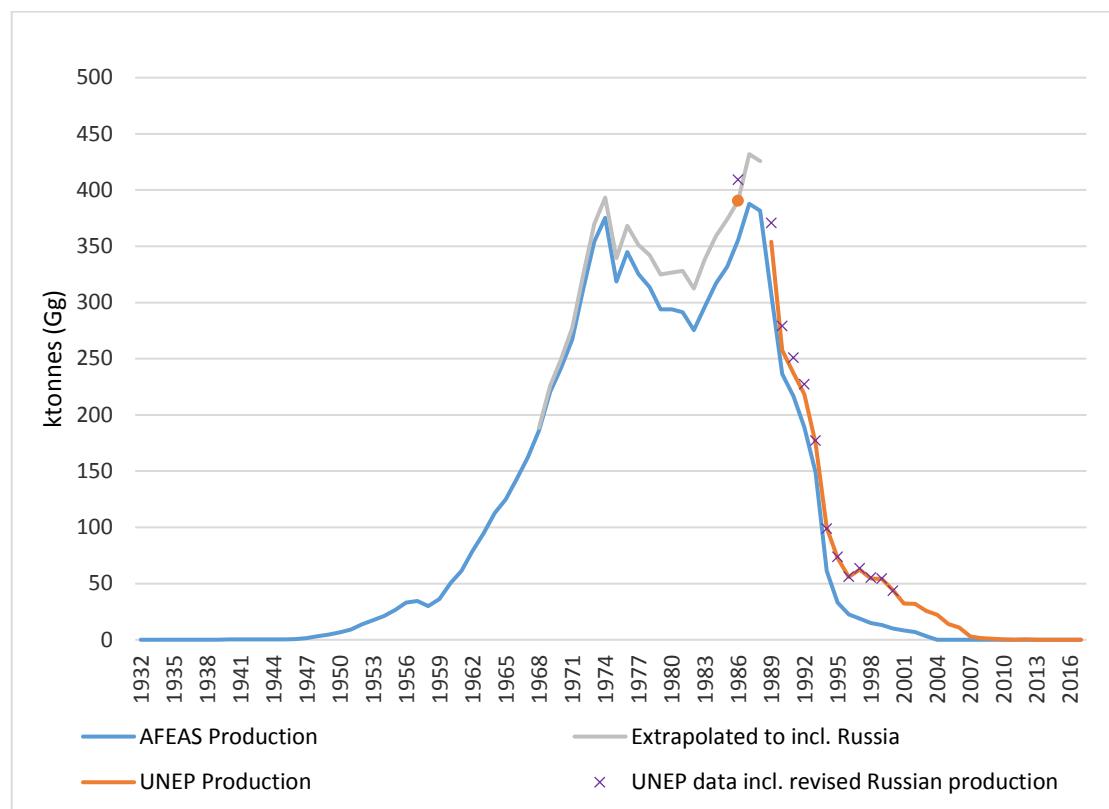
It should be noted that there is significant uncertainty in the production estimates for Russia from 1968 until 1986. Other than a single baseline report to UNEP for its 1986 production, Russia started annual reporting of its production to UNEP from 1989 onwards. By comparing the estimated production to that reported to UNEP, it becomes evident that there is a significant disparity for the years spanning 1989-1992. Figure 2.1 presents global CFC-11 production as reported to AFEAS and UNEP and extrapolated for Russia, as described above.

³³ Alperowicz, N., Cox, A., *On Course to Reform: The East European Chemical Industry*, Chemicon Surveys Ltd., London, 1987, 1986-90.

³⁴ Ibid., McCulloch A. *et al.* (2003)

³⁵ Ibid., McCulloch A. *et al.* (2003)

Figure 2.1 Global CFC-11 production as reported to AFEAS and UNEP, and extrapolated to include Russia



In this final report (September 2019), production estimates from Russia were further refined using additional sources and educated assumptions about the operation of CFC plants in the 1960s and 1970s. Russia provided the Task Force with additional production estimates for 1961-1989. These production estimates replaced the preliminary report data described above. Russia's production was not historically represented in the AFEAS data and therefore the global production data used in this report has been updated to reflect these new production volumes. However, since reporting was not mandatory at the time, the production estimates in Russia are based on production capacity and operation of chemical plants. Some production data for Russia for 1968-1975, which is used in the final report, was originally published in a journal in 1980 and reproduced in a report prepared by Rand Corporation for the US EPA in 1985.³⁶

AFEAS sales data was reported for end-use categories: non-hermetic refrigeration, closed-cell foams, and more emissive uses like aerosols, open-celled foams and solvents. The split between market sectors is significant because rates of emissions of CFC-11 from systems differ by sector during installation, the use phase, and at end of life. The AFEAS data has been used to model ODS emissions through 1985 and for 1987-8, based on assumptions of individual emissions rates for each market sector. ODS not emitted and remaining installed

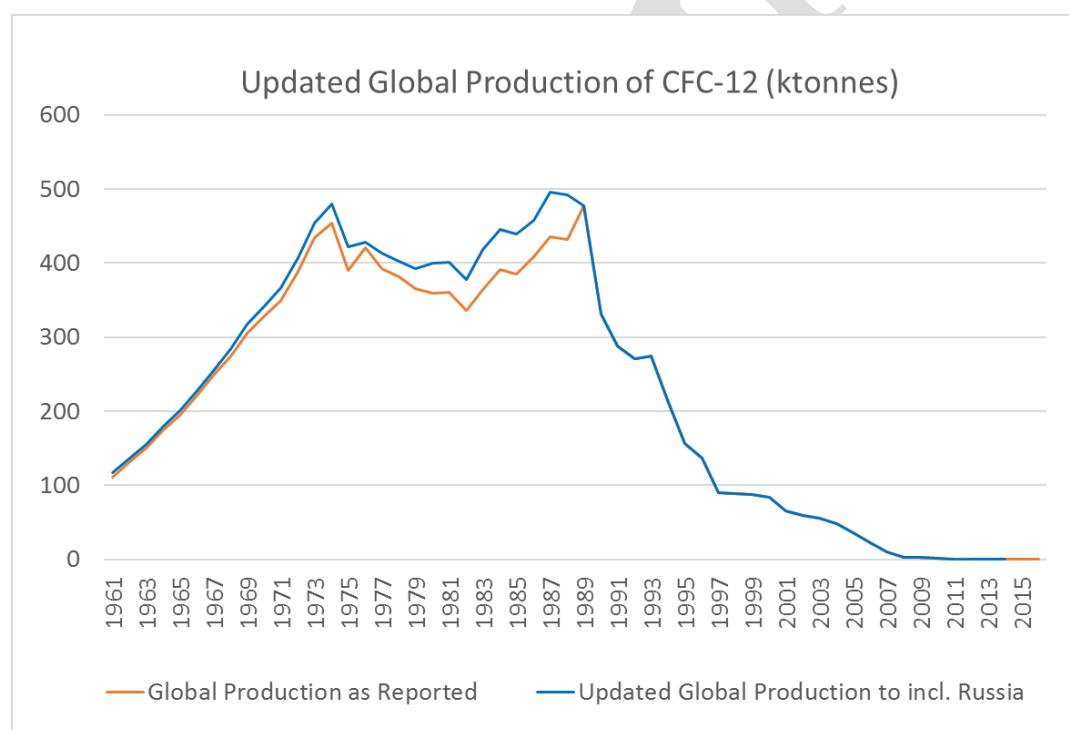
³⁶ Hammitt, James K., et al. "Product Uses and Market Trends for Potential Ozone-Depleting Substances, 1985-2000." RAND Corporation, 31 Dec. 1985.

within the systems (e.g., insulating foams and chillers for CFC-11) is described as “banked” ODS that would eventually be emitted or collected and destroyed. The gradual emissions from the “banks” are also modelled and the remaining bank calculated.

Production of CFC-11 for non-feedstock and feedstock³⁷ uses has been reported annually to UNEP under Article 7 from 1989 onwards. There appear to be no significant known current feedstock uses of CFC-11; nevertheless, small quantities (insignificant in the context of the emissions under consideration) have been reported under Article 7 and may be errors in reporting. Market sector-specific sales data are not collected, so using the UNEP data for modelling purposes requires that assumptions be made for the split between the market sectors.

The same methodology was used to update global production data for CFC-12 to include production from Russia. The impact on global production of CFC-12 is shown in Figure 2.2.

Figure 2.2 Global CFC-12 production as reported to AFEAS and UNEP, and updated to include Russia



2.4 Emissions related to CFC-11 production

Montzka³⁸ noted that “*The increase in emission of CFC-11 appears unrelated to past production; this suggest unreported new production...*”, with the corollary that the increased

³⁷ Feedstock uses refer to the use of ODS as chemical building blocks for the commercial synthesis of other chemicals.

³⁸ Montzka, S. et al., An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, 2018, **557**, 413–417. <https://doi.org/10.1038/s41586-018-0106-2>.

emissions appear to be unrelated to emissions from existing banks that were built from past, pre-2010 production. The possible sources related to the recent unexpected increase in emissions are the subject of investigation in this report.

Rigby *et al.*³⁹ reported increased emissions of CFC-11 from eastern mainland China, arising primarily from the northeastern provinces of Shandong and Hebei. The emission increase from China explains at least 40-60% of the global emission increase derived from NOAA or AGAGE measurements. Furthermore, based on several considerations, Rigby *et al.* suggested that the increase in CFC-11 emissions from eastern mainland China was likely to result from new production and use of CFC-11.

If new CFC-11 production is occurring, emissions related solely to the production stage may occur but at relatively low rates, which are dependent on the production process used.

Highly automated, tight and well-instrumented production facilities with proper, closely observed, procedures can have ODS emission levels as low as 0.05% of the ODS amount produced or used as feedstock. At the other extreme, batch processes of limited scale with less tight facilities, with less concern for operational excellence, could have emission levels up to 5%. For unregulated illegal production with inadequate controls emission levels could be even higher, possibly up to 10% of the CFC-11 produced.

Emissions are not reported under the Montreal Protocol. The Medical and Chemicals Technical Options Committee (MTOC) has estimated emissions resulting from the production of ODS. For indicative estimations of ODS emissions, an average emission factor of 0.5%⁴⁰ has been applied uniformly for the production of all controlled ODS.

Up until the year 2000, CFC-11 emissions calculated from production and use were consistent with the derived global atmospheric CFC-11 emissions based on observations.⁴¹ The recent increase in emissions of CFC-11 cannot be related to the levels of previous production that peaked in 1987.

Any stockpile accumulated from ODS production is not reported under the Montreal Protocol. The phase-out of CFCs in Article 5 parties was by 2010, and in non-Article 5 parties by 1996. Stockpiles retained as production ceased are considered production and accounted for in reported production data. At the time of phase-out, stockpiles have economic value due to scarcity and would be sold to realise this economic value. Consumption of CFC-11 stockpiles after the production phase-out is not prohibited under the Montreal Protocol.

Storage of several thousand tonnes of CFC-11 would be possible over a period of 5-10 years given the correct facilities. This would be possible in large bulk storage tanks, ISO tanks (20 tonnes) or drums (280 kgs) stored indoors in a cool, dry environment. However, these would all entail considerable costs (respectively estimated as USD200, USD800 and USD700 tons

³⁹ Rigby, M. *et al.*, Increase in CFC-11 emissions from eastern China based on atmospheric observations, *Nature*, 2019, **569**, 546-550. <https://doi:10.1038/s41586-019-1193-4>.

⁴⁰ The IPCC emission factor for HFC production of 0.5% of total production, used as an indicative emissions factor for ODS production, is currently under review by the IPCC.

⁴¹ McCulloch A., P. Ashford, P.M. Midgley, Historic emissions of fluorotrichloromethane (CFC-11) based on a market survey, *Atmospheric Environment*, 2001, **35**, 4387–4397.

per year), which, given the sales prices of the products in the market, would seem unlikely to be economical.

The Task Force has concluded that it is not commercially credible to assume that such stockpiles would be retained for many years past their production date in the eventuality that some companies may have an unexpected requirement for the substance (noting that the servicing of chillers using CFC-11 is a planned requirement requiring limited quantities and different to ‘speculative stockpiles’).

Furthermore, as these stockpiles have a commercial value, they are unlikely to be intentionally released. Unintentional leakage from such a dedicated stockpile would be theoretically nil, since the integrity of the product requires that the storage is hermetical. If the stockpile were to be sold over a several year period, the operator would be very careful to avoid losses of an expensive product. Should there have been a catastrophic leak for bulk storage tanks, it would have been a one-time event, which could not be sustained over a number of years. For drum storage, the stock management could react to potential individual failures avoiding large losses.

Irrespective of the compelling commercial rationale, the profile of unexplained CFC-11 emissions (based on observations⁴² indicating a sudden increase over one year followed by a sustained level of anomalous annual emissions from 2013 – 2016 at around a similar quantity) is not consistent with emissions directly from stockpiles if they arose from a catastrophic release or from a slow consistent leakage over time. A retained stockpile would also need to be unrealistically large to result in the increased CFC-11 emissions if stockpile had been utilised.

In conclusion:

- It is virtually impossible to store more than several thousand tonnes of CFC-11 because it requires a large investment in specialized facilities;
- Stockpiling inventory does not make economic sense, even more so when considering the stockpile size needed to account for the observed increased emissions, which would be prohibitively expensive; and
- When production of CFC-11 ceased, it would have been impossible to foresee that, in a few years hence, there would be a requirement for CFC-11, e.g., by anticipating a shortage of its replacement HCFC-141b for foam-blowing.

2.5 CFC-11 production process

2.5.1 Overview of CFC-11 production processes

2.5.1.1 Known commercialised CFC-11 production routes

Most of the historic commercial installations were so-called “Liquid Phase” plants that used the “Swarts” reaction of antimony pentachloride and hydrogen fluoride to replace chlorine atoms with fluorine in a suitable chlorocarbon. The plant consisted most simply of a heated reaction vessel charged with a pentavalent antimony catalyst dissolved in partly fluorinated organic intermediates. This reactor was surmounted by a conventional distillation column and

⁴² Ibid., Montzka *et al.*, 2018.

condenser, which returned a liquid reflux stream containing any vaporised catalyst or undesired organic intermediates. The system was pressurised and totally enclosed.

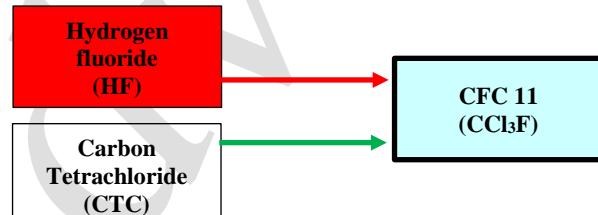
The operation was carried out by feeding anhydrous hydrogen fluoride (HF) and carbon tetrachloride (CCl₄, or CTC) into the pressurised reactor, and simultaneously (through proper control of the distillation column condenser temperature) withdrawing HCl and the desired organic products (CCl₃F and CCl₂F₂, CFCs 11 and 12) as vapour from the top of the reflux condenser.

CTC is produced either by the complete chlorination of methane or methyl chloride on chloromethanes plants, or by pyrolysis of chlorocarbons in the presence of chlorine on perchloroethylene (PCE)/CTC plants. Refined CTC undergoes a sequential substitution of the chlorine atoms by fluorine atoms.

The most common process route to mono-carbon (C1) chloro- and fluorocarbons (such as CFC-11 and CFC-12) is shown in the schematic in Figure 2.3.

The following notes are relevant to the schematic in Figure 2.3:

1. For clarity, only relevant substances are shown. Other substances, including catalysts, associated utilities (e.g., water, steam and alkalis), co-products and by-products, are not shown.
2. Arrows feeding into a box are the key raw materials used to make the substance in the box, e.g., hydrogen fluoride and carbon tetrafluoride reacting to make CFC-11 is indicated as:



3. Product selection – where there is a chain of reactions (e.g., sequential fluorine substitution of CTC) the desired product can be selected by varying the process operating parameters, such as raw material feed ratio, temperature, pressure and catalyst conditions.

Figure 2.4 shows the key production pathways in the PCE/CTC route to refined CTC.

Figure 2.3 Typical CFC, HCFC and HFC production pathways based on a chloromethanes plant sequentially chlorinating a methanol feedstock followed by liquid phase fluorine substitution using Hydrogen fluoride

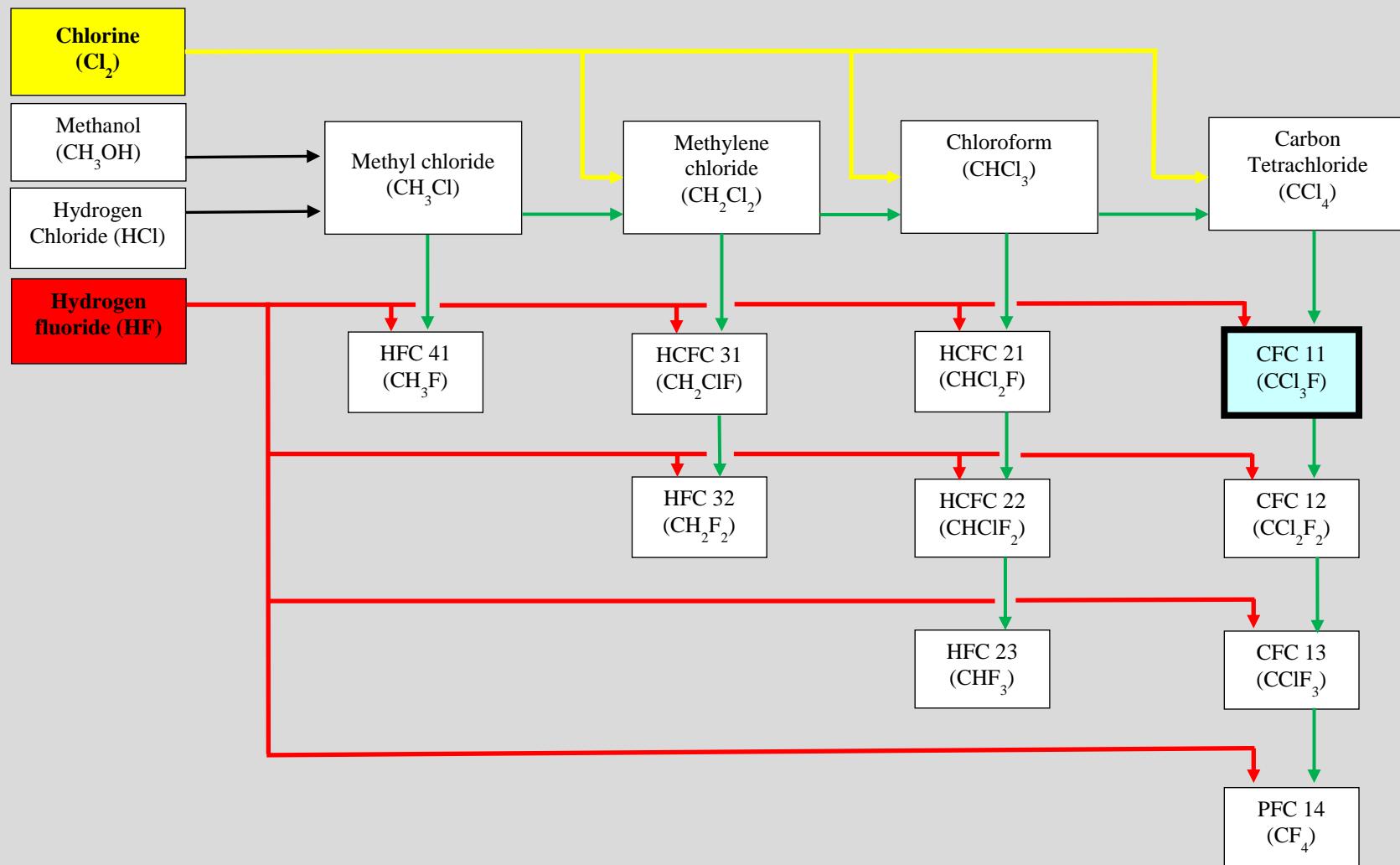
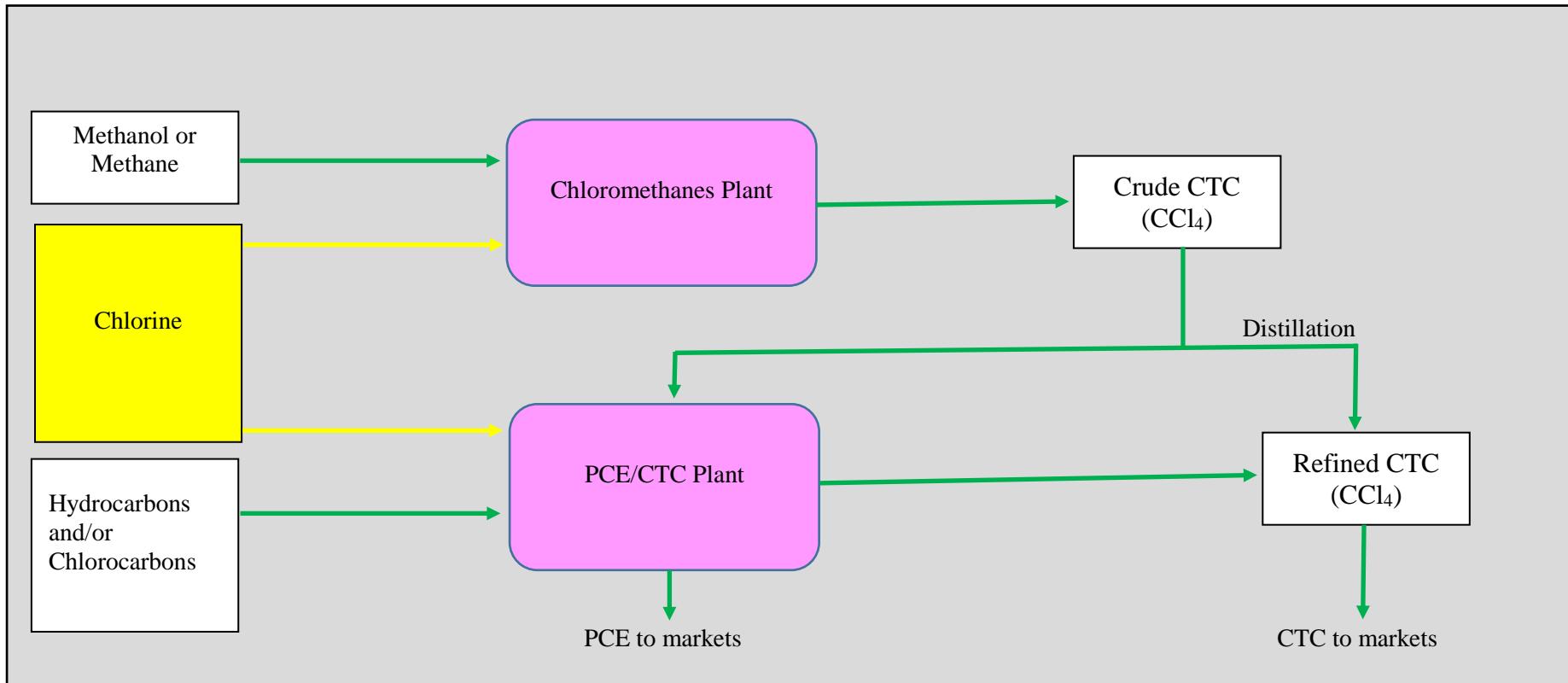


Figure 2.4 Diagram showing the key flows in the PCE/CTC route to refined CTC



The options open at the process design stage included whether or not to feed reactants as liquid or vapour, which affects the heat balance of the reactor and column, the design and efficiency of the column itself and the method of cooling of the condenser, which governed its operating temperature and so also influenced the system pressure. Downstream of the reaction system further distillation and washing systems separated the desired products (CFCs 11 and 12) from under-reacted CTC for recycle and removed the hydrogen chloride co-produced (see a simplified flow diagram in Appendix 3).

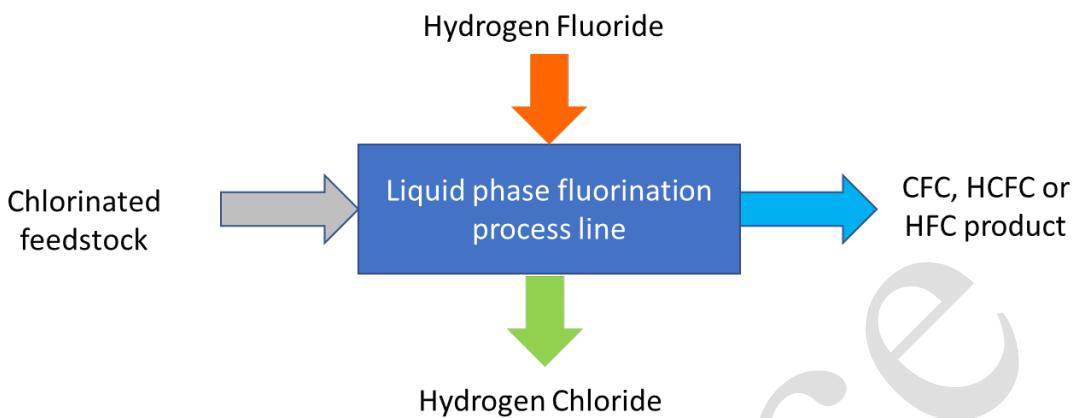
The basic design of the equipment is shared with other liquid phase processes that produced CFCs 113 and 114 and still produce HCFC-22, HCFC-141b and HFC-32 and 141b (among others). However, in an optimised plant, the actual equipment would be tailored to meet specific operating conditions for each product.

Depending on the actual equipment installed, satisfactory operating conditions cover wide ranges; pressures from 100 kPa to 35 MPa, reactor temperatures from 45 to 200°C, catalyst concentrations from 10 to 90 wt. percent, and product take off temperatures from -30 to +100°C. Because of the simplicity of the chemistry and the interdependence of the operating variables, there is no single optimum set of conditions for any one process, but rather a series of essentially equivalent combinations that yield both CFC-11 and CFC-12 products (see also section 2.5.2).⁴³

The reaction mixture can normally be contained in vessels made of simple materials, like mild steel. However, somewhat unpredictably, when process conditions are changed, the reaction mixture can become very, very corrosive, eating through fairly thick metals in a matter of hours. This makes operators wary about changing conditions drastically.

⁴³J.M. Hamilton Jr., *The Organic Fluorochemicals Industry in Advances in Fluorine Chemistry*, Volume 3, (M Stacey, J.C. Tatlow and A.G. Sharpe eds.), Butterworths, London, 1963, 281pp.

Figure 2.5 Liquid phase halocarbon production process⁴⁴



Chlorinated feedstock	Main Halocarbon products
Carbon Tetrachloride (CTC)	CFC 11 and CFC 12
Chloroform	HCFC 22
Dichloromethane	HFC 32

Notes:-

1. It is not considered likely that Chloroform and CTC would be co fed to the same process line.
2. In order to achieve suitable Halocarbon product quality the process line, including the liquid phase reactor, would need to be purged of all organic contents when switching from one chlorinated feedstock to the other

A minority of producers in non-Article 5 parties used “Vapour Phase” plants, where the reactor was a bank of heated tubes filled with granular catalyst (most commonly aluminium oxide that had been treated with HF) fed with vaporised HF and carbon tetrachloride. The downstream equipment to separate and purify the products was similar to that on a liquid phase plant but more extensive distillation was required to separate the range of products. In contrast to the liquid phase process, vapour phase reactors produced a spectrum of fluorinated products from unreacted CTC through to CFC-13. In general, vapour phase processes were more suited to producing the more highly fluorinated CFCs, such as CFCs -12 and -13 and -114 and -115 and are completely unsuitable for maximised CFC-11 production.

2.5.1.2 Uncommercialized CFC-11 production routes

A potential route to produce CFC-11 is by the chlorination of HCFC-21. It is not thought this process has ever been undertaken commercially because the route from CTC is economically much more viable. HCFC-21 can be produced on HCFC-22 plants although it is an intermediate that is not typically isolated.⁴⁵ Chlorination of HCFC-21 would then occur in a separate step. Compared to the route from CTC, it is a two-stage process involving adding fluorine and then chlorine, making it a much less attractive option. However, the route would

⁴⁴ Figure 2.5 in the final report replaces Figure 2.2 in the preliminary report.

⁴⁵ Small quantities of HCFC-21 have been reported as feedstock for the production of HCFC-225.

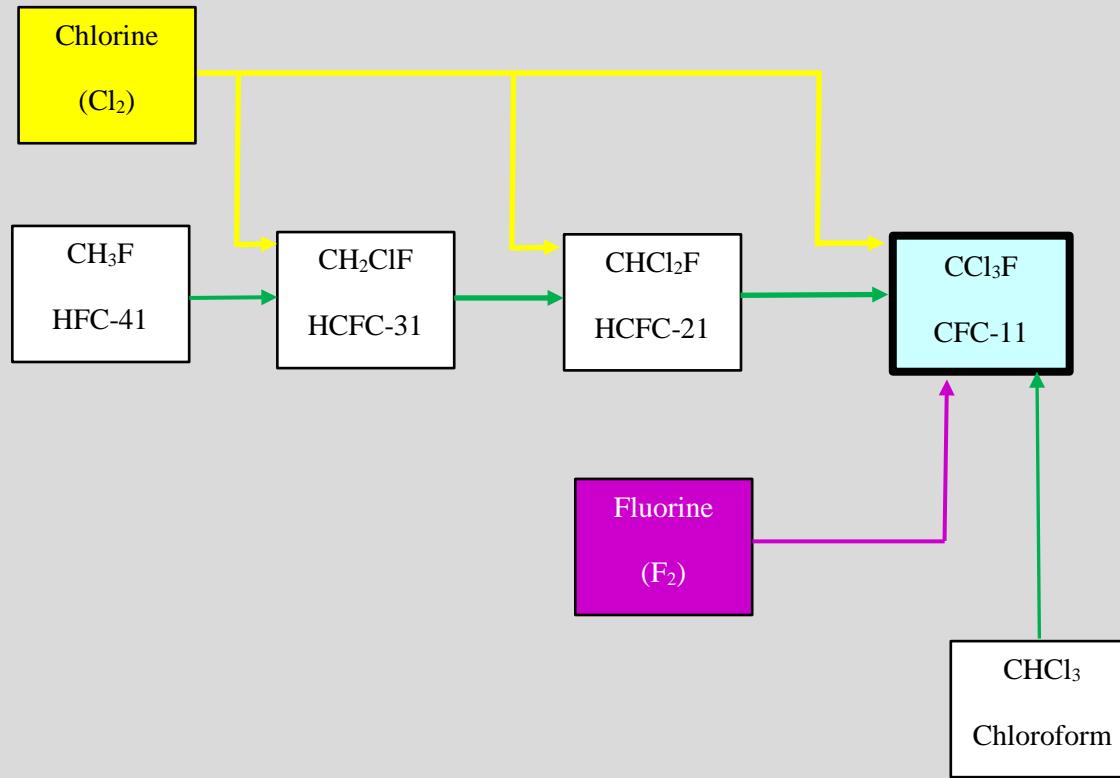
produce CFC-11 with trivial amounts of CFC-12. This process route would require available capacity on HCFC-22 plants to produce the HCFC-21 feedstock.⁴⁶ Available HCFC-22 capacity is considered in section 2.6 for the well-established and economically viable CFC-11 production process from CTC. The HCFC-21 route is not considered further in this report.

Another potential production route to CFC-11 is by the chlorination of HCFC-31. This is similar to the chlorination of the HCFC-21 (i.e., HCFC-31 would be chlorinated to HCFC-21 and then to CFC-11). It is not thought this process has ever been undertaken commercially because the route from CTC is economically much more viable. HCFC-31 can be produced on HFC-32 plants although it is an intermediate that is not typically isolated. Chlorination of HFC-31 would then occur in a separate step. Compared to the route from CTC, it is a two-stage process involving substituting fluorine and then adding chlorine, making it a much less attractive option. However, the route would produce CFC-11 with trivial amounts of CFC-12. This process route would require available capacity on HFC-32 plants to produce the HCFC-31 feedstock. The HCFC-31 route is not considered further in this report.

Similarly, while CFC-11 can be produced by the direct fluorination of chloroform, it is not thought this process has ever been undertaken commercially because the route from CTC is economically much more viable and the handling of elemental fluorine is hazardous and difficult.

⁴⁶ According to Article 7 data reporting, since 2010, a total of 86 kg of HCFC-21 has been reportedly produced for feedstock uses. HCFC-21 can be used as a feedstock for HCFC-225 production.

Figure 2.6 Production pathway schematic for some of the other possible CFC-11 synthesis routes considered in this report



2.5.2 Relationship of CFC-11 to CFC-12 production

2.5.2.1 CFC-11 to CFC-12 production ratios

When HF and carbon tetrachloride are reacted together in the presence of an antimony catalyst, a mix of CFC-11 and CFC-12 is produced, with the proportion of CFC-12 and CFC-11 controlled by varying the operating conditions. 100% CFC-12 is achieved relatively easily; 100% CFC-11 is more difficult to achieve but not impossible in well-operated facilities. An operating range of 30:70, either way, can be comfortably achieved. In well-operated facilities, emissions from production processes are low (average 0.5%).

Nevertheless, it is possible to produce more than 90% CFC-11 in a detuned⁴⁷ CFC-11/12 plant. Modifications could be made to the system pressure so that the reactor temperature could be reduced, then the antimony catalyst loading increased so that it has a lower fluoride concentration, which is less aggressive. The effect on throughput, and how close one could get to 100% CFC-11 production, would depend on the individual plant. There would be limited scope to recycle CFC-12 to extinction, implying use/disposal of remaining CFC-12.

Modern HCFC-22 plants are designed and operated to minimise HFC-23 production (principally through adjustments to the reactor and reactor distillation systems) and are typically sited with access to a thermal oxidation system (incinerator) to destroy any unwanted halocarbons before their release to atmosphere. The use of these modern HCFC-22 plants for CFC-11 production should similarly enable the plant to produce a CFC-11: CFC-12 ratio in the region of 97: 3, with any unwanted co-produced CFC-12 likely to be destroyed or emitted. On this basis, a modern 30,000 tonnes per year HCFC-22 plant could produce up to 50,000 tonnes per year CFC-11 with 1,500-2,000 tonnes CFC-12 by-product.

Near 100 % CFC-11 production is considered possible in a micro-production plant that is purposefully designed and operated on a batch basis to produce CFC-11 using similar feedstock and catalyst. Emissions from this type of illicit and unregulated plant, with inadequate controls, could be expected to be up to 10% of CFC-11 production.

As can be seen from Table 2.2, the quantity of CFC-12 co-produced as a result of any CFC-11 production is dependent on the exact production option chosen, and how the plant is set up and operated. With CFC-11 as the target chemical, for the most likely production routes⁴⁸, the range of CFC-12 co-production is between 0-30% of total CFC-11/12 production.

⁴⁷ Detuned by adjusting the production process, which results in reduced performance and efficiency, but allows more than 90% CFC-11 production.

⁴⁸ CTC to CFC-11 on micro-scale plants using minimal equipment (to make low grade CFC-11 for foam blowing use); and CTC to CFC-11/12 on a large-scale in an existing liquid phase plant (HCFC-22 and/or HFC-32 plant).

Table 2.2 Typical CFC 11/12 production ratios for the more likely production options

Production Option	Percentage of CFC-11 production	Percentage of CFC-12 production	Main destination of CFC-12 co-production	Comments
Traditional CFC-11/CFC-12 plant	30-70	70-30	Saleable product	To achieve economic viability majority of the CFC-12 produced would need to add value
Detuned traditional CFC-11/CFC-12 plant	~90	~ 10	Saleable product, although possibly released	Complete release of CFC-12 is unlikely to make process economically attractive
CFC-11/CFC-12 on traditional HCFC-22 or HFC-32 swing plants	30-70	70-30	Saleable product	To achieve economic viability majority of the CFC-12 produced would need to add value
Detuned CFC-11/CFC-12 on traditional HCFC-22 or HFC-32 swing plants	~90	~ 10	Saleable product, although possibly released	Complete release of CFC-12 is unlikely to make process economically attractive
Modern HCFC-22 plant swung to CFC-11	95- 97 %	3-5 %	Incineration, although possibly released	
New purpose design macro CFC-11 plant	~ 100 %	Trivial	Released or unlikely but possible incineration	
Micro scale plants	~ 100 %	Trivial	Left incorporated in CFC-11 product or released	

2.5.2.2 What is the possible fate of any co-produced CFC-12?

Once formed, there are a number of possible destinations for the CFC-12, these include, *inter alia*, the following.

Destruction— Destruction of CFC-12 is very expensive, requiring high temperature thermal oxidation and downstream equipment designed to handle the HF and HCl generated.⁴⁹ Nevertheless, these systems do exist and are capable of destroying the relatively minor amounts of undesired by-products associated with, for example, HCFC-22 and PTFE production.

~~A 20,000 tonne per year HCFC 22 plant might have a thermal oxidation system capable of destroying 500 tonnes per year of fluorinated by product (mainly HFC 23). If such a plant were converted to make CFC 11, the maximum amount of co-produced CFC 12 that could be destroyed by the thermal oxidation system would be certainly less than 1,000 tonnes per year.~~

A modern 30,000 tonne per year HCFC-22 plant might have an associated thermal oxidation system designed to destroy the 1,000 tonnes per year of fluorinated by-product (mainly HFC-23) that it is likely to be produced. These thermal oxidation systems usually have extra capacity in-built, to deal with spikes in flow due to different operating modes (e.g., preparation for maintenance) or possibly failures in incinerators on associated HCFC-22 lines. The potential amount of co-produced CFC-12 that could be destroyed by the thermal oxidation system is between 1,000 tonnes per year and 2,000 tonnes per year.

Emitted to the atmosphere— Set against the high cost of disposal of CFC-12 are the alternatives of venting it into the atmosphere or selling it for use. Even venting to the atmosphere has cost implications; the raw material cost of CFC-12 is roughly one and a half times that of CFC-11, because it requires twice as much HF. Therefore, venting it into the atmosphere has a significant effect on process economics. Although, this may depend on the percentage of CFC-12 in the mix.

Used as a refrigerant and/or aerosol propellant— Hence, it is more likely Given the economic costs of destruction and emitting to atmosphere, it is possible that a small co-production of CFC-12 could be sold as a refrigerant and/or aerosol propellant. This is a non-emissive use, and if the amount is small, it might be hard to detect from atmospheric measurements as distinct from current bank emissions arising from pre-phase-out production.

Used as a feedstock— If feedstock uses for CFC-12 are being employed (see section 2.10), the co-produced CFC-12 could generate revenue and add to economic viability. Feedstock uses are essentially non-emissive and do not add to the current CFC-12 bank or its emission.

How many, if any, of these possible CFC-12 destinations are being used is unclear, however the associated costs might be worth absorbing if detection of CFC-11 production is risked by leaving a trail of CFC-12 co-production. Although, it is considered unlikely that the operators would be concerned about detection of CFC-12 emissions during the period 2013 onwards, as CFC-11 emissions at a similar or higher level were occurring and not reported until 2018.

⁴⁹ Other destruction technologies are approved and used for the destruction of CFCs but high temperature thermal oxidation is widely used on production plants.

2.5.2.3 CFC-12 emission rates

If the desired product is CFC-11, with no, or even negative, economic value derived from any CFC-12 co-production, then high CFC-11 to CFC-12 ratios are likely to be targeted, e.g., through use of a combination of micro-scale CFC-11 plants, detuned CFC-11 production on an adapted HCFC-22 or HFC-32 plant or a modern HCFC-22 plant adapted to CFC-11 production. CFC-12 emissions could be further minimised by CFC-12 destruction, which has an associated cost, or by incorporation of some or all of the CFC-12 co-production into the CFC-11 product, accepting that this may limit the range of potential uses for the CFC-11 produced.

In the unlikely event that an economically valuable sink for CFC-12 can be found (e.g., through use as a feedstock or refrigerant) then higher CFC-11: CFC-12 production ratios could plausibly be targeted, albeit that the likely CFC-12 emission rates would be minimised to achieve the optimum overall plant economics.

Taking these factors into account, and excluding emissions from any CFC-12 usage, it seems plausible that economic factors could limit average CFC-12 emissions to less than say 5% of the CFC-11 production rates, i.e., less than 3,500 tonnes per year of CFC-12 emissions (based on the upper range of predicted CFC-11 production of 70,000 tonnes that could account for the increased CFC-11 emissions).⁵⁰

2.6 Capacity and raw material (CTC) availability for CFC-11 production scenarios

2.6.1 Overview

Based on modelling of CFC-11 production, usage and emissions and comparison against atmospheric observations, the “most likely” modelling scenario predicts 40,000 to 70,000 tonnes per year CFC-11 production would have been required from 2012 onwards to account for the increased CFC-11 emissions. This places CFC-11 production at the large-scale end of the production ranges considered.

Many CFC and HCFC production plants (for example, CFCs 113/114, HCFCs 22 and 141b, and HFC-32) that use a liquid phase antimony-based catalyst could, either in their entirety or by reuse of the major items of equipment (e.g., reactors, distillation columns and compressors), relatively easily be adapted to produce CFC-11 (and CFC-12). This could be done either in the same plant, re-purposed, or by reuse of the major items of equipment (e.g., reactors, distillation columns and compressors) in a rebuilt plant.

In fact, CFC-11/CFC-12 and HCFC-22 were produced in some ‘swing plants’ until phase-out of CFCs. It is straightforward to swing production from HCFC-22 to CFCs 11/12 and back again. Similarly, HCFC-22 and HFC-32 are also produced in some ‘swing plants’. It takes about one week to change from CFC-11 production to HCFC-22 or HFC-32 production and vice versa. This essentially involves removing all process chemicals from the plant (including the catalyst from the reactor) and then restarting with alternative feedstocks (chloroform and CTC). A plant might typically do this process once or twice a year coinciding with plant

⁵⁰ The economic factors surrounding the CFC-12 acceptable loss/emission rate might also be dependent on the price difference between CFC-11 and HCFC-141b.

maintenance and catalyst change schedules. Minimal additional operator training would be required to produce CFCs 11/12.

~~However, the CFC-11 production capacity of an adapted HCFC-22 plant is estimated to be in the range of 50–75 % of the HCFC-22 production capacity and a similar quantity of CFC-12 could also be co-produced. Assuming the CFC-11 capacity is 75% of the HCFC-22 production capacity then to produce each tonne of CFC-11 annually would require 1.33 tonnes of HCFC-22 capacity. It is also possible that some HCFC-22 capacity could be used for the production of HFC-32 or HCFC-142b or other products.~~

The CFC-11 production capacity of an adapted HCFC-22 or HFC-32 plant is dependent on several factors and can range from:

- Capacity based on relative molecular masses CFC-11 (137.5) and HCFC-22 (86.5) or HFC-32 (52), such that a 30,000 tonnes per year HCFC-22 plant could produce 45,000–50,000 tonnes per year CFC-11, and a 20,000 tonnes per year HFC-32 unit dedicated to CFC-11 production could similarly reach an output of 50,000 tonnes per year CFC-11; and,
- Capacity restricted by the physical constraints of the adapted plant, including, *inter alia*, such things as the heating and cooling capability of the various reactor and distillation sections, the capacity of the recycle systems and the operation of the reactor. It is estimated that these restrictions could reduce the CFC-11 capacity in the range of 50–75% of the HCFC-22 production capacity, such that a 30,000 tonnes per year HCFC-22 plant could produce ~20,000 tonnes per year CFC-11, with up to a similar quantity of CFC-12 co-product. A 20,000 tonnes per year HFC-32 unit dedicated to CFC-11 production could similarly reach an output of ~15,000 tonnes per year CFC-11.

CTC is a required feedstock for the main process routes to CFC-11 production; typically, 1.14 to 1.25 tonnes of CTC is needed to produce 1 tonne of CFC-11, depending on the CFC-11 emissions from the production unit. More CTC would be needed for any co-produced CFC-12. Anhydrous HF is the other necessary feedstock, with 0.16 to 0.18 tonnes of HF required to produce 1 tonne CFC-11. More HF would be needed for any co-produced CFC-12. CTC is essentially restricted to feedstock use, with production for feedstock use reportable under Article 7 of the Montreal Protocol. Monitoring CTC availability and capacity is regarded as a good indicator to the likelihood and location of illegal CFC-11 production and hence is considered further below. Production and supply of anhydrous HF is not restricted in the same way.

Some liquid phase HCFC-141b plants could in theory produce CFC-11. However, it is difficult to envisage technical or economic reasons that could persuade an operator to change from legitimate HCFC-141b to illegal CFC-11 production for use in the same, foam-blown, application. Even if there was spare HCFC-141b capacity, it is unlikely that the operator would choose to produce CFC-11; in those circumstances, it would be more technically and economically feasible to produce HCFC-141b, illicitly if beyond an allowed quota, as this would require no modification to the plant and no new feedstocks.

The standard package for supplying CFC-11 is the 55 US gallon (45 imperial gallon) drum, which is about 300 kg of CFC-11. Other packages such as 1-tonne refrigerant tanks could also be used. To provide the CFC-11 in drums, one or more plants configured to produce CFC-11 would either need an associated drum-filling line or a drum-filling line in a different location, with the CFC-11 being transported to it in bulk, typically in about 15–25 tonne loads. If CFC-

11 produced in one location was required for use in a different country, then this would need to be exported. Illicit international trade is considered in section 2.8.

The possible production plant options for making CFC-11 depend on the desired annual quantity and cover a range of plant types that have different capacities, economics, and times to achieve production (for example, whether the plant is rebuilt or converted).

Small-scale production (\leq 10,000 tonnes per year) could be achieved on:

- Dedicated plant(s), either constructed or rebuilt specifically to produce CFC-11;
- HCFC-22 production line(s), which, depending on its capacity, is operated solely to produce CFC-11 or operated as a swing plant; or
- HFC-32 production line(s), which, depending on its capacity, is operated solely to produce CFC-11 or operated as a swing plant.

Large-scale production (\geq 50,000 tonnes per year) could be achieved on:

- One or more HCFC-22 production lines, which, depending on how many and their capacity, are operated solely to produce CFC-11 or operated as swing plants;
- One or more HFC-32 production lines, which, depending on how many and their capacity, are operated solely to produce CFC-11 or operated as swing plants; or
- Multiple dedicated plants, either constructed or rebuilt specifically to produce CFC-11.

The production process options that might be used would depend on the annual CFC-11 output required. If larger scale production (\geq 50,000 tonnes per year) were to be required to account for the increased CFC-11 emissions, then it seems less likely that a large number of micro-scale plants would be solely responsible, although does not preclude some micro-scale plants from contributing to the production.

Medium scale production, depending on the quantity required, could be achieved using either the small and/or micro-scale (multiple units) or large-scale options. Some assumptions can be made about the operation and requirements for dedicated plants, constructed specifically for CFC-11 production.

2.6.2 Dedicated large-scale production on HCFC-22 plants

2.6.2.1 HCFC-22 plants

There are different ways that large-scale production could be achieved on a HCFC-22 plant:

- Production of CFC-11 on a single HCFC-22 line, where this must also meet HCFC-22 production requirements. In this case it might be expected to cause disruption to availability of HCFC-22 if it is required for feedstock use and would seem to bring little benefit at the cost of high risk.
- Production at a multi-line plant, where reduced HCFC-22 production requirements have resulted in idled capacity on one or more lines. Where multi-line plants have

lines with capacities greater than 20,000 tonnes per year, it would enable the large-scale production of alternative products including CFC-11.

2.6.2.2 HFC-32 plants

Large-scale production could be achieved on an HFC-32 plant:

- Production of CFC-11 on a single HFC-32 line, where this must also meet HFC-32 production requirements. In this case it would seem to bring little benefit at the cost of high risk to other site activities.
- Production at a multi-line plant, where overbuilt HFC-32 production capacity has resulted in idle capacity on one or more lines. Where multi-line plants have lines with capacities greater than 15,000 tonnes per year, it would enable the large-scale production of alternative products including CFC-11.

2.6.3 Small-scale production

2.6.3.1 Smaller scale production on illicit plants re-assembled using equipment from shutdown CFC-11/12 or HCFC-22 plants

The production of CFC-11 on one or multiple plants using re-assembled equipment potentially could, for multiple plants, require several companies to be involved in the CFC-11 production and may require several companies to be involved in the supply of CTC. It is considered less plausible that such an activity would occur in more than one country, but this possibility is also considered (section 2.8).

For each of these options, the available CFC-11 capacities of the re-assembled equipment would determine how many plants may be required to meet demand. Substantial additional operator training would be required to produce CFC-11 on a new plant.

As the location of any plant using re-assembled equipment should not be on the same sites as the previously operated CFC and HCFC production facilities, from which the equipment originated, it is less credible to use the historical data available for plant closures, for example from World Bank reports, to determine the local of any such plants. The location of these plants is more likely to be determined by the availability the key raw materials (CTC and HF) and of a suitable work force and supply route to end-users for the CFC-11.

It might be expected that CFC-11 capacities in the 6,000 to 10,000 tonne per year range would be employed for a smaller scale production plant.

2.6.3.2 Smaller scale production on illicit plants by using new plant items (including the option of designing for 100% CFC-11 production)

The possible use of all new equipment to produce CFC-11 means that none of the existing plants or disassembled equipment from historical CFC and HCFC plant has been reused to produce the CFC-11. Nevertheless, the general plant design of these all new plants would likely be based on the historical plant design, i.e., use similar feedstock, catalyst, reaction and key plant operations (e.g., reaction, distillation, washing, compression and liquefaction). The reaction mixture can normally be contained in vessels made of simple materials, like mild steel. However, somewhat unpredictably, when process conditions are changed, the reaction mixture can become very, very corrosive, eating through fairly thick metals in a matter of hours. This makes operators wary about changing conditions drastically and suggests that good process control is required even on an illicit small-scale production plant.

It might be expected that CFC-11 capacities in the 6,000 to 10,000 tonne per year range would be employed for a smaller scale production plant.

2.6.3.3 Smaller scale production on multiple HCFC-22 plants

In contrast to large-scale production on a single HCFC-22 plant or line, the production of CFC-11 on multiple HCFC-22 plants potentially requires several companies to be involved in illegal CFC-11 production and may require several companies to be involved in the supply of CTC. It is considered less plausible that such an activity would occur in more than one country, but this possibility is also evaluated. For production on multiple HCFC-22 plants, there are two options:

- Each plant would be ‘swung’ to produce CFC-11 (and possibly some co-produced CFC-12) and then ‘swung’ back to produce HCFC-22. Some swing plants operated prior to the phase-out of CFC-11/12 production. ~~It is assumed that up to 70% of capacity could be used to produce CFC-11~~; or
- Each plant operates entirely to produce CFC-11 (and possibly some co-produced CFC-12). For this activity, it is assumed that the annual plant capacities for HCFC-22 would be 20,000 tonnes or above.

For each of these options, the available HCFC-22 capacities and the CFC-11 production requirement determine how many plants may be required.

2.6.3.4 Smaller scale production on multiple HFC-32 plants

In contrast to large-scale production on a single HFC-32 plant or line, the production of CFC-11 on multiple HFC-32 plants potentially requires several companies to be involved in illegal CFC-11 production and may require several companies to be involved in the supply of CTC. It is considered less plausible that such an activity would occur in more than one country. For production on multiple HFC-32 plants, there are two options:

- Each plant would be ‘swung’ to produce CFC-11 (and possibly some co-produced CFC-12) and then ‘swung’ back to produce HFC-32.; or
- Each plant operates entirely to produce CFC-11 (and possibly some co-produced CFC-12). For this activity, it is assumed that the annual plant capacities for HFC-32 would be 15,000 tonnes or above.

For each of these options, the available HFC-32 capacities and the CFC-11 production requirement determine how many plants may be required.

2.6.3.5 Micro-scale production on illicit plants using a minimum of plant items (including the option of designing for 100% CFC-11 production)

The possible use of a minimal process equipment plant (see Appendix 3) could allow the production of low-grade CFC-11 that would still be suitable in properties and performance for blowing agent production. These micro-plants would likely use similar feedstock and catalyst to the larger plants whilst employing a batch style reaction and purification system, which would allow a reduction in the key plant operations (e.g., by removing the need for compression, liquefaction, final product purification and aqueous effluent treatment). This style of operation would mean that the reactor chemistry is changing all the time, which would be highly undesirable for a large-scale operator because it would reduce potential output and be difficult to control using an automatic control system. However, it gets away

from having to use HF pumps (which are expensive, sophisticated and difficult to maintain) and is a process that has the potential to make 100% CFC-11, given suitable skills of the operatives.

It might be expected that CFC-11 capacities in the 100 to 2,000 tonne per year range would be employed for a micro-scale production plant⁵¹.

⁵¹ These micro-scale production plants follow the style of ODS plant design suggested by the EIA and New York Times investigations into ODS production prosecutions.

Table 2.3 Technical and economic feasibility of possible commercial CFC-11 production models¹

CFC-11 production model	Technical Feasibility			Economic feasibility
	Plant availability	Operational considerations	Supply chain	
Dedicated large-scale CFC-11 production on existing HCFC-22 plants	Plant already exists	<ul style="list-style-type: none"> Minor changes to operating parameters; Suitable staff likely to be available; 30 - 50,000 tonnes/plant; Typically produces > 3-30% CFC-12. Likely change of reactor catalyst 	Likely to have access to: <ul style="list-style-type: none"> Existing HF supplies; Suitable storage and transport systems for CFC-11 and CTC. 	Reasonable economic basis: <ul style="list-style-type: none"> Small capital outlay; Risk of loss of associated HCFC-22 or HFC-32 business if illegal CFC-11 production discovered.
Dedicated large-scale CFC-11 production on existing HFC-32 plants				
Smaller scale production on re-assembled plant using equipment from shutdown CFC-11/12 or HCFC-22 plants	New or reused plant, control system and ancillary equipment will be required	<ul style="list-style-type: none"> New operating system required; Finding and training suitable staff may be a challenge; ≤ 10,000 tonnes/plant; Typically produces > 10-30% CFC-12. 	Likely to need to set up new HF, CTC and CFC-11 storage and transport systems.	Reasonable to poor economic basis: <ul style="list-style-type: none"> Expected to require moderate to large capital outlay; Dependant on achieving high CFC-11 value.
Smaller scale production on plants by using new plant items	All new equipment, structures, control systems and ancillary equipment	<ul style="list-style-type: none"> New operating system required; Finding and training suitable staff may be a challenge; ≤ 10,000 tonnes/plant; Could achieve up to 100% CFC-11 	Likely to need to set up new HF, CTC and CFC-11 storage and transport systems.	Reasonable to poor economic basis: <ul style="list-style-type: none"> Expected to require large capital outlay; Dependant on achieving high CFC-11 value over several years.
Smaller scale CFC-11 production on multiple HCFC-22 plants	Plants already exist	<ul style="list-style-type: none"> Minor changes to operating parameters; Suitable staff likely to be available; ≤ 20,000 tonnes/plant; Typically produces > 3-30% CFC-12. Likely change of reactor catalyst 	Likely to have access to: <ul style="list-style-type: none"> Existing HF supplies; Suitable storage and transport systems for CFC-11 and CTC. 	Reasonable economic basis: <ul style="list-style-type: none"> Small capital outlay; Risk of loss of associated HCFC-22 or HFC-32 business and/or discovery of illegal CFC-11 production.
Smaller scale CFC-11 production on multiple HFC-32 plants				

¹ Table 2.3 in the final report replaces Table 2.2 in the preliminary report.

CFC-11 production model	Technical Feasibility			Economic feasibility
	Plant availability	Operational considerations	Supply chain	
Micro-scale production on very simple plants, using minimal process equipment using a batch process. Likely to produce low grade CFC-11 suitable for foaming blowing only.	All new equipment, little to no structure, manual control and minimal ancillary equipment	<ul style="list-style-type: none"> Batch style reaction and purification system; Reduction in key plant operations (no need for compression, liquefaction, final product purification, aqueous effluent treatment); No need for automatic control or HF pumps; Suitably skilled operatives could make ~100% CFC-11; 100-2,000 tonnes/plant. 	Likely to use delivery cylinders and drums as feed vessels for HF, CTC and CFC-11 storage. Only simple transport systems are required (e.g., small lorries or trucks) capable of transporting 55 US gallon drums and up to 1 tonne cylinders.	Reasonable economic basis for individual operator: <ul style="list-style-type: none"> Expected to require only small capital outlay on equipment. Premises can be rented; Low production costs and direct production of blowing agents could maximise profits.

2.6.4 HCFC-22 production and capacity

Production data for HCFC-22, including for feedstock uses, is reported under Article 7 of the Montreal Protocol and has also been reported in ExCom documents. Capacity data is available through Clean Development Mechanism (CDM) Project Design Documents (PDDs) for the period before 2010, and via expert knowledge for individual plants or countries. Table 2.4 presents global HCFC-22 production⁵³, including for feedstock uses, and for each Article 5 party its production and the number of production lines. This allows average production per line to be calculated, as shown in the table. The aggregated non-Article 5 data is not split down further in this table and are only available in sum.

For the final report, Table 2.4 has been corrected to take into account two corrigenda issued for ExCom document ‘*Cost-effective options for controlling HFC-23 by-product emissions*’⁵⁴.

⁵³ Production includes all production for controlled and for feedstock uses and does not subtract any HCFC-22 that may have been produced but subsequently destroyed.

⁵⁴ Document UNEP/OzL.Pro/ExCom/82/68 1 November 2018, see UNEP/OzL.Pro/ExCom/82/68/Corr.1 and Corr.2.

Table 2.4 HCFC-22 production* for the period of 2009 to 2017 (tonnes) (Article 7 data)⁵⁵

Country	2009	2010	2011	2012	2013	2014	2015	2016	2017	Lines	2017 Average production /line
Argentina	3,914	4,251	4,018	4,190	1,951	2,286	2,446	1,743	1,823	1	1,823
China	483,982	549,265	596,984	644,485	615,901	623,899	534,930	571,976	644,721	32	20,148
Democratic People's Republic of Korea (the)	504	498	480	521	579	526	498	451	451	1	451
India	47,657	47,613	48,477	48,178	40,651	54,938	53,314	56,959	64,509	6	10,752
Mexico	12,725	12,619	11,813	7,872	7,378	9,214	4,752	4,791	5,965	2	2,983
Venezuela (Bolivarian Republic of)	2,307	2,167	2,443	2,914	2,204	1,566	677	260	273	1	273
Republic of Korea	6,913	7,634	7,262	5,704	6,673	6,833	7,180	7,344	7,587	1	7,587
Sub-total for Article 5 parties	558,002	624,047	671,475	713,864	675,336	699,262	603,796	643,523	725,329	44	16,485
Non-Article 5 parties	195,796	229,863	241,783	219,909	193,519	210,042	225,155	208,817	221,803		
Total	753,798	853,910	913,258	933,773	868,856	909,304	828,952	852,340	947,132		

* Total production includes all production for controlled and for feedstock uses and does not subtract any HCFC-22 that may have been produced but subsequently destroyed. This table is reproduced from Document UNEP/OzL.Pro/ExCom/82/68, 1 November 2018, with the two issued corrigenda. The only change to the reproduced table is an additional column added to show average production per line.

⁵⁵ Table 2.4 in the final report replaces Table 2.3 in the preliminary report.

The global production capacity for HCFC-22 in 2009 was just over 900 kilotonnes per year^{56,57} compared with 1,165 kilotonnes in 2018. This relatively modest increase can be seen from the profile of the market, in which non-Article 5 parties reduced capacity, due the phase-out of HCFC-22 in its controlled uses, while the Article 5 parties have increased capacity, in part due to a developing fluoropolymers industry in India and China for which HCFC-22 is used as feedstock.

HCFC-22 capacity in the US has reduced by a small amount and is now virtually all used for non-controlled feedstock production, for the manufacture of tetrafluoroethene (TFE), a useful monomer for a family of fluorinated polymers. In the European Union (EU), there has been a reduction in capacity as the remaining controlled uses of HCFC-22 have been phased out, resulting in a capacity which is very similar to that of the US. The remaining EU capacity is all being used as feedstock to make TFE. In Japan, the capacity is essentially unchanged because production for controlled uses was already low. Some of the capacity has been switched to the production of HFC-32 and some can switch between HCFC-22 production for feedstock use and HFC-32 production. The shortfall in domestic HCFC-22 required by the fluoropolymer market in Japan is met by importing bulk HCFC-22 from China. Russia has capacity to produce HCFC-22 that is used mainly as feedstock in the production of TFE.

India's HCFC-22 capacities, as reported in CDM PDDs, totalled about 43,000 tonnes per year in the period before 2009. Since 2009, capacity has grown to account for increased production. India has increased its capacity mainly due to larger feedstock production for TFE production. In China, almost all of the growth in HCFC-22 capacity in recent years is attributed to production of TFE. In addition to polymerisation, the TFE is used to make HFC-125 (by the reaction of TFE with HF), and more recently as part of the production process for HFO-1234yf.

Some of the HCFC-22 production capacities for individual lines are greater than 30,000 tonnes per year. The estimated available spare HCFC-22 production capacity that might be available to produce CFC-11 or other products is shown in Table 2.5.

Data submitted by parties⁵⁸ has enabled the spare capacity data for China and the EU to be updated, as shown in Table 2.5.

Parties also provided information on their compliance, monitoring and verification programs for existing HCFC-22 plants. Based on the information provided, it seems that utilising spare production capacity on an existing liquid phase HCFC-22 plant could be a less likely, although still technically possible, production route to CFC-11. Owing to the technical feasibility of this route, it remains as one of the most likely potential production routes.

⁵⁶ ktpa is kilotonnes per annum.

⁵⁷ Tecnon OrbiChem, 2010, Fluorocarbons and Chlorocarbons 2006-2016. Tecnon OrbiChem provides data and analysis to the petrochemical, chemical and plastics industry.

⁵⁸ China, EU, Japan, Mexico, Russia, USA.

Table 2.5 Estimated spare capacity of HCFC-22 (kilotonnes per annum)⁵⁹

Region/Country	Estimated Spare Capacity	Estimated Spare Capacity 2013 to 2016	Estimated Spare Capacity 2017
Argentina	<10		
China		>50	<50
EU		>50	<50
India	0		
Japan	0		
Mexico	<20		
Russia	<10		
USA	<50		
Venezuela	<10		

2.6.5 HFC-32 production and capacity

Production data for HFC-32 is not yet reported under Article 7 of the Montreal Protocol and hence only limited data on HFC-32 production capacity is publicly available. The global HFC-32 production capacity that is currently unused and could theoretically be used to produce CFC-11 is estimated at around 50,000 tonnes per year over the 2012-2016 period.

2.6.7 Availability of CTC

The Task Force considered whether CTC would be available in enough quantity to supply the CFC-11 production options under consideration.

If CTC, with the other chloromethanes, were to be produced on the same site(s) as the CFC-11, it could be transported by internal pipeline to the CFC-11 fluorination plant. China, India, Japan, and Russia are the only places with some plants that integrate chloromethanes and fluorochemicals production on the same site. In the European Union and the United States, some chloromethanes or PCE/CTC sites are adjacent to fluorocarbon customers. In some countries, the majority of CTC produced from chloromethanes can be transported and consumed internally on site, e.g., in 2017, 68% of CTC produced from chloromethanes was consumed on-site in China, where the practice is the most common. In most other countries, there has been a steady disintegration of chloromethanes and fluorochemicals production on the one site.

If there were no CTC available from on-site production, it would have to be either purchased from within the country of CFC-11 production, or imported, and transported to the CFC-11 production site(s). For those countries with no domestic supplier of CTC (i.e., Argentina, Mexico, and Venezuela), the complexity of finding a willing international supplier, along with the associated import and export regulations, is likely to be a strong deterrent, making this scenario less plausible. Illicit international trade is considered in section 2.8.

⁵⁹ Table 2.5 in the final report replaces Table 2.4 in the preliminary report.

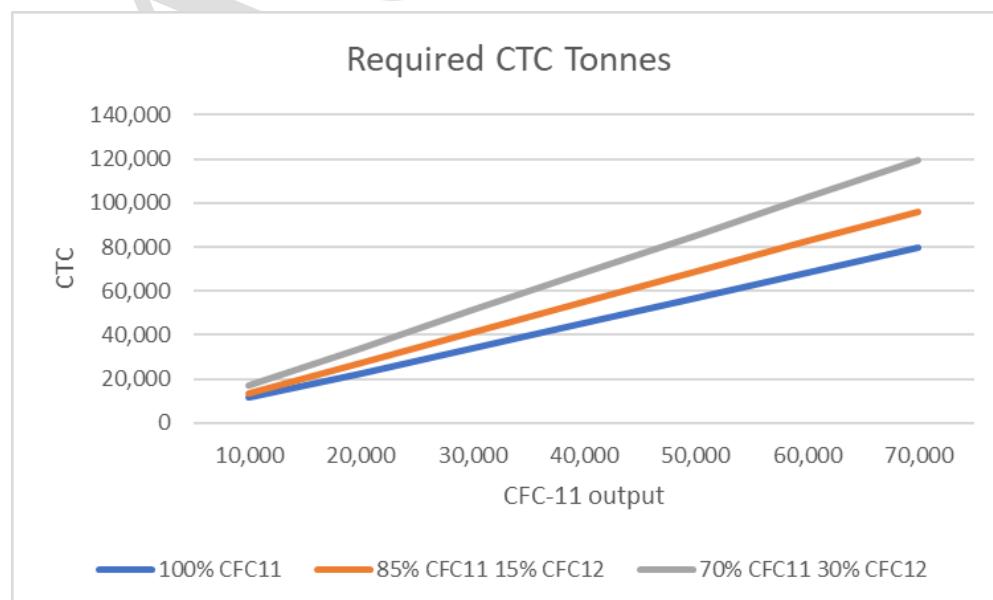
Typically, 1.14 to 1.25 tonnes of CTC are needed to produce 1 tonne CFC-11. More CTC would be needed for any co-produced CFC-12. Monitoring CTC availability and capacity is regarded as a good indicator to the likelihood and location of illicit CFC-11 production. Apart from laboratory and process agent uses, CTC can only be produced for use as a feedstock.

The quantity of CTC required for CFC-11 production depends on three factors:

- The CFC-11 output, which has been assumed to be in the range from small-scale (\leq 10,000 tonnes) to large-scale (\geq 50,000 tonnes per year up to 60,000 tonnes). The selected CFC-11 production output range allows for an analysis of possible process routes that could provide the CFC-11 annual production that might potentially be associated with the increased CFC-11 emissions;
- The quantity of co-produced CFC-12, which can be assumed to be in the range 0% to 30% of the total CFC produced (i.e., 70% CFC-11 30% CFC-12 by weight);
- The average efficiency of the process that converts CTC into CFC-11 or CFC-12 product, which can be assumed to be in the range 90-99% of the CTC fed to the plant; CTC efficiency includes emissions of CFC-11 and -12 that occur during the production process.

Figure 2.7 shows the CTC quantity required for CFC-11 output assuming various minimal scenarios of CFC-12 co-production. The range of potential amounts of CTC required to produce between 10,000 and 60,000 tonnes CFC-11 lies between 12,000 to 20,000 tonnes in the lower range and 70,000 to 100,000 tonnes in the upper range. CFC-11 production of between 40,000 to 70,000 tonnes, predicted to account for the increased CFC-11 emissions, would require supply of between 45,000 to 70,000 tonnes CTC in the lower range and 80,000 to 120,000 tonnes of CTC in the upper range. The CTC quantity required for CFC-11 production is expected to be at the lower end of the range if, as predicted, the objective is higher CFC-11 selectivity. For near 100% CFC-11 production, and almost nil CFC-12 co-production, the range is closer to 45,000 to 80,000 tonnes CTC. For 97% CFC-11 production, and 3% CFC-12 co-production, the range is between about 47,000 tonnes to 82,000 tonnes.

Figure 2.7 CTC quantity required for CFC-11 output



2.7 Carbon tetrachloride production

A complete analysis of CTC production was provided in the *SPARC Report on the Mystery of Carbon Tetrachloride*⁶⁰ and more recently in *Current sources of carbon tetrachloride (CCl₄) in our atmosphere*.⁶¹ Given the importance of the use of CTC as a feedstock for CFC-11, and previous work carried out by TEAP/SAP and SPARC (2016) on the discrepancy between quantities of CTC measured in the atmosphere and those described by “bottom-up” analyses, a comprehensive analysis of the production/availability of CTC is given below and in Appendix 2.

For the main process routes for CFC-11/12 production, CTC is the essential feedstock. The production of 10 kilotonnes of CFC-11, with minimum CFC-12 co-production, requires around 11.4 to 12.5 kilotonnes of CTC.

At the peak of CFC-11/12 production, CTC production volumes were greater than 1 million tonnes annually. There are three routes that can be used to make CTC although only two are currently used:

- The production of CTC in chloromethanes plants. Methyl chloride is chlorinated to produce dichloromethane (DCM), chloroform (CFM), and some CTC. The three products (DCM, CFM, CTC) are collectively referred to as “higher chloromethanes”. In general, plants are able to produce a DCM: CFM range from a 40:60 ratio to a 60:40 ratio, always with some by-product CTC. On a global basis, 5% CTC, as a proportion of overall DCM/CFM production, is a reasonable global minimum for the CTC unavoidably manufactured as a by-product.⁶² The proportion of CTC tends to be higher if the plant produces more chloroform than dichloromethane. At a maximum, 15-20% CTC can be achieved as the output of a chloromethanes plant without extensive plant modifications.
- The production of CTC in perchloroethylene (PCE)/CTC units, which can produce both PCE and/or CTC flexibly and according to market demand. The process involves the high-temperature chlorination of C₁-C₃ hydrocarbon or chlorocarbon streams, especially those waste streams arising from 1,2-dichloroethane (EDC)/vinyl chloride units, 1,2-dichloropropane from chlorohydrin-based propylene oxide and epichlorohydrin units, and “crude” CTC arising from chloromethanes plants.

The chlorination of carbon sulphide (CS₂) was used previously. This route depended on the availability of CS₂, as a by-product of rayon production, and the final rayon plants using this process ceased operation over 10 years ago, with most closing over 20 years ago.

⁶⁰ SPARC, 2016. *SPARC Report on the Mystery of Carbon Tetrachloride*. Q. Liang, P.A. Newman, S. Reimann (Eds.), SPARC Report No. 7, WCRP-13/2016. Available at: www.sparc-climate.org/publications/sparc-reports/sparc-report-no7.

⁶¹ David Sherry, Archie McCulloch, Qing Liang, Stefan Reimann and Paul A. Newman, Current sources of carbon tetrachloride (CCl₄) in our atmosphere, *Environ. Res. Lett.*, 2018, **13**, 024004.

⁶² Some plants claim to operate with as little as 3% CTC by-product.

2.7.1 Production of CTC from chloromethanes

Most of the production of CTC is from chloromethanes plants (SPARC, 2016)⁶³, with about 80% of CTC production achieved via this route. The production of CTC is unavoidable: the possible availability of CTC can be estimated based on minimising CTC (5%) and maximising CTC (15%) in the process, as reasonable average assumptions. Global chloromethanes capacity and the range of CTC production potential for 2016 is shown in Table 2.6. The CTC production potential is based on the global capacity of higher chloromethanes production.

Table 2.6 Global higher chloromethanes⁶⁴ capacity in 2016 and CTC production potential (kilotonnes per annum, ktpa)

Global Capacity ktpa	CTC Production Potential minimised 5%	CTC Production Potential maximised 15%
3,500	175	525

Table 2.7 shows the regional distribution of higher chloromethanes capacity, and associated potential CTC availability, in 2016, during the period of anomalous increased CFC-11 emissions. The potential CTC availability is presented as the CTC maximised. This maximum potential CTC availability then takes into account (i.e., deducts) the known CTC feedstock applications in each region (e.g., for the production of HFC-245fa, HFC-365mfc, perchloroethylene, divinyl acid chloride). China, Europe, and the United States had the largest chloromethanes capacities in the period 2012-2018. There is no production in South America, Middle East, and Africa. Compared with 2012, in 2016 chloromethanes capacity in Europe was 200 kilotonnes per year less, and that of China was 750 kilotonnes per year greater. There are 29 producers of chloromethanes globally, with average capacity of 120 kilotonnes per year/producer. No regulatory regime allows extra production of CTC (by maximising CTC on chloromethanes plants) unless it is for approved feedstock use, otherwise unwanted or unavoidably manufactured CTC must be destroyed by approved technologies.

It has been reported that global production of chloromethanes in recent years has constantly been running at 75-85% of capacity, which has decreased in the EU and the US, and increased in China and India.

⁶³ Ibid., SPARC, 2016.

⁶⁴ Higher chloromethanes are dichloromethane (DCM, or methylene chloride), trichloromethane (chloroform, CFM) and carbon tetrachloride (CTC).

**Table 2.7 Regional higher chloromethanes capacities and availability of CTC in 2016
(kilotonnes per annum, ktpa)**

Region	Chloromethanes Capacity	Maximum Potential Availability of CTC from CMs*
Europe	<500	10
Russia	<100	5
USA	<500	10
China	>2000	260
Japan	<250	10
India	<250	0
Other Asia	<100	10
TOTAL	±3500	305

*Note: The potential CTC availability is shown as the CTC maximised. The availability of CTC means the capacity available after local demand has been met.

In 2016, based on current global higher chloromethanes production, the global minimum amount of CTC that was unavoidably manufactured is estimated at 140 kilotonnes. The minimum amount of CTC produced in 2016 is based on actual production and not on capacity. Some regions will have produced more than the minimum amount.

2.7.2 Production of CTC from PCE/CTC plants

Only the US (2 plants) and the EU (3 plants) have operating PCE/CTC facilities, with a total PCE/CTC production capacity estimated at less than 350 kilotonnes per year. The production can be swung between PCE and CTC, although to produce 100% PCE (0% CTC) investment of US\$10-20 million was necessary to install additional thermal oxidation capacity. Spare capacity to produce PCE or CTC by this process from the current plants is estimated to be 50 to 100 kilotonnes per year, existing mainly in the EU. Exporting CTC from any producing region would be subject to considerable regulatory compliance, including the legal requirements of importing countries.

At least nine similar plants exist in China, but these exist solely for the purpose of transforming excess chloromethanes/CTC into PCE.

2.7.3 CTC imports and exports

CTC imports and exports are reported to the Ozone Secretariat under Article 7 data reporting requirements. Any imported CTC requires an import licence and the export is subject to export controls through licensing. Table 2.8 has reported imports and exports of CTC (excluding recovered material). The data show that imports and exports of CTC are at a low level.

Table 2.8 Reported imports and exports of CTC (metric tonnes)

Year	Imports		Exports	
	non-A5	A5	non-A5	A5
2012	678	0	3255	0
2013	751	0	652	0
2014	385	1142	1434	0
2015	1806	0	1762	0
2016	411	1255	1694	0

2.7.4 CTC feedstock uses

According to reported Article 7 data, in 2016, CTC production for feedstock use was 221,578 metric tonnes. It is not known whether any CTC produced and used for CFC-11 production is included in reported production for feedstock use under Article 7 data; the fate of ODS produced for feedstock use is not reported. Nevertheless, the production of CTC from chloromethanes plants, operating at the minimised 5% CTC level, together with CTC also available from PCE/CTC plants, broadly matches the reported CTC production for feedstock use. The available spare chloromethanes capacity, and resulting potential for increased CTC production, would allow for additional CTC production based on increased CTC demand.

The 2019 TEAP Progress Report (Table 5.2 therein) indicates ODS use as chemical feedstock, from which the CTC processes are summarized below. It is no longer reported as being used as a feedstock for CFC-11/12 production, but it is used as a feedstock in processes to produce more complex fluorochemicals and pesticides:

- The production of the chlorinated propanes and butanes, which are the precursors to HFC-245fa, HFC-236fa, and HFC-365mfc;
- The large-scale HFO/HCFO production processes, where CTC is used to make specific chloropropenes that are intermediates in the production of HFO-1234yf, HCFO-1233zd, and HFO-1234ze;
- The production of divinyl acid chloride (DVAC), a synthetic pyrethroid intermediate;
- The production of triphenylchloromethane (trityl chloride) used as an intermediate for dyes and pharmaceuticals such as antiviral drugs; and
- The production of 2,4-dichloro-5-fluorobenzoyl chloride (DCFBC) used as intermediate for example in the synthesis of highly active antibacterial agent Ciprofloxacin.

In addition to these feedstock uses, China operates three other processes to manage its by-product CTC from its large chloromethane production. These processes, shown below, take place inside the chloromethanes producers' sites and account for 68% of the 122.7 kilotonnes CTC produced in China in 2017:⁶⁵

⁶⁵ CTC Production, Conversion Technology and Management in China, Chun-xi Li, College of Chemical

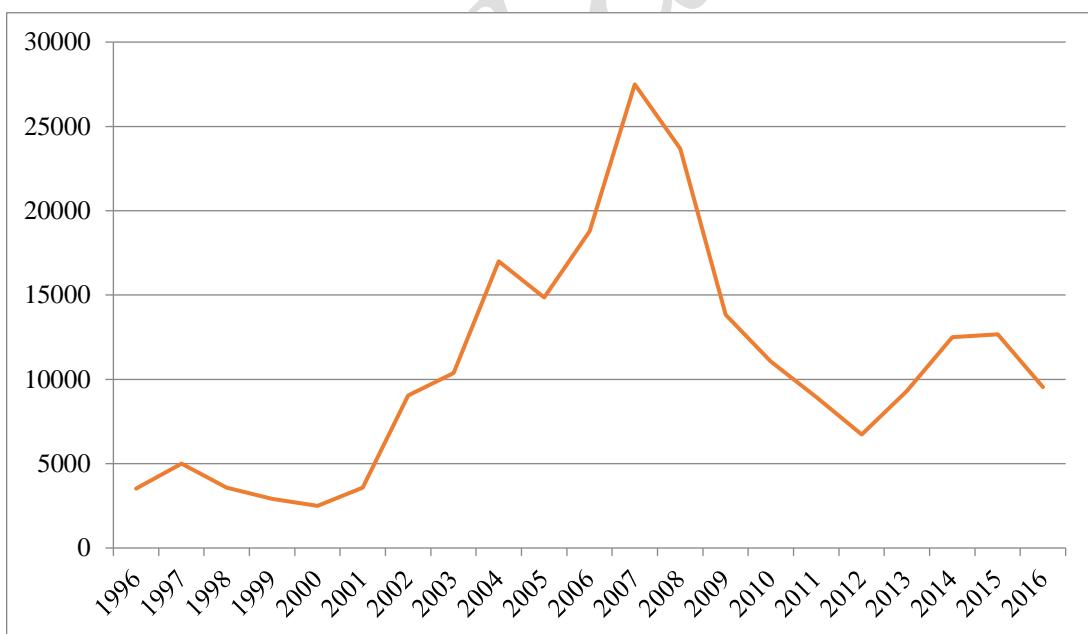
- Dehydrochlorination (two processes), by which CTC is converted either to chloroform (CHCl_3) for sales or use; or to methyl chloride (CH_3Cl) for silicone production or for re-chlorination to higher chloromethanes; and
- The production of perchloroethylene (PCE), involving the high temperature chlorination of CTC in the presence of a hydrocarbon such as methane. The process enables a high quality of PCE suitable for use in fluorocarbons or as a solvent. Mixed chloromethane feeds (unseparated dichloromethane, chloroform and CTC) are also used in these PCE production units.

CTC producers would generally be familiar with the downstream users of their product because CTC is now almost only ever supplied as a chemical feedstock.

2.7.5 CTC reported destruction

Figure 2.8 shows the total destroyed CTC as reported by parties. Most of the CTC was destroyed in non-Article 5 parties, indicating either a surplus of CTC or material that is not suitable for feedstock use in those parties. Peak destruction happened in 2007-2008 as CFC-11/12 was phased down, with the subsequent downward trend tracking the increased use of CTC in HFCs, such as HFC-245fa and HFC-365mfc. Large-scale production of HFOs will increase the use of CTC as a chemical intermediate.

Figure 2.8 CTC destruction reported by parties (metric tonnes)



2.7.6 Global CTC availability and capacity to supply CFC-11 production

This analysis indicates where CTC availability and capacity might be available from chloromethanes plants or from PCE/CTC plants.

For chloromethanes plants, China, Europe, and the United States have the largest capacity for, and production of, chloromethanes, and therefore also the largest potential availability of CTC. In 2016, the global maximum amount of potential CTC available from chloromethanes production, after existing local supply commitments had been met, was 305,000 tonnes. A number of regions have the spare annual capacity that might allow CTC production in the amounts required for small-scale CFC-11 production. Only China (with more than 60% of global chloromethanes capacity) has the spare annual capacity that might allow CTC production to supply the larger amounts of CTC required for large-scale CFC-11 production.

For a PCE production process using mixed chloromethanes (dichloromethane, chloroform and CTC), CTC can be minimised in the mix to 5% with a 50:50 ratio of dichloromethane and chloroform. A site that integrates production of chloromethanes, PCE and fluorochemicals (e.g., HCFC-22 or HFC-32 plant) provides the opportunity for liberation of CTC from chloromethanes production and concealment of on-site diversion of CTC away from mixed chloromethanes feedstock use in PCE production and into CFC-11 production (on a HCFC-22 or HFC-32 plant). This is a possible scenario for integrated sites, where integrated on-site operations might minimise the risk of detection.

For perchloroethylene/carbon tetrachloride plants, which have the flexibility to produce from 0% to 100% of either substance according to demand, five PCE/CTC plants are operative in Europe and the United States. Spare capacity to produce CTC is estimated to be between 50,000-100,000 tonnes per year, existing mainly in the European Union.

2.8 Illicit international trade in CFC-11 and CTC

Illicit international trade in controlled substances generally occurs when substances are unavailable or in short supply in one region or country, due to phase-downs, phase-outs or use bans, and are legally available in another country. It is also conceivable that globally banned substances could be manufactured in one country, taking into account the risks and rewards, and are then exported to another country. While illicit international trade may occur undetected, usually there is some evidence through customs or other agency activities, including seizures or interceptions, or market information that such trade is occurring.

According to the chapter *Illicit trade in ozone-depleting substances (ODS) from East Asia to the world* of a United Nations Office on Drugs and Crime report (2013)⁶⁶, there are different smuggling methods for ODS:

- **False Labelling:** ODS are smuggled in cylinders or packaging labelled as legal products.
- **Mis-declaration:** ODS are disguised by putting the names of other similar, legal chemicals on shipping documents and invoices. This method is often combined with

⁶⁶ United Nations Office on Drugs and Crime, *Transnational Organized Crime in East Asia and the Pacific*, Chapter 10 Illicit trade in ozone-depleting substances (ODS) from East Asia to the world, https://www.unodc.org/res/cld/bibliography/transnational-organized-crime-in-east-asia-and-the-pacific-a-threat-assessment_html/TOCTA_EAP_web.pdf, accessed April 2019.

“double-layering”; filling a shipping container with cylinders of illegal ODS except for a layer of the legitimate chemical stated on the Bill of Lading next to the container door.

- **Fake recycled material:** Trade in recycled ODS is less regulated than for newly produced ODSs.
- **Concealment:** ODS are simply hidden in ships, cars, or trucks and moved across border. This method usually involves small quantities but is lucrative and the overall volume can be significant.
- **Transhipment fraud:** Consignments of ODS ostensibly destined for legitimate end markets are diverted onto black markets. This type of fraud often involves complex shipping routes, passing through transit ports and free-trade zones where customs procedures may be more relaxed.

The main response under the Montreal Protocol to the threat of illegal trade has been the implementation of an ODS licensing system. This was agreed in 1997 and became effective in 2000. Under the terms of the system, parties are obliged to licence firms importing ODS, with a recommendation that exports are also licensed. This requires that companies wanting to import ODS obtain a licence from the national ozone unit. While the system is extremely useful for quickly identifying companies trying to illegally import ODS without a licence (so-called front door smuggling), and in managing imports through a quota system, it does not capture imports mis-labelled as non-ODS. UNEP also provides specific training to enable customs officials to identify potentially smuggled ODS, by e.g., mis-declaration or mis-labelling. Table A4.5 in Appendix contains examples of illegal shipments of ODS that were intercepted by parties.

The vast majority of the seizures have involved consignments of ODS packaged in 13.6 kg disposable cylinders (for liquified compressed gases such as CFC-12), rather than in bulk containers (ISO tanks). While large bulk shipments of ODS require facilities for repackaging, small cylinders are attractive to smugglers as they can then be sold on the market relatively easily.

During the first phase of illicit trade of ODS in the mid-1990s, it was estimated that up to 38,000 tons of CFCs were being traded illegally every year. Around 2010, based on an estimated 5% seizure rate, this would translate into 3,660 tons of illegal ODS flowing from and within the East Asia region on an annual basis.

Illicit trade continues with seizures of illegal HFCs in the EU and HCFC-22, in for example the US and Pakistan, imported from countries where these substances are readily available. Due to the phase-down of HFCs in the EU, there has been significant illegal imports. They are thought to be of the order of 10,000 tonnes, and it is known that these are occurring based on market information, seizures of HFCs or presence of illegal disposable cylinders in the market.

The recent seizure in Pakistan⁶⁷ is an example of false labelling. In the largest seizure of its kind for Pakistan, customs authorities confiscated 18,000 kilogrammes of the smuggled

⁶⁷ <https://www.unenvironment.org/news-and-stories/story/pakistan-customs-seize-massive-smuggled-shipment-ozone-depleting-gas>, November 2018.

refrigerant HCFC-22 at Karachi Port in mid-October 2018. A customs officer received information that an attempt would be made to import illegally the refrigerant. The officer had received UNEP training to identify ozone-depleting substances smuggled by mis-declaration and mislabelling, among other methods. The import of HFC-32 was claimed, but customs noticed that the bulk container tank was not classified for HFC-32. The tank was pasted with large stickers declaring its contents as HFC-32 and flammable, which HCFC-22 is not. Agents scanned the container and found the temperature and pressure readings on the tank also did not correspond to HFC-32 refrigerant. Authorities then tested a sample, which confirmed the presence of HCFC-22.

Information on illegal trade in ODS reported by the parties, pursuant to paragraph 7 of decision XIV/7, is available.⁶⁸ Most recent reports are about HCFC-22. The most recent report for CFC-11 illicit trade is from Turkmenistan (August 2014), which reported seizure of 4 cylinders with a total weight of 50 kg. There are no reports of CTC seizures in the period from 2010 onwards.

Illicit trade in newly produced CFC-11 (or CFC-12) would be different to earlier illicit CFC trade, as there are now no countries where these substances can be legally produced and traded (except in extremely small quantities for laboratory uses) as they have no feedstock applications. While recovered CFC-11 or CFC-12 could be legally shipped for destruction, the quantities available would be small and may be contained in mixtures of a range of substances. In 2016⁶⁹, all parties reported the import of 4 ODP tonnes and export of 7 ODP tonnes of recovered CFCs. Any shipments of newly produced CFC-11 cannot receive a valid export licence or a valid import licence from any country unless it is for destruction. Therefore, transhipment fraud is not a likely option, and any illegal shipments would more likely use another smuggling method such as concealment, mis-declaration, or false labelling. As the standard container for CFC-11 or for CFC-11 blended in a polyol for foam production for supply to an end-user is the 55 US gallon drum, false labelling could potentially be a plausible smuggling method, but would require illicit export and import, and absence of detection to maintain significant flows. CFC-11 could also be transported in bulk containers.

As CTC is used as a feedstock, it can be traded legally for legitimate uses. For all parties in the period 2012-2016, imports and exports reported under Article 7 were relatively small (less than 3,300 tonnes, see table 2.7). As it is a liquid, CTC can be transported in drums, but depending on the quantity required, using drums for supplying a CFC-11 production plant is not optimum. For the larger quantities required for CFC-11 production, CTC would normally be supplied in large containers (10-20 tonne ISO tanks/road barrels), or, where the infrastructure exists, for 50+ tonne railcars.

There does not appear to be evidence through customs or other agency activities, including seizures or interceptions, that illicit trade in significant quantities of CFC-11 or CTC has occurred in recent years. However, there have been indications of recent marketing of CFC-11 for use in foams (see Appendix 4). The Foams Technical Options Committee was provided with a copy of an offer for sale of CFC-11 for 2,200 USD/tonne through distribution, has seen offers for sale on internet websites, and has learned more through industry discussions.

⁶⁸ <https://ozone.unep.org/information-reported-parties-montreal-protocol-illegal-trade-ozone-depleting-substances-paragraph-7>

⁶⁹ Information provided by parties in accordance with Articles 7 and 9 of the Montreal Protocol on Substances that Deplete the Ozone Layer Report of the Secretariat UNEP/OzL.Pro.29/5–UNEP/OzL.Pro/ImpCom/59/2 page 44.

2.8.1 Illicit international trade, compliance and enforcement actions

The submissions from parties, ExCom reports, publicly available reports of enforcement action and evidence of on-line marketing have provided more information about illicit activities, measures to prevent them and enforcement actions. While the submission of information on illegal trade in ODS reported by the parties, pursuant to paragraph 7 of Decision XIV/7, is voluntary, the non-compliance procedure⁷⁰ allows parties to express concerns about other parties compliance (para 1) or parties to report its own non-compliance (para 4) if it concludes that, despite having made its best, bona fide efforts, it is unable to comply fully with its obligations under the Protocol. There are no non-compliance activities or reports that are related to unexpected CFC-11 emissions.

A main source of material on enforcement comes from the Ozone Network. The Second Global Inter-Regional Meeting and ‘Join the Experts’ Sessions for National Ozone Officers⁷¹ (February 2019 Paris) had a session⁷² on enhancing compliance and enforcement. In addition, the Global Montreal Protocol award for customs and compliance officers 2018⁷³ recognizes the crucial role of customs & enforcement officers in implementing trade restrictions and bans for hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). Both groups of chemicals are widely used as refrigerants and foam blowing agents.

The document OEWG-41-CFC-11-NotebyFundSecretariat⁷⁴ provides a detailed summary of the measures implemented to control and detect illegal production and trade and is complementary to the information in the Task Force preliminary report and information provided by parties. Annex II of the note provides a summary of customs and enforcement; UNEP OzonAction tools, products and services. The note points out that the vast majority of Article 5 parties do not produce and only import controlled substances. The regulatory frameworks necessary to ensure their compliance with the Montreal Protocol are simpler than for those Article 5 parties that also produce and/or export (e.g., trans-shipment) controlled substances. In addition, regulations and reporting related to the movement of controlled substances through free-trade zones (FTZs) bring additional complications. In particular, while Article 7 data reporting guidelines encourage the reporting of movement of controlled substances through FTZs, some Article 5 parties do not consider the movement of controlled substances to or from their FTZ to affect consumption or compliance.⁷⁵ Regulations associated with the movement of controlled substances contained in pre-blended polyols vary by country and can raise challenges when those regulations and reporting mechanisms differ.

⁷⁰ Handbook of the Montreal Protocol Section 3.5 Non-compliance procedure

⁷¹ <http://www.ozonactionmeetings.org/second-global-inter-regional-and-parallel-network-meetings-national-ozone-officers-paris-france-17-1>

⁷² http://www.ozonactionmeetings.org/system/files/session_4_compliance_and_enforcement.pdf

⁷³ http://unep.fr/ozonaction/information/mmcfiles/7930-e-Global_MP_Award_for_Customs_EnforcementOfficers.pdf

⁷⁴ Overview of the procedures under the multilateral fund by which parties review and ensure continuing compliance with the terms of agreements under the fund. Note from the Multilateral Fund Secretariat May 2019

⁷⁵ Regulatory and reporting frameworks can be adjusted to include a requirement for controlled substances passing through a FTZ in order to avoid illegal trade and to comply with paragraph 3(d) of decision XIX/12 on preventing illegal trade in ODS. Paragraph 3(d) of decision XIX/12 states that Parties wishing to improve implementation and enforcement of their licensing systems in order to combat illegal trade more effectively may wish to consider implementing domestically, on a voluntary basis, monitoring of transit movements (trans-shipments) of ODS, including those passing through duty-free zones, for instance by identifying each shipment with a unique consignment reference number.

Accordingly, the regulatory frameworks necessary to ensure compliance with the Montreal Protocol will vary based on particular national circumstances.

2.8.1.1 Information provided about enforcement

The United States has not identified any enforcement actions related to CFC-11 or CTC since 2013. A list of U.S. enforcement actions related to ODS can be found at <https://go.usa.gov/xysUM>. Illegal trade enforcement actions in recent years are related to HCFC-22 imports by individuals, companies and distributors. The sentences and penalties are reported. On this page is also a link to information on the penalties related to ozone-depleting substances on the black market.

China provided information regarding CFC-11 related Law Enforcement Action. From 2010 to the first half of 2018, 24 cases of illegal production, 44 cases of illegal use, and 5 cases of illegal sale of ODS were investigated and given penalty in China. According to ODS Management Regulation, illegal production equipment and facilities were dismantled and destroyed, illegal enterprises were given fines. Among them, there were 14 cases involving illegal production of CFC-11, about 84 tons of illegal CFC-11 were destroyed. In August 2018, MEE organized environmental authorities at provincial and municipal levels across the country to launch a specialized ODS law enforcement inspection. This specialized inspection, on the one hand, targeted the source by extensively collecting information and tracking down illegal production. Based on clues collected, two illegal CFC-11 production factories located respectively in Liaoning Province and Henan Province were demolished. On the spot 177.6 tons of production raw materials and 29.9 tons of illegally produced CFC-11 were seized. Suspects of the Henan illegal factory were transferred to the local public security organ for criminal responsibilities, the case is being considered according to judicial procedure. The suspects of the second case are on the run and listed as wanted by public security organ. The inspection, on the other hand, targeted the side of ODS use by severely cracking down illegal ODS use and tracking its source.

In the EU, Member States are responsible for enforcement and penalties for the Regulations that ensure compliance with the Montreal Protocol and there is no central database available for enforcement actions and penalties. The EU provided information from Member States about enforcement action in relation to CFC-11. There were no reports of illegal trade in CFC-11 for the period 2013 onwards, and enforcement actions reported related to CFC-11 emissions. In Spain, penalties were imposed by the court for illegal venting of CFCs from waste refrigerators.

Japan provided information that the domestic laws, which aims at securing and maintaining the complete phase-out of CFC-11 and CTC in domestic manufactures and imports as well as controlling emissions, have been in place. And no violation case has been reported since 2013.

In a report for Russia, no information was found on enforcement actions relating to CFC-11 or CTC for the years 2013 onwards.

México provided information that were no enforcement actions related neither to CFC-11 or CTC in any year.

2.8.1.2 Information provided relating to compliance monitoring and verifications of plant dismantling

The Executive Committee considered three evaluations of the CFC production sector phase-out agreements at its 40th, 42nd and 43rd meetings. The sector approach adopted by the

Executive Committee for the agreements had worked well as the phase-out planned had been achieved. During the implementation of these sector plans, mechanisms to ensure continued compliance were identified and implemented, including *inter alia* auditing of production volumes in CFC-HCFC production swing plants; for plants that are closed, documenting and verifying destruction of key equipment; providing information to the verification team about the fate of equipment not destroyed; and clarifying how net versus gross production is considered. It was also detected small illegal CFC production plants and dismantled in one Article 5 country; and in another country, some quantities of illegally imported CFC were confiscated by customs and distributed to the CFC producers.

Verifications in the production sector vary depending on whether production for exempted uses continues after the phase-out of production of controlled uses. Where closure of production facilities is not required as production for uses that are not controlled may continue, verifications include a parallel technical and financial verification, where the former focuses on the production line to determine production, total sales, internal uses, stock inventory changes, and raw material consumption from daily operation logs and original material movement records. The financial verification covers the producer's financial system and original accounting records to determine production, internal use, overall raw material consumption, domestic sales and exports for ODS use and for feedstock use, sorted by direct sales/exports (by producer) and indirect sales/exports (through dealers). In the process, a cross-check is conducted between the producer export records and customs for each individual plant being verified. Upon completion of the independent technical and financial verifications, the verification outputs from both sides are cross-checked by going through the technical data and financial data to ensure the consistency of verified results.

Where closure of the production facilities is required after phase-out of the production for controlled uses, verifications further include documentation, including photographic or video evidence, of the dismantling of key equipment so that production cannot resume after the completion of the project. Irrespective of whether the production phase-out is for closure or for the phase-out of controlled uses while exempted uses remain, all verifications of production lines covered in an Agreement are carried out according to the standard format for verification of ODS production phase-out approved by the Executive Committee at its 32nd meeting.⁷⁶

The World Bank executive summaries of China HCFC Production and Consumption Verification reports from 2014 onwards provide information on HCFC-22 plant closures and dismantling. China provided information about the closure of production lines undertaken by the companies themselves. These were a HCFC-142b facility, idle since 2011 and dismantled in 2015; a HCFC-22 production facility dismantled in 2017; a HCFC-22 production facility idled in 2017 and dismantled in 2018; and a company's HCFC-22 and chloromethanes lines,

⁷⁶ The draft guidelines and standard format for verification of ODS production phase-out approved by the Committee (decision 32/70), state that verifications should include: an analysis of daily production logs and the financial records; a comparison of actual production to annual quota assigned for each ODS production monitored and at each plant site; review of any quota trading or changes of quotas during the verification year, review and verification of conformity of raw materials consumption with the ODS production monitored; identification of each production campaign and distributed production and raw material consumption data per campaign; confirmation of production quantities and raw material consumption from production logs; verification of sales and procurements of monitored ODS products against financial records; verification of stock at the beginning and the end of year against financial records; a review of the system of record keeping at each production facility for adequacy; confirmation that cumulative inventory change of monitored ODS corresponds to annual production and sales data; integration of hourly in-plant flow rate data (corrected for concentration if necessary), over time (either graphically or analytically) to get an independent value for production; and other data.

which were dismantled by a demolition company in 2017. World Bank verification reports provide information on these closures and dismantling. China provided information that the relevant verification reports are still being collected, in response to a request for information for the years 2003-2013, to provide verification reports for closure of ODS plants that have been shut down to demonstrate they were dismantled, with the plant items destroyed and/or removed from the site.

ExCom reported⁷⁷ that a number of illegal producers have been found by SEPA (China) in the years prior to 2004, usually denounced by legal producers who noted market disturbances. The illegal plants, with small production capacities of 100 to 200 tonnes per year, were closed down and dismantled by SEPA. The evaluation mission was not informed of any illegal production in India, where inspections are the responsibility of the Pollution Control Boards at State level.

The European Union reported that the Netherlands' CFC facility was dismantled completely in 2005, the area cleaned, and it is currently a nature area. The operating permit was revoked/repealed by provincial government.

Japan provided information that, for the years 2003 to 2013, all ODS plants and related items were destroyed or removed in an appropriate way in accordance with the relevant law.

México provided information that the CFC-11 and CFC-12 production in México was shut down in 2005. The plants were not dismantled since they are swing plants and were converted to HCFC-22. There was no commitment with the Executive Committee to dismantle the plants.

In a report for Russia, CFC-11 production in the former USSR was concentrated in the Russian Federation, where CFC-11 was produced at four plants. After CFC-11 producing facilities were shut down in 2000, in 2001 the equipment at one company was partially dismantled, and partially converted to produce HCFC-22, but production has now stopped. The equipment to produce CFC-11 at another company was dismantled and in 2002 was replaced by technological line for production of HCFC-141b, HCFC-142b and HFC-143a. Two companies partially dismantled their equipment for CFC-11 production (all elements of control system and all pipelines demounted and removed from the site), residual parts which are still on the site are properly sealed (seals are the same as they were when the production was stopped in 2000). From visual point of view the remaining parts look like they are not in use for decades.

The United States provided information that production of CFC-11, along with other CFCs was phased out January 1, 1996, consistent with the Montreal Protocol's provisions.

⁷⁷ Forty-second Meeting Montreal, 29 March - 2 April 2004, Report on the intermediate evaluation of CFC production sector phase-out agreements.

2.9 Other potential sources of CFC-11 production

2.9.1 CFC-11 by-production as a result of commercialised production of other legitimate fluorocarbons

Consideration has been given to several other fluorocarbon production processes that could cause unintended CFC-11 by-production, these include:

- i) CFC-11 by-production due to CTC impurity in the chloroform fed into an HCFC-22 plant. It has been demonstrated by analysis that, due to the reactor operation conditions, any CTC in the chloroform fed to an HCFC-22 plant would be converted to CFC-12 before it escapes the reactor system and hence CFC-11 emissions would be negligible.
- ii) CFC-11 by-production due to chloroform being chlorinated to CTC in an HCFC-22 plant, for example due to over-feeding chlorine, which is used as a catalyst conditioning agent. It has been demonstrated by analysis that, due to the reactor operation conditions, any CTC formed in the HCFC-22 reactor would be converted to CFC-12 before it escapes the reactor system and hence CFC-11 emissions would be negligible.
- iii) CFC-11 by-production due to CTC impurity in the dichloromethane fed to an HFC-32 plant. It has been demonstrated by analysis that, due to the reactor operation conditions, any CTC in the dichloromethane fed to an HFC-32 plant would be converted to CFC-12 before it escapes the reactor system and hence CFC-11 emissions would be negligible.
- iv) CFC-11 by-production due to dichloromethane being chlorinated to CTC in an HFC-32 plant, for example due to over-feeding chlorine, which is used as a catalyst conditioning agent. It has been demonstrated by analysis that, due to the reactor operation conditions, any CTC formed in the HFC-32 reactor would be converted to CFC-12 before it escapes the reactor system and hence CFC-11 emissions would be negligible.
- v) CFC-11 by-production due to CTC impurity in the perchloroethylene or trichlorethylene fed to a vapour phase HFC-125 or HFC-134a plant. It has been demonstrated by analysis that, due to the vapour reactor recycle operation, any CTC in the perchloroethylene or trichlorethylene fed to a vapour phase HFC-125 or HFC-134a plant would be converted to a higher fluorinated species (e.g., CFC-12, CFC-13 or PFC-14) before it escapes the reactor system and hence CFC-11 emissions would be negligible.

Furthermore, the potential for CFC-11 to be produced from feedstock impurities and minor side reactions in other large-scale fluorocarbon (e.g., HCFC-22 and HFC-32) production processes has been assessed by manufacturers. CFC-11 is not seen in the product HCFC-22 or HFC-32 analysis (i.e., typically CFC-11 is less than 1 ppm in these products), which indicates that even with ~1,000,000 tonnes of HCFC-22 and HFC-32 being produced globally per year only ~ 1 tonne or less of CFC-11 would be produced per year by this mechanism. It has therefore been concluded that the quantity of CFC-11 production resulting from feedstock impurities and minor side-reactions occurring in other fluorocarbon production processes is likely to be insignificant.

2.9.2 Other theoretical production/by-production routes which are unlikely to be commercialised

CFC-11 can be released by several complex organic reactions however these reactions are not in large volume use so the likelihood of any of these routes being a significant source of CFC-11 is considered insignificant.

2.9.3 Other production routes that might cause an incremental increase in CFC-11 emissions

Consideration has also been given to several other processes that have been suggested to generate CFC-11 emissions, these include:

i) Volcanoes

Reports of volcanogenic CFC emissions have arisen in the literature from time to time. In a recent white paper provided by Klobas and Wilmouth⁷⁸, published studies on this topic have been reviewed. In some studies, concentrations and ratios of CFCs measured at volcanic sites did not reflect the character of the ambient background, suggesting volcanogenic production of CFCs. In the preponderance of other published studies, however, the concentrations of CFC-11 and other CFCs were found in the same ratio as with ambient air or were below detection limits.⁷⁹ Thermodynamic models have suggested that volcanic processes cannot produce emissions of significant quantities of CFCs.^{80,81} Analyses of atmospheric gases trapped in ancient freshwater and Antarctic firn sampled at depths corresponding to primarily pre-industrial air indicate that if there are any natural sources of CFCs, they likely contribute minimal or insignificant quantities relative to modern-day concentrations.^{82,83,84} Finally, volcanic activity is a natural phenomenon, occurring for geological perpetuity, and hence volcanoes are unlikely to be the cause of the sudden and significant increase in CFC-11 emissions in the East Asia region. Klobas and Wilmouth conclude that the literature evidence is weighted against significant volcanogenic production of CFC-11 and hence precludes the excess annual emissions recently reported by Montzka *et al.*⁸⁵

⁷⁸ Klobas, J.E. and Wilmouth, D.M., Volcanogenic chlorofluorocarbons and the recent CFC anomalies, 2019, <http://nrs.harvard.edu/urn-3:HUL.InstRepos:39913598>.

⁷⁹ Frische, M., Garofalo, K., Hansteen, T.H., Borchers, R. and Harnisch, J., The origin of stable halogenated compounds in volcanic gases, *Environ. Sci. Pollut. Res.*, 2006, **13**, 406–413.

⁸⁰ Povarov, V.G. and Isidorov, V.A., Thermodynamic model of formation of the organic component of volcanic gases in equilibrium degassing processes, *Russ. J. Gen. Chem.*, 2003, **73**, 1–8.

⁸¹ Symonds, R.B., Rose, W.I. and Reed, M.H., Contribution of Cl-and F-bearing gases to the atmosphere by volcanoes, *Nature*, 1988, **334**, 415–418.

⁸² Nielsen, O.J., Scott, B.F., Spencer, C., Wallington, T.J. and Ball, J.C., Trifluoroacetic acid in ancient freshwater, *Atmos. Env.*, 2001, **35**, 2799–2801.

⁸³ Sturrock, G.A., Etheridge, D.M., Trudinger, C.M., Fraser, P.J. and Smith, A.M., Atmospheric histories of halocarbons from analysis of Antarctic firn air: Major Montreal Protocol species, *J. Geophys. Res.-Atmos.*, 2002, **107** (D24).

⁸⁴ Montzka, S.A., NOAA ESRL Global Monitoring Division, Boulder, CO, 13 May 2019, via personal communications.

⁸⁵ Ibid., Montzka S. *et al.* (2018).

ii) Combustion of certain fuels

CFC-11 can be formed by the combustion of coal, glycerol and natural gas that contain the necessary elements carbon, chlorine and fluorine. The level of CFC-11 has been detected at ppb levels in combustion gases. It is unlikely that fuel combustion is the cause of the sudden and significant increase in CFC-11 emissions.

iii) Burning of rubbish

CFC-11 has been detected in the fumes given off by burning rubbish. Most of this CFC-11 is thought to be due to the release of CFC-11 already contained within the rubbish. It is unlikely that rubbish burning is the cause of the sudden and significant increase in CFC-11 emissions. The CFC-11 global emission increase from 2012 to 2017, as derived from atmospheric concentration measurements, appears inconsistent with this type of incidental and unsystematic activity.

2.10 CFC-11 and CFC-12 used as feedstocks for other chemical production

Production of CFC-11 for non-feedstock and feedstock⁸⁶ uses is required to be reported to UNEP under Article 7. No production of CFC-11 for feedstock use has been reported by parties since 2009. Between 1990 and 2009, there were sporadic reports of production for feedstock use totalling 830 tonnes, similar to the quantity imported for feedstock into the US over the same period (but it is not known for what this was used). The quantity is insignificantly small compared to the total CFC-11 production reported and may actually be a consequence of inaccurate reporting.

There is a suggested chemical reaction pathway to HFO-1234yf, through CFC-215cb and HFC-245cb, that uses CFC-11 as one of the feedstocks. This route appears theoretically plausible but there is currently no known commercial plant using this route.

Production of CFC-12 for non-feedstock and feedstock uses is required to be reported to UNEP under Article 7. Article 5 and non-Article 5 parties reported under Article 7 that CFC-12 was used as a feedstock in quantities less than 500 tonnes during the period 2000 to 2007. No production of CFC-12 for feedstock use has been reported by parties since 2007.

~~While the production of some HFCs and HFOs has created a demand for CTC as a feedstock to produce intermediates, such as chlorinated propanes and propenes, there are no identified uses of CFC-11 as a feedstock. This is consistent with the report of zero use as feedstock during the period 2009 to 2016, at a time when process routes to HFOs were under development.~~

2.10.1 Potential use of CFC-12 as a feedstock to manufacture bromotrifluoromethane (halon 1301)

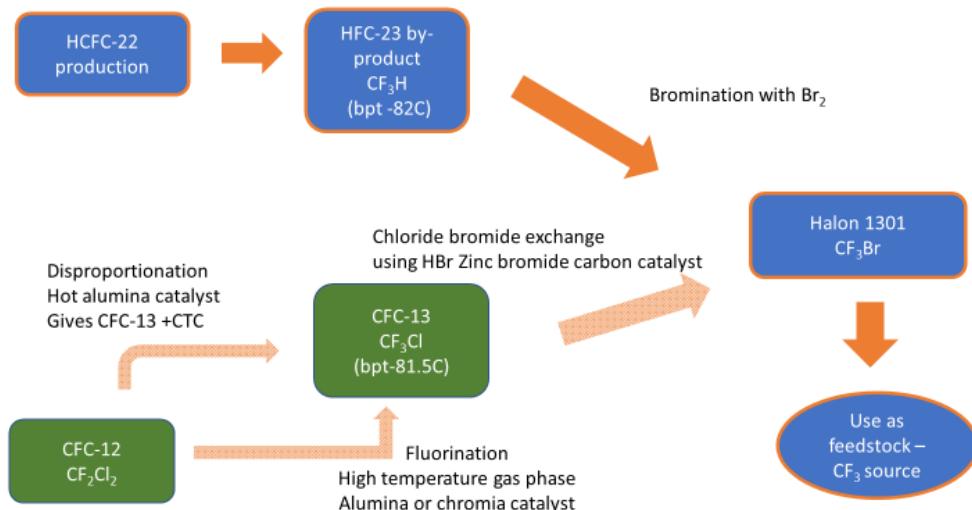
Historically, some of the HFC-23 generated as a by-product during the manufacture of HCFC-22 was recovered and used as a feedstock to produce halon 1301 (bromotrifluoromethane). When production of halon 1301 ceased in non-Article 5 parties in 1994, in accordance with the Montreal Protocol, this requirement for HFC-23 also largely

⁸⁶ Feedstock uses refer to the use of ODS as chemical building blocks for the commercial synthesis of other chemicals.

ceased.⁸⁷ However, halon 1301 is currently used as a feedstock for the manufacture of the pesticide fipronil. According to the REACH Registration Dossier on the ECHA website⁸⁸, halon 1301 is manufactured and/or imported in the European Economic Area for industrial use resulting in the manufacture of another substance (use of intermediates) for fine chemicals production.

Halon 1301 is usually produced⁸⁹ by substitution reactions involving the replacement of either hydrogen or chlorine atoms of fluorocarbons by bromine. It can be manufactured by bromination of HFC-23 (or also perfluoropropane) in a non-metallic reactor or by a zinc-bromide-carbon catalysed chloride exchange reaction of chlorotrifluoromethane (CFC-13) with hydrogen bromide. It can also be produced by disproportionation reaction of difluorodibromomethane (halon 1202) catalysed by aluminium chloride. The established commercial route is from HFC-23.

Figure 2.9 Schematic of production pathways for halon 1301



Chlorotrifluoromethane CFC-13, especially at the small scale, can be produced by a disproportionation process. For this process, CFC-12 is passed over a hot alumina catalyst that effectively "scrambles" the fluorine and chlorine atoms to give CFC-13 and CTC. It is a clean reaction that does not involve HF directly and so can be accomplished in relatively cheap equipment.⁹⁰ Alternatively, CFC-12 could be fluorinated using a vapour phase

⁸⁷ Incineration of HFC-23 Waste Streams for Abatement of Emissions from HCFC-22 Production: A Review of Scientific, Technical and Economic Aspects Prepared for United Nations Framework Convention on Climate Change by A. McCulloch Marbury Technical Consulting and University of Bristol UK, 2005

⁸⁸ <https://echa.europa.eu/registration-dossier/-/registered-dossier/10495/1> Accessed August 2019

⁸⁹ Lewis, R.J., Sr (Ed.). Hawley's Condensed Chemical Dictionary. 12th ed. New York, NY: Van Nostrand Rheinhold Co., 1993, p. 193 & Gerhartz, W. (exec ed.). Ullmann's Encyclopedia of Industrial Chemistry. 5th ed. Vol A1: Deerfield Beach, FL: VCH Publishers, 1985 to Present., p. VA4 (85) 414

⁹⁰ Rudge A.J., The Manufacture and Use of Fluorine and its Compounds, Oxford University Press, London, 1962, 87pp.

process⁹¹, operating at several hundred degrees C and high pressure over a chromia or alumina catalyst, with unreacted CFC-12 being recycled. A conventional liquid phase CFC-11/12 process can produce a range of C₁ CFCs. The exact extent of the range will be affected by the design of the plant, and how far one could skew the operating temperature/pressure and catalyst loading but even targeting a high proportion of CFC-12, the amount of CFC-13 in the product mix would be quite small.

Although CFC-12 has been used until 2007 as a feedstock to produce CFC-13 in small quantities, an additional reaction step is required to convert the CFC-13 to halon 1301. HFC-23 is readily available from HCFC-22 plants, is effectively “free”, and the production of halon 1301 from HFC-23 is well established and, therefore, is the preferred commercial production route.

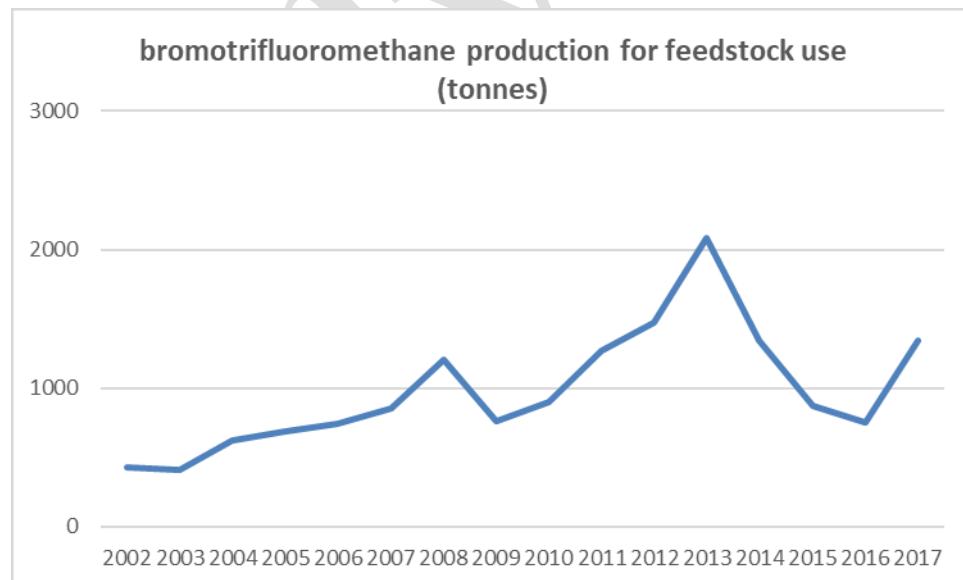
2.10.1.1 Reported production of CFC-12 and CFC-13 for feedstock

Article 5 and non-Article 5 parties reported under Article 7 that CFC-12 was used as a feedstock in quantities less than 500 tonnes during the period 2000 to 2007, after which there is no reported CFC-12 feedstock use.

CFC-13 has only been reported as produced for feedstock use in 2 years (1994 and 2007).

The use of halon 1301 as a feedstock for the manufacture of other chemicals (the pesticide fipronil) is reported annually under Article 7 and is in the range 400 to 2,100 tonnes in the period 2002 to 2017.

Figure 2.10 Bromotrifluoromethane (halon 1301) production for feedstock use (tonnes)



⁹¹ See Hamilton J.M. Jr., The Organic Fluorochemicals Industry, in Advances in Fluorine Chemistry Vol 3, Stacey M., Tatlow, J.C. and Sharpe A.G. Eds., Butterworths, London, 1963, 281pp. This describes a process for making CFC-13 from CTC involving recycle of under-fluorinated CFC-11 and CFC-12.

2.11 Conclusions

The possible production plant options for the manufacture of CFC-11 have been considered. These options depend on the desired annual quantity of CFC-11 to be produced and cover a range of plant types that have different capacities, economics, and times to achieve production (for example, whether the plant is rebuilt or converted).

The main process routes to CFC-11 production use CTC as feedstock; the possible availability of CTC has been considered to meet a range of CFC-11 production annually from small-scale ($\leq 10,000$ tonnes per year) to large-scale ($\geq 50,000$ tonnes per year).

The selected CFC-11 production output range allowed for different CFC-11 production routes to be reviewed by the Task Force to provide an overall assessment of the likelihood of each production route as a contributor to the incremental increase in CFC-11 emissions.

Appendix 3 presents a summary of the different CFC-11 production routes reviewed by the Task Force, along with some of the key technical and economic factors considered.

Of the 22 potential alternative CFC-11 production routes considered by the Task Force, the most likely production routes are: CTC to CFC-11 on micro-scale plants using minimal equipment (to make low grade CFC-11 for foam blowing use); and CTC to CFC-11/12 on large-scale existing liquid phase plant (HCFC-22⁹² and/or HFC 32 plant). Less likely but still possible is CTC to CFC-11/12 on large-scale existing vapour phase plant (dedicated CFC plant). If new CFC-11 production is occurring, emissions related solely to the production stage may occur but at relatively low rates, which are dependent on the production process used.

Based on modelling of CFC-11 production, usage and emissions and comparison against atmospheric observations, the “most likely” modelling scenario predicts 40,000 to 70,000 tonnes per year CFC-11 production would have been required from 2012 onwards to account for the increased CFC-11 emissions. This places CFC-11 production at the large-scale end of the production ranges considered.

If, as predicted, larger scale CFC-11 production ($\geq 50,000$ tonnes per year) were required to account for the increased emissions, then it seems less likely that a large number of micro-scale plants would be solely responsible, although does not preclude some micro-scale plants from contributing to the production.

The production of CFC-11 (and CFC-12) is possible in HCFC-22 plants. Depending on plant constraints, an existing 30,000 tonnes per year HCFC-22 plant could produce between 20,000 to 50,000 tonnes per year of CFC-11, with as little as 3-5 % CFC-12 co-production. Spare annual capacity to produce CFC-11 in a HCFC-22 plant is estimated to be available in: Argentina, Mexico, Russia, and Venezuela for small-scale CFC-11 production ($\leq 10,000$

⁹² Overall likelihood of production route being a significant cause has been revised in light of information received from the parties. CTC to CFC-11/12 on large-scale existing HCFC-22 liquid phase plant remains technically possible but is also considered unlikely due to compliance monitoring. Owing to the technical feasibility of this route, it remains as one of the most likely potential production routes.

tonnes); the EU and the US⁹³ for medium scale CFC-11 production (between 10,000 and 50,000 tonnes); and China and the EU for large-scale CFC-11 production ($\geq 50,000$ tonnes)⁹⁴.

Similarly, the production of CFC-11 (and CFC -12) is possible in liquid phase HFC-32 plants. The production of 50,000 tonnes per year CFC-11 would require at least 20,000 tonnes per year spare HFC-32 capacity. An estimated 50,000 tonnes per year of spare HFC-32 capacity is estimated to have been available in 2012-2016 and is likely to remain available.

It is possible to produce almost 100% CFC-11 in a detuned CFC-11/12 or adapted modern HCFC-22 or HFC-32 plant. Near 100% CFC-11 production is also considered possible in a micro-production plant that is purposefully designed and operated on a batch basis to produce CFC-11 using similar feedstock and catalyst. Emissions from this type of illicit and unregulated plant, with inadequate controls, could be up to 10 % of CFC-11 production.

The quantity of CFC-12 co-produced as a result of any CFC-11 production is dependent on the exact production option chosen, and how the plant is set up and operated. With CFC-11 as the target chemical, for the most likely production routes, the range of CFC-12 co-production is between 0-30% of total CFC-11/12 production. Excluding emissions from any CFC-12 usage, it seems plausible that economic factors could limit average CFC-12 emissions to less than say 5% of the CFC-11 production rates, i.e., less than 3,500 tonnes per year of CFC-12 emissions (based on the upper range of predicted CFC-11 production of 70,000 tonnes that could account for the increased CFC-11 emissions).

CTC is produced in chloromethanes plants as an unavoidable part of the production of methylene chloride and chloroform. China, the European Union, and the United States have the largest chloromethanes capacities, and therefore also the largest potential availability of CTC. In 2016, the global maximum amount of potential CTC available from chloromethanes production, after existing local supply commitments had been met, was 305,000 tonnes. A number of regions have the spare annual capacity that might allow CTC production in the amounts required for small-scale CFC-11 production. Only China has the spare annual capacity that might allow CTC production to supply the larger amounts of CTC required for large-scale CFC-11 production.

CTC is also produced in perchloroethylene/CTC (PCE/CTC) plants, which have the flexibility to produce from 0% to 100% of either substance according to demand. Five PCE/CTC plants are operative in Europe and the United States. Spare global capacity to produce CTC by this process is estimated to be 50,000-100,000 tonnes per year, existing mainly in the European Union. At least nine similar plants exist in China, but these exist solely for the purpose of transforming excess chloromethanes/CTC into PCE.

Between 45,000 to 120,000 tonnes of CTC would be required to supply between 40,000 to 70,000 tonnes of CFC-11 production, as predicted to account for the increased CFC-11 emissions, depending on the proportion of co-produced CFC-12. For near 100% CFC-11

⁹³ It is considered possible that maximising the CFC -11 production capabilities when adapting the HCFC -22 lines could increase the theoretically available CFC -11 production capacity of the United States to above $> 50,000$ tonnes of CFC -11 per year.

⁹⁴ For the year 2017, China and the European Union had spare capacity for HCFC-22 production of less than 50,000 tonnes. For the years 2013-2016, China and the European Union had estimated spare capacity greater than 50,000 tonnes per year.

production, and almost nil CFC-12 co-production, the range would be closer to 45,000 to 80,000 tonnes CTC.

There does not appear to be evidence, through customs or other agency activities, including seizures or interceptions, that illicit international trade in significant quantities of CFC-11 or CTC has occurred in recent years. However, there have been indications of recent marketing of CFC-11 for use in foams.

Advance

3 Foams

3.1 Summary

The Task Force plans to continue to investigate the potential use of CFC-11 in foams resulting from the marketing of CFC-11 in foams and the following.

- Based on its current assessment, the Task Force finds that they could not eliminate production of rigid or closed-cell foam products using newly produced CFC-11 as a potential source of the sudden and increased emissions of CFC-11.
- It seems unlikely that the unexpected emissions have resulted only from the traditional end-of-life handling of foams manufactured with CFC-11 produced before 2010 unless there has been a significant change from historical processes from appliances and construction for a very large volume of foams.
- Although technically feasible, the Task Force questions the economic incentive to broadly replace dichloromethane (also known as methylene chloride), given its very low cost, with CFC-11 in open-cell flexible foams. Nevertheless, the Task Force continues to explore the possibility of use of CFC-11 to reduce volatile organic compound emissions from flexible foams as limited in some parties or limitations in the use of methylene chloride due to toxicity concerns. After reviewing low-cost alternatives available to produce flexible foams, the Task Force has concluded that it is very unlikely that there has been renewed use of CFC-11 in flexible foams.
- Further investigation is warranted into the use of CFC-11 polyurethane (PU) foams and pre-blended polyol systems for PU rigid foams as it is technically feasible and more economically advantageous than reverting to use CFC-11 in flexible foams. ~~However, it seems unlikely that multi-national or other large system houses would risk their reputations by knowingly using CFC-11⁹⁵.~~ The increased CFC-11 emissions imply volumes of CFC-11 usage that would go well beyond those that could be attributed to smaller or local system houses. It is likely that there has been a resumption of newly produced CFC-11 usage in closed-cell foams.
- Concerns related to conversion of enterprises in the spray foam sector and SMEs have created the most challenging issues that might drive the further use and release of CFC-11. Whether or not this actually has resulted in any usage of previously banned blowing agents on a significant basis has not been confirmed.
- There is a gap between the projected emissions from foams in banks (including landfills) based on emission rates found in the literature and the emissions derived from atmospheric concentrations, even in regions where CFC-11 has not likely been used in decades (<1.5% versus 3-4%). It is possible that further processing of foams before disposal through shredding and crushing of foams accounts for at least some of that difference. The Foams Technical Options Committee (FTOC) proposes continued investigation into the gap between literature data related to release rates as well as reuse and disposal of foams containing CFC-11. Parties have provided information in

⁹⁵ This comment has been removed as a number of examples of large companies risking their reputations by knowingly violating laws and regulations (e.g., Volkswagen, Enron etc.)

their submissions that has helped to address the gap in the emissions (emissions) rates when foams are dismantled.

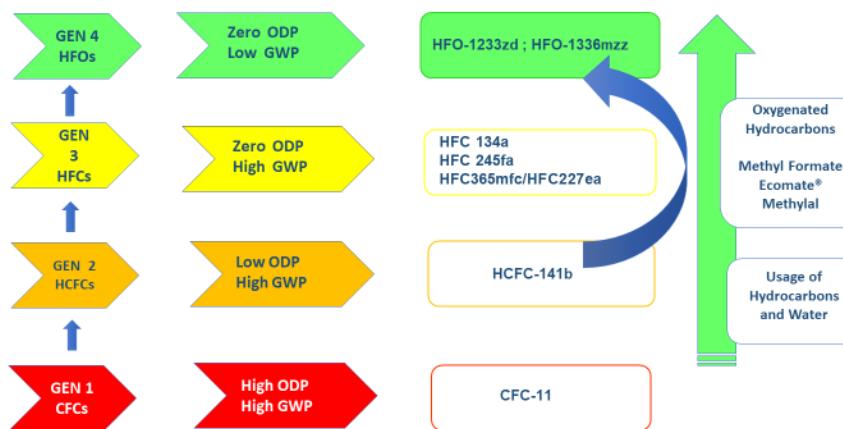
- Note that any scenario where a significant amount of CFC-11 is used in rigid foams would require significant CFC-11 production and would increase the foam bank volumes. Further analysis of the foam banks ~~is warranted~~ was completed for the final report. Even the most extreme bank emissions scenarios do not account for the unexpected emissions of CFC-11. Additional information regarding banks and emissions is included in the emissions chapter.
- It is considered economically attractive and technically straight-forward to revert to using CFC-11 from HCFC-141b, or another fluorocarbon, as the other raw materials and equipment used to produce foams are compatible with only slight modifications to ingredient ratios. In addition, there are a number of regulatory, cost and technical drivers that might further encourage the transitions backward including a shortage in HCFC-141b resulting from the phase-out.
- The Multilateral Fund Secretariat (MLFS) provided data from both Article 5 and non- Article 5 parties indicating that up to 7,500 tonnes per year blowing agent had been reported as being incorporated into foam systems and imported by various parties. Foam systems could be mislabeled and used by a recipient without knowing what blowing agent is in the system.
- The higher pricing and lack of availability of HCFC-141b related to the ozone-depleting substances (ODS) phase-out combined with the technical ease of conversion to CFC-11 could be a driver for reverting to use of CFC-11 as a blowing agent. CFC-11 as a blowing agent could also be of interest to companies who erroneously believe that it may reduce foam flammability without using expensive fire retardants.

3.2 A History of CFC-11 Usage in Foams

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

Figure 3.1 Evolution of blowing agents for polyurethane foam applications

Main blowing agents evolution – Polyurethane foam applications



CFC-11 was not known to be used in extruded polystyrene foams (XPS) which were foamed with CFC-12. PU foam formulations generally contained between 3% CFC-11 in flexible slab foams to 12% in rigid PU foams. It has been estimated that 86% to 100%⁹⁶ of the blowing agent is emitted during the foaming process for flexible foams and 4% (e.g., appliance foams) to 25% (e.g., spray foam) is emitted in the manufacture of rigid foams. Earlier literature describes emissions rates of 98% (flexible foams) and up to 30% (closed cell foams) during installation. The lower emissions rate may reflect more sophisticated technologies and application techniques.

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

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

⁹⁶ Ashford et al., 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*, Chapter 7, Emissions of Fluorinated Substitutes for Ozone Depleting Substances https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_7_Ch7_ODS_Substitutes.pdf; Industry expertise.

3.2.1 Supply Chains for Foam Manufacturers

Thermoset polyurethane foams are largely used as board stock or applied as a spray foam in construction, for industrial uses (e.g., pipe insulation), and in refrigeration (e.g., refrigerators, commercial refrigeration display cases, transportation, coolers, etc.).

3.2.1.1 Supply Chain for Large Foam Manufacturers

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

Figure 3.2. Supply chain for large and medium foam manufacturing

Rigid or Closed-Cell Polyurethane Foam Supply Chain

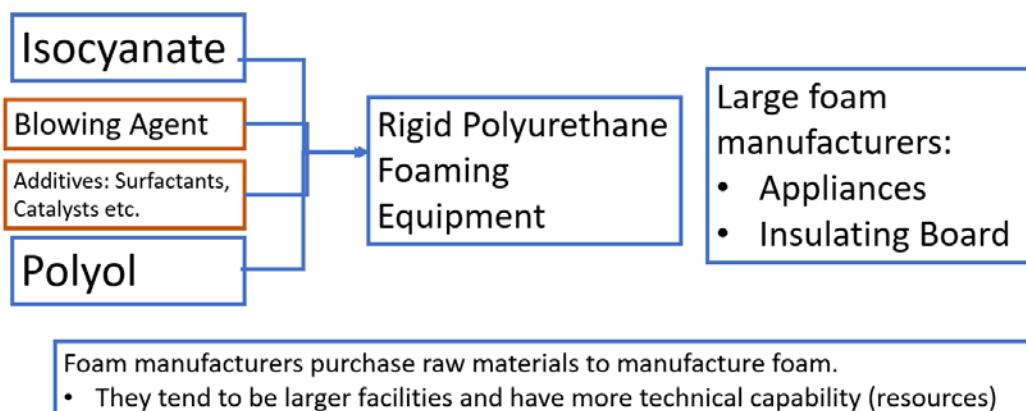


Figure 3.3 Board production process

Manufacturing Polyurethane Foams Continuous Insulation Board

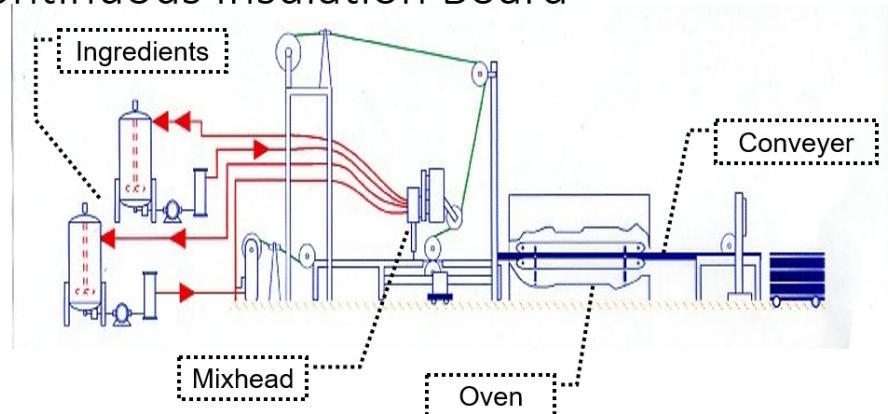


Figure 3.4 Spray foam and foam molds blending process

Polyurethane Spray Foam and Foam Molds

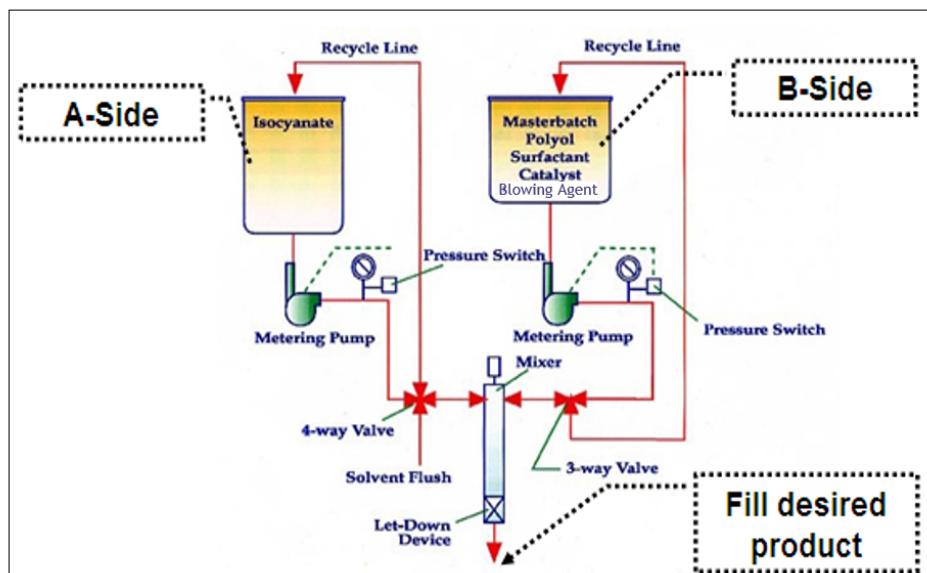


Figure 3.5 Foam products generally produced by large and medium manufacturing processes

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

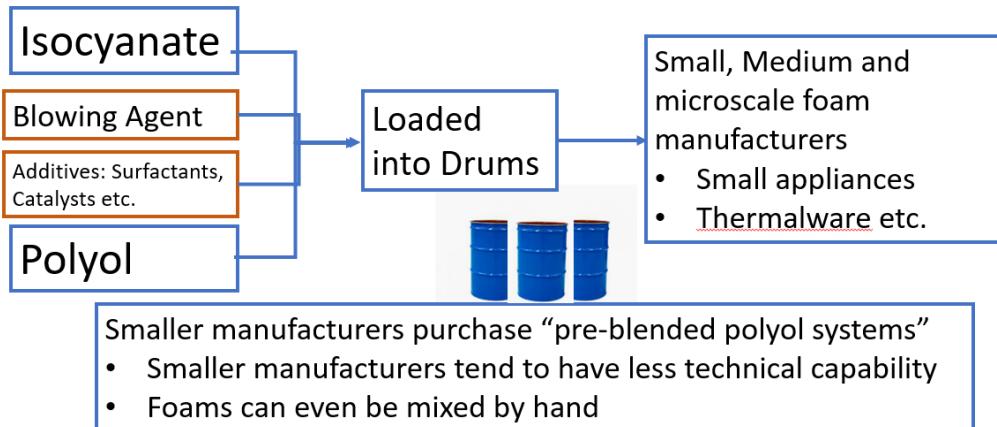


3.2.1.2 Supply Chain for Smaller Foam Manufacturers

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

Figure 3.6 Supply chain and production processes for small and medium manufacturing processes

Polyurethane Foam System Supply Chain



3.2.2 Pre-blended polyol systems

A number of parties import pre-blended polyol containing blowing agent for local foam production. According to data provided directly to the Task Force by the MLFS, 33 out of 68 parties reporting HCFC-141 consumption also reported import of pre-blended polyol systems. The summary does not state from which country these were shipped. In individual discussions with some parties, it was noted that foam system houses ship polyol systems to other countries in close proximity, especially to countries with very small foam production. There is likely additional pre-blended polyol shipped to other countries that has not been reported by these 68. As shown in the table below, as much as 7500 tonnes of HCFC-141b was reported as being shipped in pre-blended polyol to other countries in 2009. None of the parties reporting production of HCFC-141b to the Ozone Secretariat reported to the MLFS that they had received pre-blended polyols.

Table 3.1 Summary of HCFC-141b consumption as reported to MLF Secretariat summarized by region

Region	Baseline	2009	2010	2011	2012	2013	2014	2015	2016	2017
HCFC-141b										
Africa	4453	4008	4002	3659	6605	3868	3702	2569	1620	2128
Asia and the Pacific	75499	71775	78871	90130	86103	67303	66580	50471	50096	49390
Europe	1840	1825	1672	1966	6	2	4	4	4	5
Latin America and the Caribbean	15274	14419	14422	13370	14322	10589	9300	8655	6378	5933
Total HCFC-141b	97,065	92,027	98,966	109,125	107,036	81,761	79,585	61,698	58,099	57,455

**Table 3.2 Summary of HCFC-141b consumption in polyol systems as reported to
MLF Secretariat summarized by region**

Africa	1616	151	1275	767	1410	433	652	613	865	481
Asia and the Pacific	2930	6654	2775	3168	3643	3417	4103	4421	5041	3265
Europe	325	23	63	103	102	35	11	0	0	0
Latin America and the Caribbean	1079	608	698	507	1120	1938	892	936	868	925
Total HCFC-141b contained in imported pre-blended polyols	5,952	7,435	4,810	4,545	6,275	5,822	5,658	5,971	6,774	4,671

It should be noted that emissions from pre-blended polyols are similar to, or higher than, emissions from foam components that are not pre-blended as emissions from drums are not always well-controlled, especially from drums that are not cooled in high ambient temperature countries.⁹⁷

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

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

3.3.1 Patents

In addition to marketing CFC-11 for use in foams, a number of patent applications⁹⁸ describing the use of CFC-11 in various uses have recently been published. Many of the examples below describe the use of CFC-11 in concrete foams and XPS foams in spite of the fact that the boiling point of CFC-11 is higher than would normally be considered technically appropriate to produce XPS foams. FTOC is not aware of the commercialization of the products described in the patents.

Patents could be developed for a number of reasons.

- Patents incorporating a product may be a result of trying to find new ways to market and use available or excess supply.
- Companies or governments may reward patent-owners for writing new patents even if they are never used.

⁹⁷ Blowing agent emissions from loading drums can be as high as 20% in high ambient temperatures as measured by one foam system house and reported to FTOC.

⁹⁸ A quick patent search yielded 13 patents in 2017 related to the use of CFC-11 in foams. There have been many more filed in recent years.

- Patent authors could be trying to solve technical issues such as foam flammability.

A small sample of the patents includes:

- Preparation method of environment-friendly fireproof and heat-insulating material for building external wall - China (CN) 108070166 A 20180525⁹⁹,

Abstract

The invention relates to an environmentally-friendly building external wall fireproof and thermal-insulation material preparation method, wherein polystyrene, desulfurized gypsum, talc powder, trichlorofluoromethane and bis(2,4,4-trimethylpentyl) aluminum phosphinate are used as raw materials according to a certain ratio, plasticizing, pre-foaming, secondary foaming, mixing and other processes are sequentially performed through a polystyrene foam extrusion production line, extrusion molding is performed, and the self-extinguishing time is determined according to the self-extinguishing determination method in the Ministry of Light Industry Standard SG-232-81, and is 0.5-5 s. According to the present invention, the preparation method provides the idea for the application of the efficient phosphorus-based flame-retardant material in the building exterior wall thermal insulation material.

- Preparation method of fire-resistant board CN 107814543 A 20180320100

Abstract

The invention provides a preparation method of a flame retardant board. The preparation method is characterized by comprising the following steps: adding copper sulfate liquid into magnesium oxide, mixing and stirring for 20min at 40 DEG C, adding expanded perlite and cement, stirring for 10-15min according to the rotating speed of 320 revolutions per minute, adding triethanolamine, stirring for 10min, adding trichlorofluoromethane, stirring uniformly, injecting a mold, carrying out foam forming, maintaining, demolding, and cutting, thus obtaining a finished flame retardant board. The flame retardant board obtained by the preparation method of the flame retardant board is low in production cost and excellent in hydrolytic resistance, and conforms to flame retardance standard GB8624-2006 level C or above.

- Preparation method of cement foaming agent CN 107777913101 A 20180309,

Abstract

The invention discloses a preparation method of a cement foaming agent, and belongs to the field of a material. The preparation method comprises: 1) preparing raw materials including, by weight, 20-30parts of sodium fatty alcohol polyoxyethylene ether sulphate, 5-10 parts of starch, 10-20 parts of saponin, 20-30 parts of gelatin, 10-15 parts of sodium bicarbonate, 10-15 parts of hexane, and 15-20parts of

⁹⁹ <https://patents.google.com/patent/CN108070166A/en?oq=108070166>

¹⁰⁰ <https://patents.google.com/patent/CN107814543A/en?oq=+107814543+>

¹⁰¹ <https://patents.google.com/patent/CN107777913A/en?oq=107777913>

trichlorofluoromethane; 2) dissolving sodium bicarbonate in water and performing full uniform stirring; 3) adding sodium fatty alcohol polyoxyethylene ether sulphate, saponin, hexane and trichlorofluoromethane into water in sequence, and performing full uniform stirring; and 4) adding gelatin in water, and performing full uniform stirring to obtain the cement foaming agent. The cement foaming agent is available in raw materials, wide in source and low in cost. The cement foaming agent has great foaming performance, and is large in foam production per volume. The foam is quite stable, can be maintained for a long time, and is fine. The cement foaming agent is high in foam expansion and good in foam stability.

- Sandwich panel using quasi-incombustible resin composition and method for manufacturing the same Korea - (KR) 1823003 B1 20180131102
- Preparation method of Arenga engleri fiber foam mattresses CN 107513266 A 20171226103

Abstract

The invention discloses a preparation method of a arenga engleri fiber foaming mattress, which comprises the steps of weighing arenga engleri fiber, dimethylcyclohexylamine, MDI, silicone oil, polydimethyl siloxane fluid, stannous octoate, zinc oxide, water, trichlorofluoromethane, an AC foaming agent, TCEP, stearic acid, paraffin, cyclohexanone and chlorobenzene diamine; the preparation method is simple, the cost is low, the operability is strong, and the compressive strength is 300-340MPa; the product is soft, the elongation is 300 to 400%, the tear strength is 0.5 to 2.5kN/m, the tensile strength is 400 to 500MPa, and the bond strength is 360 to 380MPa; the mattress has the advantages of high durability, difficult collapse deformation, high supporting performance, antibacterial and mildew prevention performance, good process stability, long service life, and wide raw material source, is not easily damaged by worms, and can be widely produced and replace the existing materials gradually.

- Method for preparing synthetic latex foam mattress CN 107501667 A 20171222¹⁰⁴

Abstract

The invention discloses a preparation method of a synthetic latex foamed mattress. The method comprises the following steps: weighing synthetic latex, toluene diisocynate, polyether glycol, triethylenediamine, drinking water, an AC foaming agent, trichlorofluoromethane, zinc stearate, dicumyl peroxide, sodium bicarbonate, dilauryl thiodipropionate, ethylene glycol monomethylether, hexabromocyclododecane, phosphorous acid and sodium polyacrylate. The preparation method is simple, the relative density is low, the cost is low, the operability is high, the compression strength is 240 to 300 MPa, the flame-retardant efficiency is good, and the mattress is automatically extinguished after leaving fire; the elongation is 230 to 370 percent, the mattress is soft, the durability is high, the

¹⁰² No additional information found

¹⁰³ <https://patents.google.com/patent/CN107513266A/en?oq=107513266+>

¹⁰⁴ <https://patents.google.com/patent/CN107501667A/en?oq=107501667>

mattress is not easy to collapse or deform, and the bearing property is high; the resilience rate is 60 to 70 percent, the mattress is antibacterial and mildewproof, the process stability is good, the service life is long, the mattress is not easily damaged by worms, and the water absorption is low; the heat conductivity is low, the tensile strength is 160 to 380 MPa, the bonding strength is 320 to 380 MPa, the raw material sources are wide, and the mattress can be widely produced and continuously replace existing materials.

- Heat-insulating fireproof material for external wall CN 107383761 A 20171124¹⁰⁵

Abstract

The invention discloses a thermal insulation fireproof material of an external wall, which comprises the following ingredients: phenolic resin, trichlorofluoromethane, lauryl sodium sulfate, amino resin, dicyandiamide, and lithium dihydrogen phosphate aerogel. The thermal insulation fireproof material of the external wall has excellent performances such as fire resistance, low thermometric conductivity and good weatherability.

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

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

The concern about flammability has increased in Asia since 2010, following a series of major building fires which occurred during the construction of some high-rise buildings. Some parties have very stringent standards related to the design of construction foam including foam fire and smoke test demonstrations. However, this has not been true for all jurisdictions. Other parties have responded to the fires in different ways. For example, China halted the use of polyurethane and extruded polystyrene (XPS) foams for some time while new codes were developed (European fire codes were adopted and made more stringent in China in their national fire code for buildings GB50016 on May 1 2015). These changes significantly altered the landscape of thermal insulation in the construction sector. This has greatly reduced the use of rigid polyurethane foam as a thermal insulation material for buildings

3.3.2 Technical feasibility and implications of reverting to CFC-11 use in foams

A brief summary of the technical feasibility and implications of reverting to CFC-11 in foam use is provided below.

CFC-11 conversion to HCFC-141b required significant adjustments to the formulation because of HCFC-141b solvent properties. However, replacing HCFC-141b by CFC-11 in an

¹⁰⁵ <https://patents.google.com/patent/CN107383761A/en?oq=107383761>

HCFC-141b formulation would require minimal adjustment. More adjustments would be required for use of CFC-11 in hydrocarbon or HFC formulations.

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

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

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

One example of shredding and reuse of foams is its use in lightweight bricks in the construction industry in Hebei province in China. One company recently reported in a seminar the reuse of 2.86 million cubic meters of foam from 2011 through 2018. This might result in the release of up to an average of 850 tonnes¹⁰⁶ of a blowing agent per year for seven years. These volumes are not sufficient to explain the unexpected emissions of CFC-11 and the foams may not all be blown with CFC-11. FTOC proposes continued investigation into the gap between literature data related to release rates as well as re-use and disposal of foams containing CFC-11.

3.3.3 High level history of foam blowing agents in closed-cell or rigid foams

The 2006 FTOC Assessment Report¹⁰⁷ includes a detailed summary of blowing agent usage by foam type globally and regionally which has been updated in subsequent assessment reports. The 2006 report is referenced because it is the earliest and most detailed report available to extrapolate to the CFC-11 usage in closed-cell foams. The report estimates that, in 2006, 360,000 tonnes of blowing agent was consumed globally and notes that there had been a stabilization and even slight drop in blowing agent consumption due to more efficient processes with lower losses than previous years. We have used this as a basis by which to estimate CFC-11 use for this report for closed-cell rigid foams. According to the 2006 report, approximately 55% of the blowing agents at that time were used for closed-cell polyurethane foams¹⁰⁸.

¹⁰⁶ Assumptions: 100% of the blowing agent is CFC-11 and 50% of the blowing agent is released from 32kg/m³ density foam containing 13% CFC-11 by weight in the polyol side of the blend.

¹⁰⁷ https://ozone.unep.org/sites/default/files/2019-05/ftoc_assessment_report06.pdf

¹⁰⁸ Peak CFC-11 usage identified for closed-cell foams occurred in the late 1980s according to AFEAS and production and consumption data reported to the OS.

The majority of the blowing agent in use for closed-cell foam was CFC-11 in non-Article 5 parties prior to its ban before 1990. A small amount of CFC-12 was used as a propellant for foams requiring enhanced distribution across longer distances (e.g., spraying foam for refrigerated trailers or containers). CFC-11 was low-cost and easy to use and did not require high-cost additives or equipment (e.g., surfactants and catalysts, high pressure storage equipment). According to reporting through AFEAS and to the Ozone Secretariat, the Task Force estimates that usage of CFC-11 in closed-cell foams peaked in the 1980s just under 200,000 tonnes.

In non-Article 5 parties, during the 1970s, when energy efficiency became a priority, insulation for homes and commercial building increased significantly. In the 1980s, polyurethane foam replaced other types of insulation in refrigerators in non-Article 5 parties. Polyurethane foam was primarily used in appliances in Article 5 parties from 2000 until 2010 when a series of tragic fires occurred. Until concerns were addressed through building code modifications and new requirements related to fire testing of foams were required, use in construction slowed.

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

3.4 Regulations and costs impacting blowing agent selection

The major blowing agent transitions being driven by regulation at present are those in Article 5 parties resulting from the enactment of Decision XIX/6 and being funded under a series of national HCFC Phase-out Management Plans (HPMPs). Since Decision XIX/6 required a “worst first” approach, the phase-out of HCFC-141b was targeted first. CFC-11 had largely converted to HCFC-141b for rigid insulating polyurethane foams and to dichloromethane (DCM)¹⁰⁹ or water in flexible foams in both Article 5 and non-Article 5 parties. The conversion from HCFC-141b has been largely successful within larger and some medium enterprises where the critical mass of the operation is sufficient to justify investment in hydrocarbon technologies. Indeed, in several instances, individual enterprises have been willing to co-fund the investment where the funding thresholds available under the Multilateral Fund have been insufficient, despite the economies of scale.

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

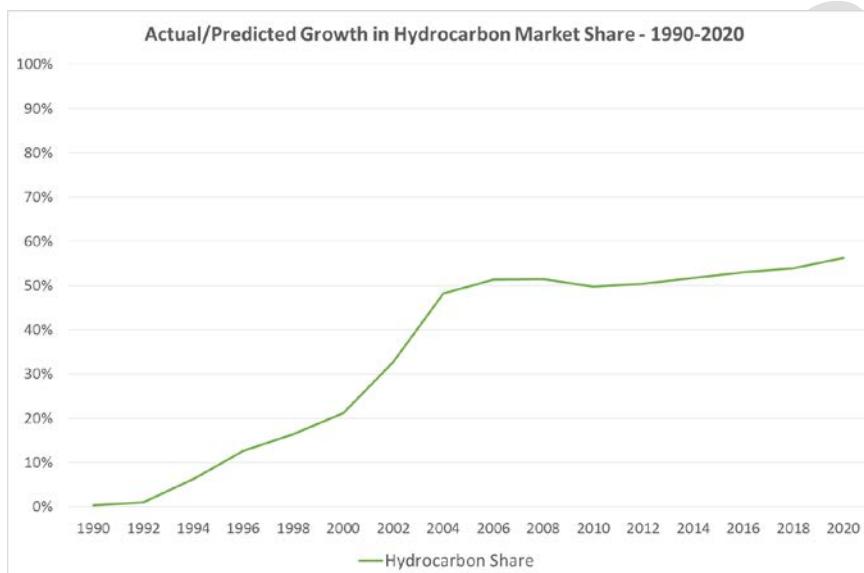
As a result of the trade-offs in properties and costs of various alternatives, the HCFC-141b conversion has resulted in more diverse transitions than the CFC-11 conversion with an estimated 2/3 of rigid PU foams converting to hydrocarbons, water (carbon dioxide), methyl

¹⁰⁹ Dichloromethane is very low cost compared to fluorocarbon alternatives.

formate and a small portion of the market converting to HFCs (e.g., HFC-245fa and HFC-365mfc blended with HFC-227ea) largely in products or facilities where it would be very costly to convert to flammable fluids such as SMEs and in spray foam and other uses that are applied in situ (The market penetration of hydrocarbon technologies is shown in Figure 3.7). In general, HCFCs are less than half of the cost of high GWP HFCs and hydrofluoroolefin / hydrochlorofluoroolefin (HFO/HCFO or unsaturated HCFCs and HFCs) blown foams remain more expensive than HFC foams due to the total cost of blowing agent and required additives.

More specifically, pricing of HCFC-141b based on historical feedback within the FTOC has been within the range of \$1.5 to \$3/kg before duties. The CFC-11 price quote that the FTOC received was \$2.2/kg and previous FTOC progress reports have cited pricing of \$11-\$17/kg for HFOs and \$8-11/kg for HFCs. Prices can vary greatly by country and these are only a snapshot. However, they do show the relative prices of various foam blowing agent products.

Figure 3.7 Evolution of market share of foam sector met by hydrocarbons



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

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

At times, rising prices have also created a “black” market for illegal trade. There have been imports of illegal substances labeled as other products; while in other cases, no effort has been made to mask the sale of the banned chemical. When discovered, these cases have

largely been addressed within the party where the illegal trade has taken place or in customs at borders. However, foams add another level of complexity in detecting illegal trade as pre-blended polyol systems containing the foam blowing agent are shipped from parties that produce polyols to parties that do not produce them. If the blowing agent is not documented, collecting and analysing a sample requires more steps than collecting a refrigerant sample.

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

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

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

3.5 Flexible foams

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

Some countries have placed limitations on the use of DCM due to health concerns. In Europe, DCM is subject to the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation which prohibits its use in paint strippers in concentrations exceeding 0.1%.¹¹⁰ Several European countries have restrictions on the use of DCM. For example, the Danish Environmental Protection Agency lists DCM as a substance that is harmful for human health and should be avoided when substitutable¹¹¹ and Sweden prohibits the use of DCM, except for use in scientific research.¹¹² In the United States (US), the EPA’s National Emission Standards for Hazardous Air Pollutants (NESHAP) for area sources limits, and in some cases prohibits, the use of dichloromethane in foam fabrication.¹¹³ In China, the

¹¹⁰ European Parliament and Council Regulation (EC) No. 1907/2006, 18 December 2006

¹¹¹ Effects List 2009, Danish Ministry of Environment, Environmental Protection Agency Document No.4, 2010

¹¹² Prohibition in Certain Cases in Connection with the Handling, Import and Export of Chemical Products Ordinance (1998:944), 5–7§§.

¹¹³ 40 CFR Part 63, Docket No. EPA-HQ-QAR-2006-0897

Ministry of Environmental Protection included DCM in the Prioritized List of Substances to be Subject to Control under the Water Pollution Control Action Plan released in 2015.¹¹⁴

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

3.6 Update on estimates of banks of foam blowing agents and emerging management strategies

Global banks of blowing agents in foams are estimated to have grown from around 3 million tonnes in 2002 to an estimated 4.45 million tonnes in 2015.¹¹⁵ Based on current consumption estimates, these will grow to well in excess of 5 million tonnes by 2020. This is in spite of the fact that some of the bank will have moved into the waste stream (typically landfill) by then.

These trends imply that there may be a need to introduce effective waste management practices. Indeed, much of the environmental benefit to the ozone layer arising with reclaiming and destroying foaming agents in appliance foams has already passed as zero ODP alternatives have been commercialized. This is being borne out in practice for many appliance recycling plants, where the associated ozone or climate benefit is not sufficient justification for capital investment. As a result, contractors are interested in minimising their upfront investment costs by adopting manual dismantling practices, even though there are associated emissions. This is especially the case in areas of low population density, where the economies of scale are more limited.

Once in the waste stream, such banks are broadly unreachable and the environment needs to rely on natural mechanisms to avoid the some of the impacts of eventual blowing agent emission. Increasingly, ODS-containing foam is being treated as hazardous waste in a number of regions in an effort to avert uncontrolled landfilling, but the over-riding challenge is to be able to police shipments sufficiently well to avoid landfilling when there is no standard procedure for determining the identity of the foam blowing agent routinely. Training and use of detection equipment would allow for the characterisation of waste and would also assist customs officials on cross-border trade of foam products where blowing agent restrictions may already be in force.

A further option for limiting the quantity of ODS-containing and other high-GWP blowing agent foams going to landfill is to encourage voluntary intervention at the point of decommissioning by assigning value to the recovery and destruction of the foam or its blowing agent. At present, this value is most likely to arise from the climate benefits associated with avoiding emissions. However, an additional point of concern is that the

¹¹⁴ Chemical Inspection and Regulation Service (CIRS), China MEP Published List of Priority Chemicals, 5 January 2018, <http://www.cirs-reach.com/news-and-articles/China-MEP-Published-List-of-Priority-Chemicals.html>

¹¹⁵ Data adapted from IPCC/TEAP Special Report on Ozone and Climate (SROC), 2005 – values include hydrocarbons.

average global warming potential (GWP) of the waste stream will decrease with time as the very high GWP blowing agents i.e., CFCs) become less prevalent decreasing the potential climate and ozone benefits and their value.

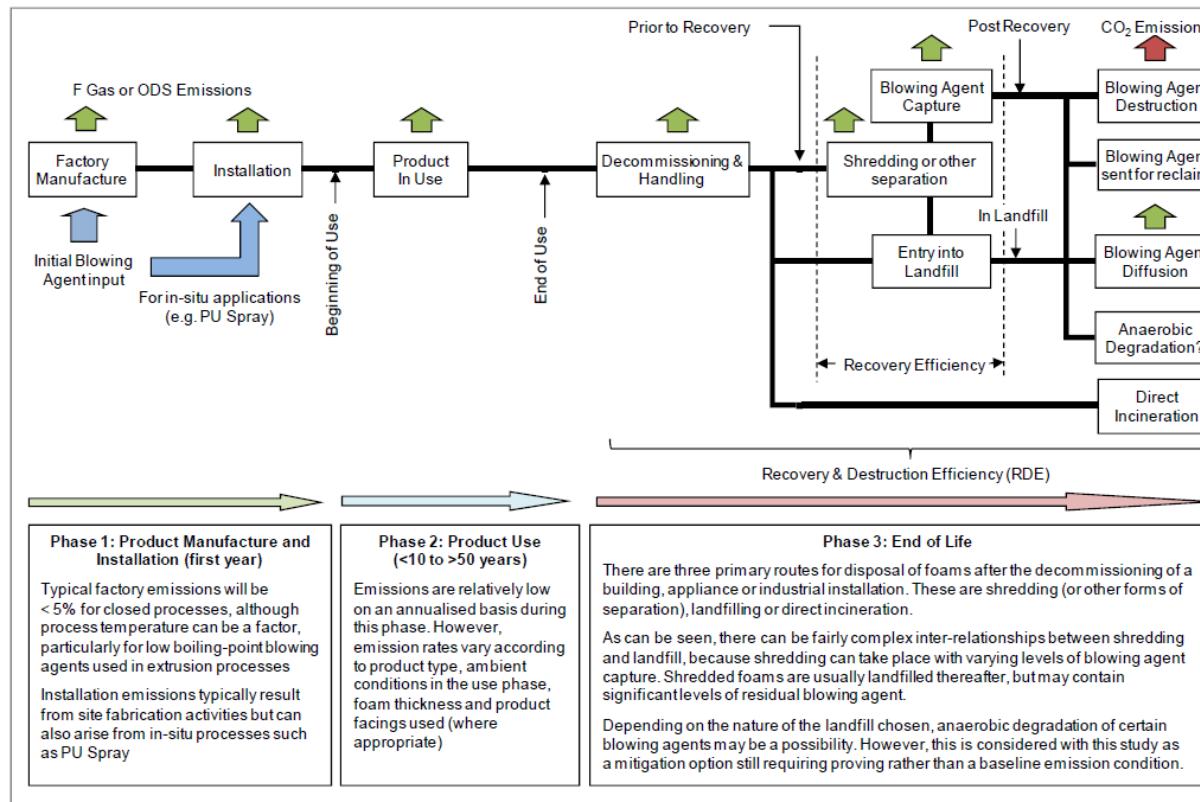
That said, there is a requirement in Europe that appliance components be recycled. Foams are used in waste-to-energy incineration facilities in some cases. Appliance recycling facilities can have closed processing systems to avoid emissions of blowing agents. Waste foam from appliance recycling facilities is sometimes shredded, powdered and bonded to make thin foam sheets and used for flooring and walls or mixed with concrete in limited quantities in some regions.

3.6.1 Best practice in the management of insulation foams and the importance of segregation

Figure 3.8 provides a schematic diagram of the lifecycle of an insulation foam, illustrating the points at which blowing agent releases are likely. Since most new production and installation is now taking place with non-ODS blowing agents, the focus of ODS emission minimisation is at the point of decommissioning and thereafter. The effectiveness of this whole process is measured by the Recovery and Destruction Efficiency (RDE). The ability to maximise RDE lies in the degree to which insulation foams being decommissioned can be separated and segregated from other building demolition waste. The level of waste segregation varies substantially by jurisdiction and those with high levels of segregation achieve the best results in ODS recovery/destruction at lowest incremental cost.

The choice exists to either directly incinerate the insulating foam or to shred it and recover the blowing agent for subsequent destruction. The latter approach is only really cost-effective where there are economic benefits from other components of the building element (e.g., steel from metal-faced panels). In Europe and Japan, where efforts to recover blowing agents have been most extensive to date, there is an increasing tendency to move to direct incineration in order to minimise cost, although this depends largely on the availability and permissibility of use of Municipal Solid Waste Incinerators.

Figure 3.8 Schematic of emission sources and blowing agent management options for insulating foams¹¹⁶ (Source: SKM Enviro/Caleb)



¹¹⁶ Further Assessment of Policy Options for the Management and Destruction of Banks of ODS and F-Gases in the EU (March 2012) SKM Enviro/Caleb.

In 2005, TEAP was instructed by the parties in Decision XV/10 to provide useful information on the handling and destruction of ODS contained in thermal insulation foams with particular focus on economic and technological aspects of those contained in buildings and to clarify the distinction between destruction efficiencies achieved when blowing agents are extracted from foams prior to destruction. The report provided information about the efficiencies of various end-of-life product scenarios as well as technical and economic aspects of blowing agent recovery and destruction from appliance and building insulation foams.

The report concluded that although there are technologically feasible processes that had the potential to reach a recovery and destruction efficiency of greater than 90%, most processes were not economically viable with a recovery cost from appliances of approximately \$25-40/kg plus transportation costs. There was also discussion of “managed attenuation” through anaerobic microbial degradation of ODSs in landfills which would include the over 60% of refrigerators that had been disposed of in non-Article 5 parties by 2003 and nearly all of them now. However, there has been no further development of this process since that time to the Task Force’s knowledge.

3.6.2 Foam end-of-life and emissions from banks

At the end-of-life of products containing foam (e.g., coolers, appliances, thermal ware, etc.), are either landfilled intact or dismantled and the foam removed for disposition. Foams have historically, primarily been landfilled. However, some parties now have incentives or regulations that encourage or require destruction of foams or collection and destruction of blowing agents. There is also some recycling and reuse of foams.

The majority of the global CFC-11 bank in foams is located in North America and the European Union and was installed in the 1970s and 1980s and is now 40 to 50 years old. The majority of products containing CFC-11 blown foams (e.g., refrigerators) were landfilled or dismantled more than twenty years ago. Buildings containing CFC-11 blown foam insulation are likely still in service and will be for some time. In addition, emissions during dismantling have been estimated to be negligible to up to 15%. The primary dispensation of foams in North America is landfill while Europe now uses a number of techniques including foam destruction to dispose of foams.

Blowing agents generally emit slowly from foams over time as they are soluble in the foam matrix, especially chlorinated ones like CFC-11. As noted earlier, even when foams are shredded and crushed, emissions have been measured at approximately 50%.

It is unlikely that emissions from the dismantling of foams from 2012 through 2016 was significantly different than those from 2008 through 2012. The Task Force created a scenario forcing assumptions to maximize emissions during that period (changing the lifetime of foams, increasing emissions during dismantling as if all of the foam dismantled during that period were crushed and shredded with an emissions rate of 50%). In this case, the emissions are an average of 5 kilotonnes greater from 2013-2016 than from 2009-2012. As shown in the scenario just discussed, the Task Force cannot envision any technically or economically feasible scenario where emissions from banks are the source of the unexpected CFC-11 emissions.

3.7 Drivers and feasibility of converting to CFC-11

It would be economically attractive and technically straight-forward to revert to using CFC-11 from HCFC-141b, or another fluorocarbon, as the other raw materials and equipment used to

produce foams are compatible with only slight modifications to ingredient ratios. In addition, there are a number of drivers that might further encourage the transition back to CFC-11.

- Conversion from HCFC-141b back to CFC-11 in PU foams and pre-blended systems would be low-cost with almost no technical changes needed.
 - A single instance of a recently quoted CFC-11 price is lower than market price of HCFC-141b.¹¹⁷
- The phase-out of HCFC-141b in the spray foam sector and in SMEs has created technical and economic challenges that might promote the use of CFC-11, although actual usage has not been confirmed.
 - Lack of available HCFC-141b supply due to production phase-out.
 - Increasing price of HCFC-141b due to the allocation-based supply and demand imbalance.
 - Negative aspects to alternatives:
 - Flammability of hydrocarbons and associated conversion investment
- Higher cost of HFCs and HFOs
- Not all companies in Article 5 parties are funded by MLF. MLF funding for HCFC-141b conversions for funded companies is limited to a single year.
- There may also be a belief that the use of CFC-11 may reduce flammability of foams which has been a challenge for some parties during the last decade.
 - Fire Retardants are high priced compared to the quoted price of CFC-11

In summary, the higher pricing and lack of availability of HCFC-141b related to the ODS phase-out combined with the technical ease of conversion to CFC-11 could be a driver for reverting to use of CFC-11 as a blowing agent. CFC-11 as a blowing could also be of interest to companies who believe that it may reduce foam flammability without using expensive fire retardants.

¹¹⁷ Single quoted price was \$2.2/kg while HCFC-141b is advertised at \$3.5-3.7/kg which is a price that has been confirmed with industry. https://www.alibaba.com/product-detail/Direct-factory-Dichlorofluoroethane-Hcfc-Refrigerant-141b_60622055923.html?spm=a2700.7724857.normalList.21.19567508vByNqX

4 Refrigerant uses

4.1 Summary

- Centrifugal chillers using CFC-11 (some used CFC-12) have always been a relatively small part of the total CFC refrigerant inventory and emissions of all refrigeration and air-conditioning (R/AC) sub-sectors.
- While CFC-12 centrifugal chillers have been virtually phased out, a small number of CFC-11 chillers are still in operation and expected to reach their end of life in the next 1 to 5 years, at the latest.
- The Task Force has estimated the amount of CFC-11 involved in CFC-11 chiller inventories. From leakage assumptions, and from estimates regarding the emissions at end-of-life, an annual emission in the order of 4.5 kilotonnes (2002) to 2 kilotonnes (2015) is derived for non-Article 5 parties (assuming no recovery and recycling). In the case of Article 5 parties, an annual total CFC-11 emission of around 2.5 kilotonnes (2002) to 1.3 kilotonnes 2015) is estimated (assuming no recovery and recycling), where emissions steadily decrease during the period 2002-2015.
- Total CFC-11 emissions of the order of magnitude of 7 to 3.3 kilotonnes per year, decreasing during the period 2002-2015, are estimated for global R/AC uses (for chillers) for the period 2002-2015, based on data available from the Special Report on Ozone and Climate (SROC)¹¹⁸ and the TEAP Supplement Report¹¹⁹, which have been used in Appendix 6 on emissions models and analysis. Appendix 6 presents comparisons with the total global amount of emissions derived from atmospheric observations (in the order of 50 kilotonnes per year for the period 2002-2012) and considers these R/AC emissions as insignificant given that total of 50 kilotonnes (and the increase by 13±5 kilotonnes after the year 2013).
- Based on estimates of CFC-11 banks and emissions, emissions from chillers do not constitute a major portion of the global CFC-11 emissions calculated from atmospheric observations in 2002-2012, and similarly emissions from chillers cannot be a cause for the sudden increase of global CFC-11 emissions since 2013, as derived from atmospheric calculations.
- It is unlikely that CFC-11 production would be employed to maintain a very small number of centrifugal (low pressure) CFC-11 chillers in operation (at presumably very low energy efficiencies compared to the current business as usual practices for refrigerant operation with HCFC-123, and olefins, i.e., HCFO-1233zd(E)).
- It is unlikely that there is a significant resumption of CFC-12 usage in any R/AC sub-sector in both non-Article 5 and Article 5 parties. This implies that no significant new

¹¹⁸ IPCC/TEAP Special Report on Ozone and Climate (SROC), 2005. *Special Report, Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbon and Perfluorocarbons*, Intergovernmental Panel on Climate Change and Technology and Economic Assessment Panel, Cambridge University Press, 2005, ISBN 100-521-68206-1 (Report and Supplementary Material).

¹¹⁹ TEAP, 2005. *Supplement to the IPCC/TEAP Report*, Technology and Economic Assessment Panel, November 2005, ISBN 92-807-2733-8.

CFC-12 production would be needed for all R/AC sub-sector uses, and that this would not be the reason for possible CFC-11 co-production.

- There might be a continuing small CFC-12 demand for a limited number of CFC-12 mobile ACs in certain vehicles, namely some luxury or special vehicles built before 2002 in Article 5 parties. However, this small demand is likely to be supplied from the recycling of refrigerant from aged CFC-12 equipment.

4.2 Introduction

For the refrigeration and air-conditioning (R/AC) sector, the only sub-sector that used, and still uses, CFC-11 is the air conditioning sub-sector, specifically in centrifugal chillers.

Based on the quantities and usage reported by the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS)¹²⁰ around 1990, 8% of the CFC-11 production was used for non-hermetic refrigeration (mostly large chillers), about 30% was for blowing closed cell foam, and 62% for open cell foams, aerosol propellants, solvents, and other emissive uses. For CFC-12 it was different, i.e., for the year 1990, AFEAS reported 68% of annual sales to refrigeration and air conditioning (of which only 2% was used for hermetic systems), 22% for all emissive uses, and about 10% for closed cell foam.¹²¹

Clodic and co-workers reported (Clodic¹²², 2006 and RTOC¹²³, 2010) on the annual demand, banks and emissions of CFCs, HCFCs and HFCs. This concerned the period from 1990 onwards, where the analysis applied data from many years before 1990 to build up a bank of CFC-11 and CFC-12 in the various R/AC sub-sectors. Calibration of the 1990-1996 demand (sales) data was performed using the AFEAS sales data, the only database then available for this type of analysis. Since AFEAS data do not include most developing country production quantities, and developed country production decreased rapidly after 1996, the AFEAS reporting effort was discontinued at end 2003. The accuracy of the relative values of banks and emissions from the Clodic¹²⁴ analysis (2006) for Article 5 parties is based on assumptions made about similarities in CFC production reported to UNEP.

In Appendix 6, global banks and emissions from SROC¹²⁵ and the TEAP Supplement¹²⁶ are studied for the years 2002 and 2015. Special attention is given in this chapter to CFC-11 chiller inventories and emissions during 1990-2020, to be used in Appendix 6.

¹²⁰ AFEAS data is digitally available only on third party websites, including the following:
<https://agage.mit.edu/data/afeas-data>. Accessed May 2019.

¹²¹ The sentence has been modified from the preliminary report to correct for annual sales instead of cumulative sales.

¹²² Clodic, D., 2006. *Global Inventories of the Worldwide Fleets of Refrigerating and Air-Conditioning Equipment in Order to Determine Refrigerant Emissions: The 1990 to 2006 Updating*, Armines, Paris, 2006.

¹²³ RTOC, 2010. *Refrigeration Technical Options Committee 2010 Assessment Report*, Annex on the RIEP emissions estimating program. UNEP, Nairobi, 2010, ISBN 978-9966-20-002-0.

¹²⁴ Ibid., Clodic, 2006.

¹²⁵ Ibid., IPCC/TEAP Special Report on Ozone and Climate, 2005.

¹²⁶ Ibid., TEAP, 2005.

4.3 CFC-11 use in chillers

4.3.1 CFC-11 use in chillers and related emissions

CFC-11 was, and still is, used in centrifugal chillers, an air-conditioning (AC) sub-sector. Already since the 1950s, most of the AC units used HCFC-22 (from small to large units), however, large units also used CFC-12. Centrifugal chillers have used (and some chiller units still use) CFC-11 or CFC-12, with the majority using CFC-11. HCFC-22 use has been phased out in non-Article 5 parties for manufacturing of new AC units and for some of the servicing operations (with a virtual phase-out in the European Union countries as of 2010). However, while it is difficult to check, the Task Force believes that there are currently still a very small number of CFC-12 chillers, probably only in some Article 5 parties in operation. A small number of CFC-11 centrifugal chillers is still in operation in both non-Article 5 and Article 5 parties, where the number is expected to rapidly decrease (to virtually zero) between 2018 and 2025.

Since the CFC-12 (centrifugal or non-centrifugal) AC unit operates on high pressure, leakage is a major issue. The units that were installed in the early 1990s, and before, showed high leakage, and, in fact, also low energy efficiency, which made them prone to replacement. However, this is likely not to have resulted in a complete phase-out, since several chiller owners may have considered the total investments necessary for the replacement exercise, and, in a relatively small number of cases, may have waited for a long time for the right replacement to present itself.

It is likely that the CFC-12 centrifugal chillers have ceased operation, although this is not entirely clear. The only reference available is a 2004 TEAP report¹²⁷ where there was an accounting of CFC-12 chillers in non-Article 5 and Article 5 parties, although this inventory lacked comprehensive data (developing country data were only available from one source).¹²⁸ With the high CFC-12 leakage of these units, and the need for servicing, it is difficult to imagine that any significant number of units have been kept in operation.

In contrast to CFC-12, chillers using CFC-11 operate at low or negative pressure where losses are mainly related to the efficiency of the air-purge system. Based on a recent study by Carrier¹²⁹, an equipment manufacturer, the amounts of CFC-11 chillers and their CFC inventories can be derived. The study makes an analysis of the time-dependent inventory of CFC-11 chillers in North America and elsewhere; it also splits chiller inventories (and emissions) between non-Article 5 and Article 5 parties.

Based on the Carrier¹³⁰ study, the numbers for chiller sales data in non-Article 5 and Article 5 parties are presented in Figure 4.1. Global CFC-11 centrifugal chiller sales were around 4,000 per year during the period 1970-1997; a substantial decrease (due to the non-Article 5 CFC phase-out) can be observed as of the years 1996-97. Based on this analysis, it can also be

¹²⁷ Technology and Economic Assessment Panel, 2004. *Chiller Task Force Report*, UNEP Nairobi, 2004, ISBN: 92-807-2461-4.

¹²⁸ ICF, 2003. *International Chiller Sector Energy Efficiency and CFC Phaseout*, Draft Revised Report Prepared for the World Bank, ICF International Inc., Washington, May 2003.

¹²⁹ Lord, R., 2019. Richard Lord, Carrier, Investigations into CFC-11 chiller inventories, via personal communications, January-February 2019.

¹³⁰ Ibid., Lord, R., 2019.

observed that, around the year 1997, the number of CFC-11 chillers produced in Article 5 parties steadily grew to surprisingly high numbers, after which it rapidly decreased.

Figure 4.1 CFC-11 chiller unit sales in non-Article 5 and Article 5 parties by year, based on Carrier¹³¹ study

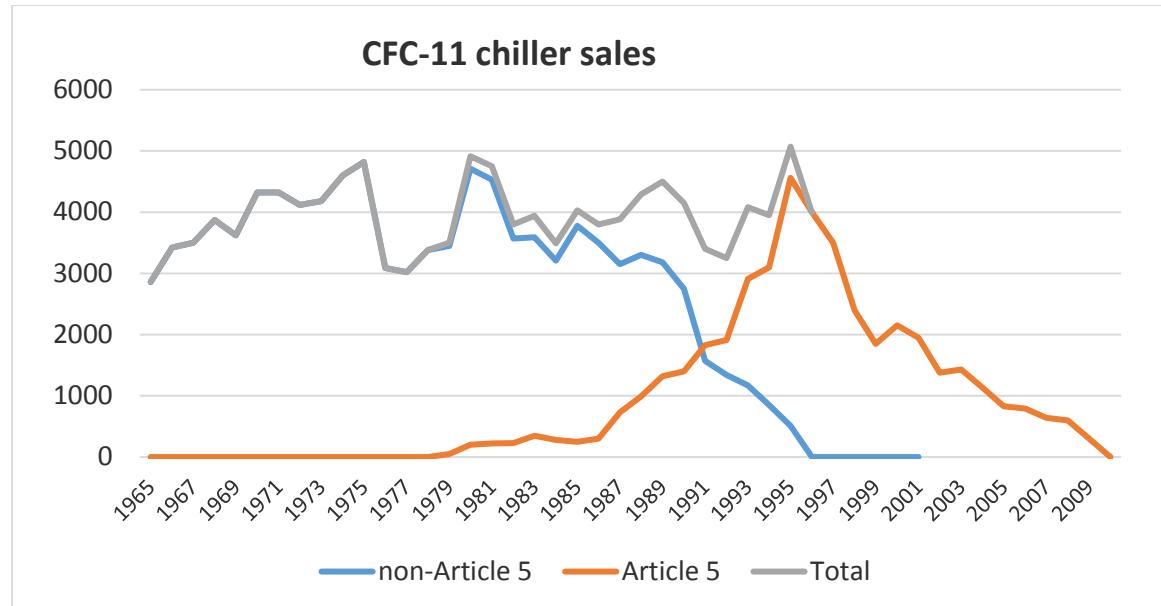
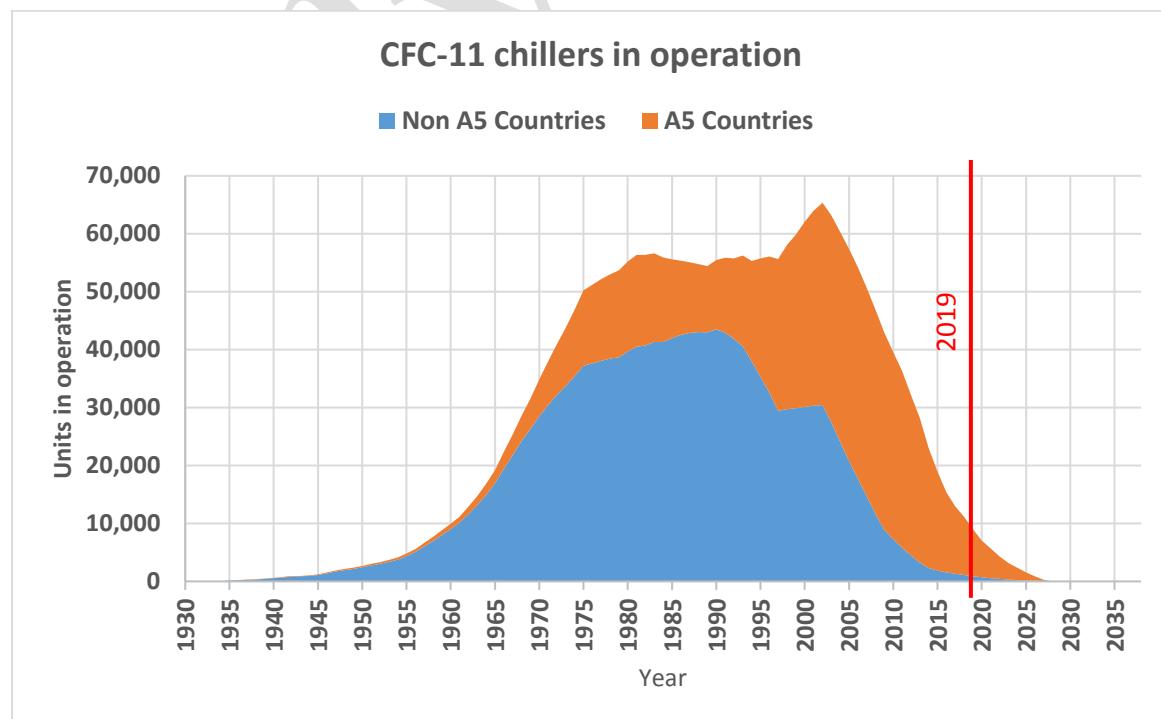


Figure 4.2 CFC-11 chiller units estimated to be in operation by year

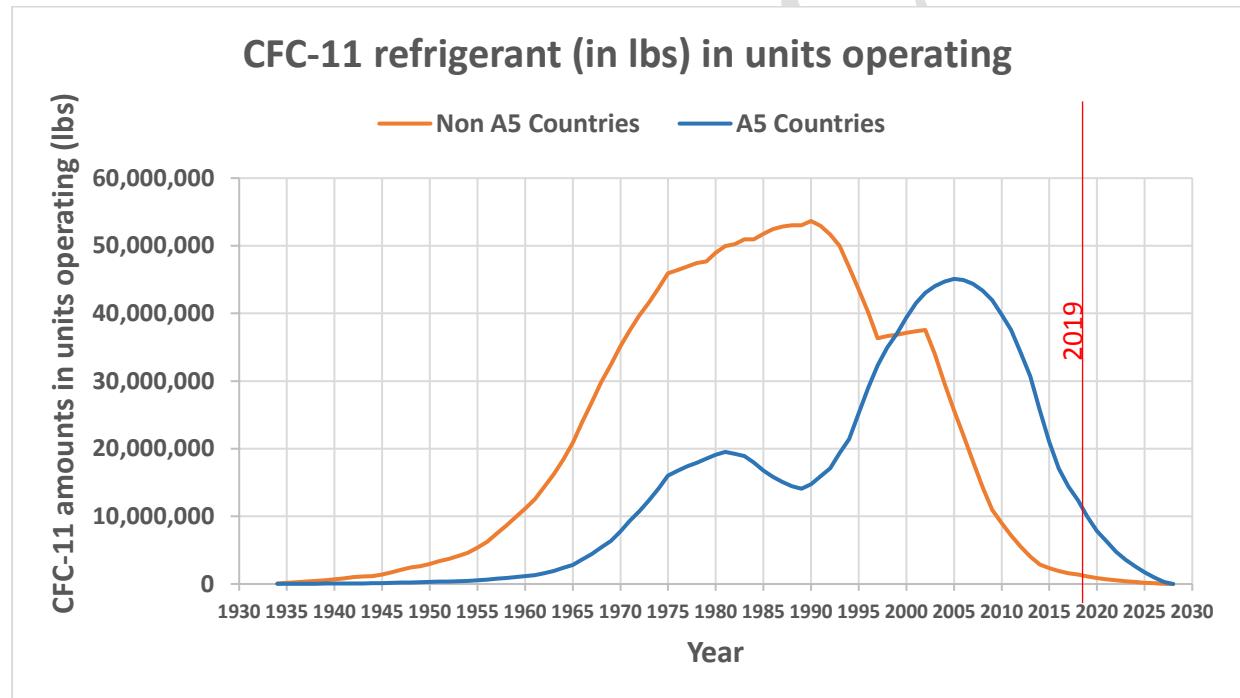


¹³¹ Ibid., Lord, R., 2019.

Figure 4.2 presents the number of CFC-11 chillers estimated to be in operation since the year 1940. It shows that the total global numbers of chillers in operation have been relatively constant between the years 1980 and 2000. The number of CFC-11 chillers in operation decreased rapidly after reaching a maximum in the year 2002. With the number of chillers in operation steadily decreasing, the best estimate is that there would be less than 10,000 CFC-11 chillers in operation globally in the year 2019. This assumes that there could still be some chillers operated in non-Article 5 parties.

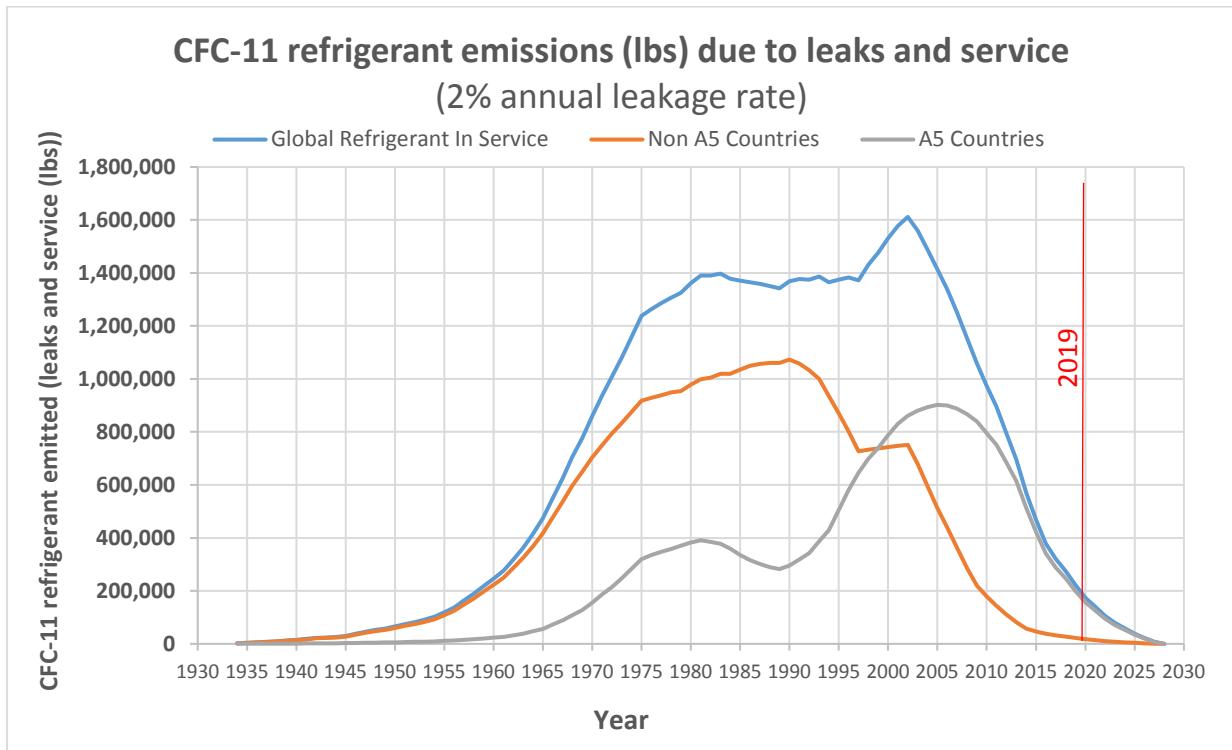
Figure 4.3 presents the annual amounts for the refrigerant in operating units (i.e., banks) in CFC-11 chillers, based on average charge size per kW chiller refrigeration capacity. Based on the assumption of 2% annual leakage rate (and none at disposal; i.e., full recovery) from CFC-11 chillers in operation, which is considered relatively high, CFC-11 amounts emitted can be derived by year, as presented in Figure 4.4.

Figure 4.3 Estimated CFC-11 inventory for CFC-11 chillers in operation by year



Note: Units in lbs. 100,000 lbs is equivalent to 45,360 kg; 60,000 lbs is equivalent to 272,160 kg

**Figure 4.4 Estimated CFC-11 amounts emitted from chillers in operation by year
(assuming a 2% annual leakage rate)**



Note: Units in lbs. 100,000 lbs is equivalent to 45,360 kg; 60,000 lbs is equivalent to 272,160 kg

Uncertainties associated with the CFC-11 chiller operations and resulting CFC-11 emissions are mainly due to different types of maintenance undertaken in the various regions; these leakage numbers may benefit from further investigation, if required. It should be noted that the 2% leakage number is relatively high compared with past (1980-1995) experiences by developed country manufacturers. With the estimates from SROC¹³² and the TEAP Supplement¹³³, from the Clodic¹³⁴ study (2010), from various other sources, and given by Carrier¹³⁵, further study could result in a better estimate of leakage amounts.

At a maximum, annual leakage of 800 tonnes of CFC-11 from CFC-11 chillers is estimated globally for the period 2000-2005 (see Figure 4.4, which gives the amounts in lbs). This leakage amount decreases to a global amount of about 200 tonnes in 2015. The leakage from chillers is therefore not a major factor in CFC-11 emissions.

Another factor is the leakage from chillers that are taken out of operation and dismantled. From the estimates of the amounts of refrigerant in chillers in operation, annual (hypothetical maximum) emissions of 4.5 kilotonnes (2002) to 2 kilotonnes (2015) can be calculated for the

¹³² Ibid., IPCC/TEAP Special Report on Ozone and Climate, 2005.

¹³³ Ibid., TEAP, 2005.

¹³⁴ Ibid., RTOC, 2010.

¹³⁵ Ibid., Lord, R., 2019.

chillers taken out of operation in non-Article 5 parties in the period 2002-2015, if no recovery and recycling operations took place during that period. For Article 5 parties, the annual (hypothetical maximum) emissions from CFC-11 chillers taken out of operation would amount to about 2.5 kilotonnes (2002) to 1.3 kilotonnes (2015), assuming no recovery and recycling, for the period 2002-2015. The CFC-11 emissions of the magnitudes mentioned above, combining emissions from annual leakage during operation and assumed full inventory emissions at end-of-life (no recovery and recycling), have been used (also based on SROC¹³⁶ data) in the analyses of CFC-11 emissions in Appendix 6.

In conclusion, total CFC-11 emissions from chillers cannot contribute to a significant (dominant) degree to the total, global emissions of CFC-11 during the period 2002-2015, nor to the 13 ± 5 kilotonnes of extra CFC-11 emissions per year concluded for the years after 2013 (Montzka¹³⁷, see further Appendix 6). The latter can be further emphasised because, based on models and experience, the annual emissions from leakage and end-of-life processes are expected to decrease gradually during the period from 2002 onwards.

4.3.2 Scenario relating to the shipment and reuse of old CFC-11 chillers

One hypothesis suggested is whether it is possible that old CFC-11 chillers were shipped to another location, e.g., Asia, the CFC-11 refrigerant recharged and put into operation. Then, during the demolition of buildings, could the CFC-11 refrigerant have been released to the atmosphere?

It is possible that a small amount of relatively new CFC-11 chillers have been shipped from non-Article 5 to Article 5 parties. If this occurred, it would mainly have been in the period 1995-1999. However, these exports are unlikely to amount to CFC-11 inventory that is significant.

The following arguments against this hypothesis also need to be considered:

- If this had happened, e.g., in Asia, the (huge) numbers of chillers that would need to be imported (to accumulate the large inventory that could account for the large increase in annual CFC-11 emissions) would have damaged local production and sales of chillers using HCFC-123;
- If it had happened, this would likely have been reported in the press;
- It does not seem likely that (apart from some relatively new chillers) that an old chiller would be shipped to Asia or elsewhere, where the chiller has to be built into an existing or new machine room (with lots of adaptations), at considerable expense and not knowing how long the equipment would reliably be in operation and at which energy efficiency it would operate, particularly as, for example, 1997 vintage chillers were significantly more efficient than 1977 vintage chillers. In addition, for relatively new chillers in non-Article 5 parties, there was the option to retrofit to HCFC-123 if cost effective;

¹³⁶ Ibid., IPCC/TEAP Special Report on Ozone and Climate, 2005.

¹³⁷ Montzka, S. et al., An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, 2018, **557**, 413–417. <https://doi.org/10.1038/s41586-018-0106-2>.

- Since Article 5 parties were struggling to limit their CFC consumption towards the freeze in CFC consumption in 1997, why would those parties have imported CFC-11 units with uncertainty surrounding the ability to service equipment for an extended period, and that could not be retrofitted to non-ozone-depleting alternatives?
- If shipping complete CFC-11 chillers had been a normal operation would export and import statistics not show these numbers?
- As mentioned above, would building owners, in Asia or elsewhere, not choose to install a new chiller (which was possible using HCFCs or HFCs after 1995), rather than take on the costs for this whole operation, ending up with a second-hand chiller, that may not function reliably or efficiently?

There would be several more, smaller arguments that would counter the above export hypothesis.

There is one additional issue that needs to be considered. Figure 4.1 gives a best estimate of the CFC-11 chiller sales in Article 5 parties. These sales data are based on a number of considerations, including estimates from manufacturers and estimates concerning the market absorption capacity for CFC-11 chillers in Article 5 parties in the period 1990-2000. All CFC-11 chillers installed in that period are assumed to go out of operation during, or even before, 2015-2025. It is difficult to see direct relationships with the demolition of the buildings (which are assumed to happen much later) in which the chillers had been installed and the recent increase in CFC-11 emissions. Any emissions related to end-of life would then occur gradually over a longer period (one could almost define this as “business-as-usual”) and would not contribute to a sudden unexpected increase of CFC-11 emissions as of 2013, as observed (Montzka¹³⁸).

In summary, it is not considered technically or economically feasible that there were any such large CFC-11 chiller exports from non-Article 5 parties in the late 1990s; any significant contribution to increased CFC-11 emissions is therefore unlikely, if not impossible.

4.4 CFC-12 banks and emission estimates

Due to the possibility of co-production of CFC-12 with any new CFC-11 production, the potential for any newly produced CFC-12 to be entering the R/AC bank and to be emitted needs to be considered. To account for these possibilities, an analysis of CFC-12 R/AC banks and emissions is presented below. The following section describes historic CFC-12 R/AC banks and emissions estimates based on SROC¹³⁹ data.

For the use of CFC-12, the R/AC sub-sectors normally considered are domestic, commercial, transport and industrial refrigeration, some stationary AC and mobile AC. In the case of stationary air conditioning, HCFC-22 has always been used in this sub-sector to a very large percentage (greater than 90% in all AC equipment); however, in the “early” years some CFC-12 was also used in this sub-sector (even in centrifugal – medium pressure – chillers).

A major CFC-12 consumer in the early 1990s was mobile AC, where the decision was already taken in 1993 to completely convert to HFC-134a in non-Article 5 parties. In the case

¹³⁸ Ibid., Montzka, S. *et al.*, 2018

¹³⁹ Ibid., IPCC/TEAP Special Report on Ozone and Climate, 2005.

of chillers, it concerns smaller capacity non-centrifugals using CFC-12 or HCFC-22, and centrifugal chillers using CFC-11, and, as mentioned, some using CFC-12.

Table 4.1 CFC-12 global bank quantities for the various R/AC sub-sectors and the total, 1990-2006¹⁴⁰

CFC-12 (tonnes)								
Year	Domestic	Comm.	Transp.	Indus.	AC	MAC	Chillers	TOTAL
1990	97,448	87,783	5,274	39,471	4,383	223,110	71,707	529,176
1991	101,325	89,336	5,234	40,723	4,121	221,587	76,457	538,783
1992	105,204	91,060	5,284	41,966	3,836	229,327	81,051	557,728
1993	109,099	92,610	5,292	43,071	3,531	228,150	84,067	565,820
1994	110,696	93,588	5,135	43,823	3,206	220,026	85,585	562,059
1995	109,590	89,760	4,670	43,470	2,862	208,078	85,472	543,902
1996	108,323	85,688	4,209	42,709	2,500	194,896	78,956	517,281
1997	106,608	82,010	3,764	42,250	2,119	180,616	65,794	483,161
1998	104,204	78,982	3,273	39,951	1,744	163,166	55,663	446,983
1999	101,151	74,868	2,790	36,066	1,399	147,205	47,145	410,624
2000	97,438	70,982	2,303	30,384	1,086	129,018	41,079	372,290
2001	93,033	66,836	1,888	25,200	809	112,559	37,852	338,177
2002	88,012	63,329	1,570	22,350	568	95,570	34,649	306,048
2003	82,332	60,607	1,357	21,541	369	73,718	31,313	271,237
2004	76,012	56,512	1,151	21,173	210	60,644	27,799	243,501
2005	69,179	54,032	943	20,526	95	49,816	24,380	218,971
2006	62,419	51,463	795	19,896	25	41,303	21,467	197,368

¹⁴⁰ For the industrial and the commercial sub-sectors, the banks and emissions quantities indicated for CFC-12 also include a very small percentage of R-502, a mixture of CFC-115 and HCFC-22.

Figure 4.5 Global total CFC-12 banks for the period 1990-2006, and for several sub-sectors

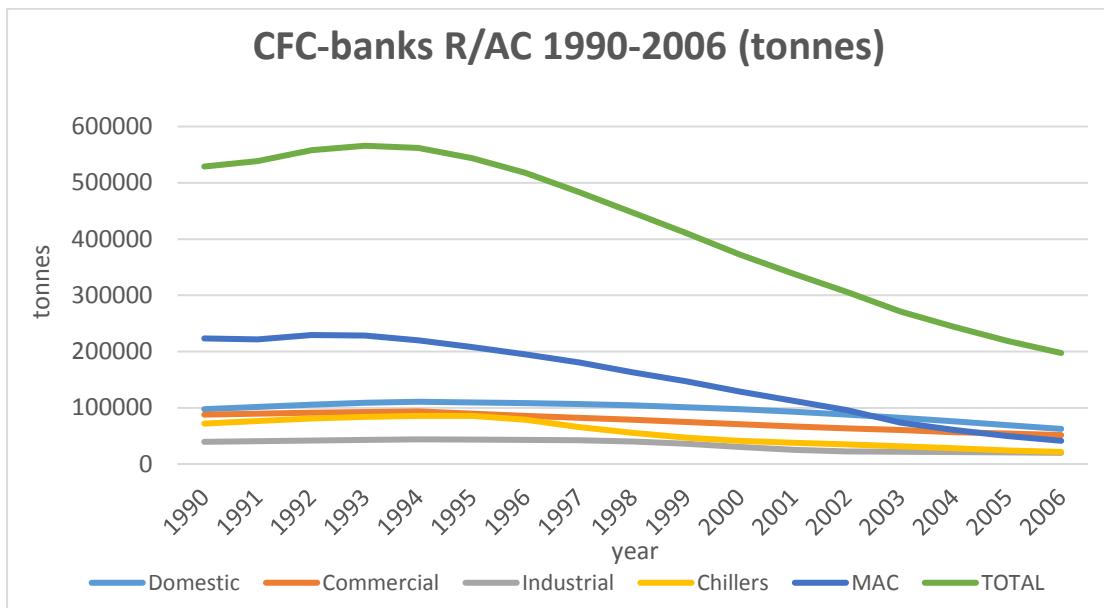


Table 4.1 and Figure 4.5 present the CFC-12 banks for the R/AC subsectors.¹⁴¹ There is a clear difference between the industrial sub-sector, with a relatively smaller bank build up in the longer term, and the domestic and commercial sub-sectors that have relatively larger banks but very different emission patterns. Furthermore, there is the mobile AC sub-sector, which constitutes the largest CFC-12 bank in the early 1990s. The total bank of CFC-12 shows an almost linear decrease between 1995 and 2003, after which these CFC-12 banks in some sub-sectors essentially disappear after a few years.

An important observation is that (when applying a simple extrapolation) the CFC-12 banks in the domestic, MAC and AC sub-sectors will have disappeared by 2015-2020. However, some CFC-12 equipment in the commercial and industrial sub-sectors may remain in use after 2015, although this will be relatively small, i.e., marginal in the total context.

After 2005, the majority of the CFC-12 bank for MACs is mainly located in Article 5 parties. It can be assumed that this CFC-12 bank had mostly disappeared after 2015 (with specific exceptions of small on-going use)).

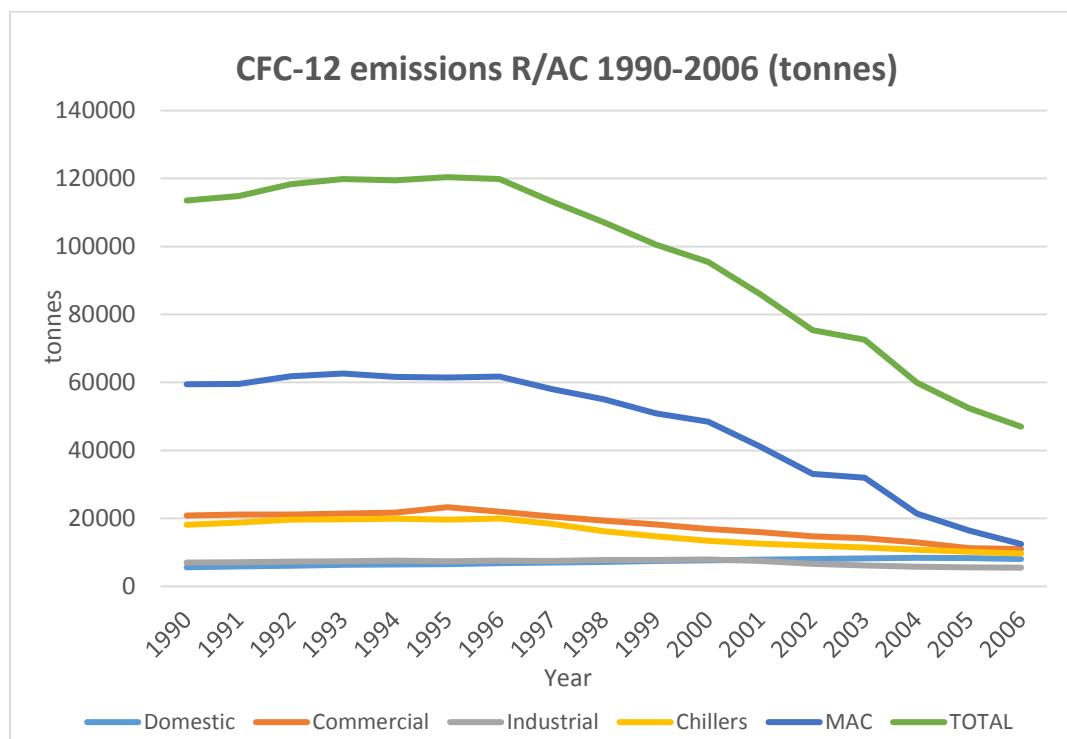
¹⁴¹ For the industrial and the commercial sub-sectors, the banks and emissions quantities indicated for CFC-12 also include a very small percentage of R-502, a mixture of CFC-115 and HCFC-22.

Table 4.2 CFC-12 global emission quantities for the various R/AC sub-sectors and the total, 1990-2006¹⁴²

CFC-12 EMISSIONS (tonnes)								
Year	Domestic	Comm.	Transp.	Indus.	AC	MAC	Chillers	TOTAL
1990	5,626	20,838	1,628	7,017	837	59,468	18,086	113,500
1991	5,852	21,110	1,619	7,136	825	59,547	18,818	114,907
1992	6,080	21,151	1,633	7,277	807	61,839	19,600	118,387
1993	6,325	21,412	1,539	7,381	781	62,638	19,737	119,813
1994	6,443	21,673	1,508	7,577	750	61,628	19,897	119,476
1995	6,551	23,303	1,284	7,427	710	61,503	19,631	120,409
1996	6,789	21,962	1,196	7,539	666	61,725	19,979	119,856
1997	7,015	20,615	1,110	7,507	617	58,029	18,391	113,284
1998	7,218	19,313	1,017	7,777	550	55,019	16,238	107,132
1999	7,442	18,256	927	7,785	466	50,945	14,699	100,520
2000	7,658	16,927	732	7,933	387	48,428	13,409	95,474
2001	7,871	15,988	630	7,452	313	41,102	12,599	85,955
2002	8,073	14,727	547	6,666	248	33,114	12,000	75,375
2003	8,242	14,147	488	6,132	188	31,999	11,421	72,617
2004	8,418	12,945	409	5,834	135	21,404	10,824	59,969
2005	8,330	11,287	338	5,647	89	16,471	10,209	52,371
2006	8,029	10,998	278	5,512	49	12,468	9,667	47,001

¹⁴² For the industrial and the commercial sub-sectors, the banks and emissions quantities indicated for CFC-12 also include a very small percentage of R-502, a mixture of CFC-115 and HCFC-22.

Figure 4.6 Global total CFC-12 R/AC emissions for the period 1990-2006, and for several sub-sectors



Global emissions of CFC-12 are estimated at almost 120,000 tonnes in the mid-1990s, calculated to decrease to about 80,000 tonnes by 2002, and can be extrapolated to less than 20,000 tonnes by the year 2010.¹⁴³ Of the total CFC-12 emissions, CFC-12 emissions from mobile AC are much larger than those from other stationary R/AC sub-sectors (which, for CFC-12, are relatively small). In fact, the CFC-12 emissions from mobile AC constitute about 50% of the total in the period 1990-2000, and the CFC-12 emissions for commercial and chillers combined are about one third of the total in that period, with the remainder from the other sub-sectors.

Based on this analysis, and particularly on the trend in banks and emissions from the MAC sub-sector, it can be concluded that no CFC-12 would be needed to supply servicing requirements after 2012-2015. This may not apply to some small amounts of CFC-12 required for special vehicles in some countries, namely some luxury or special vehicles built before 2002 in Article 5 parties. This minimal demand, if any, will be easily supplied from recycled CFC-12 (e.g., from recycling of CFC-12 contained in discarded appliances in the domestic and commercial refrigeration sub-sectors in Article 5 parties). It is implausible that this minor market would stimulate any new CFC-12 production. Even if CFC-12 was not available, for such vehicles retrofit to HFC-134a would be possible.

¹⁴³ For the industrial and the commercial sub-sectors, the banks and emissions quantities indicated for CFC-12 also include a very small percentage of R-502, a mixture of CFC-115 and HCFC-22.

The proportions of the sub-sectors of the total CFC-12 banks and emissions can also be considered. Figure 4.7 shows the percentage of several sub-sector banks of the total CFC-12 bank during the period 1990 to 2006. The proportion of the MAC bank of the total bank decreases the most during this period compared to other sub-sectors. It is then interesting to note that the percentages of many “smaller” sub-sectors increase as part of the total inventory (not in absolute amounts) and that the percentage of MAC decreases.

Figure 4.7 Share of the total CFC-12 R/AC bank by several sub-sectors for the period 1990-2006

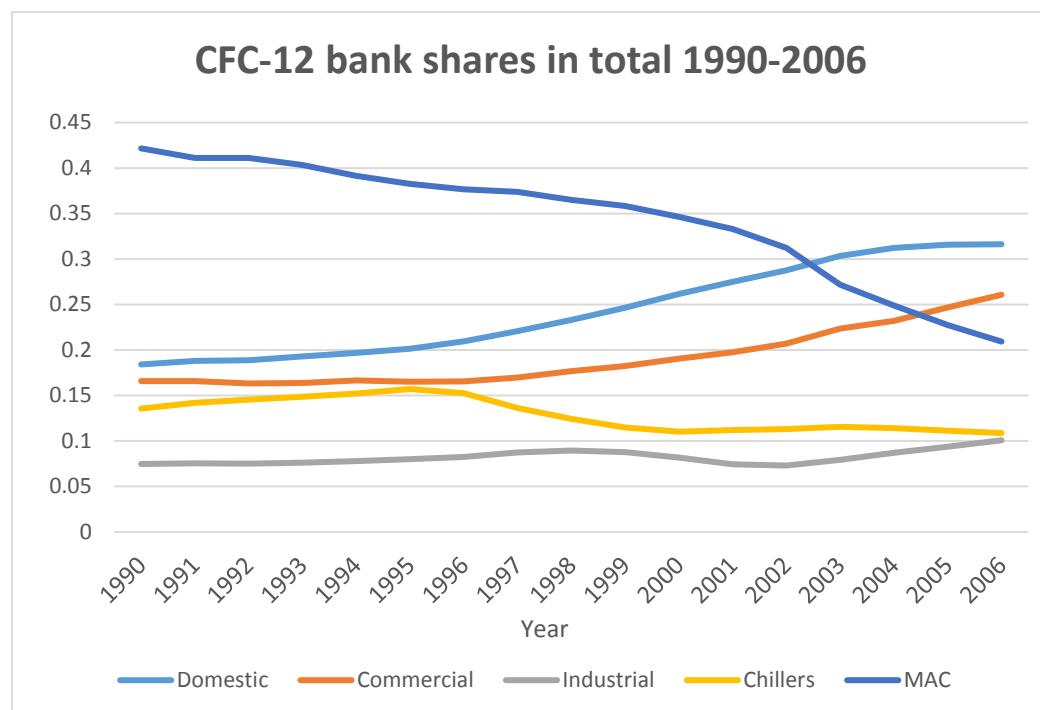
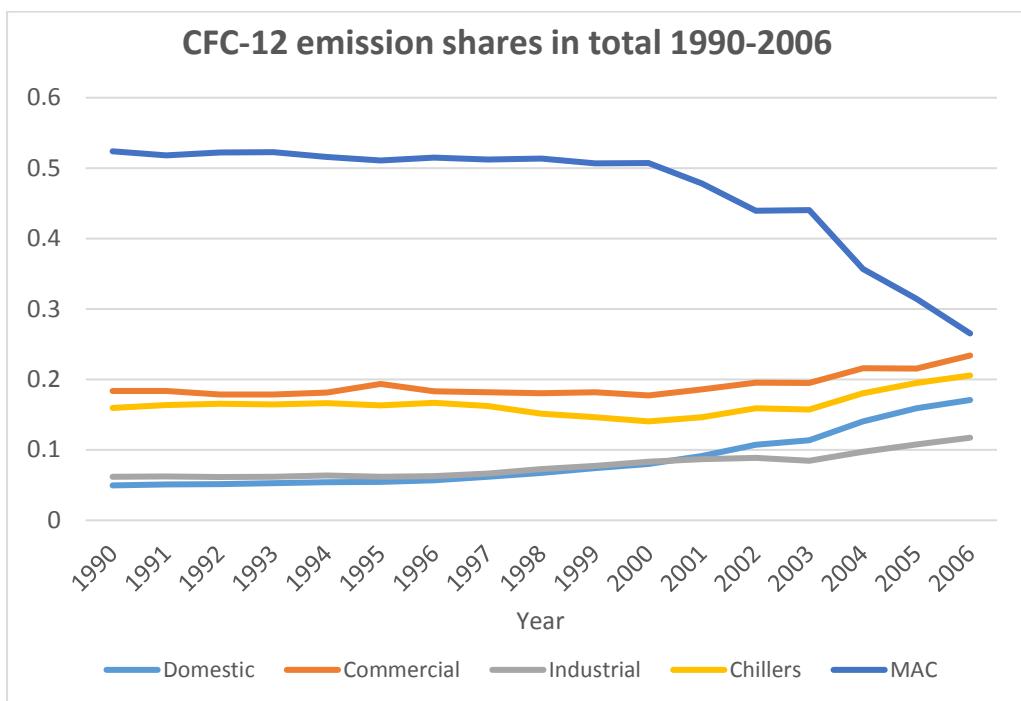


Figure 4.8 presents the percentages of emissions for the various sub-sectors of the total CFC-12 R/AC emissions for that same period 1990-2006. The percentages of many sub-sectors remain virtually constant or increase (as in the case of domestic refrigeration), although this applies to decreasing total amounts. It is clear from Figure 4.8 that the MAC sub-sector percentage of the total CFC-12 R/AC emissions decreases substantially after the year 2000 (this is, of course, also related to the MAC equipment lifetime that causes this rapid decrease).

Figure 4.8 Share of total CFC-12 R/AC emissions by several sub-sector for the period 1990-2006



4.4 Retrofits and resumption of CFC usage in non-CFC equipment

With the emergence of the CFC-11 emission issue (based on Montzka¹⁴⁴), and more generally with the question of CFCs that may be put on the market, it is often asked which R/AC sub-sectors might consider resumption, i.e., going back to the use of CFCs. The following information has been taken from several TEAP-RTOC assessment reports in response to this question.

1. For domestic refrigeration, conversion from CFCs to HFC-134a occurred after 1991, and, after 1993, to isobutane (HC-600a) initially in Europe and increasingly in other parts of the world. The use of CFC-12 in converted refrigerators is not technically feasible due to the type of POE oil used in case of HFC-134a. It is also not technically feasible in the case of isobutane-based refrigerators, where isobutane has completely different thermodynamic properties (smaller density at the same pressure) and requires different types of compressors.
2. For commercial refrigeration, mass produced units using CFC-12 are characterised by the same technical issues relating to CFC-12 resumption as domestic refrigerators, so there would be no reason to consider going back to CFC-12.
3. Transport refrigeration and industrial refrigeration (relatively small usage) also used some CFC-12 (and also R-502). Retrofits and resumption of CFC-12 usage is also not

¹⁴⁴ Ibid., Montzka, S. et al., 2018.

technically feasible for these R/AC sub-sectors. Moreover, it should be noted that once new non-CFC products are put on the market, or once retrofits have taken place, it would be far too expensive (from the equipment conversion point of view) to revert to CFC usage.

4. Stationary AC, including chillers, presents no real issue for the resumption of CFC-11 or for CFC-12 use. This subsector has always mainly used HCFC-22 (greater than 90%), with some CFC-12 also used in the early days. In the case of chillers, where it concerns smaller capacity non-centrifugals operating with CFC-12 (and even on HCFC-22), and the larger centrifugals on CFC-12 or CFC-11, once converted in manufacturing, to e.g., HFC-134a and HCFC-123, chillers cannot be (easily) retrofitted back to CFCs (CFC-12 or CFC-11). There is incidental reporting of retrofits; however, these retrofits have been to hydrocarbons (for both small and larger chillers).
5. For the main sub-sector that used CFC-12 in the 1990s, i.e., mobile AC, figures above show the relatively large inventory and emissions. However, the conversion of vehicle manufacturing to HFC-134a with specialised lubricants started in the early 1990s, and somewhat later in Article 5 parties. A reversion to CFC-12 servicing of HFC-134a units is technically possible, where a price difference for workshops between CFC-12 and HFC-134a servicing might provide this incentive. In that case, a bit of topping up of HFC-134a systems with CFC-12 would cause no technical problems. However, a retrofit back to CFC-12 would require cleaning, oil exchange, and would involve other technical considerations, which is the reason why this would normally not be done. As in stationary AC, there is reporting of retrofits; however, these are to hydrocarbons, or retrofits from CFC-12 to HFC-134a, hydrocarbons or other various blends. It is also worth noting that charging an HFC-134a unit with a large proportion of CFC-12 (larger amounts, i.e., to a significant degree), would lead to the formation of an azeotrope, that is characterised by much higher system pressures, resulting in improper functioning.

In summary, there are no real reasons to assume a significant resumption of CFC-12 refrigerant usage. Without any major amounts of CFC-12 refrigerant required, CFC-12 new production would not be necessary, with recycling from old equipment enough to satisfy any small market requirements (particularly in Article 5 parties). It seems likely that any new CFC-11 production has occurred is completely independent of CFC-12 use in all R/AC sub-sectors.

4.5 Conclusions

1. Centrifugal chillers using CFC-11 (some used CFC-12) have always been a relatively small part of the total CFC refrigerant inventory and emissions of all R/AC sub-sectors.
2. Where CFC-12 centrifugal chillers have been virtually phased out, a small number of CFC-11 chillers are still in operation and expected to reach their end of life in the next 1 to 5 years, at the latest.
3. The Task Force has estimated the amount of CFC-11 involved in CFC-11 chiller inventories. From leakage assumptions, and from estimates regarding the emissions at end-of-life, an annual emission in the order of 4.5 kilotonnes (2002) to 2 kilotonnes (2015) is derived for non-Article 5 parties (assuming no recovery and recycling). In the case of Article 5 parties, an annual total CFC-11 emission of around 2.5

kilotonnes (2002) to 1.3 kilotonnes (2015) is estimated (assuming no recovery and recycling), where emissions steadily decrease during the period 2002-2015.

4. Total CFC-11 emissions of the order of magnitude of 7 to 3.3 kilotonnes per year, decreasing during the period 2002-2015, are estimated for global R/AC uses (for chillers) for the period 2002-2015, based on data available from SROC¹⁴⁵ and the TEAP Supplement¹⁴⁶, which have been used in Appendix 6 on emissions models and analysis. Appendix 6 presents comparisons with the total global amount of emissions derived from atmospheric observations (in the order of 50 kilotonnes per year for the period 2002-2012) and considers these R/AC emissions as insignificant given that total of 50 kilotonnes (and the increase by 13±5 kilotonnes after the year 2013).
5. Based on estimates of CFC-11 banks and emissions, emissions from chillers do not constitute a major portion of the global CFC-11 emissions calculated from atmospheric observations in 2002-2012, and similarly emissions from chillers cannot be a cause for the sudden increase of global CFC-11 emissions since 2013, as derived from atmospheric calculations.
6. It is unlikely that CFC-11 production would be employed to maintain a very small number of centrifugal (low pressure) CFC-11 chillers in operation (at presumably very low energy efficiencies compared to the current business as usual practices for refrigerant operation with HCFC-123, and olefins, i.e., HCFO-1233zd(E)).
7. It is unlikely that there is a significant resumption of CFC-12 usage in any R/AC sub-sector in both non-Article 5 and Article 5 parties. This implies that no significant new CFC-12 production would be needed for all R/AC sub-sector uses, and that this would not be the reason for possible CFC-11 co-production.
8. There might be a continuing small CFC-12 demand for a limited number of CFC-12 mobile ACs in certain vehicles, namely some luxury or special vehicles built before 2002 in Article 5 parties. However, this small demand is likely to be supplied from the recycling of refrigerant from aged CFC-12 equipment.

¹⁴⁵ Ibid., IPCC/TEAP Special Report on Ozone and Climate, 2005.

¹⁴⁶ Ibid., TEAP, 2005.

5 Aerosols, solvents and miscellaneous uses

5.1 Summary

- The main use of CFCs until the 1980s was as a pressurized liquid in aerosols. While CFC-11 worked very well in combination with CFC-12 to obtain variations in propellant pressure, CFC-11 could not be used alone as a propellant.
- The original attraction of CFC propellants was that they did not require all the safety measures that are needed to handle highly flammable hydrocarbons. However, once aerosol fillers made the necessary investment to handle hydrocarbons, they could adjust easily the pressure of the propellants at a lower cost than they would incur if they were to use CFC-11.
- It is technically feasible to use mixtures of hydrocarbon propellants and CFC-11 in aerosols to regulate the pressure much in the same way as it was done with CFC-12. If CFC-11 were readily available, it would be technically feasible to use it in aerosol products. However, it seems unlikely that CFC-11 would be produced or used nowadays for aerosols; the main reason is that hydrocarbons are much cheaper than CFCs.
- CFC-11 was used in the production of metered dose inhalers (MDIs), where the active ingredient would be slurried in CFC-11, then filled in the can prior to the crimping of the metering valve. While it would be technically possible to make an MDI mixing CFC-11 and HFC-134a or HFC-227a, it seems highly unlikely that any MDI producer would choose this route.
- CFC-113 and 1,1,1-trichloroethane were the main ODS used as solvents. CFC-11 has better solvency than CFC-113; however, because of its low boiling point, CFC-11 had to be packed hermetically as an aerosol to avoid vaporization. This is the reason why CFC-11 was used in aerosols, and not in regular solvent uses.
- Decision XXIX/7 Table A lists the production of synthetic fibre sheet with CFC-11 as a process agent, which is permitted for use only in the United States (US). Total emissions for all process agent applications in the US were 24.65 ODP tonnes in 2017.
- It seems extremely unlikely that CFC-11 might be used as a solvent. Similarly, it is extremely unlikely that CFC-11 would be used as a highly emissive process agent in a newly established (illicit) plant to manufacture synthetic fibre sheet.
- With the alternatives available, there are no technical or economic reasons to believe that the recent increase in CFC-11 emissions would be due to tobacco expansion or the processing of uranium.

5.2 Introduction

Trichlorofluoromethane (CFC-11) has some unique properties that set it apart from other CFCs. Namely, its boiling point of 23.77°C (74.79°F) is substantially higher than that of dichlorodifluoromethane (CFC-12), which boils at -29.8°C (-21.64°F), but lower than typical solvents like trichlorotrifluoroethane (CFC-113), which boils at 47.5°C (117.5°F).

Like other CFCs, CFC-11 has a high density as a liquid and it is non-flammable and non-toxic. Although chemically stable it is liable to hydrolyze, which constrained its use in aerosols to anhydrous formulations.

These physical properties explain the widespread use of CFC-11 as an aerosol propellant/solvent, its limited use as a solvent outside aerosol products, and its application in some niche uses as tobacco expansion and uranium enrichment

5.3 CFC-11 in aerosols

The main use of CFCs in aerosols was as a type of propellant, specifically: a pressurized liquid filled in a metal canister that, when released through a valve, vaporizes suddenly creating the fine mist that one associates with most aerosol products. That not all aerosol products produce a mist, shows how this package form has expanded to include products that are dispensed as foams, as jets or even gels. These types of aerosol products have no relation to the aerosol particles that gave their name to this type of package.

Formulators made this market expansion of aerosol products possible, by changing different parameters, which included inter alia:

- Ratio of liquid to propellant
- Pressure of propellant
- Homogeneity of content inside the aerosol
- Valve design

By mixing different ratios of CFC-12 and CFC-11 it was possible to obtain pressures that went from 37.4 psig at 21 °C (70 °F) for a 50/50% mixture to the 70.2 psig of pure CFC-12 at the same temperature. Given that for an aerosol formulator, it is generally better to put more propellant at a lower pressure than a smaller amount of propellant with a higher pressure, the mixtures of CFC-11 and CFC-12 were very popular and could be purchased premixed from the CFC producers.

It is important to note that while CFC-11 worked very well in combination with CFC-12, it could not be used alone as a propellant. This is due to its low vapor pressure that by itself is not enough to act as a true propellant. However, inside the aerosol can both CFCs behaved as solvents and served to carry active principles like silicones and perfumes. The difference in boiling points of these two CFCs was useful to design dryer or wetter sprays.

It is also possible to mix CFC-11 with hydrocarbons to regulate the pressure much in the same way as it was done with CFC-12. The composition of the mixture CFC11/hydrocarbon might change slightly during the use of the aerosol, but this change will not be noticeable to the consumer. The advantages of such a mixture would be more weight to the can and lower flammability.

However, it seems unlikely that CFC-11 would be produced nowadays for this use, the main reason is that hydrocarbons are much cheaper than CFCs. The attraction of CFC propellants was that they did not require all the safety measures that are needed to handle highly flammable hydrocarbons. Once aerosol fillers made the necessary investment to handle

hydrocarbons, they could adjust easily the pressure of the propellants at a lower cost than they would incur if they were to use CFC-11.

CFC-11 was commercialized alone in drums (280 kg), in tonne-tanks or in truck-tanks of around 20 tonnes. These last two presentations allowed for the combination of CFC-11 with CFC-12 because they withstand higher pressures than drums. The amount of CFC-11 that could be used in an aerosol can depended on its size, but typically could range for household and industrial aerosols between 50 to 100 g/can. Hence one drum could be used to fill up to 5,600 cans whereas a 20 tonne-tank truck would be used to fill up to 400,000 units.

When CFC-11 was purchased in drums it was often cooled below 20 °C (68 °F) to avoid significant losses due to evaporation. CFC-11 was then handled as a liquid at atmospheric pressure and could be mixed with other solvents, but not with water. The main advantage of CFC-11 as a solvent was its high density that made it possible to form stable dispersions of solid particles; these particles would otherwise sink if dispersed in less dense solvents.

It was precisely for this reason that CFC-11 was used in the production of MDIs, where the active ingredient would be slurred in CFC-11, then filled in the can prior to the crimping of the metering valve. The CFC-12 propellant would be charged through the valve after it had been crimped although in some cases with high speed machines the propellant could also be charged “under the valve” prior to its crimping.

While it would be technically possible to make an MDI mixing CFC-11 and HFC-134a or HFC-227a, it seems highly unlikely that any MDI producer would choose this route. Not only are these products heavily regulated, the introduction of HFCs required considerable investment, and ethanol is used as a solvent in some MDIs, but even if one could assume that a “rogue” producer was using CFC-11 in some MDIs, the amounts of CFC-11 per can would only be between 5 to 10 grams and the emissions would likely be small.

5.3.1 Worldwide production of aerosols

According to the European Aerosol Federation (FEA) in 2017 the major aerosol producers were:

Country or Region	Number in million units
Europe	5,766
USA/Mexico	4,470
Argentina/Brazil	2,139
China	2,123
Australia/Thailand	540
Japan	534
South Africa	290
Total for countries reported above	15,862

If 13,000 tonnes of CFCs -11 and -12 were used in aerosols at the average estimate consumption of 75 g per can, it would be possible to fill approximately 173 million cans, which is roughly 1% of the total world aerosol production. Thus, while economically unlikely, the aerosol market could account easily for CFC-11 production of the amount consistent with the unexplained increase in CFC-11 emissions. However, it is also a fact that any aerosol filling plant that makes more than 20 million cans per year has necessarily a

physical size, and movement of raw materials and finished goods that are likely to be easily noticeable.

5.4 CFC-11 as a solvent

The 1998 *Assessment of the Solvents Technical Options Committee* defined solvents as “substances, usually liquid, in which another substance (the solute) is dissolved to form a solution. In practice, the term is used for a liquid capable of dissolving the solute. For cleaning purposes, a solvent is a liquid capable of dissolving the contamination that must be eliminated. For adhesives and coatings, it is a (usually) volatile liquid used as a carrier for the solids which it is desired to place on a part”.

The 1998 Assessment considered ODS that were used as solvents and dealt mainly with CFC-113 and 1,1,1-trichloroethane, which were the ODS widely used for this application. CFC-11 has better solvency than CFC-113, which is almost just an inert carrier rather than a solvent, but because of its low boiling point, CFC-11 had to be packed hermetically as an aerosol to avoid vaporization. This is precisely the reason why the main uses of CFC-11 were either in aerosols or in foams, where its vaporization would cause the formation of bubbles in the polymer.

CFC-11 was first listed as a process agent for the manufacture of fine synthetic polyolefin fibre sheet in Table A of Decision X/14. This use was described in detail by the *Process Agents Task Force in May 2001 in Case Study #10* and takes advantage of the physical properties of CFC-11 to vaporize it and recover it for reuse. This process has been used in the US and in the European Union. Total emissions were cut down from 2,323 tonnes in 1986 to 52 tonnes by 2000. The current Decision XXIX/7 Table A continues to list the production of synthetic fibre sheet with CFC-11 as a process agent, which is permitted for use only in the US. Total emissions for all process agent applications in the US were 24.65 ODP tonnes in 2017; production of synthetic fibre sheet is one of five process agent applications that constitute those emissions.

It seems extremely unlikely that CFC-11 might be used as a solvent. Similarly, it is extremely unlikely that CFC-11 would be used as a highly emissive process agent in a newly established (illicit) plant to manufacture synthetic fibre sheet.

5.5 CFC-11 in tobacco expansion

In the 2002 *Assessment of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride Technical Options Committee* it was reported that “China is believed to be the only remaining country to use significant quantities of CFC-11 for tobacco expansion, using about 1,000 ODP tonnes per year.” It explained that “it is a patented physical process that uses CFC-11 to restore cured, aged tobacco to its original field volume. The process is an effective and non-hazardous method of expanding tobacco and has been widely used to increase tobacco volume so that finished cigarettes will use less weight of tobacco, thereby reducing tar and nicotine...”. However, there were different replacements that included carbon dioxide, nitrogen, propane and iso-pentane; all these replacements required significant investments to accommodate either higher pressure or non-flammable equipment.

The China Tobacco Sector Plan for CFC-11 Phase-out in China. Project Completion Report lists detailed actions in 56 eligible factories out of 73 tobacco factories identified in the country. In cooperation with UNIDO, a number of CFC-11 expansion plants were dismantled between 2001 and 2006 and replaced by either CO₂ expanded tobacco or by online tobacco

expanded equipment. The total funds disbursed for equipment amounted to 9,095,000 USD. By 2006, the consumption of CFC-11 for this purpose had decreased to 21 tonnes.

China's ODS in tobacco expansion represented 1.2% of consumption of ODS expressed in ODP value in 1997. The fact that a consumption of about one thousand tonnes was divided between 73 facilities indicates that individual consumption at every site was small. While tobacco expansion with CFC-11 could be economically attractive at new sites if the substance was available at low prices, the quantities required are nowhere near the numbers that have been discussed in this report.

5.6 CFC-11 used in the processing of uranium

The Report of the Chemical Process Agents Working Group of the TEAP (1995) includes a brief description of the use of CFC-11 in the processing of uranium. CFC-11 is reacted with dried uranium trioxide (UO_3) to form uranium tetrafluoride, carbon tetrachloride, phosgene and chlorine at 200-300 °C. Alternatives are direct fluorination with hydrogen fluoride or other fluorinating agents. While the TEAP working group listed this CFC-11 application as a process agent, under working definitions for process agents developed later by the TEAP, this application might more likely be considered as a feedstock use, where the CFC-11 is reacted and emissions are insignificant. With the alternatives available, there is no technical or economic reason to believe that the recent increase in CFC-11 emissions would be due to the processing of uranium.

CFCs were used for 60 years as the primary refrigerant in gaseous diffusion plants for nuclear enrichment, where CFC-114 was used. There is no reported use of CFC-11 as a refrigerant for this purpose. Considerable heat is generated in the recompression of the uranium hexafluoride (UF_6) and must be removed from the system. It is believed that most countries have now replaced gaseous diffusion processes with gas centrifuge technology that is more efficient and reduces energy consumption significantly.

6 Emissions modelling and analysis

In chapter 6, the Task Force describes new banks and emissions modelling, using available data testing previous assumptions, and ~~working to~~ concludes which of the causes considered might be possible sources for the increase in CFC-11 emissions ~~for further exploration in the Final Report~~. The Task Force eliminates scenarios that it has concluded as highly unlikely causes of the unexpected emissions of CFC-11.

The chapter includes a section describing a new “bottom-up”¹⁴⁷ emissions model for CFC-11, followed by a “sensitivity analysis”¹⁴⁸ to evaluate the importance of specific parameters in estimating atmospheric emissions through 2016. The “bottom-up” emissions model was compared to the derived global atmospheric emissions to see if modifying a particular variable (e.g., production) might better describe the derived emissions. Similarly, a “bottom-up” model is constructed for CFC-12, the results of which are compared to atmospherically derived emissions.

Finally, the chapter also includes a regional analysis of emissions and banks of CFC-11 related to closed-cell foams to compare to total emissions regionally and to quantify better unexpected emissions.

6.1 Summary

- A number of assumptions were made in the development of the CFC-11 emissions and banks model developed for this final report ~~preliminary report~~ by the Task Force. The sensitivity of the model to uncertainties in assumptions (e.g., emissions rates from potential sources, production, etc.) were analyzed by varying those assumptions substantially to determine the potential correlation to the unexpected emissions. Varying the key assumptions still does not account for the unexpected emissions of CFC-11. It is unlikely that past production and historic usage can fully account for the unexpected emissions unless there has been a significant change in the treatment of large quantities of banked CFC-11.
- Atmospheric-measurement derived emissions from banks, measured in Mace Head Ireland coming from Western Europe, where CFC-11 has not been used for several decades, continue to generally decline.¹⁴⁹ If it is assumed that CFC-11 emissions from banks in other regions generally decline in a similar fashion, it appears that the unexpected increases in global CFC-11 emissions cannot be explained by bank emissions. Unless banks are treated very differently in other regions where CFC-11

¹⁴⁷ In this chapter, we refer to the emissions model as a “bottom-up” model built using basic assumptions regarding independent variables to develop an understanding of the influence of these independent variables on resulting emissions. In this case, total production reported to AFEAS and Ozone Secretariat divided into market sectors and using assumed losses during the charging, operation and decommissioning of chillers, the foam blowing process and the use of aerosols, and solvents are used to calculate total CFC-11 emissions. In contrast, this chapter refers to a “top-down” analysis as one that uses the dependent variable or derived atmospheric emissions to back-calculate the dependent variables. Note that other sources may refer to “bottom-up” and “top-down” differently (e.g., 2006 IPCC Guidelines for National Greenhouse Gas Inventories.)

¹⁴⁸ A sensitivity analysis is used to determine the importance of specific independent variables (e.g., CFC-11 production) in a resulting dependent variable (e.g., emissions and banks).

¹⁴⁹ 2-4% per year.

has been used more recently, or where there is no atmospheric data collected, it seems unlikely that the source of the increased CFC-11 emissions is from CFC-11 banks. Further analysis of regional banks was completed for the final report, incorporating the duration of foam use and the subsequent timing for emissions from dismantling foams. The Task Force concluded that in no region are the unexpected emissions likely to have originated from the existing foam banks.

- A decline in HCFC-141b emissions globally in recent years was expected given that global production was frozen in 2013 and then reduced due to the phase-out. Atmospheric measurements suggest that global HCFC-141b emissions have, indeed, started to decline. The global derived emissions for higher boiling, fluorocarbon blowing agents for polyurethane rigid foams in total (e.g., CFC-11, HCFC-141b, HFC-245fa, HFC-365mfc) have been gradually increasing since 2004. This growth is consistent with the increased use of insulating polyurethane foam. However, CFC-11 emissions increase during the period when HCFC-141b emissions decrease. This is not conclusive, nor does it indicate a direct replacement of HCFC-141b with CFC-11 globally. However, the increase in CFC-11 when HCFC-141b decreases is not inconsistent with some replacement of HCFC-141b with CFC-11.
- As noted in chapter 4, and further validated through modelling discussed in this chapter, it seems unlikely that CFC-11 use as a refrigerant has contributed significantly to the unexpected increase in CFC-11 emissions. Very high consumptions would be needed to result in unexpected emissions of this magnitude. The scale of unexpected emissions cannot be reconciled with the very low emissions rates associated with this application in the relevant refrigeration sub-sectors (i.e., low-pressure chillers).
- There are scenarios in which newly produced CFC-11 used in open-celled foam could align with the unexpected increase in emissions of CFC-11. However, the overall balance of foam blowing agents¹⁵⁰ is inconsistent with this use. It also seems unlikely that it would be economically advantageous to revert to using CFC-11 from the use of methylene chloride (dichloromethane) unless there is some factor other than cost requiring its replacement (e.g., the regulation of methylene chloride consumption).
- In contrast, none of the analyses of the available data eliminates the possibility that newly produced CFC-11 might have resumed use in closed cell foams. There are scenarios modelling the potential use of CFC-11 in closed cell foams that align with the derived emissions of CFC-11. Based on this overall evaluation, the Task Force recommends continued exploration into the potential use of CFC-11 in closed-cell foams to explain the unexpected increased emissions of CFC-11.
- Scenarios were evaluated combining estimated sales of newly produced CFC-11 into multiple markets (combinations of foams, emissive uses, and chillers). Although technically feasible, the Task Force believes that widespread use of newly produced

¹⁵⁰ The Task Force explored the sum of the derived emissions of the fluorocarbon replacement products for closed cell foams over time. The trend of the total emissions of all four blowing agents together was a gradual increase (averaging 2% per year since 2003) similar, but lower than the rate of polyurethane foam market growth globally which is expected as there are non-fluorocarbon blowing agents in use for significant segments of the market (e.g., hydrocarbons for appliances). If CFC-11 were used to replace significant quantities of methylene chloride, total emissions of the four blowing agents would be higher than the growth rate for closed cell polyurethane foam.

CFC-11 in sectors other than closed-cell foams is unlikely. It is likely that there has been a resumption of newly produced CFC-11 usage in closed-cell foams.

- Most of the closed-cell foam as of 2006 was produced in Europe and North America as of 2006 with smaller quantities produced regions in the Southern Hemisphere. It is anticipated that most of the global emissions of CFC-11 would have occurred in those regions during foam manufacturing and installation and during the lifetime of products containing those foams. Destruction of foams is increasing in these regions and there are significant quantities of CFC-11 blown foams still in use in building.
- Based on modelling using reported CFC-11 production data, it seems that the expected emissions from the CFC-11 foam banks in Northeast Asia are insufficient to account for the atmospheric-derived emissions from eastern mainland China in Rigby *et al.*
- Estimated bottom-up CFC-12 emissions are consistently lower than the atmospheric-measurement derived emissions, indicating high underlying uncertainty in the bottom-up model's assumptions. As a result, estimates of bottom-up CFC-12 emissions are inconclusive.

6.2 Introduction

The Task Force evaluated potential sources of the unexpected CFC-11 emissions through modelling the total mass balance of production, emissions and banks to determine whether potential sources were unlikely to occur. Potential sources that are eliminated as unlikely will be explored further by the Task Force for the final report.

Two types of mass balance models developed for this analysis are “top-down” and “bottom-up” models. The “bottom-up” emissions model was built starting from total production volumes as reported to AFEAS and to the Ozone Secretariat.¹⁵¹ The production data is divided into market sectors (i.e., closed-cell foams, chillers or refrigeration) with a category described as “emissive uses” which included propellants, open-cell flexible foams and solvents. In the foam sector, this information can also be compared with data on sales of relevant polymeric chemicals for the foam sector in order to help validate the blowing agent allocations.

Assumptions are made regarding emissions losses during the charging, operation and decommissioning of refrigeration and air-conditioning (R/AC) equipment, the foam blowing process and during the life of the foam *in situ* as well as the use of aerosols, and solvents, to calculate total CFC-11 emissions. For example, it was historically assumed that 98% of the CFC-11 used in “emissive uses” was emitted very quickly from the products. The portion of CFC-11 (2%) that was not emitted immediately in the first two years of use was assumed to be in the CFC-11 bank and would be emitted in subsequent years, with 98% of the remainder being lost each year. This time-series approach is the typical model for all foam types and allows differing assumptions to be applied depending on the foam type, thickness and cell properties.

¹⁵¹ In constructing the bottom-up model, production data was adjusted to include estimates of CFC-11 produced in Russia between 1968-2000, as discussed in section 2.3 of this report.

CFC-11 banks were also calculated using the “bottom-up” approach as an important part of CFC-11 emissions in future years. The banks can be described as “active” banks where CFC-11 is still in use in foam insulation, chillers or other uses. Meanwhile, banks can be described as “inactive” at the end-of-life of the product when they enter the waste stream (i.e., foams in landfills or remaining CFC-11 in an aerosol can). Other terms that are used to describe banks are “accessible” meaning that the CFC-11 could be relatively easily collected and destroyed or recovered at a cost. Inaccessible banks describe CFC-11 that would be difficult to recover (i.e., from a landfill). The Task Force ~~intends to~~ differentiated and ~~quantify~~ quantified the banks based on these categories for the final report, ~~to which~~ supports further understanding of the unexpected emissions of CFC-11 as emissions rates may differ somewhat by category.

In contrast, a “top-down” analysis uses atmospherically derived emissions to back-calculate the dependent variables such as emissions rates, the size of the bank and the total production. Atmospherically derived global emission magnitudes are calculated from a consideration of changes in global-scale atmospheric concentrations in light of expected losses due to atmospheric removal (for CFC-11 and CFC-12), which is primarily from photolytic degradation in the stratosphere. Atmospheric emissions can also be derived for regions upwind of the measurement location with an accurate understanding of air-transport to the site and inverse modelling. These regional emissions are independent of loss or lifetime considerations.

By comparing the emissions estimated by “bottom-up” models to “top-down” emissions, the Task Force ~~can better quantify~~ quantified emissions related to historic legal production and use of CFC-11 and CFC-12 to identify emissions potentially related to illegal production ~~and better quantify potential illegal production and use of CFC-11~~. In addition, these analyses can be used to identify scenarios and potential sources that are of low probability. Finally, these analyses can also be used to evaluate the importance of specific variables (i.e., total production or emissions rates for a specific sector) to understanding the unexpected increase in CFC-11 emissions. The Task Force ~~can used~~ that screening information to focus its work for the final report on critical variables and on uses that are more likely to be the source of the unexpected emissions.

6.3 Historic CFC-11 emissions and banks modelling

The IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System (the “SROC” report) was developed in response to requests by the parties to the *United Nations Framework Convention on Climate Change* (UNFCCC) and to the *Montreal Protocol on Substances that Deplete the Ozone Layer* for policy-relevant, scientific, and technical information regarding alternatives to ozone-depleting substances (ODS) that may affect the global climate system. In 2003, the important driver for the SROC report was the interlinkage between policy decisions and technical options chosen to protect the ozone layer that were assumed to have a potential significant influence on climate change. The report was prepared by the IPCC and the Technology and Economic Assessment Panel (TEAP) in 2003-2005.

The SROC report was limited in scope and had no reason to investigate possible causes for a sudden increase in emissions. It should also be noted that the SROC report did not probe the full range of possible uncertainties. SROC did estimate the maximum possible emissions in a business as usual (BAU) scenario from 2002-2015 and that has been compared to the unexpected emissions derived from atmospheric measurements (see Appendix 6). This analysis is preliminary and concludes that bank decreases from the end-of-life (not the emissions from installation, charging and use of equipment or foams) as calculated in the

SROC report are not big enough to explain the atmospheric derived emissions. It is well understood that foams that have been discarded do not generally have significant emissions (i.e., landfill, incineration or collection of emissions from crushed foams as in the European Union (EU)) unless there has been a significant change in the treatment of discarded foams. Additional information has been provided in chapter 3 regarding foams, and the Task Force ~~will~~ has provided more information in the final report further exploring the life-cycle of closed-cell, rigid foams.

The SROC report identified the impact of choosing high global warming potential replacements for ozone depleting substances. Apart from deriving numbers for banks and emissions for the years 2002 and 2015 for ODS and for a large number of HFCs and PFCs, the technical performance, potential assessment methodologies, and indirect emissions related to energy use as well as costs, human health and safety, and future availability were considered.

The SROC report was structured in three parts. The first part described scientific linkages between stratospheric ozone depletion and climate change. It assessed relevant interactions between the two environmental issues pertinent to the consideration of replacement options. The second part assessed options to replace ODS. The report assessed practices and alternative technologies to reduce emissions and net warming impacts within each use sector, including consideration of process improvement in applications, improved containment, end-of-life recovery, recycling, disposal, and destruction as well as relevant policies and measures. The third part of the report aggregated the banks and emissions information from the various sectors and regions, and then considered the balance between supply and demand, with consideration of issues relevant to developing countries.

6.3.1 Development of estimated banks and emissions projected for the period 2002 to 2015

The 2002 emission profiles were largely determined from historic use patterns, resulting in a relatively high contribution (now and in the coming decades) from CFCs and HCFCs banked in equipment and foams. Annual emissions of CFCs, HCFCs, HFCs and PFCs in 2002 were about 2.5 GtCO₂-eq. Refrigeration applications together with stationary air conditioning (SAC) and mobile air conditioning (MAC) contributed the bulk of global direct GHG emissions. About 80% (in t CO₂-eq) of the 2002 emissions are attributed to CFCs and HCFCs. Remaining fluorocarbons in equipment and foams may be emitted while the products are used and at the end of the product lifecycle unless they are recovered or destroyed. Releases from banks vary significantly from application to application from months (e.g., solvents), to several years (refrigeration applications) to over half a century (foam insulation installed in buildings). The 2002 banks were estimated at about 21 GtCO₂-eq [CFCs (16 GtCO₂-eq), HCFCs (4 GtCO₂-eq), HFCs (1 GtCO₂-eq)]. The build-up of the banks of (relatively) new applications of HFCs was expected to assist in estimating future (after 2015) emissions if no additional bank management measures were taken.

All seven sector chapters in the SROC report developed “business-as-usual”¹⁵² (BAU) projections for the use and emissions of CFCs, HCFCs, halons, HFCs and some PFCs (where

¹⁵² “Business-as-usual” scenarios describe what the future might be with current or no regulatory or other intervention. For example, if refrigerant were completely released at end-of-life of equipment instead of captured and recycled or destroyed.

used as replacements for ozone depleting substances). These projections have assumed that all existing measures continue, including Montreal Protocol (phase-out) and relevant national regulations. The usual practices and emission rates were kept unchanged up to the year 2015. Inactive banks were not modelled, and end-of-life recovery efficiency was assumed not to increase. Best practices in use, recovery, and destruction were identified for each sector and aggregated as total global emission reduction potentials for 2015 in comparison to the BAU scenario.

During the last phase of the SROC report, tables of banks and emissions were developed by IPCC (Technical Support Unit) in the Technical Summary of the SROC report. Further detailed tables for both BAU and mitigation (MIT) scenarios were published in an additional 2005 TEAP Report “Supplement to the IPCC TEAP Report”. There were also TEAP Task Force reports on end-of-life in 2005 and on emissions discrepancies in 2006, which identified potential end-of-life issues and identified discrepancies between emissions from “top-down” and “bottom-up” analyses, but did not develop further, new quantitative information on banks and emissions.

In 2009, the TEAP XX/7 Task Force report on the environmentally sound management of banks used SROC data for CFCs. In 2009 also, the TEAP XX/8 Task Force report updated data from the Supplement Report providing banks and emissions estimates for foams combining CFC-11 and CFC-12. The data were very similar to the SROC and SROC Supplement data.

The Task Force is unaware of any further qualitative or quantitative analysis of the banks, particularly foam banks including CFC-11 and CFC-12. From 2014-2016, Task Force reports analysed scenarios for future HFC consumption (banks and emissions) but the CFC issue (data on banks and emissions) was not considered important anymore. In 2016, reports noted that foam HFC emissions were considered of minor importance compared to R/AC HFC emissions.

6.4 Sensitivity analysis by using an emissions model for CFC-11

Sections 6.4 through 6.6 describe the new model and sensitivity analysis developed for this report. As noted in Section 6.3, previous analyses were limited in scope and did not investigate possible causes for a sudden increase in emissions.

The Task Force developed a new “bottom-up”¹⁵³ emissions model followed by a “sensitivity analysis”¹⁵⁴ to evaluate the importance of specific parameters in estimating atmospheric emissions through 2016. The “bottom-up” emissions model was compared to the derived global atmospheric emissions to see if modifying a particular variable (e.g., production) might

¹⁵³ In this chapter, we refer to the emissions model as a “bottom-up” model built using basic assumptions regarding independent variables to develop an understanding of the influence of these independent variables on resulting emissions. In this case, total production reported to AFEAS and Ozone Secretariat divided into market sectors and using assumed losses during the charging, operation and decommissioning of chillers, the foam blowing process and the use of aerosols, and solvents are used to calculate total CFC-11 emissions. In contrast, this chapter refers to a “top-down” analysis as one that uses the dependent variable or derived atmospheric emissions to back-calculate the dependent variables. Note that other sources may refer to “bottom-up” and “top-down” models differently (e.g., 2006 IPCC Guidelines for National Greenhouse Gas Inventories.)

¹⁵⁴ A sensitivity analysis is used to determine the importance of specific independent variables (e.g., CFC-11 production) in a resulting dependent variable (e.g., emissions and banks).

better describe the derived emissions. After assumptions were varied one at a time, the Task Force modified multiple sets of assumptions in an attempt to better describe the potential source of the unexplained emissions of CFC-11 from past CFC-11 production and the resulting CFC-11 banks.

Emissions model parameters considered in the sensitivity analysis included those related to CFC-11 production, installation (e.g., into foams or chillers) and disposal at end-of-life.¹⁵⁵

- Production: emissions from chemical plants during production, maintenance, drum heel and packaging;
- Installation: *de minimis* emissions when charging air-conditioners and refrigeration systems, emissions from the foaming process, and discharge of a propellant in aerosol products or as a solvent; and,
- Banks: emissions during a product's lifetime (active banks) as well as at the end-of-life when the foam product or refrigerants from R/AC equipment is landfilled, recycled or destroyed (inactive banks). CFC-11 from banks leak gradually to the atmosphere or leak abruptly when refrigerant is vented or partially released when foam is shredded or crushed.¹⁵⁶

In the “bottom-up” calculation of the bank size, the bank is divided into three sectors: refrigeration, closed-cell (rigid) foams and emissive uses (open-cell foams, aerosols and solvents). Production, installation, and bank emission rates were estimated based on industry knowledge and literature. The uncertainty surrounding release rates during installation, useful life and disposal is relatively low due to the extensive research that has been performed over the years for the different products and for different stages in their life-cycle, from cradle to grave.

However, the value of the release rate from the chemical plants during production of CFC-11 is uncertain. Emissions during production vary significantly from plant to plant and are dependent on operating conditions, system setup and handling. An outline assessment of the likely CFC-11 emission points and rates from a large-scale CFC-11 production facility suggests that a 4% CFC-11 emission would be a reasonable base case for production emission assumptions, and account for variations in production emission rates over the time period for which data is available, from 1930 onwards. This assumption is also consistent with the current draft refinements to the IPCC estimate of the default emission rate for fluorocarbon production.¹⁵⁷ For smaller scale, less sophisticated production plants (micro plants), where there are likely to be fewer process steps and recovery systems, and more manual operations, an overall CFC-11 emission rate of 10-15% is considered a reasonable assumption.

¹⁵⁵ Emissions rates throughout the product lifecycle were considered.

¹⁵⁶ As noted earlier, blowing agents are integrated into the polyol foam matrix and do not solely reside in the foam cell. As a result, crushing or shredding foams results in only a partial release of the blowing agent regardless of the particle size of the shredded foam.

¹⁵⁷ 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3: Chemical Industry Emissions (Advanced Copy).

6.5 Historic CFC-11 consumption, emissions and banks

Understanding historic emissions, including the size and emissivity of CFC-11 banks, is essential in order to understand whether the unexpected CFC-11 emissions occurring since 2012 can be attributed to emissions resulting from past production and in determining the magnitude and duration of the unexpected emissions.

Production data was originally and voluntarily reported through the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS).¹⁵⁸ The companies reporting to AFEAS were almost exclusively operating in non-Article 5 parties which was representative of the vast majority of global production before 1989. The geographical coverage of the companies submitting data to AFEAS included, among others, facilities in Argentina, Australia, Brazil, Canada, the European Union, Japan, Mexico, the Republic of South Africa, the United States (US), and Venezuela. However, coverage for China, India, Korea and Russia is not provided through AFEAS.¹⁵⁹ This omission is insignificant until the 1990s since prior to then the vast majority of CFC-11 was produced in the countries reporting to AFEAS. Production shifted to Article 5 parties in the mid-1990s. Following the signing of the Montreal Protocol, parties started reporting their production of CFC-11 to UNEP in 1989.¹⁶⁰

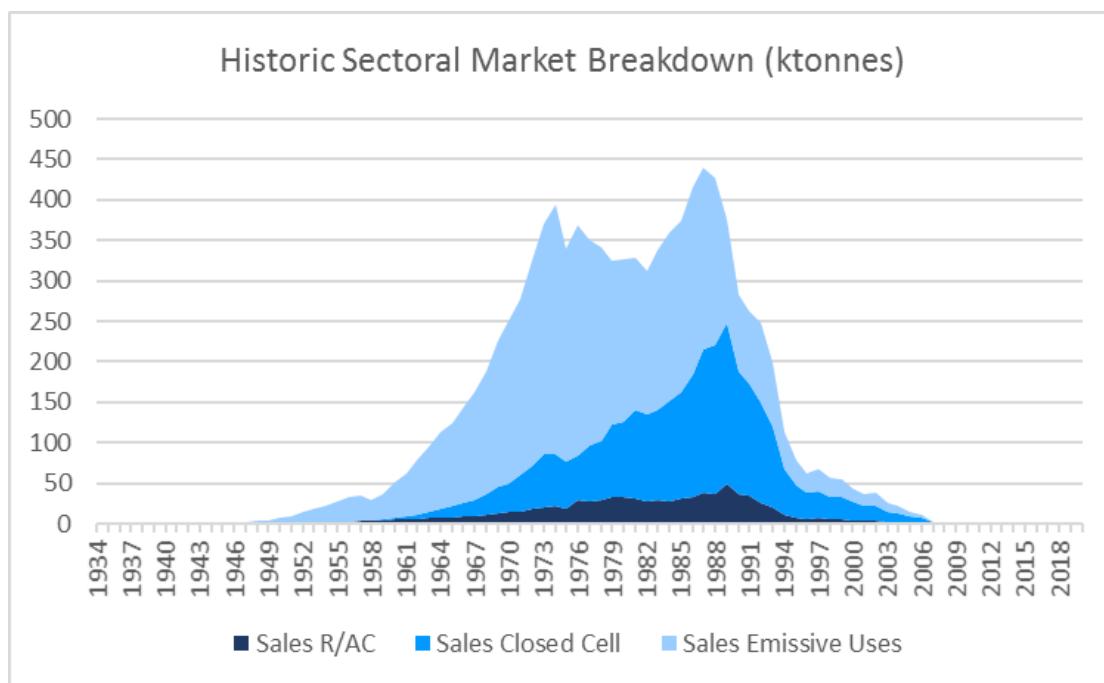
According to AFEAS data, CFC-11 production started in the mid-1930s with small amounts used almost exclusively as a refrigerant in chillers. By the 1940s through the mid-1960s global production gradually increased and the dominant use was for emissive applications such as solvents, aerosols and flexible (open-cell) foams (85-90% of total sales). From 1965 onwards, CFC-11 was used less in emissive applications and more in rigid foams used as insulating material, reaching 50% of total sales in the late 1980s when there was an increased focus on energy efficiency and insulation became more broadly used.

¹⁵⁸ AFEAS data is digitally available only on third party websites, including the following:
<https://agage.mit.edu/data/afeas-data>. Accessed May 2019.

¹⁵⁹ McCulloch, Archie, et al. “Releases of Refrigerant Gases (CFC-12, HCFC-22 and HFC-134a) to the Atmosphere.” *Atmospheric Environment*, Pergamon, 11 Feb. 2003.

¹⁶⁰ Unlike AFEAS, the data reported to UNEP does not include sectoral breakdown of different uses and thus assumptions are made as to what the market split looks like.

Figure 6.1 Historic sales sectoral market breakdown based on AFEAS data¹⁶¹



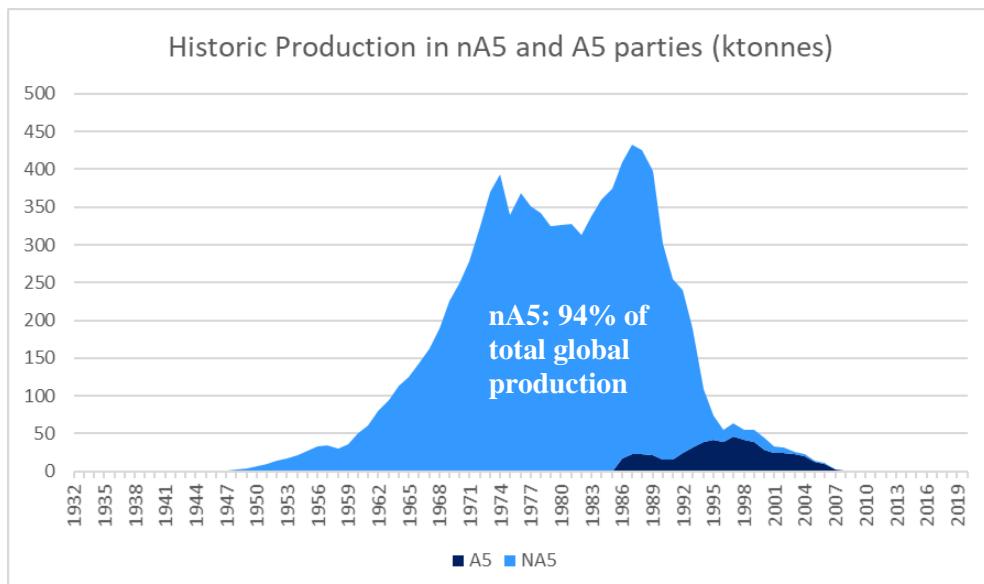
Note: Sales sectoral breakdown was reported in the AFEAS data. From 1989 onwards when data was consistently reported to UNEP, the sectoral breakdown was no longer reported, and the assumption made is that the market comprised of 10% R/AC, 50% rigid foam and 40% emissive uses.

The United States (US) and the European Union (EU) phased out the production of CFCs between 1994 and 1996¹⁶² except for limited quantities for essential uses and the basic domestic needs of Article 5 parties. Therefore, CFC emissions from 1997 onward originate predominantly from existing banks in non-Article 5 parties plus production. They also consist of *de minimis* emissions when charging, operating and decommissioning chillers and of emissions from the foam manufacture processes in Article 5 parties and of a small amount of emissions from banks in Article 5 parties. The US and EU enforced a ban of CFC-11 for many uses (e.g., foams) by 1996, but the majority of manufacturers transitioned to non-ozone depleting chemicals in 1992. By 1997, most CFC-11 was produced in Article 5 parties. However, only 6% of the cumulative total global amount of CFC-11 (through 2009) was produced in Article 5 parties (Figure 6.2). As a result, the lack of market sales data from the UNEP data (predominantly Article 5 parties) does not significantly impact global modelling and analysis.

¹⁶¹ Figure 6.1 was incorrect in the preliminary report and has been replaced in this final report.

¹⁶² EU phased out production by 1/1/1995 and US phased out production by 1/1/1996.

Figure 6.2 Historic production in non-Article 5 and Article 5 parties



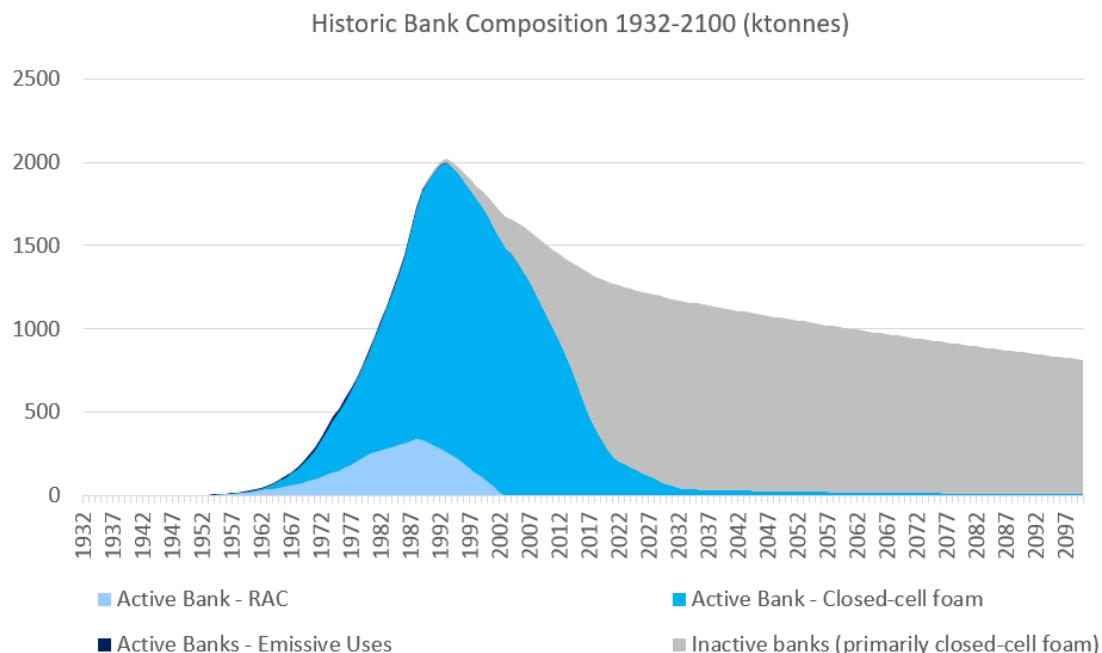
Note: Production shifted to Article 5 parties in the 1990s. Of the 9.7 billion tonnes of CFC-11 produced, 6% of the total was produced in Article 5 parties and the other 94% was produced in non-Article 5 parties.

According to modelling completed for this report, cumulatively to date, bank¹⁶³ emissions account for approximately one fourth of the total CFC-11 emissions. The bank was primarily comprised of R/AC equipment until the mid-1960s when CFC-11 use became more common as a foam blowing agent for closed cell foams. The composition of the bank (Figure 6.3) and the emissions rate of each type of product are used to predict CFC-11 bank emissions.

For the final report, the CFC-11 bottom-up model was further refined to include additional granularity on end-of-life emissions. The resulting figures below represent both active (still in use) and inactive (landfilled) banks.

¹⁶³ The bank was calculated based on production and sales data from AFEAS using assumed emissions rates for each market. Emissions from the banks by market were also incorporated into the overall bank model.

Figure 6.3 Historic bank composition¹⁶⁴



Note: CFC-11 active banks are mostly comprised of R/AC equipment and rigid foams. R/AC and emissive uses do not contribute to the inactive bank and thus are barely visible since it is assumed that CFC-11 in R/AC is vented, destroyed or reclaimed at the end of life and the vast majority of emissions from emissive uses occurs within one year of the product's lifetime. Data started being consistently reported to UNEP¹⁶⁵ in 1989. The sectoral breakdown of CFC-11 uses is not included in the UNEP reporting so assumptions were made from 1989 onwards (see Table 6.3).

6.6 Sensitivity analysis of the CFC-11 emissions “bottom-up” model

In the “bottom-up” calculation of the bank size, the bank is divided into three sectors: refrigeration, closed-cell (rigid) foams and emissive uses (open-cell foams, aerosols, etc.). Production and installation emission rates and bank emission rates were estimated based on industry knowledge and literature (see Appendix 5 for a full range of assumptions). Combining the production data, market composition and sector-specific emission rates, the model provides an estimate of the emissions during production, the bank size and the installation emissions (i.e., emissions during application). In this model, emission rates are held constant. In reality, emission rates are more likely to vary over time as use-patterns and conditions change.¹⁶⁶ The total emissions and bank size vary depending on the set of assumptions used, as seen in Figures 6.4 and 6.5.

¹⁶⁴ Figure 6.3 in the final report replaces Figure 6.3 in preliminary report.

¹⁶⁵ UNEP CFC-11 production data: <https://ozone.unep.org/countries/data>.

¹⁶⁶ The TEAP 2006 report indicates that variation and uncertainties in emission factors are less impactful than uncertainties introduced by variation in use patterns and the market oscillating between rapid-release (e.g., propellants or open-celled foams) and delayed-release applications (e.g., chillers and close-cell foams). The current analysis is in agreement with this observation. However, market oscillations for approximately 80% of the cumulative total global production is known through AFEAS.

Figure 6.4 shows the emissions over time under the low, medium and high scenarios based on reported production using the variables in Table 6.1.

The Task Force also investigated whether the emissions profile could be explained by data being under reported. An increase of reported production up to 20% was investigated. Pairing the high production test with the low emissions rates scenario (shown in Table 6.1) delivers emissions that are close to the atmospherically observed emissions between 1993–2004. The Task Force intends to further investigate this.¹⁶⁷

For the final report (September 2019), the Task Force further expanded and refined the model to include more granularity regarding emissions from different steps in the products' lifetime. The banks were split into active (still in use) and inactive banks (after the product's end of life), and assumptions were made about the handling of products at end of life. For R/AC equipment, assumptions are made regarding venting and reclaim, whereas for foam products assumptions are made concerning landfill practices, shredding and destruction of closed-cell foams. The range of assumptions tested for this model is shown in Table 6.1.

Table 6.1 Range of dependent variables used in the sensitivity analyses resulting in the calculated CFC-11 “bottom-up” emissions and banks shown in Figures 6.4 and 6.5¹⁶⁷

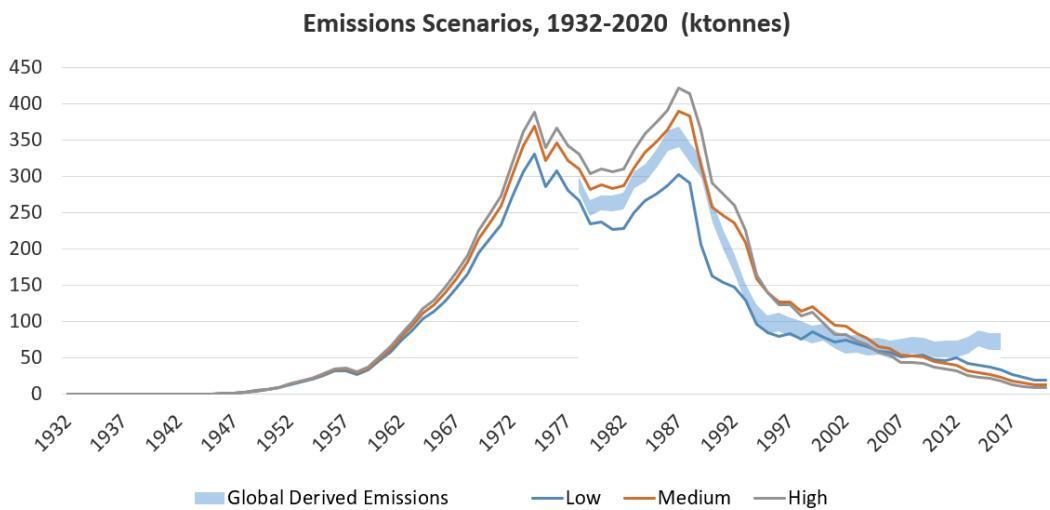
Variables	Low	Medium	High
Production & Distribution Emissions Rate	4%	7%	10%
R/AC: Installation Emissions Rate	0.5%	5%	10%
Closed-cell Foam: Installation Emissions Rate	17%	30%	35%
Emissive uses: Installation Emissions Rate	86%	93%	98%
R/AC: Active Banks Emissions Rate	1%	5%	10%
Closed-cell Foam: Active Banks Emissions Rate	1.5%	8%	10%
Emissive Uses: Active Bank Emissions Rate	86%	93%	98%
Closed-cell Foam: Disposal 1st year	2%	11%	20%
Inactive Bank Annual Emissions Rate	0.5%	4%	7.5%
Sectoral Breakdown (%): Refrigeration/Closed cell/Emissive	13/53/34	10/50/40	10/40/50

Note: Production data as reported to AFEAS and UNEP.¹⁶⁸

¹⁶⁷ Table 6.1 of the final report replaces Table 6.1 of the preliminary report.

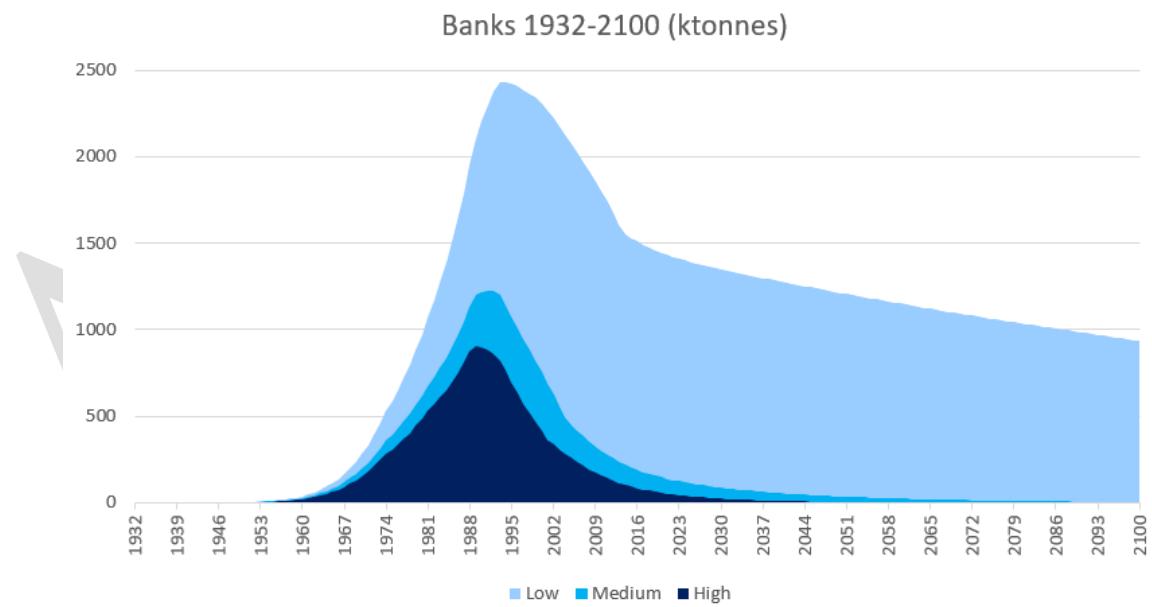
¹⁶⁸ The production volumes were adjusted during the sensitivity analysis. The baseline of that analysis assumes AFEAS plus the data reported to the Ozone Secretariat. This is described as 100% of that baseline. Alternate scenarios for the sensitivity analysis were adjusted as a percentage of this baseline.

Figure 6.4 Range of calculated “bottom-up” emissions as derived from the scenarios shown in Table 6.1¹⁶⁹



Note: Production data as reported to AFEAS and UNEP.

Figure 6.5 Range of “bottom-up” bank sizes as derived from the scenarios shown in Table 6.1¹⁷⁰



Note: Production data as reported to AFEAS and UNEP.

¹⁶⁹ Figure 6.4 of the final report replaces Figure 6.4 of the preliminary report.

¹⁷⁰ Figure 6.5 of the final report replaces Figure 6.5 of the preliminary report.

The emissions predicted by the model are particularly sensitive to the assumptions made regarding the emissions rate during CFC-11 production, as well as to the emissions rates from rigid foam banks.¹⁷¹ The full range of uncertainty has not been probed here, but the calculations are illustrative of expected behaviour. Even with the limited uncertainty tests, the range in calculated recent emissions is large. However, none of the scenarios align with the recent emissions increase. Therefore, based on the broad range of scenarios examined, it seems unlikely that previous production and historic usage can account for the recent emissions rise unless there has been a significant change in the treatment of a large volume of banked CFC-11.

The Task Force included a range of scenarios. The highest and lowest emissions scenarios and largest and smallest bank scenarios are included here based on learnings from the Sensitivity Analysis which showed that the model was most sensitive to production rates and emissions from production and foams. All of the other scenarios examined fell into the range of these scenarios. These combine highest production rates with highest and lowest emissions rates and, separately, lowest production rates with highest and lowest emissions rates. The outcomes of these scenarios bracketing the highest and lowest emissions and largest and smallest banks scenarios, have been included in Appendix 5.

The Task Force also investigated whether the emissions profile could be explained by data being under-reported. In an attempt to depict the impact of the assumptions, coupled with the potentially under-reported production on bottom-up emissions estimates, the Task Force tested several increased production hypotheses, i.e., where production was assumed to be higher than reported (the high production test, see Appendix 5, Figures A5.14-16). The production quantities were adjusted during the sensitivity analysis. The baseline of that analysis is production as reported to AFEAS and the Ozone Secretariat. The high production tests assumed 10%, 20% and 40% increases, respectively, in reported production consistently over the years.

6.7 Estimating release rates from banks using “top-down” regional emissions estimates

Section 6.7 examines the trend in emissions from banks over 20 years to better understand how expected emissions might change over time.

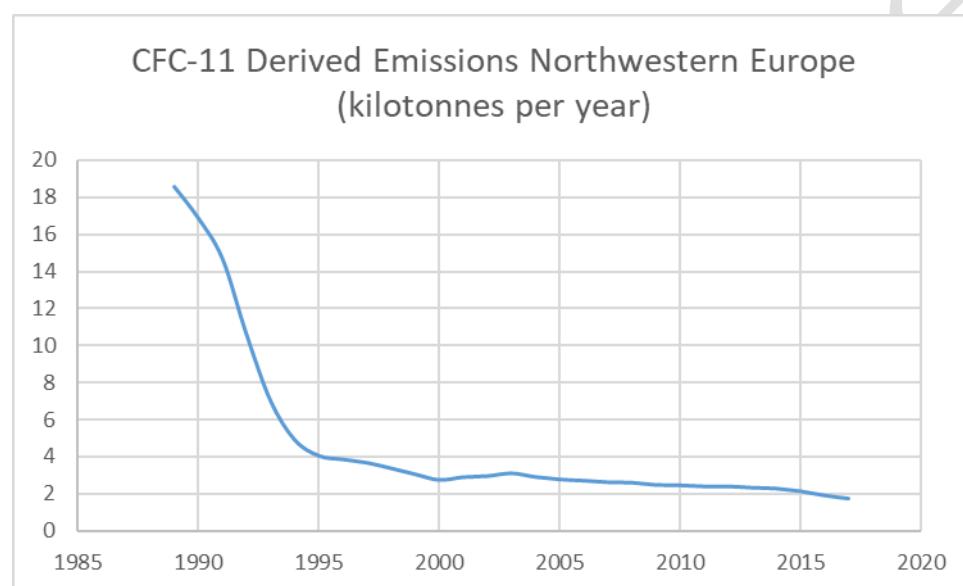
Long-term atmospheric emissions, presumed to be from banks (e.g., from installed insulating foams, chillers, refrigerator foams landfills, etc.), were explored to better understand the expected emissions globally. Emissions rates were derived from atmospheric emissions originating from Western Europe (non-Article 5 parties), where no new CFC-11 has been “consumed” (as defined by the Montreal Protocol) for 20 years. The trend in emissions and the total derived emission rates provides an alternate view of expected emissions and how they might change over time. In the future work of the Task Force, this may be offset based on the year that consumption ended in a particular region. For example, in eastern Asia, the curve might be adjusted by 14 years from 1996 to 2010, which is the year that “consumption” ended in eastern Asia. Of course, alternate treatment of banks (e.g., destruction versus landfill

¹⁷¹ See Appendix 4 for additional detail.

of foams) or a difference in the percentage of the bank in foams might result in some variation.

Concentrations of CFC-11 from Northwestern Europe are monitored in Mace Head Ireland and used to derive emissions rates. The emissions have been generally declining since before 1990, as shown in Figure 6.6. The steep decline from 1990 through 1995 is likely a result of the transition from CFC-11 to other alternatives in anticipation of the production ban in non-Article 5 parties in 1996. The derived emissions have been generally stable to declining since 1997.

Figure 6.6 CFC-11 atmospheric emissions in northwestern Europe (in kilotonnes or gigagrams) as derived from the Mace Head monitoring site in Ireland (UK NIR)¹⁷²



Emissions rates were estimated during various time periods. Shorter time periods show anomalies as there is some variability to the derived emissions data year over year. Longer term approximations of emissions rates were consistent with some previous emission rates reported in literature.

Alternative methods were also used to calculate emission rates based on derived atmospheric emissions during different time periods. Variable and steady emission rates were estimated using a number of techniques including simple regression analyses with strong statistical correlation to derived emissions data. The time period from 1996 through the latest data was used to develop combinations of emission rates with the closest statistical correlation at an

¹⁷² The UK Department for Business, Energy & Industrial Strategy (BEIS) provided support through contract 1028/06/2015 to the University of Bristol for Mace Head and Tacolneston atmospheric composition data and to the UK Met Office for InTEM analysis.

annual loss rate of 3 to 4% per year. The associated emissions and emissions rates were used to develop an approximation of associated bank volumes.¹⁷³

6.8 Derived atmospheric emissions of replacement foam blowing agents¹⁷⁴

Section 6.8 examines the derived atmospheric emissions of CFC-11 and the foam blowing agents that replaced it for use in rigid or closed-cell polyurethane foams to explore their behaviour relative to the unexpected emissions of CFC-11.

The Task Force also examined the measurement-derived atmospheric emissions of higher boiling point (or “liquid”) fluorocarbons used as polyurethane closed-cell foam blowing agent replacements of CFC-11 to make comparisons and look for anomalies that might provide additional insight into the unexpected emissions of CFC-11.

Figure 6.7 shows the global atmospheric derived emissions of CFC-11, HCFC-141b¹⁷⁵, HFC-245fa, and HFC-365mfc¹⁷⁶. The figure shows a slight decline in HCFC-141b emissions that aligns with the period when non-Article 5 parties stopped using HCFC-141b by 2010. It was anticipated that CFC-11 would continue to decline from 2010 onward when it was banned globally and HCFC-141b would start to decline and continue to do so after 2013 when the global production and consumption phase-out started. It was also anticipated that there might be an increase in HFC-245fa and HFC-365mfc emissions as HCFC-141b was partially replaced by HFCs. It was also anticipated that the total emissions from the four chemicals would continue to increase slightly as polyurethane foam usage continued to increase.

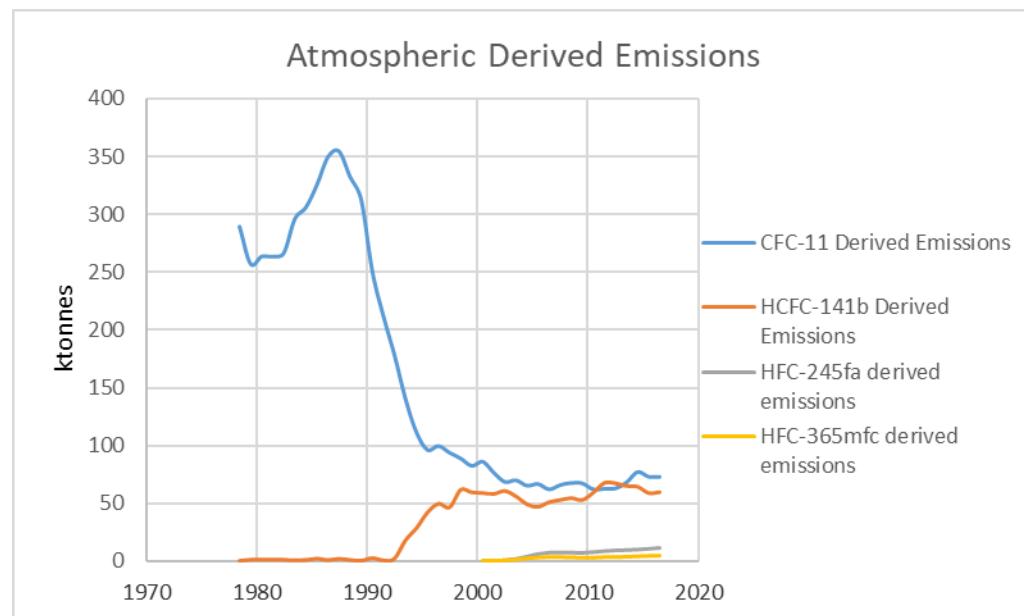
¹⁷³ Ashford *et al.*, 1999. *Development of a global emission function for blowing agents used in closed cell foam*, Final Report to AFEAS, and also what Montzka *et al.*, (2018) derived on a global scale considering reported production for the mid-2000s.

¹⁷⁴ WMO (World Meteorological Organization), *Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project—Report No. 58*, Derived emissions data source for this section from the Scientific Assessment of Ozone Depletion: 2018 (World Meteorological Organization United Nations Environment Programme National Oceanic and Atmospheric Administration National Aeronautics and Space Administration European Commission) Chapters 1 and 2
https://www.esrl.noaa.gov/csd/assessments/ozone/2018/report/FrontMatter-ExecutiveSummary_2018OzoneAssessment.pdf.

¹⁷⁵ Although HCFC-141b was used for other emissive purposes such as solvents, its overwhelming primary use was as a foam blowing agent in rigid polyurethane closed-cell foams.

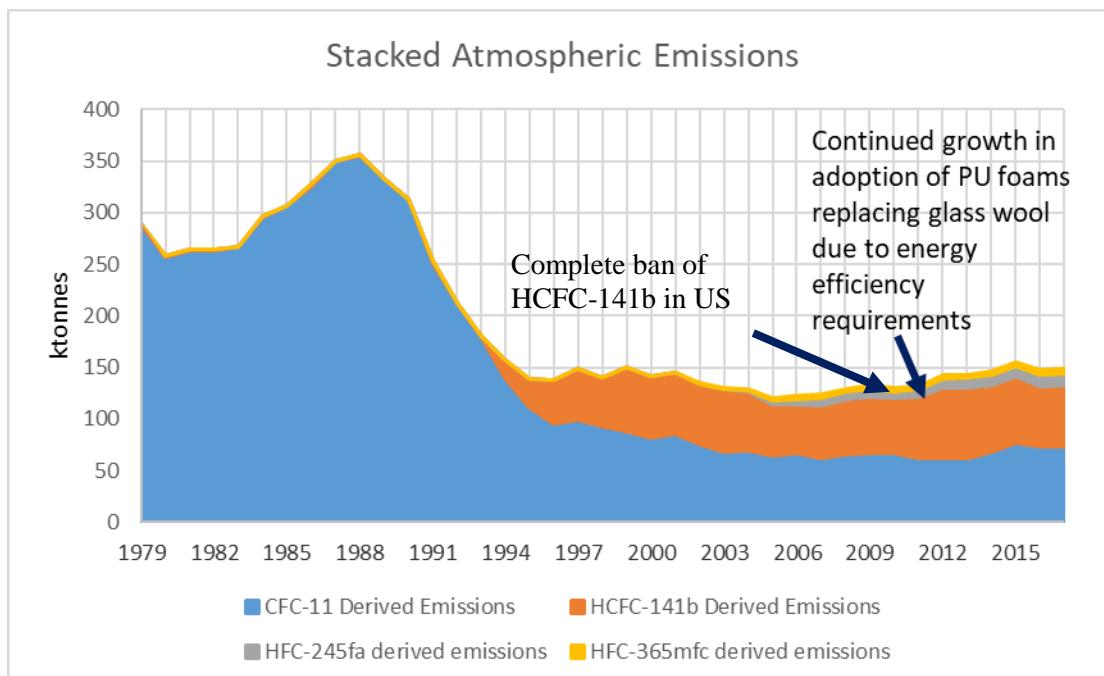
¹⁷⁶ The derived mass emissions were adjusted by molecular weight compared to CFC-11 because foam blowing agents are used commercially by volume or mole rather than by mass.

Figure 6.7 Atmospheric derived emissions of CFC-11, HCFC-141b, HFC-245fa and HFC-365mfc CFC-11 equivalent (kilotonnes per year)



The data were then stacked to explore whether the derived emissions might reflect the overall market changes in the use of various foam blowing agents (Figure 6.8). The derived global atmospheric emissions appear to reflect the transitions away from ozone-depleting substances as foam blowing agents, as well as overall foam market growth and the introduction of HFCs.

Figure 6.8 Stacked graph showing atmospheric derived emissions of CFC-11, HCFC-141b, HFC-245fa and HFC-365mfc (kilotonnes)¹⁷⁷



Total emissions from the four liquid blowing agents continue to increase from 2003 through 2014, followed by a decrease. This could be due to some replacement of HCFC-141b with HFOs/HCFOS or with non-fluorocarbon blowing agents. HFC-245fa and HFC-365mfc emissions continue to increase slightly through the period. As noted earlier, instead of continuing to decline as anticipated, CFC-11 emissions increased unexpectedly from 2013¹⁷⁸ onward during this same period (Figure 6.8).

If companies reverted to CFC-11 in their transition from HCFC-141b as a foam blowing agent, then the derived emissions of CFC-11 would be expected to increase after 2011 when global HCFC-141b emissions decreased.¹⁷⁹ These are shown in Figure 6.9. The increase in the derived global emissions of CFC-11 does occur after 2012. The total emissions of CFC-11 and HCFC-141b slowly increase. The overall trend is not conclusive, but it is not inconsistent with some replacement of HCFC-141b with CFC-11 in polyurethane closed cell foams or polyurethane foam systems globally.

If CFC-11 were being used in open-cell foams, the sum of the four polyurethane rigid foam blowing agents would grow rather than having relative stability. Based on this, and the very low cost of dichloromethane and water which are used in open cell foam, it seems unlikely

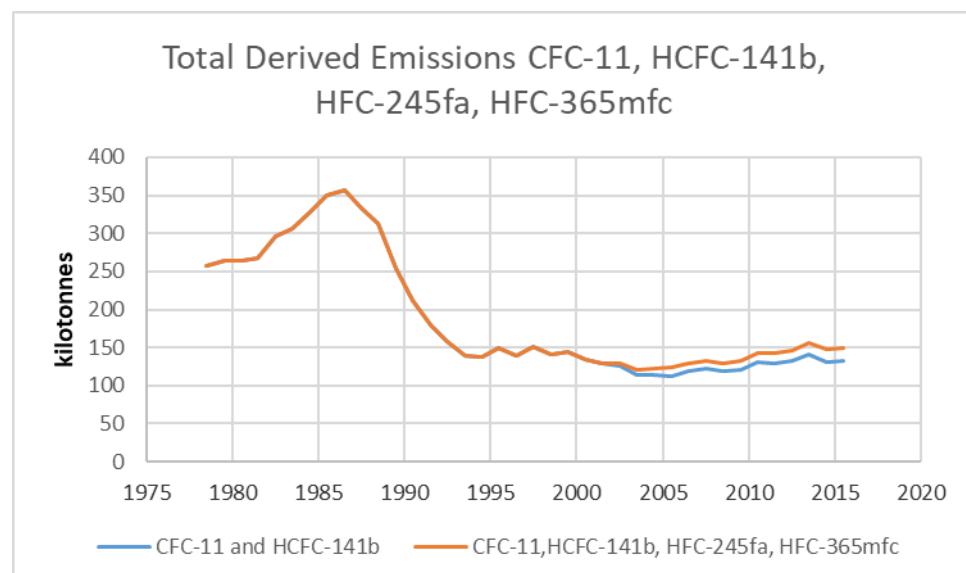
¹⁷⁷ WMO (World Meteorological Organization), *Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project—Report No. 58*, 588 pp., Geneva, Switzerland, 2018.

¹⁷⁸ 2013 when taking into account uncertainties in atmospheric measurements.

¹⁷⁹ Although HCFC-141b was used for other emissive purposes such as solvents, its overwhelming primary use was as a foam blowing agent in rigid polyurethane closed-cell foams.

that CFC-11 has been used in any significant amount since the mid-1990s in open-cell foams formulations.

Figure 6.9 Total derived atmospheric emissions of “liquid” foam blowing agents (kilotonnes)



6.9 Emission source scenarios attempting to duplicate derived atmospheric emissions of CFC-11

Section 6.9 describes the development of more extreme scenarios in an attempt to duplicate the derived atmospheric emissions.

As the sensitivity analysis described in Sections 6.2, 6.3, and 6.4 provided no scenarios that explained the unexpected emissions given reported production magnitudes (or up to 20% higher than reported production), more extreme potential scenarios were considered.

Examples follow:

- Emissions directly associated with production were increased by 100% or more and bank emissions rates were increased to 150% of the previous assumptions in the medium scenario above. The resulting emissions did not align with the derived atmospheric emissions; the deviation was delayed and increased in later years as bank levels dropped quickly due to higher emissions rates.
- Emissions rates while charging refrigerant and creating closed-cell foam were varied by 50%. This also did not align with the unexpected emissions.
- Small, and even very large, changes to the bank emissions rates did not result in alignment with the derived atmospheric emissions without extreme increases in the later years for which there are no practical causes known or evidence for the unexplained emissions.

- If there were use of newly produced CFC-11 for new production of chillers, this would increase the size of the banks but would not result in sufficient emissions increases to align with the derived atmospheric emissions.¹⁸⁰
- There are scenarios where new production or inventory is directly released to the atmosphere; however, it seems unlikely that this would be a source of the unexplained emissions as this would result in significant commercial losses.
- There were scenarios using newly produced CFC-11 in open-celled foam that align with the increased emissions of CFC-11. It is doubtful that it would be economically advantageous to revert to using CFC-11 from using dichloromethane¹⁸¹ unless there is some other factor requiring its replacement (e.g., regulation of dichloromethane).
- Scenarios were evaluated combining estimated sales of newly produced CFC-11 into multiple markets (combinations of foams, emissive uses, and chillers). Although technically feasible, each market has the same economic challenges as scenarios run independent of closed-cell foams.

These scenarios (Appendix 5) have been shown to be highly unlikely sources of the unexpected CFC-11 emissions. In contrast, none of the analyses of the available data called into question the possibility that new CFC-11 production might be used in closed cell foams or polyol systems. Based on this overall evaluation, the Task Force recommends continued exploration into the use of CFC-11 in closed-cell foams to explain the unexpected emissions of CFC-11.

¹⁸⁰ Newly produced CFC-11 could be used in chillers, but given the global market for chillers, it does not explain the unexpected emissions of CFC-11.

¹⁸¹ Dichloromethane is currently advertised at 0.35 to 0.70 USD/kg on the internet compared to the offer for sale of CFC-11 of 2.2/USD/kg in the offer in Appendix 4. <https://www.alibaba.com/showroom/methylene-chloride.html>.

Table 6.2 Emission source scenarios attempting to duplicate derived atmospheric emissions of CFC-11

Emissions Source Scenario ¹⁸²	Aligned with Derived Emissions?	Extreme Assumptions		Conclusions and any Additional Recommendations
Bank Emissions Rate Increases or Decreases	No	Emissions rate increase or decreased by 50%		No known practical emissions source or evidence of sufficient volumes to explain the unexpected emissions
Bank Emissions Rate Increases for foams and chillers as per table	Yes	<u>Range</u> 1934 to 2002 2003 to 2006 2007 to 2011 >2012	<u>Chiller/Foam emissions rates</u> 5%/8% 7%/11% 10%/16% 15%/24%	No known practical emissions source Especially for foams
New CFC-11* used in chillers	No	35 ktonnes in 2002-2010 70 ktonnes >2010		Commercially unlikely
New CFC-11 used in Closed Cell Foam	Yes	35 ktonnes in 2002-2009 70 ktonnes >2009		Additional exploration recommended
New CFC-11* used in Open Cell Foam	Yes	25 ktonnes 2002-2010, 50 ktonnes >2010		Commercially unlikely and overall balance of foam blowing agents inconsistent
New CFC-11* used in Combination of Uses	Yes	25 ktonnes 2002-2010, 50 ktonnes >2010		Commercially unlikely, but technically feasible
New CFC-11* released	Yes	25 ktonnes 2002-2010 50 ktonnes >2010		Commercially unlikely

* New CFC-11 could come from new production and/or previously stockpiled inventory

6.10 Most-likely bottom-up emissions scenario and implied illicit CFC-11 production

In the previous sections, a sensitivity analysis was performed that helped to identify the range of expected bottom-up emissions and to demarcate the uncertainties inherent to the model. Taking into consideration several factors affecting the model assumptions regarding production practices, especially in the 1970s and 1980s when production of CFC-11 was at its highest, the Task Force was able to identify what it believes to be a reasonable set of plausible assumptions. This scenario was then used to back-calculate the additional, unreported production that would be needed to explain the top-down emissions trend from 2012-2017.

¹⁸² Red color denotes unlikely source of unexpected emissions.

The assumptions used in the “most likely” scenario are shown in Table 6.3. The “most likely” scenario assumes that production has been historically under-reported by approximately 5%. The market breakdown among the three sectors (R/AC, closed cell foams, emissive uses) is provided by the AFEAS market breakdown through to the 2000s. After 1999, different assumptions are made about the market breakdown among the three sectors.

Table 6.3 List of assumptions used in the “most likely” scenario

Assumptions	Most-likely Scenario
Production Emissions	4.0%
Sold into RAC sector but used as solvent	1.0%
Installation closed cell foam	21.0%
Installation opened cell foam, aerosols & others	92.0%
Installation RAC	2.0%
Accumulating Active bank: RAC	5.0%
Accumulating Active bank: Closed Cell Foam	2.0%
Accumulating Active bank: Emissive uses	92.0%
RAC Bank Vented (post 2001/post 2010)	85%/60%
RAC Bank Reclaimed (post 2001/post 2010)	10%/35%
RAC Bank Destroyed (post 2001/post 2010)	5%/5%
Foam Bank Lost from Shredding	5.0%
Foam Bank Destroyed	1.0%
Foams Emissions: 1st Year of Disposal	5.0%
Accumulating Inactive banks (dominated by foams)	0.5%
Banks: Annual Release from Inactive Bank	0.5%
Market Breakdown: %RAC/%Foams/%Emissive (1988-1999)	4/52/44
Market Breakdown: %RAC/%Foams/%Emissive (post 1999)	4/87/9
RAC Average Lifetime	25 years
Closed-cell Foam Average Lifetime	30 years
Emissive Uses Average Lifetime	Instant release

According to industry knowledge, approximately 1% of the CFC-11 sold into the R/AC sector was used as a solvent in the R/AC manufacturing industry and therefore emitted instantaneously upon use instead of entering the R/AC bank.

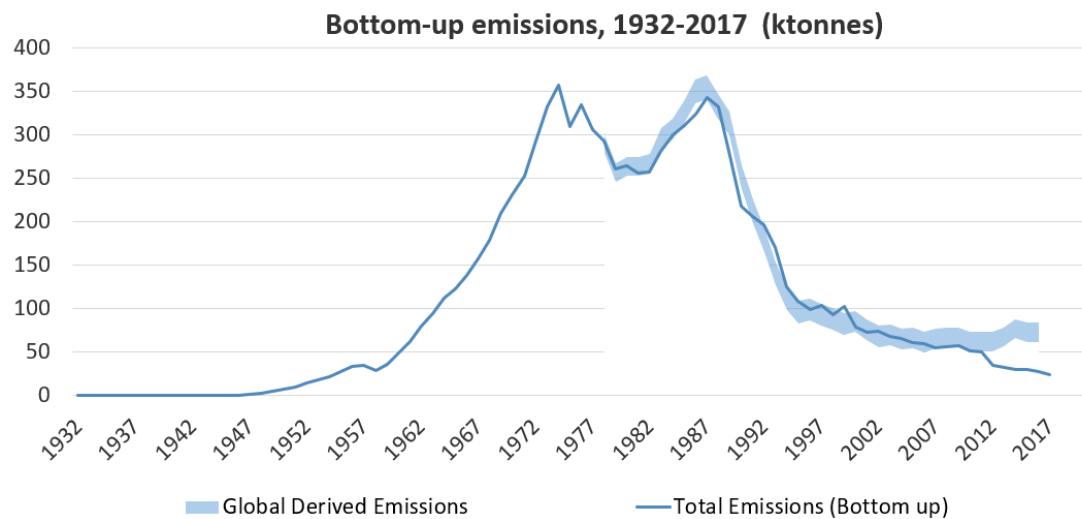
Regarding handling of R/AC bank at the end of life, it is assumed that no refrigerant was reclaimed or destroyed until 2000 because use of reclamation technology was not widespread. From 2001 onwards, it is assumed that upon dismantling of the equipment, 85% of the initial charge is vented, 10% is reclaimed for use in servicing equipment and 5% is recovered and destroyed. Post 2010, when the CFC-11 phase-out came into effect for all parties, the incentive to reclaim and re-use refrigerant for servicing of existing equipment was higher. Therefore, the “most likely” scenario assumes that post 2010, 35% of the CFC-11 in R/AC equipment being retired was reclaimed and re-used for servicing while 60% was vented and the remaining 5% was destroyed.

When closed-cell rigid foam products reach the end of their useful life it is assumed that 5% of the initial blowing agent content is released due to shredding and 1% is collected and destroyed. Some of the remaining blowing agent has been solubilized in the foam matrix and some slowly leaks into the atmosphere from the landfill at a rate of 0.5%. The leakage rate is higher during the first year of disposal due to disposal practices and landfill compaction.

Assuming no illicit production of CFC-11, the bottom-up model under the “most likely” scenario results in emissions estimates that resemble those derived from atmospheric measurements until 2012 (see Figure 6.10). The bottom-up model indicates that the rate of

reduction of the CFC-11 emissions should be higher than that derived from atmospheric measurements. An approximate 40-70 kilotonnes of additional CFC-11 production would be required to explain the profile of emissions derived from atmospheric measurements.

Figure 6.10 Bottom-up emissions under the “most likely” scenario



6.11 Regional CFC-11 emissions from closed-cell foams

In an attempt to better quantify the unexpected emissions of CFC-11, the Task Force has evaluated expected emissions from banks so that they might be differentiated from total emissions. The key focus of this effort has been related to foam banks as banks from other uses have largely been released. For reference, banks related to emissive uses such as aerosols, propellants and open-celled foams have been estimated to have been very small as they are largely emitted during manufacturing or use, and any remaining solvents would have been either recycled or emitted. CFC-11 used in chillers has been carefully contained and remaining CFC-11 used as a refrigerant has largely been reclaimed, recycled or destroyed. Also, as noted in the chapter on refrigerants in the preliminary report, less than 35,000 tonnes of CFC-11 remained in the chiller bank as of 2008. In contrast, CFC-11 used in closed-cell foams is emitted throughout the product lifecycle: during the foam manufacture process (manufacture and installation of foam in a refrigerator or building), while the foam is in use, during the dismantling process and from landfills (unless the foam or blowing agent is collected and destroyed).

In the 2006 Rigid and Flexible Foams Assessment Report, a detailed breakdown was developed of the use of blowing agents in foams by global sub-region and foam type. This has been used as the basis for this methodology evaluating CFC-11 foam emissions and banks for this final report. These numbers were used from 1980 through 1996.

Note that in 1986, Article 5 parties produced only 4% of the total production of CFC-11. Because Article 5 parties produced and consumed very small quantities of CFC-11 prior to 1981, the model has been simplified assuming that no CFC-11 was used in Article 5 parties prior to 1981. By 1996, CFC-11 was banned from use in non-Article 5 parties. For the periods of time prior to significant use by Article 5 parties and after the ban for non-Article 5 parties,

the distribution by foam type and region has been normalized to the total for non-Article 5 and Article 5 parties respectively. It is also important to note that no allowance has been made for the legal export of goods containing CFC-11 from Article 5 parties to non-Article 5 parties in appliances and other finished products such as refrigerated containers. This will bias the banks and emissions from those banks to be higher in Article 5 parties that are large exporters of those finished products such as China, Thailand, South Korea, Brazil, Mexico and other locations.

Documented emissions rates from a number of sources were considered including the Flexible and Rigid Foams Technical Options Committee (FTOC) as well as the 2007 IPCC report for a number of types of foams in this analysis. The FTOC included the latest research related to emissions by product type as well as handling losses in their emissions rates. There is a limited body of information related to emissions rates from landfills. It was largely assumed that emissions rates from landfills would be approximately equivalent to the emissions rates from products taking into consideration that the foam would not be encapsulated as they are during use (coated or in an appliance, etc.), but conservatively there would be some cover of the landfill. Conservative emissions rates were used to maximize the size of the banks for this analysis during later years so that the maximum possible emissions would be described as “expected”.

The duration of the use stage of the product lifecycle was evaluated by the FTOC based on available information from IPCC¹⁸³ and other sources noting that there are some regionally specific descriptions of the lifetime of buildings¹⁸⁴. Where very different data were available, multiple datasets were tested.

Finally, one party provided data describing emissions during dismantling and disposal at 15%, which was incorporated into the analysis along with higher emissions rates bounded by the limitations noted in the foams chapter in the preliminary report due to the solubility of blowing agents in the foam matrix. Destruction of CFC-11 in foams was not included in most analyses unless a party specifically noted it as a local disposal method.

Figures for each region are included in Appendix 5.

For clarification:

- “Cumulative CFC-11 installed in foams” is the initial amount used as a blowing agent in closed-cell foams in Europe based on the data described above.
- “Remaining bank in use” is the CFC-11 remaining in foams in use in buildings, refrigerators, etc.
- “Cumulative entering the waste stream” is the sum total of the CFC-11 that has been dismantled excluding the 15% emissions during the dismantling process

¹⁸³ 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 3 Industrial Processes and Product Use https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_7_Ch7_ODS_Substitutes.pdf

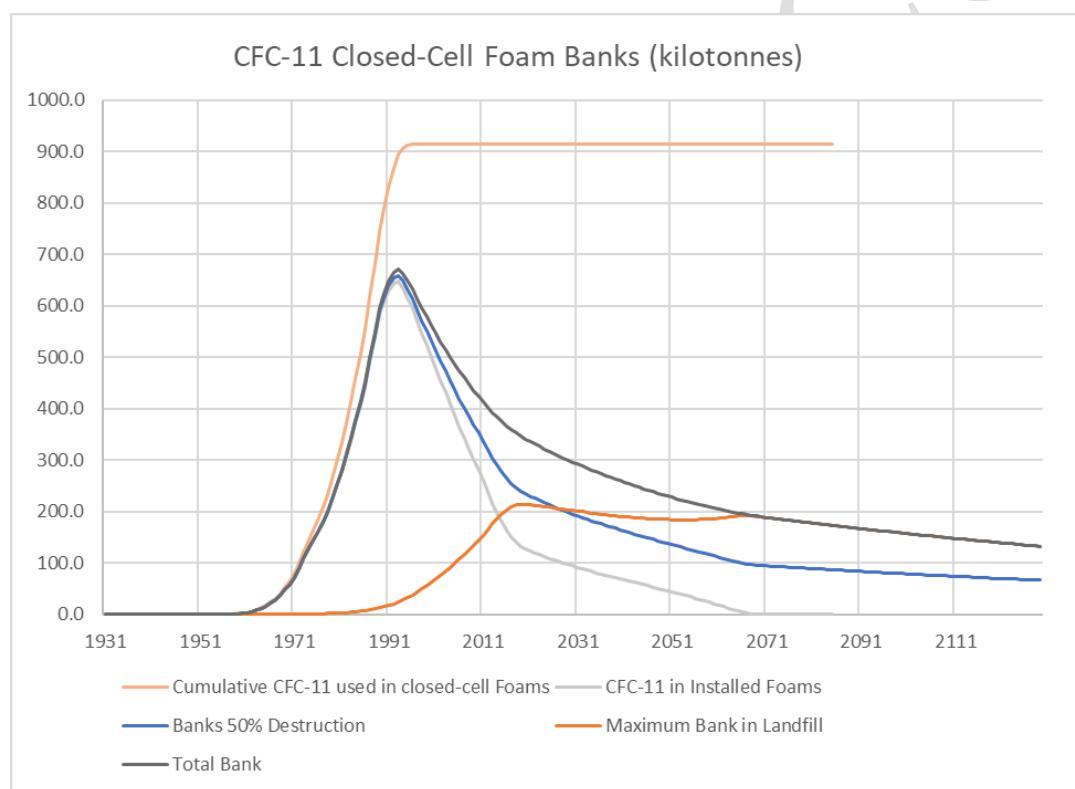
¹⁸⁴ For example, Estimating Lifetimes and Stock Turnover Dynamics of Urban Residential Buildings in China by Wei Zhou,,Alice Moncaster, ,David M Reiner, and Peter Guthrie which noted that the estimated lifetime of buildings in China is 34 years. <https://www.mdpi.com/2071-1050/11/13/3720/htm>

- “Maximum bank in landfill” (with or without destruction) is the CFC-11 remaining in the landfill excluding emissions from landfilled foams.

As the graphs of the banks show, the initial CFC-11 used as a blowing agent in foam (“Cumulative CFC-11 installed in foams”) is greater than the “CFC-11 in installed foam” as emissions are subtracted from the “CFC-11 in installed foam” banks during the foaming process and as they occur over time from the foam. Gradually over time, the CFC-11 in the foam bank continues to be reduced as it is emitted to the atmosphere.

. Two scenarios for the inaccessible bank in the landfills are included in the graph below comparing a scenario with no destruction (which is not the case in Europe) with a more representative scenario showing 50% destruction of the CFC-11 after dismantling the building. .

Figure 6.11 CFC-11 banked in foams in Europe over time using 2006 FTOC Assessment Report foam manufacturing estimates



An estimate of CFC-11 emissions during the foaming process and from the CFC-11 banked in foams is shown next.

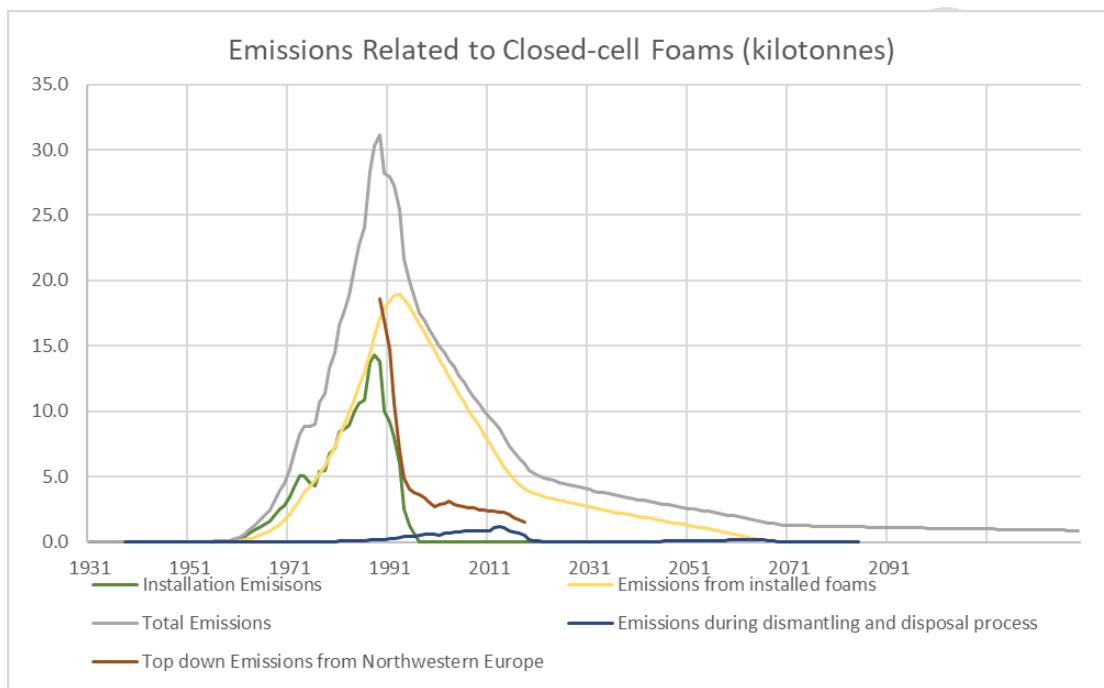
For clarification:

- “Installation emissions” are blowing agent losses during the foaming process;
- “Emissions from installed foams” are blowing agent emissions from foams in use in buildings, refrigerators, etc.;

- Emissions during the “dismantling and disposal” process describes the CFC-11 emitted when the foam in a building or refrigerator or other use is removed at the end of its useful life.

The derived atmospheric emissions from Northwestern Europe are included in the graph below as reference. The expected total emissions of CFC-11 describe all of the emissions in Europe and are expected to be greater than those in Northwestern Europe. It was assumed in this example that 50% of the foams containing CFC-11 were destroyed.

Figure 6.12 CFC-11 banked in foams in Europe over time, using 2006 FTOC Assessment Report foam manufacturing estimates



The same methodology was used globally and for other regions. The global results and the results for Northeast Asia (Northeast Asia consists of China, Mongolia, the Democratic People’s Republic of Korea, and The Republic of Korea) follow. The global model developed in the preliminary report indicates that closed-cell foam banks are the source of greater than 95% of CFC-11 emissions from 2008 onward when CFC-11 bans started taking place in various jurisdictions (e.g., China halted the use of CFC-11 in 2008).

Figure 6.13 Global banks related to closed-cell foams

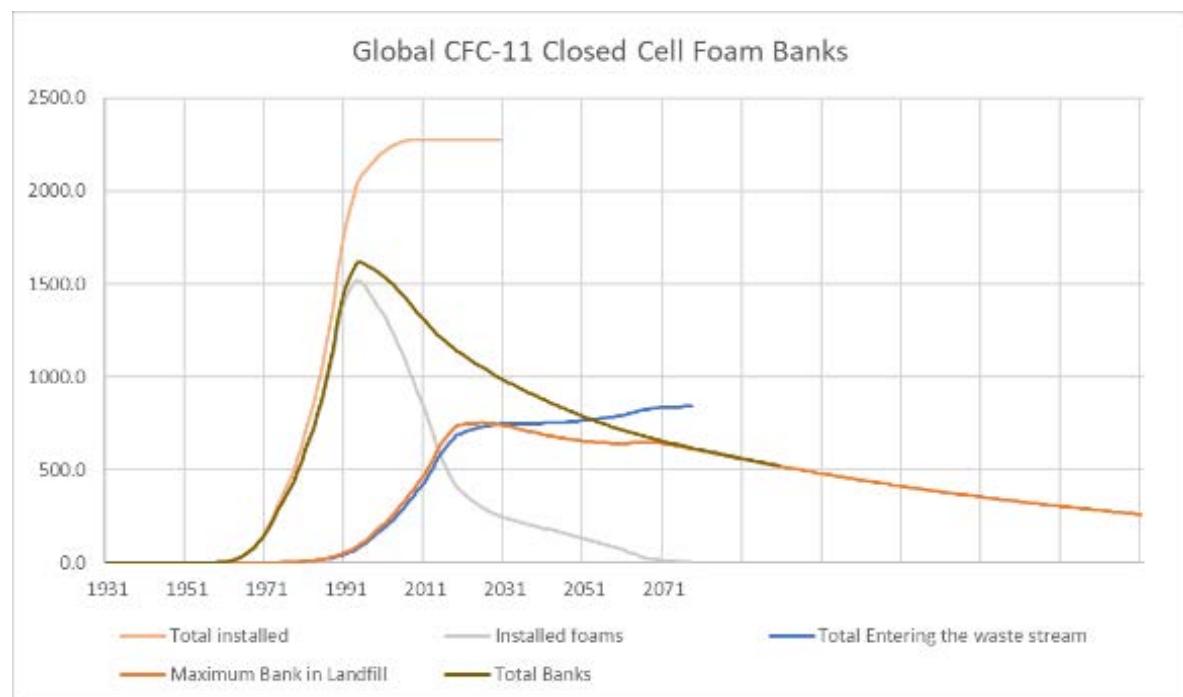


Figure 6.14 Global emissions related to closed-cell foams

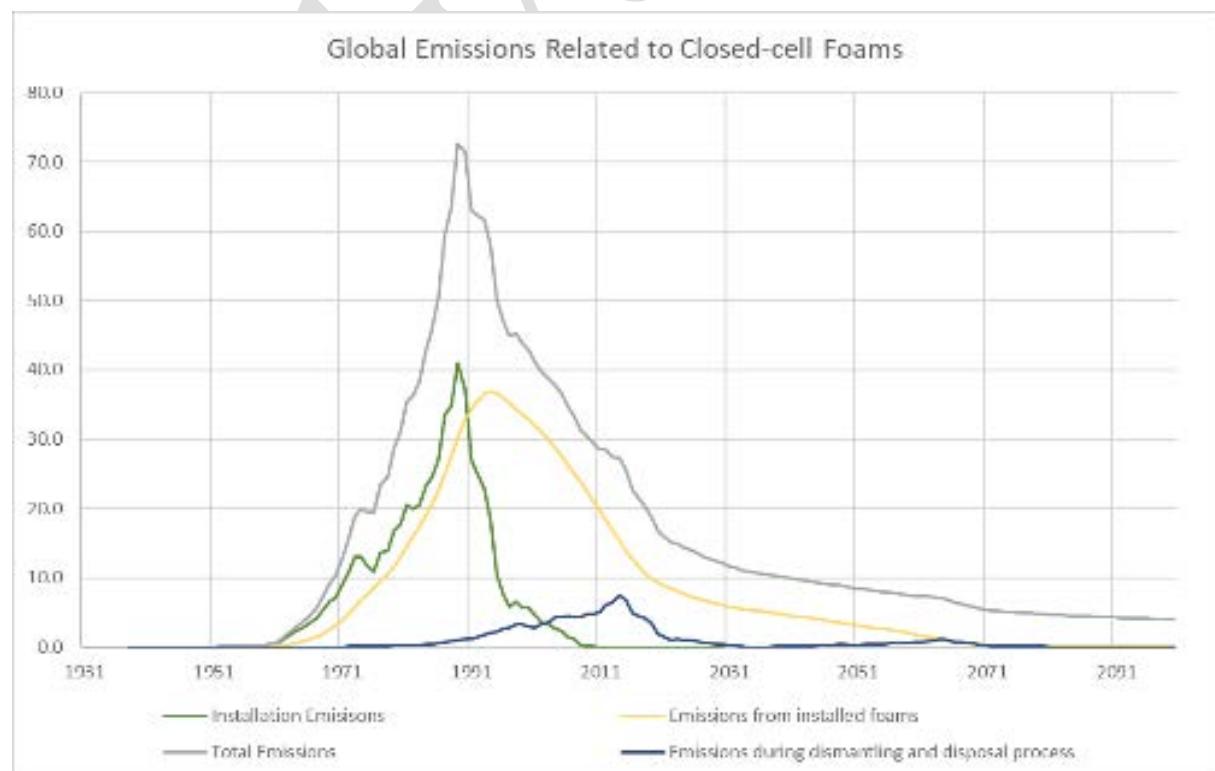


Figure 6.15 below shows estimated emissions from Northeast Asia using the same approach. The 2006 FTOC Assessment report was used to determine blowing agent consumption based on the weighted average of foam types manufactured in Northeast Asia along with emissions rates and foam lifetimes by foam type to estimate CFC-11 emissions in Northeast Asia over time. The Task Force used a range of 120 kilotonnes to 280 kilotonnes of CFC-11 for closed-cell foam.

The “maximum emissions” scenario was created to maximize emissions from closed-cell foams after 2005 in Northeast Asia. In this scenario, 280 kilotonnes¹⁸⁵ were used in closed-cell foams. Approximately 60 kilotonnes of CFC-11 were emitted during the foaming process, and 155 kilotonnes were emitted while the foam was in use in the closed-cell foam, leaving approximately 105 kilotonnes to be emitted during the dismantling and disposal.

- For reference, the total derived emissions from eastern mainland China dominated by Shandong and Hebei provinces (Rigby *et al.*¹⁸⁶) were nearly 100 kilotonnes from 2008 through 2017.
- For further context, this would require the use of greater than 55% of all of the CFC-11 production for usage (as opposed to feedstock) reported by Article 5 parties to the Ozone Secretariat from 1986.

As background, atmospheric measurements from many sites across the globe were considered in Rigby *et al.*¹⁸⁷. The atmospheric measurements that point to increases in emissions from eastern China were taken from the Gosan station in South Korea and the Hateruma station in Japan. These stations are sensitive to and enable quantification of emissions from western Japan, the Korean Peninsula, and eastern mainland China, which includes the provinces of Anhui, Beijing, Hebei, Jiangsu, Liaoning, Shandong, Shanghai, Tianjin and Zhejiang. The measurements from these stations suggested that emissions from eastern mainland China are substantially larger than those from western Japan and the Korean Peninsula, and that emissions from two Chinese provinces in particular increased after 2012. No significant emission increase was derived for other eastern Asian countries or regions where atmospheric data enables the quantification of regional emissions, although this existing measurement network does not provide regional emission estimates for many populated regions of the world. The region contributing the remaining fraction of the global CFC-11 emission increase is not identifiable at this time, given the limited regional emission information supplied by the existing measurement network. It is possible that variations in atmospheric circulation may have contributed in part to the slow-down of CFC-11’s global atmospheric concentration decline, but the available evidence compiled in Montzka *et al.*¹⁸⁸ and Rigby *et al.*¹⁸⁹ papers

¹⁸⁵ Note that 280 kilotonnes represents approximately 55% of the CFC-11 production reported by all Article 5 parties to the Ozone Secretariat.

¹⁸⁶ Rigby, M. *et al.*, Increase in CFC-11 emissions from eastern China based on atmospheric observations, *Nature*, 2019, **569**, 546–550. <https://doi.org/10.1038/s41586-019-1193-4>.

¹⁸⁷ Ibid., Rigby, M. *et al.*, 2019.

¹⁸⁸ Montzka, S. *et al.*, An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, **557**, 413–417 (2018). <https://doi.org/10.1038/s41586-018-0106-2>.

¹⁸⁹ Ibid., Rigby, M. *et al.*, 2019.

clearly point to a global emission increase in CFC-11 emissions that is explained in large part by increased emissions from two provinces in eastern China.

Figure 6.15 “Most likely case” Northeast Asia CFC-11 emissions from closed-cell foam scenario combined with derived atmospheric emissions from eastern mainland China from Rigby et al.

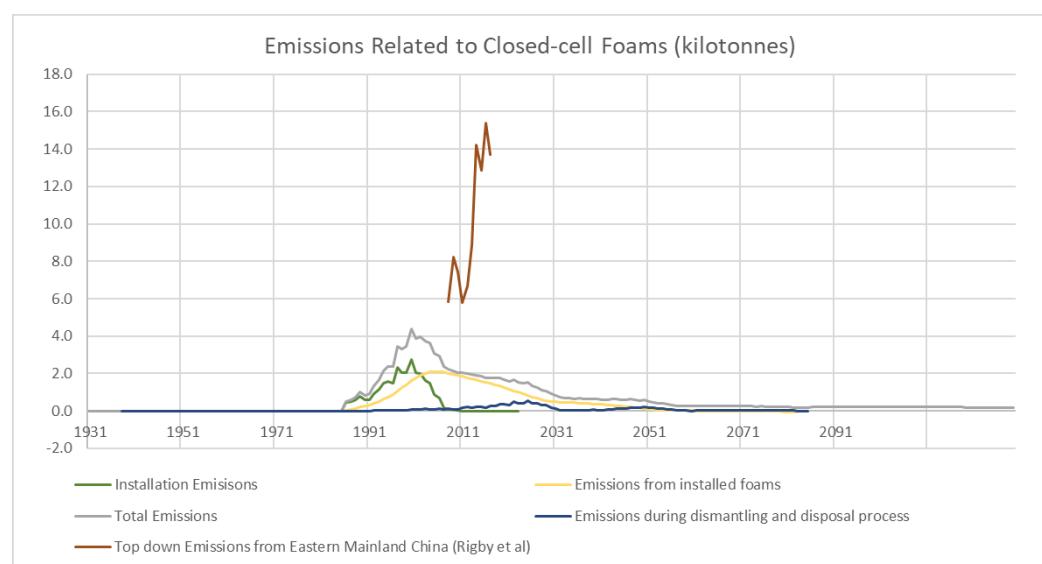


Figure 6.16 “Maximum” Northeast Asia emissions scenario combined with derived atmospheric emissions from eastern mainland China from Rigby et al.

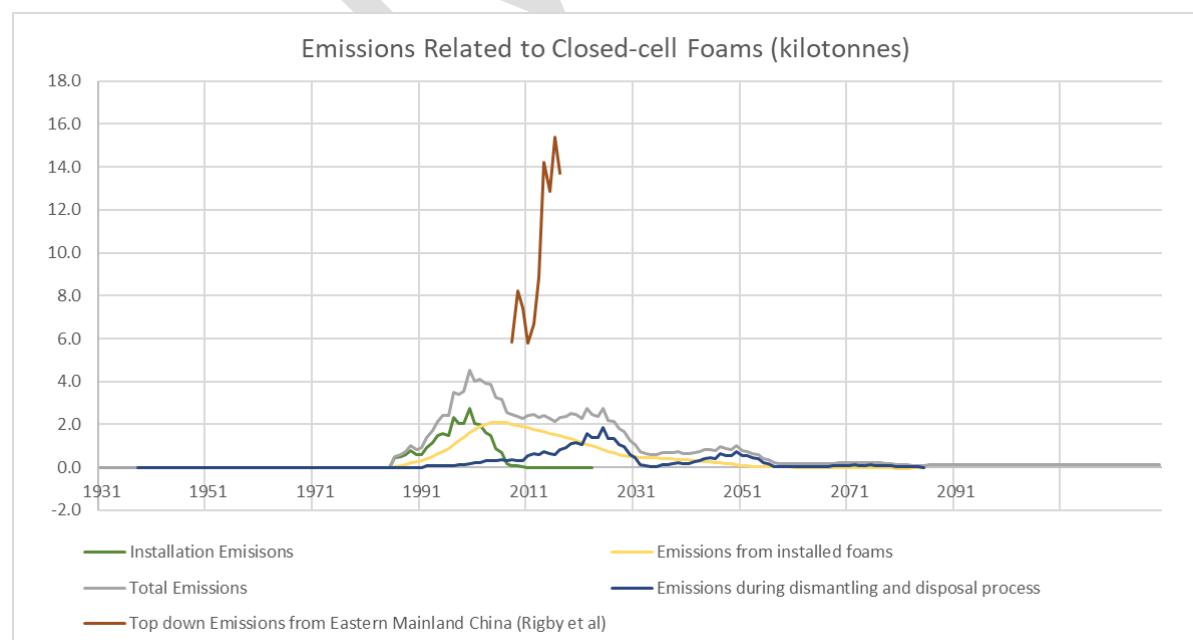
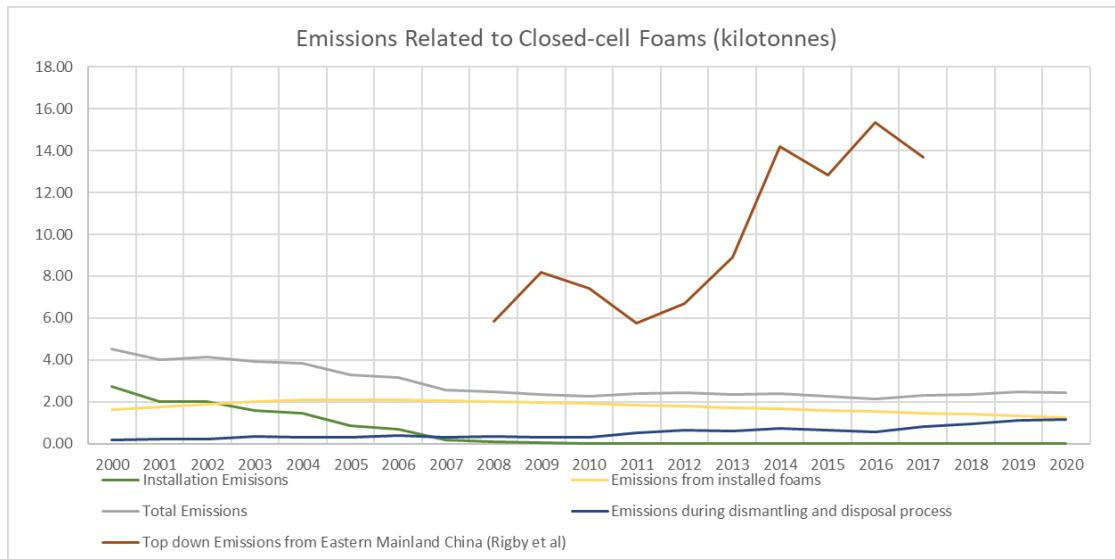


Figure 6.17 “Maximum” Northeast Asia emissions scenario combined with derived atmospheric emissions from eastern mainland China from Rigby *et al.*



For the high emissions case shown in the graph above, it was estimated that twice the quantity of foam produced in Northeast Asia was shipped to eastern mainland China (Rigby *et al.*¹⁹⁰), where it remained throughout its lifetime and was disposed of, emitting 50% of the CFC-11 at the end-of-life.¹⁹¹ Foam lifetimes were limited to a maximum of thirty four years.

The derived emissions from eastern mainland China dominated by Shandong and Hebei provinces (Rigby *et al.*¹⁹²) were added to the scenario depicted in the graph. This does not account for the fact that:

- Some foams and polyol systems produced in Northeast Asia were exported from the region rather than all shipped to eastern mainland China, so not all of the CFC-11 used to create closed-cell foams remained in eastern mainland China;
- Not all of the foam in Northeast Asia was shipped to eastern mainland China for to be dismantled;
- Not all foam is dismantled in a way that maximizes emissions. ;

¹⁹⁰ Ibid., Rigby, M. *et al.*, 2019.

¹⁹¹ China is an important supplier of foam products globally exporting nearly 13 million standard refrigerators in 2000 growing to more than 70 million units by 2010 according to Statista. The Task Force estimates that the refrigerators exported from 2000 through 2007 would require approximately 65 to 100 kilotonnes of blowing agent depending on the size of the appliance.

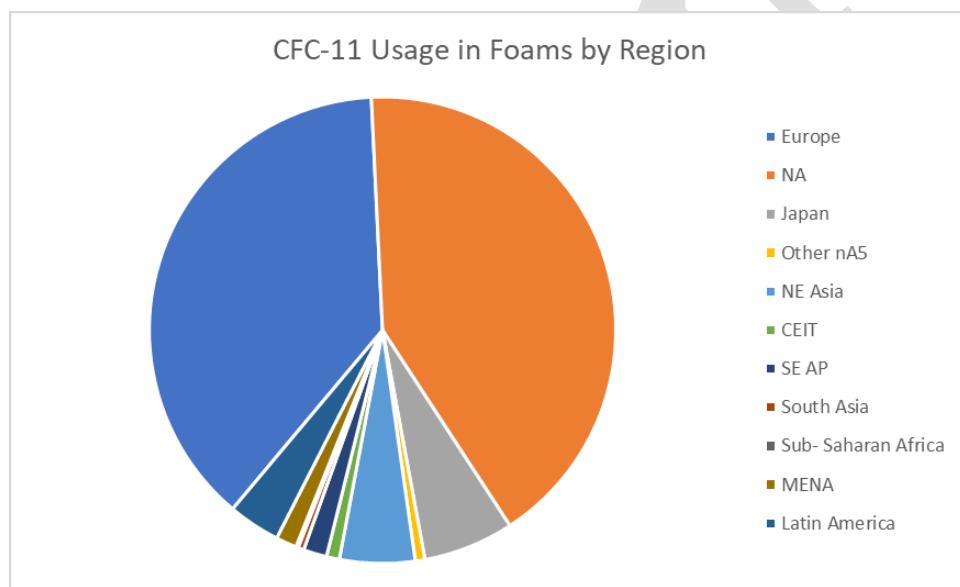
¹⁹² Ibid., Rigby, M. *et al.*, 2019.

- Not all foams produced in Northeast Asia have a lifetime less than or equal to thirty-four years;

As shown in the graphs above, the derived emissions from eastern mainland China in Rigby *et al.*¹⁹³ from 2008 through 2017 are just under 100 kilotonnes. Even if the lifetime of foams in northeastern China were shifted by 5 years, they are not sufficient to explain the derived emissions from eastern mainland China in Rigby *et al.* Expected emissions from CFC-11 foams produced in Northeast Asia, from the production in Northeast Asia reported to the Ozone Secretariat, seem to be insufficient to account for the derived emissions from the eastern mainland China in Rigby *et al.*

Finally, it should be noted that most of the closed-cell foam as of 2006 was produced in Europe and North America with smaller quantities produced in other regions. It is likely that most of the global emissions of CFC-11 would have occurred during foam manufacturing and installation and during the lifetime of products containing those foams within Europe and North America. The majority of the foams in these regions was historically landfilled. Destruction of foams is increasing in these regions and there are significant quantities of CFC-11 blown foams still in use in buildings.

Figure 6.18 Historic CFC-11 usage in closed-cell foam by region



6.12 Historic CFC-12 consumption, emissions and banks

CFC-12 has been used historically as a propellant in aerosol products, in the production of closed-cell foam (XPS) and in the R/AC sector, primarily in mobile air-conditioning (AC). As with CFC-11, production of CFC-12 was voluntarily reported by various companies to AFEAS. AFEAS covered most of the producing non-Article 5 parties. The AFEAS data was gradually rendered irrelevant during the late-1980s when production started shifting to Article

¹⁹³ Ibid., Rigby, M. *et al.*, 2019.

5 parties. Once the Montreal Protocol entered into force in 1989, parties started reporting CFC-12 production data to UNEP under Article 7.

6.12.1 CFC-12 uses

6.12.1.1 Refrigeration and air-conditioning

For the use of CFC-12, the R/AC sectors normally considered are domestic, commercial, transport and industrial refrigeration, some stationary AC and mobile AC. In the case of stationary air conditioning, HCFC-22 has always been used in this sub-sector to a very large percentage (greater than 90% in all AC equipment); however, in the “early” years some CFC-12 was also used in this sub-sector (even in centrifugal – medium pressure – chillers). Since the 1950s, most of the AC units used HCFC-22 (from small to large units); however, large units also used CFC-12.

It is likely that the CFC-12 centrifugal chillers have ceased operation, although this is not entirely clear. The only reference available is a 2004 TEAP report¹⁹⁴ where there was an accounting of CFC-12 chillers in non-Article 5 and Article 5 parties, although this inventory lacked comprehensive data (developing country data were only available from one source).¹⁹⁵ With the high CFC-12 leakage of these units, and the need for servicing, it is difficult to imagine that any significant number of units have been kept in operation. However, while it is difficult to check, the Task Force believes that there currently still is a very small number of CFC-12 chillers in operation, probably only in some Article 5 parties.

A major CFC-12 consumer in the early 1990s was mobile AC, where the decision was already taken in 1993 to completely convert to HFC-134a in non-Article 5 parties. Article 5 parties continued to use CFC-12 in mobile AC until 2005, however some parties ended the use of CFC-12 in new vehicles earlier (2001 in Brazil, 2002 in China and in India).¹⁹⁶

6.12.1.2 Aerosols

Another major use of CFC-12 was as a pressurized liquid in aerosols. CFC-11 worked very well in combination with CFC-12 to obtain variations in propellant pressure in a wide variety of applications such as personal care products, as well as household and industrial products (insecticides, spray paints, lubricants). CFC use in aerosols was banned in the US in 1978 and several European countries followed suit, voluntarily phasing-down the use of CFCs in aerosol products from 1978 onwards.¹⁹⁷

6.12.1.3 Closed-cell foams

CFC-12 has been also widely used in the production of closed-cell foam since the early 1960s. Its primary use has been as a foam blowing agent in non-urethane foams and

¹⁹⁴ Technology and Economic Assessment Panel, 2004. *Chiller Task Force Report*, UNEP Nairobi, 2004, ISBN: 92-807-2461-4.

¹⁹⁵ ICF, 2003. *International Chiller Sector Energy Efficiency and CFC Phaseout*, Draft Revised Report Prepared for the World Bank, ICF International Inc., Washington, May 2003.

¹⁹⁶ Clodic, D. (Paristech, Armines), 2006. *Global inventories of the worldwide fleets of refrigerating and airconditioning equipment in order to determine refrigerant emissions. The 1990 to 2006 updating*. Armines, Paris, 2006

¹⁹⁷ Hammitt, James K., et al. “Product Uses and Market Trends for Potential Ozone-Depleting Substances, 1985-2000.” RAND Corporation, 31 Dec. 1985.

specifically extruded polystyrene (XPS) foam board and sheet. XPS board is used for thermal insulation in the construction industry. CFC-12 is a low thermal conductivity gas and therefore when trapped in the pores of the low density, closed-cell polymeric matrix it provides great insulation properties. XPS sheet foam is generally expanded using hydrocarbons and, in some cases, using CFC-12. Sheet foam is used mainly as packaging material. Sheet foam producers using CFC-12 started converting to HCFC-142b in the 1980s.¹⁹⁸

Lastly, CFC-12 was used in small quantities in several miscellaneous applications such as a diluent in hospital and industrial sterilants, in fire warning devices, boat horns, dehumidifiers and pressurized blowers. The contribution of these uses in the overall banks and emissions is insignificant.

6.12.2 CFC-12 emissions and banks

As with CFC-11, the Task Force developed a “bottom-up” model for CFC-12. The model calculates expected annual emissions based on reported production and assumptions regarding use patterns and equipment leakage rates. The “bottom-up” emissions were then compared to the derived global atmospheric emissions.

Several assumptions were made, and a range of emissions is produced based on what is believed to be a reasonable range of assumptions. The variables considered in each scenario include those relating to CFC-12 production, installation and disposal at end-of-life.¹⁹⁹

- Production: emissions from chemical plants during production, packaging, transport, and disposal of cylinders;
- Installation: *de minimis* emissions when charging air-conditioners, emissions from the foaming process for XPS foam, and discharge of a propellant in aerosol products or as a solvent; and,
- Banks: emissions during a product’s lifetime as well as at the end-of-life when the product or equipment is landfilled, recycled or destroyed. CFC-12 from banks leak gradually to the atmosphere or leak abruptly when refrigerant is vented or partially released when foam is shredded or crushed.²⁰⁰

The market is divided into four sectors: hermetic refrigeration (vending machines, household refrigeration), non-hermetic refrigeration (mobile AC, cold storage, retail food refrigeration), closed-cell foams (XPS board) and emissive uses (aerosols). Production and installation emission rates and bank emission rates were estimated based on industry knowledge and literature.

¹⁹⁸ Shankland, Ian R. “CFC Alternatives for Thermal Insulation Foams.” International Journal of Refrigeration, vol. 13, no. 2, Mar. 1990, pp. 113–121., doi:10.1016/0140-7007(90)90010-t.

¹⁹⁹ Emissions rates throughout the product lifecycle were considered.

²⁰⁰ As noted earlier, blowing agents are integrated into the polyol foam matrix and do not solely reside in the foam cell. As a result, crushing or shredding foams results in only a partial release of the blowing agent regardless of the particle size of the shredded foam.

Emissions during production of CFC-12 vary significantly from plant to plant and are dependent on operating conditions, system setup and handling. The estimates used in this report were informed by, among others, the current draft refinements to the IPCC guidelines for National GHG Inventories for the default emission rate for fluorocarbon production plant.²⁰¹

Global production of CFC-12 ceased in 2010, therefore any continuing emissions should be originating from existing banks. This model attempts to build a bottom-up profile of the banks and the related emissions over the years.

The production data used for this model originate from the AFEAS database, where companies voluntarily reported production volumes since 1931. The AFEAS database covered Argentina, Australia, Brazil, Canada, the European Union, Japan, Mexico, the Republic of South Africa, the US and Venezuela. However, it did not include production data for China, India, Korea and Russia.²⁰² As a result, once production started shifting from non-Article 5 to Article 5 parties in the mid-1980s, the AFEAS database was no longer relevant. Following the signing of the Montreal Protocol, parties started reporting their production of CFC-11 to UNEP in 1989.²⁰³ The model uses the production data reported to UNEP from 1989 onwards.

Table 6.4 List of assumptions used in the low, medium and high emissions scenarios for CFC-12

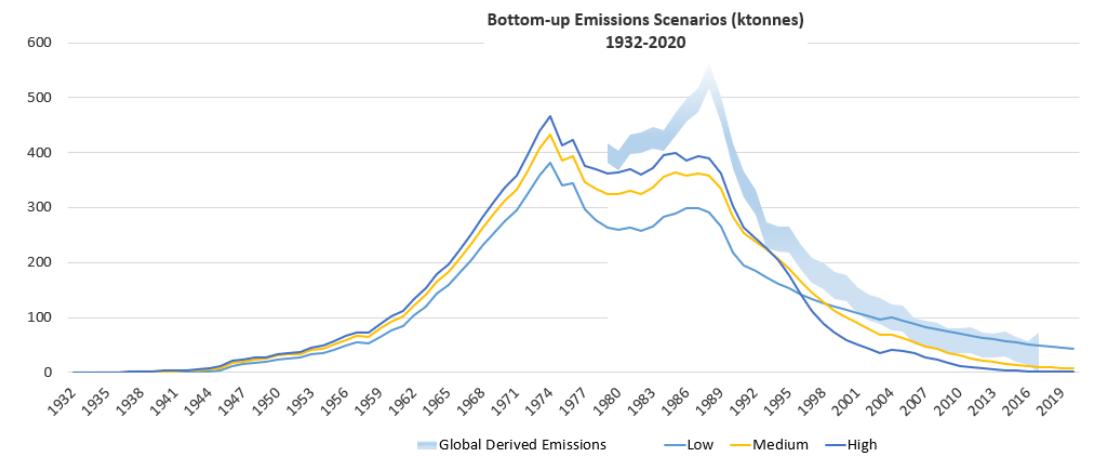
List of Assumptions			
	Low	Medium	High
Production Emissions	1%	4%	7%
Refrigeration Hermetic: Installation Emissions	1.5%	5%	10%
Refrigeration Non-hermetic: Installation Emissions	2%	5%	10%
Closed-cell Foam: Installation Emissions	25%	30%	55%
Emissive Uses: Installation Emissions	86%	93%	98%
Refrigeration Hermetic: Annual Leakage	2.0%	5%	10%
Refrigeration Non-hermetic: Annual Leakage	5%	15%	30%
Closed-cell Foam: Annual Leakage	30%	45%	55%
Emissive uses: Annual Leakage	98%	98%	98%
Sectoral Breakdown, 2003 onwards (%hermetic/non-hermetic/foams/emissive)	3/76//0/21		

²⁰¹ 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3: Chemical Industry Emissions (Advanced Copy).

²⁰² McCulloch, Archie, et al. "Releases of Refrigerant Gases (CFC-12, HCFC-22 and HFC-134a) to the Atmosphere." Atmospheric Environment, Pergamon, 11 Feb. 2003.

²⁰³ Unlike AFEAS, the data reported to UNEP does not include sectoral breakdown of different uses and thus assumptions are made as to what the market split looks like.

Figure 6.19 Bottom-up emissions of CFC-12 under the scenarios described in Table 6.4



The bottom-up model as it currently stands does not provide an accurate representation of the historic use and expected emissions of CFC-12 and cannot describe the atmospherically derived emissions. Cognisant of the need to develop a more accurate bottom-up model for CFC-12, the Task Force does not use this model to estimate potential current releases of CFC-12 into the atmosphere.

7 Additional considerations

Chapter 7, “Additional Considerations”, was included in the preliminary report to identify topics for which the Task Force considered further work might be needed in determining the likelihood of potential sources of CFC-11 emissions and associated controlled substances. The final report has addressed these additional considerations and therefore this chapter is deleted.

7.1 Areas for further assessment

The following are areas identified by the Task Force where further work may be needed to determine the likelihood of potential sources of CFC-11 emissions and associated controlled substances:

- The use of CFC-11 for polyurethane foams and polyol systems for PU rigid foams as it is technically feasible and more economically advantageous than reverting to use CFC-11 in flexible foams.
- CFC-11 could be used in flexible foams to reduce volatile organic compound (VOC) emissions or toxicity concerns related to dichloromethane. VOC emissions are limited in some parties, and some parties regulate the use of dichloromethane in flexible foams.
- Further validation of CFC-11 emissions rates from installed foams and from landfills would be helpful; although, unless the emissions rates vary significantly, it is unlikely to impact the main conclusions made here. However, this information may be helpful in determining the magnitude of this issue and the potential timing for emissions release from banks.
- Further analysis of CFC-11 banks, by geographic location and by market sector, may be helpful to better understand background emissions levels from banks to help to better understand the magnitude of unexpected emissions. Note that any scenario where significant CFC-11 is used in rigid foams would require significant CFC-11 production and would increase the foam banks.
- Details of recent enforcement and/or prosecutions undertaken relating to CFC-11 production and/or associated usage would be helpful in further determining the scope of the issue and the resulting banks.

7.2 Additional information

The Task Force would benefit from additional information on a range of topics and from a variety of potential sources. In particular, the Task Force is interested in receiving further information about:

- CTC production quantities and the uses to which CTC was put, by quantity, including export amounts and locations;
- CTC and HCFC-22 plant capacities;
- Validation of ODS plant shutdowns and dismantling;

- Quantities of CFC 11 inventory in stockpiles at the cessation of production and the fate of inventory thereafter;
- Any evidence of illegal CFC 11 or CTC shipments;
- The capacities and production quantities for CFC 11/12 and CTC plants for parties where less is known about historic ODS production;
- CFC 11 emission sources related to equipment and foams recycling and destruction;
- Foam blowing agent emissions rates from foams that may be used for any purpose (i.e. to determine insulating capability or exposure from a public health perspective);
- Specific end-of-life practices especially for foams; and,
- Regulations impacting the use of dichloromethane.

Appendix 1: Article 5 party production sector phase-out agreements

Argentina

In 2002, at its 32nd meeting, the Executive Committee decided²⁰⁴ to approve the Agreement for the Argentina Production Sector, resulting in the total permanent closure and dismantling of all capacity for the production of CFCs by 2010. In 2007, the Executive Committee decided²⁰⁵ to approve the agreement for the accelerated phase-out of CFC-11 and CFC-12 production in Argentina by January 1, 2008. The terms of the accelerated agreement included independent verification “*that dismantling of CFC production lines is done appropriately by ensuring that the control and monitoring equipment are dismantled and rendered unusable for future ODS production, and are disposed of.*”

Table A1.1 Argentina Accelerated Production Sector Phase-out Schedule

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010
Maximum allowable production (metric tonnes)	3,015*	3,018*	3,016*	1,645*	1,645	686	0	0	0

* Verified production

To enforce against illegal production, Argentina agreed to monitor the production of CFC until 2010. As the implementing agency, the World Bank conducted independent verifications of the plant in 2008 and 2009 and confirmed sustained production closure.

China

A number of agreements related to China’s production sector were approved by the Executive Committee as early as 1999, and as recently as 2015. Some key decisions related to those agreements are highlighted below:

- In 1999, at its 27th meeting, the Executive Committee decided²⁰⁶ to approve the Agreement for the China Production Sector.
- In 2004, at its 44th meeting, the Executive Committee decided²⁰⁷ to approve the agreement for the accelerated phase-out plan for CFCs, CTC, and halon 1301 in China.
- In 2008, at its 56th meeting, the Executive Committee decided²⁰⁸ to continue monitoring activities and utilization of project balance beyond the end of the agreement.

²⁰⁴ UNEP/OzL.Pro/ExCom/38/70/Rev.1, Decision 38/74, para. 136.

²⁰⁵ UNEP/OzL.Pro/ExCom/53/67, Decision 53/33, para. 158.

²⁰⁶ UNEP/Oz.L.Pro/ExCom/27/48, Decision 27/82(a, b), para. 120 (a, b).

²⁰⁷ UNEP/Oz.L.Pro/ExCom/44/73, Decision 44/59, para. 247 (a, b).

²⁰⁸ UNEP/Oz.L.Pro/ExCom/56/64, Decision 56/13, para. 77.

- In 2009, at its 57th meeting, the Executive Committee decided to request the Government of China and the World Bank to include the review of licenses for the sale of CFCs in MDIs manufacturers in 2008 and 2009 as part of the verification report to be submitted to the Executive Committee in 2010.
- In 2013, at its 71st meeting, the Executive Committee decided to modify the CFC production sector agreement for China to allow the production for export of pharmaceutical-grade CFCs in 2014, with an annual review, for the purposes of meeting the 2014 essential use exemption for MDIs authorized by the parties in Decision XXV/2 for the other parties, provided that the exporting country had reporting and verification systems in place and that the reporting and verification systems collected and reported specified information. The World Bank, as the implementing agency for the CFC production phase-out plan for China, was to carry out the verification/audit.

The Agreement for the China production sector provided funding for the total permanent closure and dismantling of all capacity for the production of CFCs. The 1999 CFC reduction plan included verified dismantling and destruction of primary CFC production equipment from the following 14 CFC plants, which represented over 22,500 tonnes of capacity:

1. Shandong Dongyue Chemical Co. Ltd.: One CFC-12 line of 5,000 tonne capacity
2. Hunan Yiang Chlor-Alkali Chemical Co. Ltd. One CFC-12 line of 1,000 tonne capacity
3. Inner Mongolia Baotou Chemical Plant #1: One CFC-12 line of 700 tonne capacity
4. Jiangsu Jianhu Phosphine Fertilizer Plant: One CFC-12 line of 500 MT capacity
5. Sichuan Zigong Fujiang Chemical Plant: One CFC-11 line of 1,500 MT capacity and one CFC-12 line of 1000 MT capacity
6. Zhejiang Linhai Jianxin Chemical Plant: One CFC-12 line of 800 MT capacity
7. Guangdong Huiang Chemical Plant: One CFC-11 line of 1,000 MT capacity and one CFC-12 line of 3000 MT capacity
8. Henan Hebi Chemical Plant #1: One CFC-12 line of 1,500 MT capacity
9. Hebei Longwei Floro-Chem Plant #1: Two CFC-12 lines of 1080 total MT of capacity
10. Guizhou Wiling Chemical Plant: One CFC-12 line of 1,500 MT of capacity
11. Guangdong Zhaoqing Chemical Co. Ltd.: One CFC-12 line of 500 MT capacity
12. Shaanxi Shanzhou Chemical Plant: One CFC-12 line of 2,000 MT capacity
13. Shanghai Shuguang Chemical Plant: One CFC-12 line and one CFC-113 line of 1,000 MT total capacity
14. Zhejiang Linhai Shuiyang Chemical Plant: One CFC-12 line of 500 MT of capacity

The terms of the agreement included that China agreed “to ensure that HCFC production is not subsequently diverted to production of CFCs, [it agreed] to prepare annually a list of plants producing HCFCs and ensure that such production is not diverted to CFC production.” Independent technical audits by the Implementing Agency, and as directed by the Executive Committee, were to verify that agreed, annual CFC production levels and conditions related to plant dismantling, destruction or HCFC diversion were actually met. The World Bank was the implementing agency for the China production sector phase out. Below are tables showing the production sector phase-out agreement schedules and related enforcement and penalties activities under the agreement.

Advance

Table A1.2 Existing agreements between China and the Executive Committee on the phase-out of ODS production and consumption

(ODP tonnes)	Baseline	2004	2005	2006	2007	2008	2009	2010
CFCs								
CFCs Production	47,004	25,300	18,750	13,500	9,600	7,400	3,200	0 ¹
Annual national CFC-11 consumption limit in the agreement for the FSP)		13,100	10,400	7,700	4,130	3,800	300	0
Annual CFC-11 consumption limit in PU foam sector as per the agreement for the foam sector plan		11,666	9,646	7,164	3,821	3,553	102	0
CFC-11 consumption limit as per the agreement for the Tobacco sector		500	300	150	0			
CFC-113 consumption control targets as per the agreement for the solvent sector		1,100	500	0 ²				
CFCs consumption limits in I&C refrigeration sector for manufacturing				0 ³				
CFCs consumption limits in domestic refrigeration sector for manufacturing					0 ³			
Max allowable CFC-113 consumption as per the agreement for the PA sector	17.2	14	14	10.8	8.4	0		
Max allowable CFCs consumption in the servicing sector		5,083	4,572	3,790	2,997	2,317	1,786	1,181
CTC								
Max allowable sum of production and net imports as per the agreement for the PA/CTC sector plan for CTC ⁴	55,903.8	54,857	38,686	32,044	26,457	23,583	17,592	11,990
Max allowable consumption in the 25 PA applications as per the agreement for the PA/CTC sector plan (phase I)	3,825	5,049	493	493	493	493	493	220
CTC used as feedstock for CFC production as per the agreement for the PA/CTC sector plan (phase I)	N/A	39,306	28,446	21,276	15,129	11,662	5,042	0 ⁵
CTC consumption control targets in solvent sector as per the agreement for the Solvent Sector Plan		0 ²						

Halons								
Halon 1301 production	40,993	6,000	6,000	1,500	1,500	1,500	1,500	0
Halon 1301 consumption	/34,187	1,500	1,500	1,000	1,000	1,000	1,000	0
Halon 1211 production	(production/consumption)	5,970	5,970	0				
Halon 1211 consumption		5,670	5,670	0				

Source: UNEP/Ozl.Pro/ExCom/44/73, Decision 44/59, para. 247 (a,b)

Table A1.2 Notes:

1. Save for any CFC production that may be agreed by the parties to meet essential uses for China.
2. Save for any CFC-113 consumption or CTC solvent consumption that may be agreed by the parties to be essential for China after 2010.
3. Not including CFC consumption in servicing sector.
4. Including CTC production for CFC production and ODS feedstock applications but does not include CTC production for non-ODS feedstock.
5. Excluding CTC as CFC feedstock for CFC production for essential uses.

Table A1.3 Enforcement and penalties related to illegal production, trade and export in CFCs and halons for China

Year of effectiveness	Actions
January 2005	<ol style="list-style-type: none"> 1. China will continue on-site monitoring of the production of CFC until 2010 as currently implemented under the CFC production sector plan. 2. China will strengthen monitoring of the halon 1301 production and sales by quarterly on-site review of production and sales records until 2010.
December 2008	<ol style="list-style-type: none"> 1. Issuance of a new regulation by the State Council, for a penalty system which constitutes a significant penalty, e.g., confiscation of any sales value in any illegal ODS production activity and a penalty several times of its sales value
December 2009	<ol style="list-style-type: none"> 1. Update the Air Pollution Prevention and Control Law with the same level of financial penalties as in the regulatory system mentioned above with addition of prison terms for illegal ODS related activities.

India

In 2008, at its 56th meeting, the Executive Committee decided²⁰⁹ to approve the agreement on the accelerated phase-out of CFC production by 1 August 2008 in India, with the World Bank as the Implementing Agency. In 2015, at its 75th meeting, the Executive Committee approved the revised agreement to include UNDP as an additional Implementing Agency. The conditions of the agreement included that:

- a) India would produce no more than 690 MT of CFCs, primarily for the manufacturing of metered-dose inhalers (MDIs) up until 1 August 2008;
- b) India's CFC producers would sell no more than 825 MT of CFCs for MDI production in the years 2008 and 2009, comprising 690 MT of new production and 135 MT reprocessed from existing stock;
- c) India would export 1,228 MT of CFCs no later than 31st December 2009;
- d) India would not import any new virgin CFCs;
- e) any by-product non-pharmaceutical grade CFCs generated from the production under (a) are counted against the limit (in production under the agreement) and could be released to the market;
- f) this Agreement does not cover any CFC production that may be agreed by the parties to meet essential uses for India.

Table A1.4 India accelerated production sector phase-out schedule

Year	2008	2009	2010
Production targets (ODP tonnes)	690	0	0

The terms of the agreement included India agreeing “that within 18 months of any of its existing plants ceasing production of CFCs and HCFCs, that [India] will take action to ensure that such plants are incapable of producing [ODS] in the future, and that key ODS production components are dismantled and destroyed.” India also agreed “to ensure that any HCFC production is not subsequently diverted to production of CFCs, [it agreed] to prepare annually a list of plants producing HCFCs and ensure that such production is not diverted to CFC production.” Independent technical audits by the Implementing Agency and as directed by the Executive Committee were to verify that agreed, annual CFC production levels and conditions related to plant dismantling, destruction or HCFC diversion were actually met.

²⁰⁹ UNEP/Oz.L.Pro/56/64, Decision 56/63, para. 226.

Korea, DPR

In 2002, at its 36th meeting, the Executive Committee decided²¹⁰ to approve the agreement for the phase-out in ODS production sector in the Democratic People's Republic of Korea. Funding provided was for the total permanent closure and dismantling of all capacity for the production of CFC-11, CFC-12, CFC-113), carbon tetrachloride, 1,1,1-trichloroethane (methyl chloroform). The agreed level of funding was paid out according to Table A1.5 below for the schedule of closing the facilities upon the submission and the Executive Committee approval of the independent verification report on the permanent closure of the ODS production and dismantling of the production facilities.

Table A1.5 Korea, DPR, schedule of closures

Processing facility	Time of closure	Time of verification	Time of disbursement
CFC-113	May 2001	August 2001*	Upon satisfactory verification of permanent closure of the CFC-113 production and dismantling of the production facility.
Methyl chloroform	May 2001	August 2001*	Upon satisfactory verification of permanent closure of the methyl chloroform production and dismantling of the production facility.
CFC-11, CFC-12	2003	2003	Upon satisfactory verification of permanent closure of the CFC-11/12 production and dismantling of the production facility.
CTC	2005	2005	Upon satisfactory verification of permanent closure of the CTC production and dismantling of the production facility.

* Verified by Wakim Consulting during the technical audit and to be confirmed by UNIDO.

UNIDO, as the implementing agency, was responsible for verifying to the Executive Committee the appropriate “dismantling of all ODS production lines..[and] ensuring that the reactor, distillation towers, receiver tanks for finished products, and control and monitoring equipment [were] dismantled and rendered unusable for future ODS production, and...disposed of.”

Mexico

In 2003, at its 40th meeting, the Executive Committee decided²¹¹ to approve the Agreement for the Mexican CFC Production Sector resulting in the total permanent closure of all capacity for the production of CFCs by 2010. In 2007, the Executive Committee decided²¹² to approve the agreement for the accelerated phase-out of CFCs in Mexico by 2006.

²¹⁰ UNEP/Oz.L.Pro/36/36, Decision 36/55, para. 116(c).

²¹¹ UNEP/OzL.Pro/ExCom/40/50, Decision 40/54, para. 107(h).

²¹² UNEP/OzL.Pro/ExCom/53/67, Decision 53/33, para. 158.

Table A1.6 Mexico Accelerated Production Sector Phase-out Schedule

Year	2003	2004	2005	2006	2007	2008	2009	2010	Total
Maximum allowable production (metric tonnes)*	12,355	12,355	6,739	6,739	2,808	2,808	2,808	0**	
Maximum production levels agreed (metric tonnes)			22,000***		0	0	0	0	22,000

(*) Including 10% of its baseline production for meeting the basic domestic needs of other Article 5 parties.

(**) Save for any CFC production that may be agreed by the parties to meet essential uses for Mexico.

(***) Total maximum production for the years 2003 to 2005. It is understood that Mexico may not exceed its allowable production limit during any one year.

Mexico agreed to ensure accurate monitoring of the phase-out and to allow for technical audits. [As the implementing agency, UNIDO conducted independent verification to the Executive Committee to ensure that the phase-out targets and associated activities had been met.]

Romania

In 2005, at its 47th meeting, the Executive Committee decided²¹³ to approve the agreement for the Romanian ODS production sector with funding for the phased reduction and closure of the entire ODS production capacity in Romania consisting of 19,800 ODP tonnes of CTC, 4,750 ODP tonnes of CFC, and 90 ODP tonnes of methyl bromide. Table XX provides the scheduled reduction of production in accordance with the maximum allowable production under the agreement.

Table A1.7 Romania Accelerated Production Sector Phase-out Schedule

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Max. annual allowable production of CFC (ODP tonnes)	0.0	0.0	0.0	0.0	0.0	0.0					
Max. annual allowable production of CTC for controlled uses* (ODP tonnes)	170.0	170.0	170.0	0.0	0.0	0.0					
Max. annual allowable production of methyl bromide (ODP tonnes)	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max. annual allowable production of TCA (ODP tonnes)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Uses exempted by a Decision of the parties to Montreal Protocol

²¹³ UNEP/OzL.Pro/ExCom/47/61, Decision 47/54, para. 209(a).

As the implementing agency, UNIDO was responsible for verification to the Executive Committee the ODS production sector phase-out according to the above schedule.

Venezuela

In 2004, at its 44th meeting, the Executive Committee decided²¹⁴ to approve the Agreement for the Venezuela CFC Production Sector with funding for the phased reduction and closure of the entire CFC production capacity in Venezuela. The scheduled reductions according to the maximum allowable production is in Table XX.

Table A1.8 Venezuela Production Sector Phase-out Schedule

Year	2004	2005	2006	2007	2008
Max. allowable production (metric tonnes)	4,400	2,913	2,913	0	0

As the implementing agency, the World Bank and the Government of the Bolivarian Republic of Venezuela implemented an audit for 2008 to confirm the sustained cessation of CFC production. [The World Bank continued verification of the production facility activities in 2009 with a report to the Executive Committee in 2010, ensuring the permanent closure of the CFC production capacity at the plant.]

Activities by the Executive Committee of the Multilateral Fund

Paragraph 6 of Decision XXX/3 states:

“To request the Secretariat, in consultation with the secretariat of the Multilateral Fund for the Implementation of the Montreal Protocol, to provide the parties with an overview outlining the procedures under the Protocol and the Fund with reference to controlled substances by which the parties review and ensure continuing compliance with Protocol obligations and with the terms of agreements under the Fund, including with regard to monitoring, reporting, and verification; to provide a report to the Open-ended Working Group at its forty-first meeting and a final report to the Thirty-First Meeting of the Parties;”

Given the above request by parties, the TF defers to the overview on procedures for compliance under the Protocol and with the terms of agreements under the Fund, which is currently being prepared by the Ozone Secretariat, in consultation with the Multilateral Fund Secretariat, for the 41st OEWG. Below is an update on recent, related activities by the Executive Committee of the Multilateral Fund.

Noting *inter alia* the concerns expressed by parties at the 40th Open-ended Working Group and 30th Meeting of the Parties on the issue of the unexpected increase in global emissions of CFC-11, and Decision XXX/3 by the 30th meeting of the parties, the Multilateral Fund Secretariat presented a Note²¹⁵ to the 82nd meeting of the Executive Committee in December 2018.

²¹⁴ UNEP/OzL.Pro/ExCom/44/73, Decision 44/59, para. 247(c).

²¹⁵ UNEP/OzL.Pro/ExCom/82/70, 17 November 2018.

The Note from the Secretariat included preliminary information on policies and procedures relating to monitoring, reporting and verification to ensure continuing compliance with the obligations of Article 5 parties with the Montreal Protocol and with their Agreements with the Executive Committee. The Note emphasized the following:

- a) The regulatory framework established by Article 5 parties under the Multilateral Fund;
- b) The relevance of the institutional strengthening projects through which funding has been provided to the national ozone units;
- c) The mandatory reporting on consumption and production of controlled substances by Article 5 parties, and the consistency of the data reported under country programme reports and Article 7 data;
- d) The monitoring and evaluation activities under the Multilateral Fund, with a list of those desk studies and field evaluations relevant to the request by the OEWG to the Fund Secretariat;
- e) The conditions in multi-year agreements that need to be met before releasing funding tranches, including: independent verification of compliance with the ODS reduction targets stipulated in the phase out Agreements; the monitoring of the activities included in the Agreements; the roles and responsibilities of the national institutions; the roles and responsibilities of the bilateral and implementing agencies; and the implications of non-compliance with the Agreements; and
- f) The role of the Compliance Assistance Programme in providing compliance assistance to Article 5 parties, and the tools, products and services that it has developed for customs and enforcement officers.

At its December 2018 meeting, the Executive Committee considered the Note of the Secretariat and tasked a contact group with making concrete recommendations regarding future steps. Related to Decision XXX/3, the group was instructed to provide specific guidance on how to revise the information to be provided to the Ozone Secretariat for the report to be submitted to the 41st OEWG pursuant to the decision, keeping in mind that the information was to be a factual account of existing procedures within the Multilateral Fund. Following the report by the contact group, the Executive Committee decided (ExCom Decision 82/86):

- a) To note document UNEP/OzL.Pro/ExCom/82/70 by the Secretariat on matters relevant to the Multilateral Fund pursuant to Executive Committee consideration at its 81st meeting of three issues relating to discussions that were due to be held at the 40th Meeting of the Open-Ended Working Group of Parties to the Montreal Protocol and the Thirtieth Meeting of the Parties to the Montreal Protocol:
 - i. Energy efficiency related to the cost guidelines for the phase-down of HFCs;
 - ii. Cost guidelines for the phase-down of HFCs in Article 5 parties;
 - iii. The increase in global emissions of CFC-11;
- b) To request the Secretariat to provide the Ozone Secretariat, with information as required and in a timely manner, to enable it to provide parties with an overview to

the 41st Open-Ended Working Group, outlining the procedures under the Protocol and the Multilateral Fund with reference to controlled substances by which the parties review and ensure continuing compliance with Protocol obligations and with the terms of Agreements under the Fund, including with regard to monitoring, reporting and verification, in line with paragraph 6 of decision XXX/3, based on the information contained in document UNEP/OzL.Pro/ExCom/82/70, and reiterating decision 81/72, whereby the Executive Committee had requested the Secretariat to provide relevant information, as necessary, to the Ozone Secretariat, in accordance with the guidelines, procedures, policies and decisions of the Multilateral Fund and the Montreal Protocol; and

- c) To request the Secretariat to develop a document for consideration by the Executive Committee at the 83rd meeting that would include an overview of current monitoring, reporting, verification and enforceable licensing and quota systems, including the requirements and practices of the systems for reporting back to the Executive Committee that had been developed with support from the Multilateral Fund.

Advance

Appendix 2: Production and availability of CTC

Availability of CTC²¹⁶

The Task Force considered whether CTC would be available in enough quantity to supply the CFC-11 production options under consideration. If CTC, with the other chloromethanes, were to be produced on the same site(s) as the CFC-11²¹⁷, it could be transported by internal pipeline to the CFC-11 fluorination plant. If there were no CTC available from on-site production, it would have to be either purchased from within the country of CFC-11 production, or imported, and transported to the CFC-11 production site(s). Strict regulations control the export and import of CTC regardless of quantity.

The quantity of CTC required for CFC-11 production depends on three factors:

- The CFC-11 output, which has been assumed to be in the range from small-scale (\leq 10,000 tonnes) to large-scale (\geq 50,000 tonnes per year up to 60,000 tonnes). The selected CFC-11 production output range allows for an analysis of possible process routes that could provide the CFC-11 annual production that might potentially be associated with the increased CFC-11 emissions;
- The quantity of co-produced CFC-12 - assumed to be in the range 0% to 30% of total CFC production (i.e., 70% CFC-11 30% CFC-12 by weight);
- The average efficiency of the process that converts CTC into CFC-11 or CFC-12 product, which can be assumed to be in the range 90-99% of the CTC fed to the plant; CTC efficiency includes emissions of CFC-11 and -12 that occur during the production process.

Figures A1.1 and A1.2 show co-produced CFC-12 and the CTC quantity required for the CFC-11 output, assuming 0%, 15%, and 30% CFC-12 as a co-product.

²¹⁶ While the Appendix remains correct, additional new information can also be found in Chapter 2 of the final report.

²¹⁷ In some countries, the majority of CTC produced from chloromethanes can be transported and consumed internally on site, e.g., in 2017, 68% of CTC produced from chloromethanes was consumed on site in China.

Figure A1.1 Co-produced CFC-12 quantity for CFC-11 output

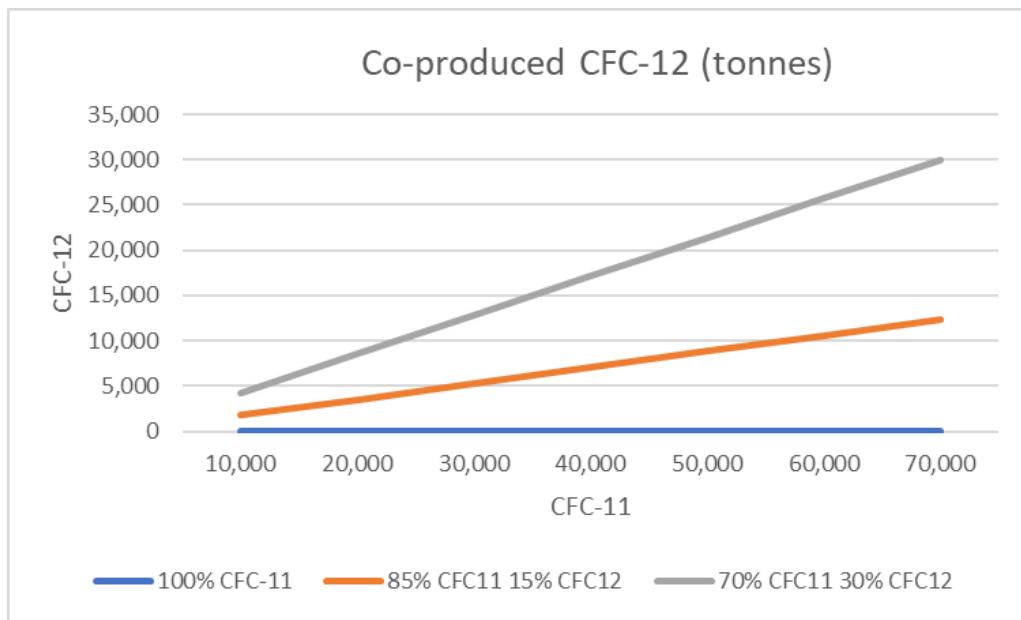
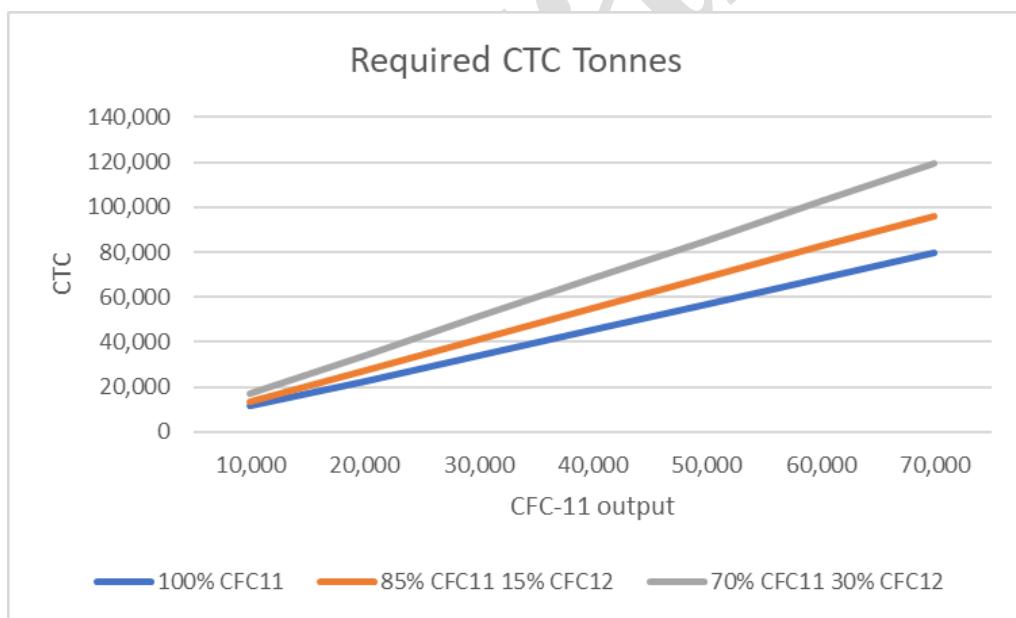


Figure A1.2 CTC quantity required for CFC-11 output



From Figures A1.1 and A1.2, it is clear that the general magnitude of CTC required is similar irrespective of the CFC-12 co-production. For example, for 10,000 tonnes CFC-11 the CTC quantity is in the range 11,400 to 17,000 tonnes and for 60,000 tonnes CFC-11, 68,000 to

100,000 tonnes CTC would be required. The higher ratios of CFC-12 also have a considerable climate burden, since its GWP is 10,900, whilst that of CFC-11 is 4,750.²¹⁸

CTC emissions from CFC-11 production

The emissions of CTC are expected to be relatively small. The MTOC 2018 Assessment Report stated that estimates of emissions from feedstock use of CTC throughout the world varied according to the scale of the processes and were 0.3 percent for perchloroethylene and HFC production, rising to 4.8 percent of the quantity used to make the pesticide intermediate DVAC. The largest volumes of feedstock use are likely to be at the least emissive end of the scale because large capacity plants have the most investment and are better able to control emission levels.

For small-scale production of CFC-11 (10,000 tonnes) in rebuilt plants with poor operation emissions of CTC could be 5% resulting in about 700 tonnes of CTC emissions. For production of 50,000 tonnes of CFC-11 on well- operated HCFC-22 plants emissions could be 0.3% resulting in about 200 tonnes of CTC emissions.

Global emissions of CTC are about 50,000 tonnes per year.²¹⁹ Therefore, the use of CTC as precursor to CFC-11/12 would have almost no impact on emissions

CTC production

At the peak of CFC-11/12 production, CTC production volumes were greater than 1 million tonnes annually. Two routes are used to make CTC, as outlined below.

The chlorination of chlorinated C₁-C₃ chlorinated waste streams

This is performed in what became known as PCE/CTC plants.²²⁰ Such plants would consume large waste streams such as those arriving from EDC/vinyl chloride units, 1,2-dichloropropane from chlorhydrin-based propylene oxide and epichlorohydrin, and importantly, the “crude” CTC arising from chloromethanes plants, which alone would be unsuitable for fluorocarbons. The process requires high temperature chlorination of these streams

The output of the plants is a combination of pure streams of PCE and CTC. They were designed to be CTC plants for CFC production; but PCE as the co-product was useful as a dry-cleaning and metal cleaning solvent, and it became a fluorocarbon intermediate when CFC-113 was introduced to the market. The initial plants could produce up to 95% CTC (5% PCE) but were flexible enough, by changing process conditions, to make 70% PCE (30% CTC). As PCE became more valuable, and CTC was losing its key outlet of CFCs, the balance of product on these plants swung to 80:20 or even 90:10 PCE: CTC, and in early 2000s when open CTC use as process solvent was being phased out, producers had to make

²¹⁸ IPCC Fifth Assessment Report, 2014 (AR5).

²¹⁹ SPARC, 2016. *SPARC Report on the Mystery of Carbon Tetrachloride*. Q. Liang, P.A. Newman, S. Reimann (Eds.), SPARC Report No. 7, WCRP-13/2016. Available at: www.sparc-climate.org/publications/sparc-reports/sparc-report-no7.

²²⁰ Perchloroethylene, tetrachloroethylene.

the choice: exit the market, or invest perhaps \$10-20 million to convert the output to 100% PCE (0% CTC). Inevitably, many foresaw no future in the business and closed down.

The following box outlines the PCE/CTC production process.

PCE/CTC PLANT RATIOS

Importantly, chloromethane CTC readily introduces into PCE/CTC reactors. CTC acts as a reactive diluent and is used to control the reaction temperature. At about 600 °C, in vapour phase and by a series of substitution and cracking reactions, the most stable products are PCE and CTC. In the presence of an excess of chlorine, an equilibrium condition exists between carbon tetrachloride and perchloroethylene.



Recycling the less desired product to the reaction zone can therefore control the product distribution between CTC and PCE. By shifting the equilibrium towards PCE, by-product non-recyclable hexachloro-derivatives formation increases because of increased recycling, and overall capacity is reduced.

A global assessment has been made to consider if additional CTC could have been made available from a PCE/CTC plant, of which only five are operational.

Table A1.1 Regional CTC capacity from PCE/CTC plants

Region	Capacity (kilotonnes per annum)	Comment
Europe	<250	One plant with spare capacity
USA	<150	Limited spare capacity after current PCE/CTC commitments
China	0	Only one PCE/CTC plant: believed not operating
RoW	0	Russia, Brazil, Canada all closed
Total PCE/CTC	<400	Small spare capacity²²¹

Due to the nature of PCE/CTC plants, production of CTC would be made on demand rather than inevitably, as with chloromethanes plants.

The production of CTC on chloromethanes plants

The chloromethanes are:

- Methyl chloride (monochloromethane, CM1, MC)
- Methylene chloride (CM2, dichloromethane. DCM)

²²¹ Import/export regulations prohibit EU/US supply.

- Chloroform (trichloromethane, CM3, CFM)
- Carbon tetrachloride (CTC, tetrachloromethane, (rarely) perchloromethane)

The production of the higher chloromethanes (DCM, CFM, and CTC) carries the unavoidability of producing all of them. It is not possible to simply choose to make chloroform and nothing else, for example. In general, plants are able to produce a DCM: CFM range from a 40: 60 ratio to a 60:40 ratio, and sometimes squeeze to 70:30 of one or the other depending on the market situation. In China the ratio is currently close to 50: 50.

Methyl chloride is made by the reaction of anhydrous hydrochloric acid (AHCl) with methanol, and is largely used as a precursor for silicones, or as a precursor for the “higher chloromethanes”.

Methylene chloride (DCM), and the other two higher chloromethanes, are produced by the chlorination of methyl chloride. DCM is largely used as a solvent and is also used in foam blowing. The largest individual use is as a process solvent in pharmaceuticals and polycarbonate production. It is used in increasing quantities as a feedstock to produce HFC-32, replacing HCFC-22 in air-conditioning systems.

Chloroform (CFM) is almost all used as feedstock to HCFC-22, with possibly less than 1,000 tonnes in annual emissive use in pharmaceutical preparations.

CTC is not allowed to be sold as a solvent anywhere, with some minor derogations for some laboratory uses. A small quantity is still used as a process agent. Its use as a feedstock to CFCs decreased rapidly in line with CFC phase-out.

More recently it is being used in increasing quantities for production of the chlorinated propanes and butanes which are the precursors to HFC-245fa, HFC-236fa, and HFC-365mfc. It is also used in the larger scale HFO plants which use CTC as a feedstock in the preparation of specific chloropropenes *en route* to HFO-1234yf, HFO-1233zd, and HFO-1234ze There are two such plants currently operating, both in USA.

The synthetic pyrethroid (di-vinyl acid chloride) DVAC is manufactured using the reaction of CTC with acrylonitrile as the first stage of processing. In India, all CTC from chloromethanes is consumed by this process, and China now also has production of DVAC.

In China, important additional routes to use the unavoidable quantity of CTC are:

- The dehydrochlorination of CTC to either chloroform (for use in HCFC-22) or to methyl chloride, which is either used again for chloromethane production or used as the primary reactant with silicon metal for the production of a vast range of silicone derivatives.
- The high-temperature chlorination of CTC, in the presence of hydrocarbons such as methane, to produce perchloroethylene (PCE), useful as a general solvent or in the production of HFC-125.

In 2017, 83.5 kilotonnes (68%) of CTC in China was processed inside chloromethane factories by these routes. Much of the balance was used in the production of fluorocarbons.

Any excess CTC by-product from chloromethanes is unwanted (illegal), and efforts have been strenuous globally to achieve the minimum possible quantity, to at least avoid the cost of incineration. Figure A1.3²²² shows CTC destruction as reported by parties under Article 7.

Figure A1.3 Total CTC destruction reported by parties (tonnes)

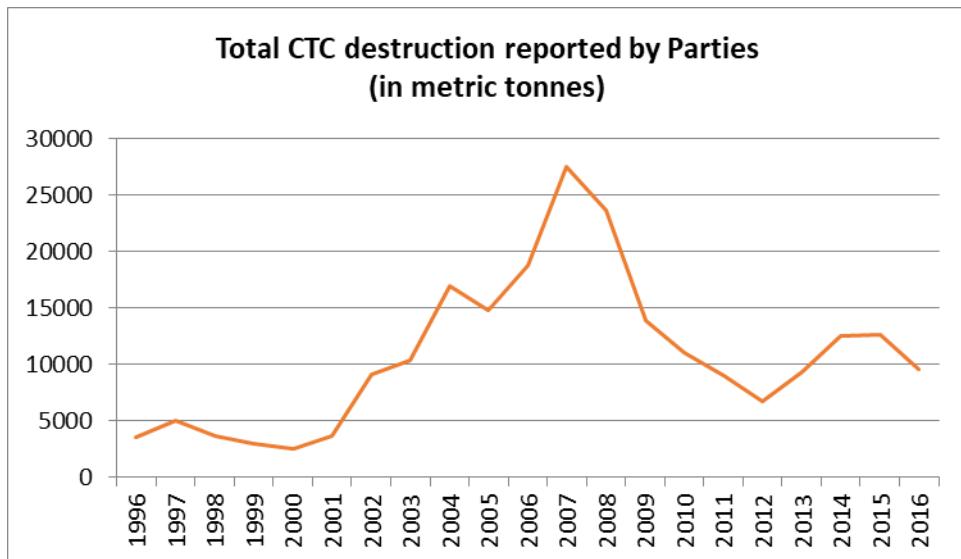


Figure A1.3 indicates the over-production of CTC as CFCs were phased out, and the subsequent jump in consumption as new fluorocarbons such as HFC-245fa began replacing older CFCs and HCFCs.

On a global basis, the amount of CTC as an unavoidable by-product is generally taken at 5% of the production of methylene chloride and chloroform. Recent figures from China show that 4.8% of CTC (123 kilotonnes) was produced in 2017. The quantity of CTC tends to be higher if the plant produces more chloroform than methylene chloride, which can be done by, for instance, recycle of the DCM to the chlorination zone.

Recycling of the DCM to the chlorination zone is not an infinite possibility, because each reaction will contribute more of the tars that “crude” CTC contains when it exits the plant. This must be distilled away and incinerated. The tars occur with over-chlorination, causing a build-up of heavier C₂ and C₄ species, including trichloroethylene, perchloroethylene, chlorinated ethanes, hexachloroethane, hexachlorobutadiene, and some uncharacterised species. Some of this can be avoided by using a lighter chlorination in a first standard vapour phase reactor, and transferring the mass to a cooler second photochlorination, favouring a high ratio of CFM and also CTC.

All CTC used in fluorination reactions must eliminate the tars or heavy ends, and this may be done by distillation or by sending the crude CTC to a PCE/CTC reactor.

Discussions with established CM producers indicate a consensus that a maximum of 20% of CTC on the higher chloromethanes could be achieved, at the expense of some chloroform

²²² This is a simplified version of Figure 10.2 from the MTOC 2018 Assessment Report.

capacity and without extensive plant changes. It would necessitate approved disposal methods for such tars. This report takes a cautious approach of 15% maximisation, or deliberate production, of CTC.

Most of the production of CTC is from chloromethanes plants, according to the previously mentioned SPARC (2016) report²²³, with about 80% of CTC production achieved via this route, and 20% via the PCE/CTC route. For the chloromethane route, the possible production of CTC can be estimated based on minimising CTC (5%) and maximising CTC (15%). This is shown in Table A1.2.

Table A1.2 Global higher chloromethanes capacity for 2016, and CTC production potential (kilotonnes per year)

Global Capacity	CTC Production Potential minimised 5%	CTC Production Potential maximised 15%
3,500	175	525

Table A1.3 shows the estimated region and country capacities for the higher chloromethanes, with the EU, the USA and China having the largest installed capacities.

Table A1.3 Regional higher chloromethanes capacities and availability of CTC in 2016 (kilotonnes per year)

Region	Chloromethanes Capacity	Maximum Potential Availability of CTC from CMs*
Europe	<500	10
Russia	<100	5
USA	<500	10
China	>2000	260
Japan	<250	10
India	<250	0
Other Asia	<100	10
TOTAL	±3500	305

*Note: The potential CTC availability is shown as the CTC maximised. The availability of CTC means the capacity available after local demand has been met.

²²³ SPARC, 2016. *SPARC Report on the Mystery of Carbon Tetrachloride*. Q. Liang, P.A. Newman, S. Reimann (Eds.), SPARC Report No. 7, WCRP-13/2016. Available at: www.sparc-climate.org/publications/sparc-reports/sparc-report-no7.

It should be noted with that, with the exception of China, the regional capacities for chloromethanes are similar to those in 2012, although 180 kilotonnes per year was taken down in Europe in early 2016. In 2018, China's chloromethanes capacity has increased by nearly 1,000 kilotonnes per year since 2012.²²⁴

According to reported Article 7 data, in 2016, CTC production for feedstock use was 221,578 metric tonnes. The production of CTC from chloromethanes plants, operating at the minimised 5% CTC level, together with CTC also available from PCE/CTC, broadly matches the feedstock demand. The available chloromethanes capacity and potential for increasing CTC production would allow for CTC availability additional to requirements that meet current demand. Average plant capacity globally is 120 kilotonnes per year, with a number of plants having capacities over 200 kilotonnes per year. No regulatory regimes allow extra production of CTC (by maximising CTC on chloromethanes plants), unless it is for approved feedstock use, otherwise unwanted or unavoidably manufactured CTC must be destroyed by approved technologies.

Export of CTC would require a valid export licence and a corresponding valid import licence, and there are no significant imports or exports of CTC in the period 2012-2016. Chinese chloromethane producers are legally obliged to demonstrate that CTC is being used as feedstock or is being incinerated. When the regulation was put in place, enterprises were obliged to reveal their CTC outlet, and these are published. Between the seventeen CM producers in China today, six of the largest, with plants that exceed 200 kilotonnes per year CM capacity, are fully integrated to a large array of fluorinated derivatives, including HCFC-22, HFC-32, HFC-125, HFC-134a, HFC-227ea, HFC-236fa, HFC-245fa, and HFC-365mfc, and usually produce their own AHF from fluorspar mining assets. In addition, some produce their further monomer derivatives such as TFE, hexafluoropropene (HFP) and vinylidene fluoride (VDF). One additional producer of 100 kilotonnes per year chloromethanes, with integration to HCFC-22, closed its chloromethanes plant in 2014, and has since closed both its fluorocarbon and chloromethanes factories.

Based on current chloromethane manufacturing globally, there is a minimum volume of 140 kilotonnes per year of CTC that is unavoidably manufactured, which must be used or destroyed. More can be made on chloromethanes plants quite readily, and, if required, PCE/CTC plant capacity is available in Europe.

²²⁴ Tecnon OrbiChem.

Appendix 3: Assessment of CFC-11 production routes

Appendix 3 presents a summary of the different CFC-11 production routes reviewed by the Task Force, along with some of the key technical and economic factors considered, to give an overall assessment of the likelihood of each production route as a contributor to the incremental increase in CFC-11 emissions.

Table A3.1 Possible CFC-11 production routes reviewed by the Task Force

Description of process route considered	Key raw materials	Relevant comments on route
Known commercialised CFC-11 production routes		
1. Carbon Tetrachloride (CTC) to CFC-11/12 on large-scale existing plant e.g., using spare capacity on HCFC-22 liquid phase plant. < 2 % direct CFC-11 emissions	CTC and Hydrogen Fluoride (HF) with liquid phase antimony chloride catalyst	Typically produces > 30 % CFC-12 but could be tuned to around 15 % CFC-12. A modern HCFC-22 plant that has been designed to minimise HFC-23 production may be able to make as little as 3-5 % CFC-12. Trained operators, suitable feedstock and product handling and logistics already available
2. Carbon Tetrachloride (CTC) to CFC-11/12 on large-scale existing plant e.g., using spare capacity on HFC-32 liquid phase plant. < 2 % direct CFC-11 emissions	CTC and Hydrogen Fluoride (HF) with liquid phase antimony chloride catalyst	Typically produces > 30 % CFC-12 but could be tuned to around 15 % CFC-12. If a modern plant designed to minimise over-fluorination is used then, it may be able to make as little as 3-5 % CFC-12. Trained operators, suitable feedstock and product handling and logistics already available
3. CTC to CFC-11/12 on large-scale existing plant e.g., using spare capacity on vapour phase plants. < 1 % direct CFC-11 emissions	CTC and HF with vapour phase catalyst	Typically produces higher fluorinated species (e.g., CFC-12, CFC-13 or PFC-14) Vapour phase plants have been used to produce such fluorocarbons as CFC-114/115, HFC-134a and HFC-125
4. CTC to CFC-11/12 on medium scale plant including reuse of existing ODS equipment. < 5 % direct CFC-11 emissions	CTC and HF with liquid phase antimony chloride catalyst	Typically produces > 30 % CFC-12 could be tuned to around 15 % CFC-12. Equipment could include redundant ODS reactors, etc., but this type of equipment was put out of service if decommissioning paid for under the MLF.
5. CTC to CFC-11/12 on small-scale plant using new equipment + process automation. < 5 % direct CFC-11 emissions	CTC and HF with liquid phase antimony chloride catalyst	Could probably be tuned to less than 10 % CFC-12 and more than 90 % CFC-11. If a modern plant designed to minimise over-fluorination is used then, it may be able to make as little as 3-5 % CFC-12. Trained operators, suitable feedstock and product handling and logistics may not be available
Uncommercialised CFC-11 production routes		
6. Chlorination of HCFC-21. < 5 % direct CFC-11 emissions	HCFC-21 and Chlorine	Would require separation of the HCFC-21 within the HCFC-22 production process and a separate process step to chlorinate to CFC-11. Reported HCFC-21 production for feedstock use is small
7. Chlorination of HCFC-31. < 5 % direct CFC-11 emissions	HCFC-31 and Chlorine	Would require separation of the HCFC-31 within the HFC-32 production process and a separate process step to chlorinate to CFC-11. No reported HCFC-31 production for feedstock use

Description of process route considered	Key raw materials	Relevant comments on route
8. Direct fluorination of Chloroform. < 5 % direct CFC-11 emissions	Chloroform and fluorine	Considered very unlikely to produce 10,000 tonnes/year of CFC-11. Use of elemental fluorine increases both costs and hazard. Material of construction requirements will also increase costs.
9. CTC to CFC-11/12 on large-scale existing plant with subsequent hydrogenation of CFC-12 to HCFC-22 and/or HFC-32. < 1 % direct CFC-11 emissions	CTC and HF. Followed by hydrogenation of the CFC-12 to HCFC-22 or HFC-32	Would require separation of the CFC-12 and a separate process to hydrogenate the CFC-12. This route is therefore unlikely to be cost competitive compared to large commercial plant producing HCFC-22 or HFC-32 directly
CFC-11 by-production as a result of commercialised production of other legitimate fluorocarbons		
10. CTC contamination of Chloroform (CFM) used in HCFC-22 reaction. Trivial direct CFC-11 emissions from plant	CFM (Including CTC) and HF with liquid phase antimony chloride catalyst	Actual observations suggest that it is unlikely to produce much CFC-11 by this route as CTC predominately reacts through to CFC-12.
11. CTC contamination of dichloromethane (DCM) used in HFC-32 reaction. Trivial direct CFC-11 emissions from plant	Dichloromethane (Including CTC) and HF with liquid phase antimony chloride catalyst	Actual observations suggest that it is unlikely to produce much CFC-11 by this route as CTC predominately reacts through to CFC-12.
12. Excess chlorine addition to HCFC-22 or HFC-32 plant reactor. Trivial direct CFC-11 emissions from plant	CFM or DCM, chlorine and HF with liquid phase antimony chloride catalyst	Actual observations suggest that it is unlikely to produce much CFC-11 by this route as CTC predominately reacts through to CFC-12. It would not be economically beneficial to deliberately over feed chlorine
Other theoretical CFC-11 production/by-production routes which are unlikely to be commercialised		
13. By product in preparing CF_3SSCF_3 (bis(trifluoromethyl) Disulphide)	trichloromethyl chlorothiane and Potassium fluoride	Considered very unlikely to produce 1,000s tonnes/year of CFC-11 using this route
14. Disproportionation reaction of CTC and HCFC-22 to CFC-11	CTC and HCFC-22	Considered very unlikely to produce 1,000s tonnes/year of CFC-11 using this route
15. CFC-11 elimination from 2,2 -dichloro-1,1,2- trifluoro – N - chloroethylamine	2,2 -dichloro-1,1,2- trifluoro – N - chloroethylamine	Considered very unlikely to produce 1,000s tonnes/year of CFC-11 using this route
16. CFC-11 elimination from chlorofluoroalkylsulfenyl	chlorofluoroalkylsulfenyl	Considered very unlikely to produce 1,000s tonnes/year of CFC-11 using this route
17. CFC production from fluorination of CTC using a fluorinating agent	CTC and fluorinating agents e.g., SiF_4 or XeF_2	Considered very unlikely to produce 1,000s tonnes/year of CFC-11 using this route
18. CFC-11 could be formed in many synthesis reactions, e.g., elimination or disproportion reactions	Various	Considered very unlikely to produce 1,000s tonnes/year of CFC-11 using this route

Description of process route considered	Key raw materials	Relevant comments on route
Other production routes that might cause an incremental increase in CFC-11 levels		
19. Volcanic activity	Naturally occurring carbon, chloride and fluoride	The estimated global volcanic flux of CFC-11 is less than 10 tonnes/year. ²²⁵
20. Fossil fuel burning	Coal, natural gas or crude glycerol containing chloride and fluoride	~ 12 ppb of CFC found in flue gas measurements. Considered very unlikely that 10,000 tonnes/year of CFC-11 would be produced using this route.
21. Trash burning - excludes CFC-11 bank already present in trash	Trash containing CFC-11	Unlikely as a production route as little fluoride present but could be a mechanism to increase the rate of release of existing CFC-11 foam bank

²²⁵ Schwandner, F.M., Seward, T.M., Gize, A.P., Hall, K. and Dietrich, V.J., Diffuse emission of organic trace gases from the flank and crater of a quiescent active volcano (Vulcano, Aeolian Islands, Italy), *J. Geophys. Res.-Atmos.*, 2004, **109**(D4).

Table A3.2 Summary of the technical and economic assessment of possible CFC-11 production routes, along with an indication of the overall likelihood of the various CFC-11 production routes being a significant contributory cause of the increase in CFC-11 emissions in the atmosphere

Description of process route	Technical Assessment factors					Economic Assessment factors			Overall likelihood of production route being a significant contributory cause of the incremental increase in CFC-11 considering all factors
	Chemistry route viability at commercial scale	Raw materials availability at > 10,000 tpa CFC-11 scale in period of interest ~ 2011-2018	Commercially utilised at > 10,000 of tpa of CFC-11 scale, including on multiple small plants	CFC-12 co-production (A comparable atmospheric trend has not been seen for CFC-12)	Potential for CFC-11 to be emitted e.g., directly from emissive uses e.g., foam blowing, aerosols or the production process	Variable cost of CFC-11 produced	Plant capital outlay	Domino business risk of CFC-11 production	
Known commercialised CFC-11 production routes									
1. CTC to CFC-11/12 on large-scale existing HCFC-22 liquid phase plant	Well established commercial route for CFC-11/12 production	Enough HF & CTC can be produced annually	Known historically at commercial scale	CFC-12 production would need to not be released e.g., by destruction captive or feedstock use	CFC-11 produced would be OK for foam blowing, solvent and aerosol use	Cost of CTC, HF and associated materials could be reasonable	Plant for HCFC-22 production already exists	Likely impact on linked HCFC-22 business if illegal CFC-11 production discovered. Production plant output monitored	Technically possible ²²⁶
2. CTC to CFC-11/12 on large-scale	Well established commercial	Enough HF & CTC can be	Known historically at	CFC-12 production would need	CFC-11 produced would be OK	Cost of CTC, HF and associated	Plant for HFC-32	Likely impact on linked HFC-	Possible to likely

²²⁶ Overall likelihood of production route being a significant cause has been revised in light of information received from the parties. CTC to CFC-11/12 on large-scale existing HCFC-22 liquid phase plant remains technically possible but is also considered unlikely due to compliance monitoring. Owing to the technical feasibility of this route, it remains as one of the most likely potential production routes.

Description of process route	Technical Assessment factors					Economic Assessment factors			Overall likelihood of production route being a significant contributory cause of the incremental increase in CFC-11 considering all factors
	Chemistry route viability at commercial scale	Raw materials availability at > 10,000 tpa CFC-11 scale in period of interest ~ 2011-2018	Commercially utilised at > 10,000 tpa of CFC-11 scale, including on multiple small plants	CFC-12 co-production (A comparable atmospheric trend has not been seen for CFC-12)	Potential for CFC-11 to be emitted e.g., directly from emissive uses e.g., foam blowing, aerosols or the production process	Variable cost of CFC-11 produced	Plant capital outlay	Domino business risk of CFC-11 production	
existing HFC-32 liquid phase plant	1 route for CFC-11/12 production	produced annually	commercial scale	to not be released e.g., by destruction captive or feedstock use	for foam blowing, solvent and aerosol use	materials could be reasonable	production already exists	32 business if illegal CFC-11 production discovered	
3. CTC to CFC-11/12 on large-scale existing vapour phase plant	Known route but not in common use for CFC-11 production	Enough HF & CTC can be produced annually	Known for other Fluorocarbons	CFC-12 production would need to not be released e.g., by destruction captive or feedstock use	CFC-11 produced would be OK for foam blowing, solvent and aerosol use	Cost of CTC, HF and associated materials could be reasonable	Possibly viable if suitable plant already exists	Likely impact on linked fluorination business if illegal CFC-11 production discovered	Unlikely
4. CTC to CFC-11/12 on medium scale plant including reuse existing equipment	Well established commercial route for CFC-11/12 production	Enough HF & CTC can be produced annually	Known historically at commercial scale	CFC-12 production would need to not be released e.g., by destruction captive or	CFC-11 produced would be OK for foam blowing, solvent and aerosol use	Cost of CTC, HF and associated materials could be reasonable	Large capital outlay for size of CFC-11 output	Possible impact on associated production if illegal CFC production discovered	Unlikely to highly unlikely

Description of process route	Technical Assessment factors					Economic Assessment factors			Overall likelihood of production route being a significant contributory cause of the incremental increase in CFC-11 considering all factors
	Chemistry route viability at commercial scale	Raw materials availability at > 10,000 tpa CFC-11 scale in period of interest ~ 2011-2018	Commercially utilised at > 10,000 of tpa of CFC-11 scale, including on multiple small plants	CFC-12 co-production (A comparable atmospheric trend has not been seen for CFC-12)	Potential for CFC-11 to be emitted e.g., directly from emissive uses e.g., foam blowing, aerosols or the production process	Variable cost of CFC-11 produced	Plant capital outlay	Domino business risk of CFC-11 production	
5. CTC to CFC-11/12 on small-scale plant using new equipment	Well established commercial route for CFC-11/12 production	Enough HF & CTC can be produced annually	Known historically at commercial scale	Small CFC-12 co-production	CFC-11 produced would be OK for foam blowing, solvent and aerosol use	Cost of CTC, HF and associated materials could be reasonable	Large capital outlay for size of CFC-11 output	Unlikely to have associated production	Unlikely to highly unlikely
6. CTC to CFC-11 micro scale plant using minimal equipment to make low grade CFC-11 for foam blowing use	Evidence of route being used for CFC-11 production	Enough HF & CTC can be produced annually	Plants of suitable scale have been reported in various media articles	Minimal CFC-12 co-production	Low quality CFC-11 produced could only be used in foam blowing	Cost of CTC, HF and minimal associated materials could be reasonable	Small capital outlay for small CFC-11 output	No associated production business	Possible to likely
Uncommercialised CFC-11 production routes									
7. Chlorination of HCFC-21	Known chemistry	Sufficient HCFC-21 capacity exists however HCFC-21 feedstock use is not reported in large enough quantities	Not known to be used commercially – considered an unlikely route	Minimal co-production of CFC-12	CFC-11 produced should be OK for foam blowing, solvent and aerosol use	Cost of HCFC-21, chlorine and associated materials could be reasonable	Large capital outlay for size of CFC-11 output	Likely impact on linked HCFC-22 business if illegal CFC-11 production discovered	Unlikely to highly unlikely

Description of process route	Technical Assessment factors					Economic Assessment factors			Overall likelihood of production route being a significant contributory cause of the incremental increase in CFC-11 considering all factors
	Chemistry route viability at commercial scale	Raw materials availability at > 10,000 tpa CFC-11 scale in period of interest ~ 2011-2018	Commercially utilised at > 10,000 of tpa of CFC-11 scale, including on multiple small plants	CFC-12 co-production (A comparable atmospheric trend has not been seen for CFC-12)	Potential for CFC-11 to be emitted e.g., directly from emissive uses e.g., foam blowing, aerosols or the production process	Variable cost of CFC-11 produced	Plant capital outlay	Domino business risk of CFC-11 production	
8. Chlorination of HCFC-31	Known chemistry	Sufficient HCFC-31 capacity exists however HCFC-31 feedstock use is not reported in large enough quantities	Not known to be used commercially – considered an unlikely route	Minimal co-production of CFC-12	CFC-11 produced should be OK for foam blowing, solvent and aerosol use	Cost of HCFC-31, chlorine and associated materials could be reasonable	Large capital outlay for size of CFC-11 output	Likely impact on linked HFC-32 business if illegal CFC-11 production discovered	Unlikely to highly unlikely
9. Direct fluorination of Chloroform	Known Chemistry	Unlikely for fluorine	Not known to be used commercially - considered a very unlikely route	Minimal co-production of CFC-12	CFC-11 produced should be OK for foam blowing, solvent and aerosol use	Total cost of raw materials likely to be extremely high	Large capital outlay for size of CFC-11 output	Possible impact on associated production if CFC-11 discovered	Highly unlikely
10. CTC to CFC-11/12 on large-scale existing plant with subsequent hydrogenation of CFC-12 to HCFC-22 and/or HFC-32	Known chemistry but would require significant catalyst development.	Enough hydrogen, HF & chloroform can be produced annually	Not known to be used commercially – considered an unlikely route	CFC-12 subsequently consumed as feedstock	CFC-11 produced should be OK for foam blowing, solvent and aerosol use	Total cost of raw materials likely to be high	Large capital cost for additional process steps	Likely impact on linked HCFC-22 or HFC-32 business if illegal CFC-11 production discovered	Unlikely to highly unlikely

Description of process route	Technical Assessment factors					Economic Assessment factors			Overall likelihood of production route being a significant contributory cause of the incremental increase in CFC-11 considering all factors
	Chemistry route viability at commercial scale	Raw materials availability at > 10,000 tpa CFC-11 scale in period of interest ~ 2011-2018	Commercially utilised at > 10,000 tpa of CFC-11 scale, including on multiple small plants	CFC-12 co-production (A comparable atmospheric trend has not been seen for CFC-12)	Potential for CFC-11 to be emitted e.g., directly from emissive uses e.g., foam blowing, aerosols or the production process	Variable cost of CFC-11 produced	Plant capital outlay	Domino business risk of CFC-11 production	
CFC-11 by-production as a result of commercialised production of other legitimate fluorocarbons									
11. CTC contamination of Chloroform used in HCFC-22 reaction	Usual reaction process shown to produce CFC-12 not CFC-11	Commercial chloroform is unlikely to contain enough of CTC	600 ktpa of HCFC-22 with 1 ppm of CFC-11 is only ~0.6 tpa of CFC-11	Usual reaction process shown to produce CFC-12 not CFC-11	Low potential for immediate CFC-11 release as HCFC-22 mainly used for feedstock and refrigerant applications	Low level impurity will be 'lost' in HCFC-22 plant economics	Negligible as impurity formation in existing plant	Large CFC-11 impurity level could make HCFC-22 less attractive for refrigerant or feedstock use	Highly unlikely
12. CTC contamination of dichloromethane used in HFC-32 reaction	Usual reaction process shown to produce CFC-12 not CFC-11	Dichloromethane is unlikely to contain enough CTC	500 ktpa of HFC-32 with 1 ppm of CFC-11 is only ~0.5 tpa of CFC-11	Usual reaction process shown to produce CFC-12 not CFC-11	Low potential for immediate CFC-11 release as Low as HFC-32 mainly used for refrigerant applications	Low level impurity will be 'lost' in HFC-32 plant economics	Negligible as impurity formation in existing plant	Large CFC-11 impurity level could make HFC-32 less attractive for refrigerant use	Highly unlikely

Description of process route	Technical Assessment factors					Economic Assessment factors			Overall likelihood of production route being a significant contributory cause of the incremental increase in CFC-11 considering all factors
	Chemistry route viability at commercial scale	Raw materials availability at > 10,000 tpa CFC-11 scale in period of interest ~ 2011-2018	Commercially utilised at > 10,000 tpa of CFC-11 scale, including on multiple small plants	CFC-12 co-production (A comparable atmospheric trend has not been seen for CFC-12)	Potential for CFC-11 to be emitted e.g., directly from emissive uses e.g., foam blowing, aerosols or the production process	Variable cost of CFC-11 produced	Plant capital outlay	Domino business risk of CFC-11 production	
13. Excess chlorine addition to HCFC-22 or HFC-32 plant liquid phase reactor	Usual reaction process shown to produce CFC-12 not CFC-11	Enough chlorine, HF & chloroform can be produced annually	600 ktpa of HCFC-22 with 1 ppm of CFC-11 is only ~0.6 tpa of CFC-11	Usual reaction process shown to produce CFC-12 not CFC-11	Low potential for immediate CFC-11 release as HCFC-22 mainly used for feedstock and refrigerant applications	High chlorine usage would be noticeable in production costs	Negligible as impurity formation in existing plant	Large CFC-11 impurity level could make HCFC-22 less attractive for refrigerant or feedstock use	Highly unlikely
Other theoretical CFC-11 production/by-production routes which are unlikely to be commercialised									
14. By product in preparing CF ₃ SSCF ₃ (bis(trifluoromethyl) Disulphide)	Highly unlikely as complex feedstock	Raw material production not known at this scale	Not known to be used commercially	Process route unlikely to produce CFC-12	CFC-11 maybe suitable for solvent, aerosol and foam blowing use	Cost of raw materials likely to be very high	Expected significant capital outlay for CFC-11 output	Likely Impact on business due to CFC-11 production	Highly unlikely
15. Disproportionation reaction of CTC and HCFC-22 to CFC-11	Known chemistry	Enough HCFC-22 & CTC produced annually	Not known to be used commercially	An undetermined quantity of CFC-12 would be produced	CFC-11 maybe suitable for solvent, aerosol and foam blowing use	Cost of raw materials could be reasonable	Large capital cost likely due to process complexity	Likely Impact on business due to CFC-11 production	Highly unlikely

Description of process route	Technical Assessment factors					Economic Assessment factors			Overall likelihood of production route being a significant contributory cause of the incremental increase in CFC-11 considering all factors
	Chemistry route viability at commercial scale	Raw materials availability at > 10,000 tpa CFC-11 scale in period of interest ~ 2011-2018	Commercially utilised at > 10,000 tpa of CFC-11 scale, including on multiple small plants	CFC-12 co-production (A comparable atmospheric trend has not been seen for CFC-12)	Potential for CFC-11 to be emitted e.g., directly from emissive uses e.g., foam blowing, aerosols or the production process	Variable cost of CFC-11 produced	Plant capital outlay	Domino business risk of CFC-11 production	
16. CFC-11 elimination from 2,2 -dichloro-1,1,2- trifluoro – N (Trifluoromethyl) - chloroethylamine	Highly unlikely as complex feedstock	Raw material production not known at this scale	Not known to be used commercially	Process route unlikely to produce CFC-12	CFC-11 maybe suitable for solvent, aerosol and foam blowing use	Cost of raw materials likely to be very high	Large capital cost due to process complexity	Likely Impact on business due to CFC-11 production	Highly unlikely
17. CFC-11 elimination from chlorofluoroalkylsulfenyl	Highly unlikely as complex feedstock	Raw material production not known at this scale	Not known to be used commercially	Process route unlikely to produce CFC-12	CFC-11 maybe suitable for solvent, aerosol and foam blowing use	Cost of raw materials likely to be very high	Large capital cost due to process complexity	Likely Impact on business due to CFC-11 production	Highly unlikely
18. CFC production from fluorination of CTC using a fluorinating agent	Known chemistry	Enough CTC and some of the fluorinating agents produced annually	Not known to be used commercially	Process route likely to produce CFC-12	CFC-11 maybe suitable for solvent, aerosol and foam blowing use	Cost of raw materials likely to be high	Large capital cost likely due to process complexity	Likely Impact on business due to CFC-11 production	Highly unlikely
19. CFC-11 formed in other synthesis reactions, such as disproportion	Highly unlikely as typically complex feedstock	Raw material production not known at this scale	Not known to be used commercially	Process route could produce CFC-12	CFC-11 maybe suitable for solvent, aerosol and	Cost of raw materials likely to be very high	Large capital cost due to process complexity	Likely Impact on business due to CFC-11 production	Highly unlikely

Description of process route	Technical Assessment factors					Economic Assessment factors			Overall likelihood of production route being a significant contributory cause of the incremental increase in CFC-11 considering all factors
	Chemistry route viability at commercial scale	Raw materials availability at > 10,000 tpa CFC-11 scale in period of interest ~ 2011-2018	Commercially utilised at > 10,000 tpa of CFC-11 scale, including on multiple small plants	CFC-12 co-production (A comparable atmospheric trend has not been seen for CFC-12)	Potential for CFC-11 to be emitted e.g., directly from emissive uses e.g., foam blowing, aerosols or the production process	Variable cost of CFC-11 produced	Plant capital outlay	Domino business risk of CFC-11 production	
reaction, elimination reaction					foam blowing use				
Other production routes that might cause an incremental increase in CFC-11 levels									
20. Volcanic activity	Known chemistry	Highly Unlikely to produce required increment in CFC-11		CFC-12 also measured in the fumarolic samples	CFC-11 emitted directly	Natural process	Natural process	Natural process	Highly unlikely
21. Fossil fuel burning	Known chemistry	Highly Unlikely to produce required increment in CFC-11		CFC-12 also measured in the combustion gases	CFC-11 emitted directly	'Lost' in power station economics	No additional equipment	Could force change in fuel source	Highly unlikely
22. Trash burning - excludes CFC-11 bank already present in trash	Known chemistry	Trash unlikely to contain enough fluoride			CFC-11 emitted directly	Negligible costs as burning of a waste	No additional equipment	Unlikely to affect other businesses	Highly unlikely to be a production route

Figure A3.1 Example of simplified CFC-11/12 large-scale liquid phase production plant, e.g., on existing HCFC-22 or HFC-32 plants

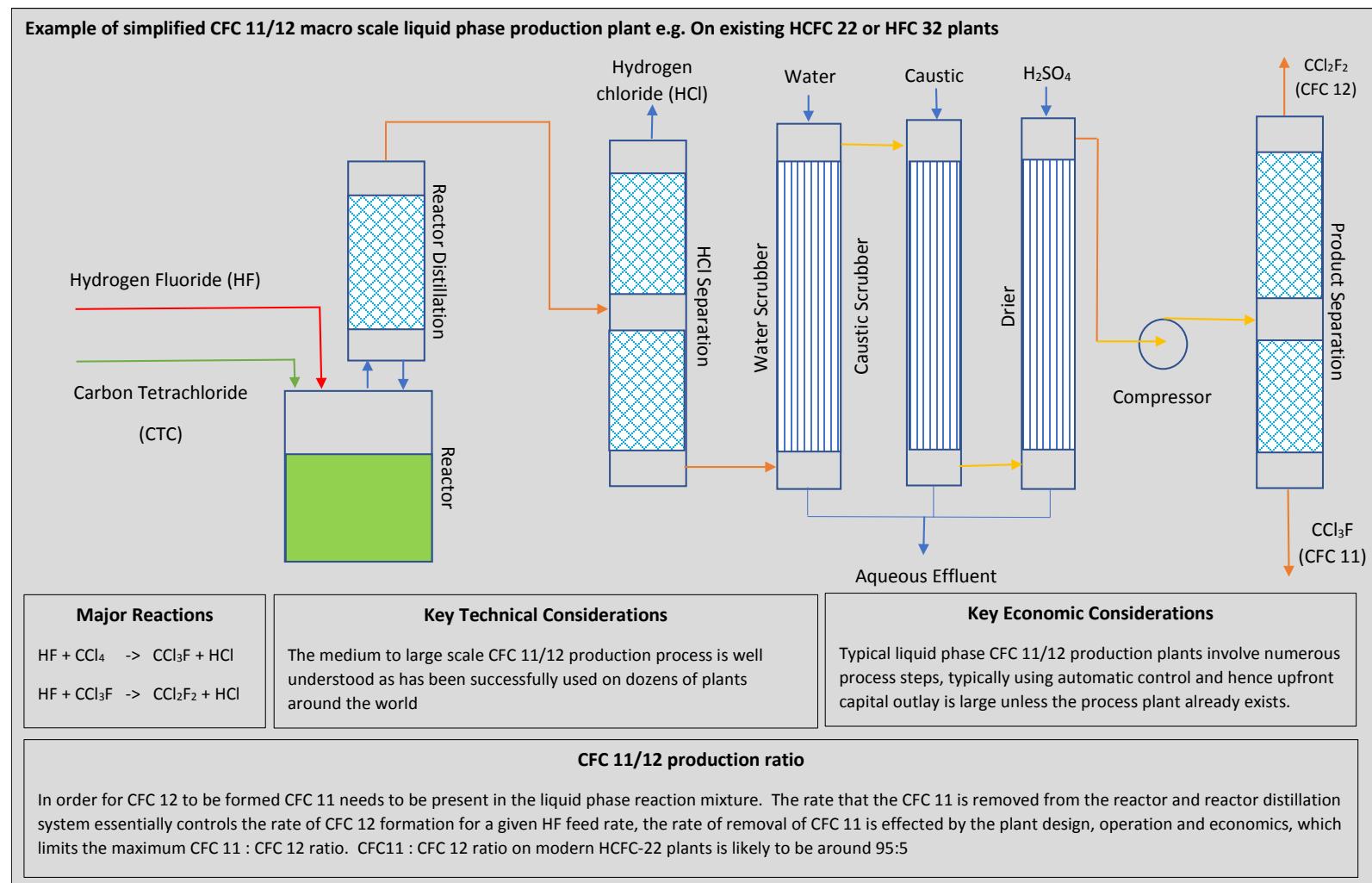
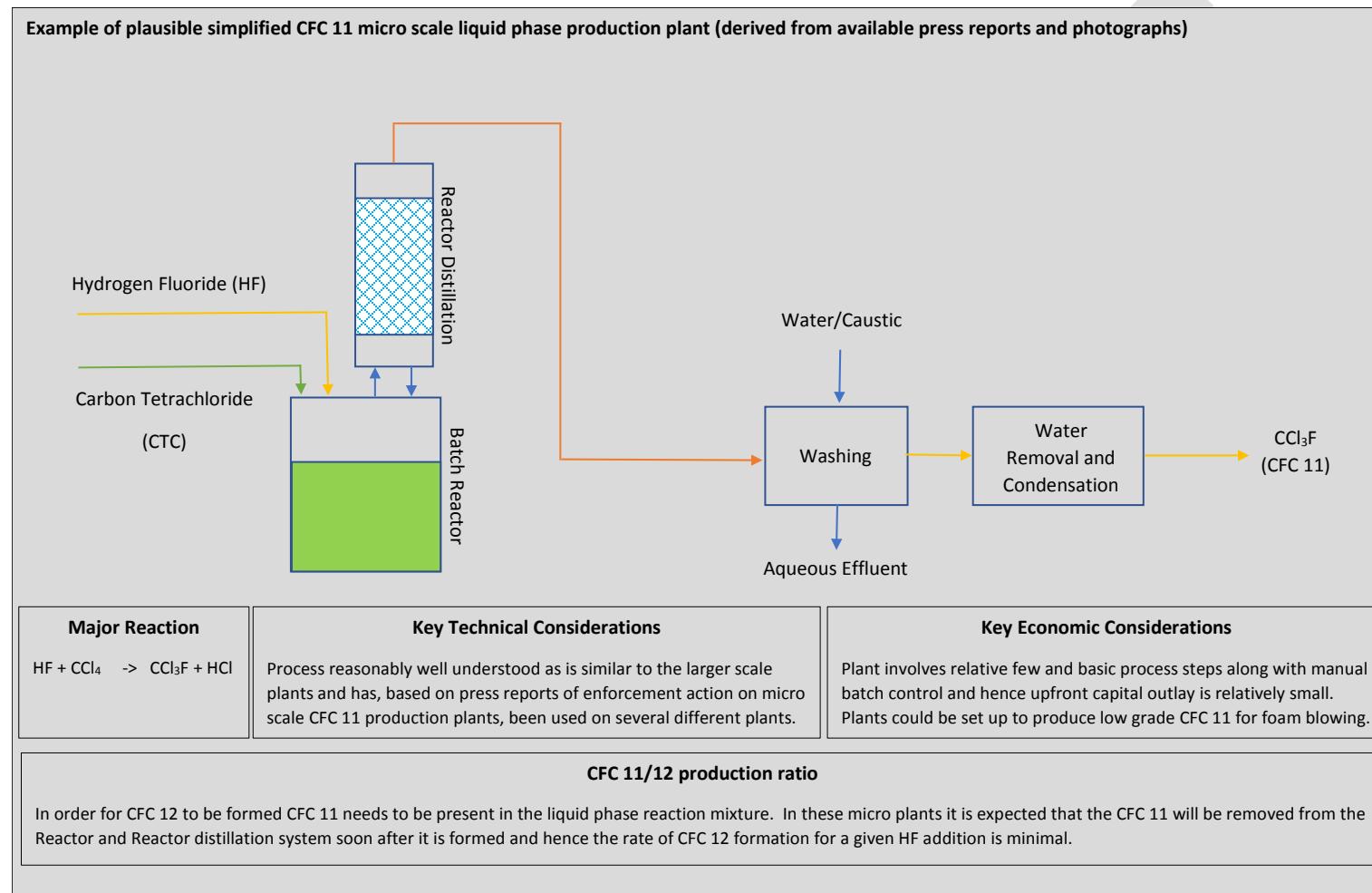


Figure A3.2 Example of plausible simplified CFC-11 micro-scale liquid phase production plant (derived from available press reports and photographs)



Appendix 4: Foams

Foam Market Background

According to the most recent Foams Technical Options Committee (FTOC) Assessment Report, total global production of polymeric foams continues to grow (3.9% per year), from an estimated 24 million tonnes in 2017 to 29 million tonnes by 2023. Production of foams used for insulation is expected to grow in line with global construction and continued development of refrigerated food processing, transportation and storage (cold chain). Based on average blowing agent percentages of 5.5% w/w for polyurethane and 6% w/w for XPS, the estimated demand of greater than 400,000 tonnes with a further 10,000 tonnes being consumed by other foam types. Further, it is estimated that blowing agent demand would grow to above 500,000 tonnes by 2023 based on the growth rates presented below.

Table A4.1 Estimated Global Polymer Foam Production 2017-2023 (tonnes)

Estimated Global Polymer Foam Production	2017	2023	CAGR ²²⁷ %
Polyurethane			
Rigid	5,352,900	6,831,808	5.00%
Flexible	7,447,700	9,100,541	4.09%
Total PU Foam Production	12,800,600	15,641,391	4.54%
Polystyrene			
EPS	8,523,575	9,890,000	3.02%
XPS	1,750,000	1,850,000	1.12%
Total Polystyrene Foam Production	10,273,575	11,740,000	2.70%
Phenolics, Polyolefins, EVA, ENR	1,613,000	2,150,000	5.92%
Total Estimated Polymeric Foams	24,687,175	29,531,391	3.87%

The market size of polymer foam is projected to grow at a Compound Annual Growth Rate of 3.9% from 2017 to 2023 in volume from just over 24 million tonnes to 29 million tonnes. The rate of growth is estimated to be slowing due to concerns about plastics in the environment and legislation regarding disposal of polymeric foams.²²⁸ Additional details related to polyurethane foams are provided in the table below.

²²⁷ Compound Annual Growth Rate

²²⁸ Market & Market Global Polymeric Foam Report 2017-2022.

**Table A4.2 Estimated Global Rigid and Flexible Polyurethane Foam Production
2017 (tonnes)²²⁹**

Global Rigid PU	EMEA	NAFTA	CHINA	APAC	LATAM	Global
Panels	990,000	610,000	120,000	90,000	50,000	1,860,000
Slabstock	7,000	22,000	60,000	6,000	1,000	96,000
Pipe Insulation	75,000	18,000	190,000	30,000	1,000	314,000
Spray Foam	115,000	320,000	80,000	50,000	5,000	570,000
Pour in place & OCF	45,000	30,000	260,000	15,000	5,000	355,000
Total Construction	1,232,000	1,000,000	710,000	191,000	62000	3,195,000
Total refrigeration	365,000	265,000	1,002,500	250,000	108,000	1,990,500
Others *	80,000	27,000	40,000	10,400	10,000	167,400
Total Rigid PU Foam	1,677,000	1,292,000	1,752,500	451400	180,000	5,352,900
Global Flexible PU						
Slabstock	1,700,500	835,000	2,080,000	600,000	420,000	5,635,500
Total Automotive	440,000	354,200	380,000	278,500	75,000	1,527,700
Non-Automotive	50,000	57,000	150,000	45,000	6,000	308,000
Total Moulded Foam	490,000	411,200	530,000	323,500	81,000	1,835,700
Total Flexible Foam	2,167,000	1,246,200	2,610,000	923,500	501,000	7,447,700
Total Foams	3,844,000	2,538,200	4,362,500	1,374,900	681,000	12,800,600
*Others rigid	packaging, moulded furniture, craft and hobby, miscellaneous					

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

Polyurethane, polystyrene and phenolic foams contribute substantially to the energy efficiency in buildings. Global construction is forecast to increase by 8 trillion USD by 2030, creating a global annual growth in demand for thermal insulation of 4-5%.²³⁰ The main drivers for thermal insulation are legislation and building standards to reduce heat loss. The EU and North America are currently leading proponents of building codes to reduce energy consumption in the construction industry. Emerging countries in Asia Pacific are fast growing markets for polymeric foams that offer thermal insulation.²³¹

In all buildings, the demand for thermal insulation has increased substantially as their role in reducing energy dependency and greenhouse gas emissions has been recognised. New or

²²⁹ Estimated Global PU Foam Production (ICF, Technical Experts, EPA, HPMPs.

²³⁰ Oxford Economics – Global Construction Trends to 2030.

²³¹ Ialconsultants.com – EU Thermal Insulation Markets 2018.

improved thermal insulation requirements have emerged across the Middle East and throughout India, China, South Africa and Latin America. Even though there has been some shift between fibre (mineral/slag wool) and foam market shares in China during the period, mostly as a result of fire concerns, the production of polyurethane chemicals had grown globally. Other competing foam insulation materials are expanded polystyrene (never used ozone depleting substances), extruded polystyrene (XPS), phenolic and polyethylene foams.

Current foam projections²³² predict on-going growth to 2019 of 4% per year. On this basis global blowing agent consumption will exceed 520,000 tonnes by 2020 unless there are further gains in blowing efficiency as technologies develop. Based on these trends, the historic, current and future demand for physical blowing agents is summarised in Figure 1 below:

Rigid polyurethane foam accounts for 30 % of the total estimated polymeric foam produced, the major drivers being regulation and energy efficiency, especially in construction and the cold chain.²³³

An estimated one third of global food production requires refrigeration. The Food and Agricultural Organization estimates that food production needs to increase globally by 70% to feed an additional 2.3 billion people by 2050, therefore refrigeration has an increasing role to play in food preservation.²³⁴

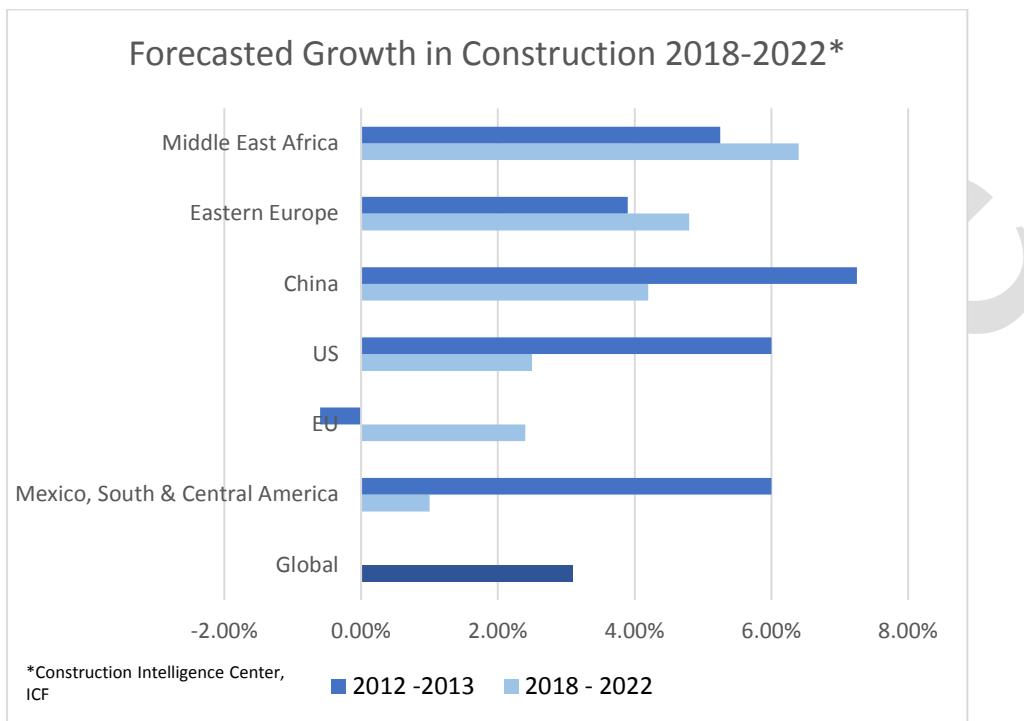
²³² RAPRA Report, *The Future of Polymer Foams: Market Forecasts*.

²³³ JRC Technical Report on the Competition Landscape of Thermal Insulation.

²³⁴ Cooling and refrigeration sector: the centre of the EU's energy system, Cory Alton May 2017, Published in Blog.

Trends in global foam use and impacts on blowing agent consumption including growth in Global Construction and Foam Use

Figure A4.1 Growth in construction investment, 2012/13 versus 2018-22 (%)²³⁵



*Source: Construction Intelligence Center and IHS Global Insight

Typically, Article 5 parties are focused primarily in new construction, while non-Article 5 parties are increasingly turning to renovation strategies. This is partly a recognition that, in most non-Article 5 parties, over 50% of the buildings that will be operational in 2050 have already been built and might be renovated only.

In both new construction and renovation, the demand for thermal insulation has increased substantially as the role of buildings in reducing energy dependency and greenhouse gas emissions has been recognised. New or improved thermal insulation requirements have emerged across the Middle East and throughout India, China, South Africa and Latin America. Investment in new construction in Article 5 parties is forecasted to continue to slow in China and Mexico and South and Central America. This is indicated in the Figure 1 above.

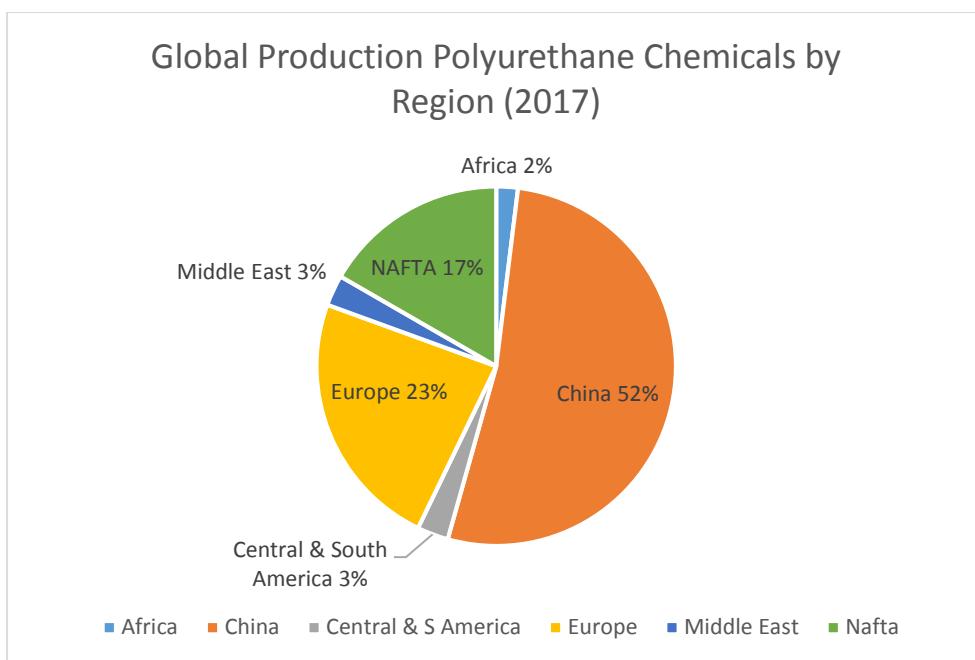
Although there has been some shifting between fibre and foam market shares in China during the period, partially as a result of a temporary moratorium²³⁶ on the installation of organic insulation materials (including polyurethane and polystyrene) arising from fire concerns, the production of polyurethane chemicals globally from 2012 to 2017 by 5 million tonnes to just 23 million tonnes. Figure A4.2 illustrates the geographic spread of this production and indicates the growing importance of Article 5 regions in both the production and consumption

²³⁵ Construction Intelligence Center, IHS Global Insight.

²³⁶ Rescinded in December 2012.

of polyurethane chemicals. Figure A4.3 shows the global polyurethane foam breakdown by type.

Figure A4.2 Regional distribution of PU chemical production in 2017 (~23 million tonnes)*



Impact on blowing agent consumption

Of the total polyurethane production, 12 million tonnes were estimated in 2017 to be consumed in the foam sector annually with approximately 5.8 million tonnes being in the rigid insulation foam sector, where it consumes blowing agents of interest to the Montreal Protocol. Other competing foam insulation materials are expanded polystyrene (never used ozone depleting substances), extruded polystyrene (XPS), phenolic and polyethylene foams. XPS foams are understood to consume approximately several million tonnes of polystyrene globally. Based on average blowing agent percentages of 5.5% w/w for polyurethane and 6% w/w²³⁷ for XPS, this leads to an estimated demand of greater than 400,000 tonnes between them with a further 10,000 tonnes being consumed by other foam types.

Projection of Business-as-Usual trends to 2020

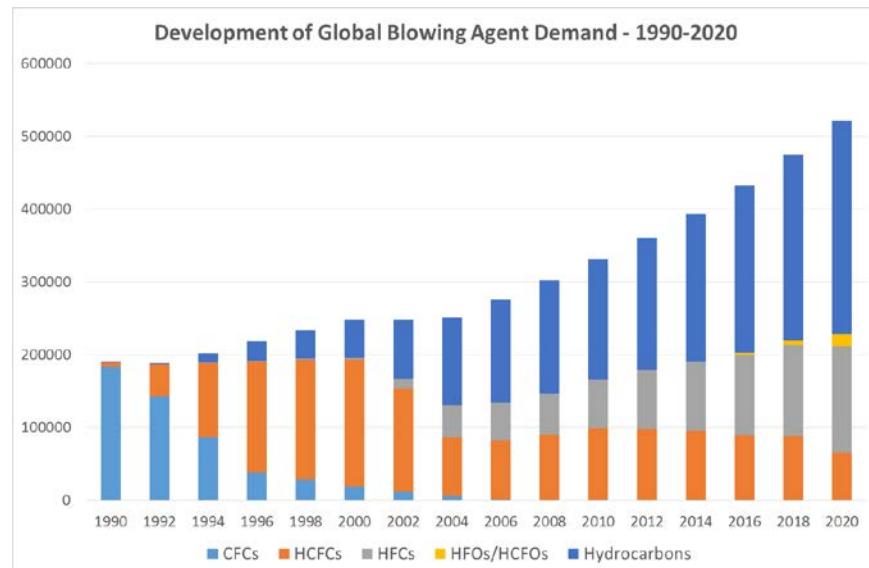
Current polymer foam projections²³⁸ suggest on-going growth to 2019 of an average of 4.8% per year, which is slightly more rapid than the 4.4% per year achieved in the period 2009-2014. On this basis global blowing agent consumption can expect to exceed 520,000 tonnes by 2020 unless there are further gains in blowing efficiency as technologies develop. Based

²³⁷ Weight percent as a global average would vary depending on the molecular weight of the foam blowing agent. One industry source notes that the weight percent of blowing agent in XPS foam could be as high as approximately 6 to 10 percent depending on the formulation while historically, FTOC has used a level of 4.5%.

²³⁸ RAPRA Report, *The Future of Polymer Foams: Market Forecasts to 2019*.

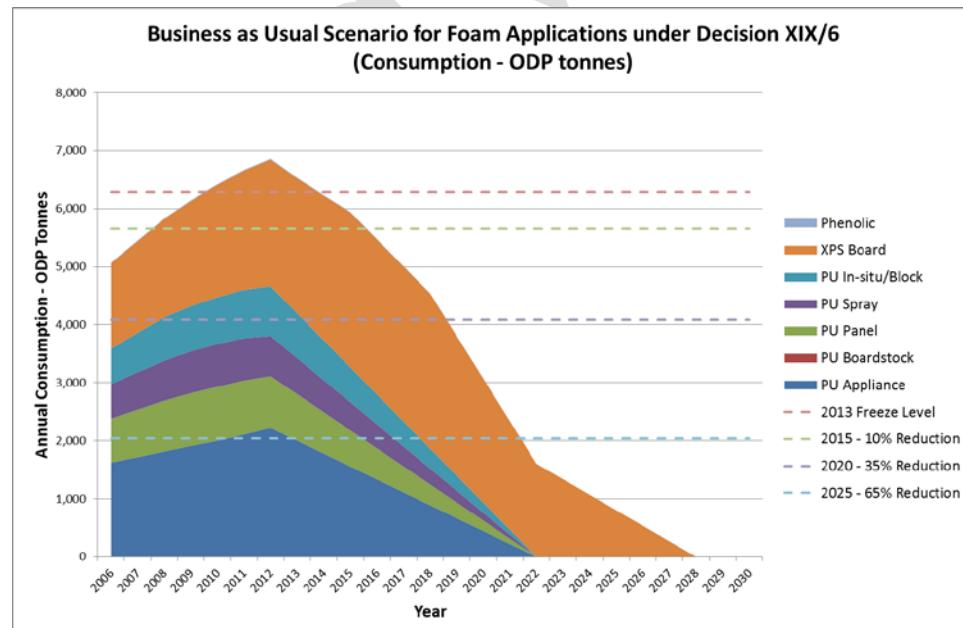
on trends in blowing agent selection monitored by the Foams Technical Options Committee, the historic, current and future demand for physical blowing agents is summarised in Figure A.4.3 and Figure A.4.4 below.

Figure A4.3 Growth in the use of physical blowing agents by type over the period from 1990 to 2020 (tonnes)



Source: FTOC

Figure A4.4 Evolution of consumption patterns for blowing agents in Article 5 parties with time (ODP tonnes)



Possible foam emissions scenarios

As noted in Chapter 6, the Task Force estimated closed-cell CFC-11 foam banks and developed emissions scenarios using the 2006 FTOC Assessment Report. The background data is noted in the tables below divided by the following geographic regions.

Latin America Caribbean (LAC): Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and The Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela.

Middle East/North Africa (MENA): Algeria, Bahrain, Egypt, Iran, Islamic Republic, Iran, Islamic Republic of Iraq, Israel, Jordan, Kuwait, Lebanon, Libyan Arab Jamahiriya, Mauritania, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, Turkey, United Arab Emirates, Yemen.

Sub-Saharan Africa (SSA): Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Congo, Democratic Republic of, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, United Republic of Togo, Uganda, Zambia, Zimbabwe.

South/Central Asia (SCA): Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka.

South-East Asia (SEA): Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Viet Nam.

North-East Asia (NEA): China (including Taiwan), Mongolia, North Korea, South Korea
Japan: Japan

Europe: Albania, Andorra, Austria, Bosnia and Herzegovina, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Holy See, Hungary, Latvia, Iceland, Ireland, Italy, Liechtenstein, Lithuania, Luxembourg, Macedonia, Malta, Moldova, Monaco, Netherlands, Norway, Poland, Portugal, Romania, San Marino, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, Yugoslavia

North America: Canada, USA

Australia, New Zealand & The Pacific (ANZP): Australia, Cook Islands, Fiji, Kiribati, Marshall Islands, Micronesia, Nauru, New Zealand, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu

Countries with Economies in Transition (CEIT): Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

Table A4.2 2006 FTOC Assessment Report breakdown of closed-cell foam by region and type of foam.

2006 UNEP Report	Europe	NA	Japan	Other nA5	NE Asia	CEIT	SE AP	South Asia	Sub-Saharan Africa	MENA	Latin America	Totals
Domestic Refrigeration	4.4%	2.7%	0.7%	0.2%	3.4%	0.7%	0.7%	0.3%	0.2%	1.2%	2.6%	17.1%
Commercial Refrig & other Appliances	0.7%	1.0%	0.1%	0.1%	0.4%	0.0%	0.0%	0.1%	0.0%	0.0%	0.2%	2.5%
Refrigerated Containers	0.3%	0.3%	0.1%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	1.4%
PU Boardstock	4.0%	10.8%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	15.2%
PU Continuous Panels	3.7%	0.8%	0.2%	0.0%	0.3%	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	5.3%
Discontinuous Panels	1.7%	1.1%	0.3%	0.0%	0.4%	0.0%	0.4%	0.1%	0.0%	0.2%	0.9%	5.1%
PU Spray Foam	0.8%	1.3%	1.0%	0.0%	0.7%	0.0%	0.4%	0.0%	0.0%	0.1%	0.5%	4.9%
PU Block & Pipe	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.1%	0.0%	0.7%
PU Pipe in Pipe	0.5%	0.1%	0.0%	0.0%	0.9%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	1.7%
PU Block	0.3%	0.1%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.1%	0.0%	0.7%
PU Block Foam Slab	0.4%	0.2%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.1%	0.0%	0.9%
% of Total Closed Cell Foam Blowing Agent	17.0%	18.6%	2.8%	0.3%	6.6%	1.1%	2.0%	0.5%	0.2%	1.8%	4.5%	55.5%
% Usage in closed cell foams	30.7%	33.5%	5.1%	0.5%	11.8%	2.0%	3.7%	0.9%	0.4%	3.3%	8.2%	100.0%

Table A4.3 Closed-cell foam emission rates from various sources by foam-type.

	FTOC: Installation Emissions Rates	IPCC Installation Emissions rates	Emissions from Finished Product	Emissions from Landfill
Domestic Refrigeration	10.00%	12.00%	0.50%	0.50%
Commercial Refrig & other Appliances	20.00%	25.00%	0.50%	0.50%
Refrigerated Containers	20.00%	25.00%	0.50%	0.50%
PU Boardstock	10.00%	6.00%	1.00%	1.00%
PU Continuous Panels	10.00%	5.00%	0.50%	0.50%
Discontinuous Panels	20.00%	12.00%	0.50%	0.50%
PU Spray Foam	25.00%	15.00%	1.50%	1.50%
PU Block & Pipe	45.00%	45.00%	75.00%	1.00%
PU Pipe in Pipe	10.00%	6.00%	25.00%	1.00%
PU Block	15.00%	15.00%	0.50%	0.50%
PU Block Foam Slab	20.00%	20.00%	1.00%	1.00%

The duration of the use stage of the product lifecycle was used based on available information. There are some regionally specific descriptions of the lifetime of buildings. Where very different data were available, multiple datasets were tested.

A4.3 Closed-cell foam lifetime

	NE Asia Foam Lifetime	FTOC Foam Lifetime	IPCC Foam Lifetime
Domestic Refrigeration	15	25	15
Commercial Refrig & other Appliances	15	15	15
Refrigerated Containers	7	7	7
PU Boardstock	25	25	25
PU Continuous Panels	20	75	50
Discontinuous Panels	20	75	50
PU Spray Foam	20	75	50
PU Block & Pipe	15	15	15
PU Pipe in Pipe	20	75	50
PU Block	20	75	50
PU Block Foam Slab	15	15	15

In Montzka *et al.*²³⁹, it was estimated that $13,000 \pm 5,000$ tonnes per year of CFC-11 were released into the atmosphere from 2014 to 2016. The observational evidence strongly suggested that at least some of the increased CFC-11 emissions was from eastern Asia after 2012. A number of possible emissions scenarios have been considered. As the majority of CFC-11 was historically used in foams, many of these scenarios are related to foams.

By 2010, CFC-11 consumption and production was phased out, therefore it seems that the most reasonable source of emissions would be from banks specifically from landfills, building demolition, or crushing or shredding CFC foams. However, the increase is in addition to background emissions levels from banks, which would require an additional significant source of emissions from the banks without abatement. The Task Force is not aware of any new releases or unusual destruction of banks without abatement.

At the end of life, foams are generally landfilled where CFC-11 would slowly emit over time (estimated at 0.5% per year) minus any amount that might be bioremediated (chemical breakdown of CFC-11 by bacteria) in the land fill. Most of the known bank of CFC-11 (estimated total: 1,420,000 tonnes in 2008) is believed to be in insulating foams (SROC 2005), particularly closed-cell polyurethane that was used in cladding panels for buildings and appliances like refrigerators. Foam bank emissions after destruction of buildings or appliances

²³⁹ Montzka, S. *et al.*, An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, 2018, **557**, 413–417. <https://doi.org/10.1038/s41586-018-0106-2>.

would likely occur over time from a landfill. For the observed trends to be related to the foams bank (leakage or disposal), there would need to have been an acceleration of the pre-existing trend after 2012.

During the foam dismantling and disposal process, there are generally additional emissions from foams. A sudden increase in emissions from foam banks would require sudden destruction of closed foam cells with no abatement of this release. For context, 13,000 tonnes per year emissions would have required the destruction and release of the foam blowing agent would be dependent on the remaining bank in the foams. If the foam contained 13% blowing agent and 50% of the blowing agent were released during the crushing or shredding process, 6.25 million cubic meters of foam.

CFC-11 emissions can result from recovery and recycling of the metal and plastic contents of insulating foam panels or refrigerators if the CFC-11 blowing agent is allowed to be released. However, approximately 40 to 60% of the blowing agent is integrated into the foam matrix and remains there even when the foam is crushed or shredded to small particle size density. As an indication of magnitude for comparison purposes, disposal of 26 million US large-sized refrigerators would be required to release 13,000 tonnes CFC-11, every year since 2013. 35 to 50 million smaller European or Asian refrigerators would be needed to release this much CFC-11. The largest market for domestic refrigerators in Asia is China with a reported estimated disposal rate of 15 million per year which is less than the needed number to result in these emissions.

CFC-11 was used as a blowing agent in rigid polyurethane foams has largely been replaced by HCFC-141b. According to testing and literature, approximately 3% to 10% of the blowing agent used to produce PU foams molds and appliances is emitted during the foaming process and approximately 20% of the blowing agent is released in the installation of spray foam. The FTOC also noted that 5-15% of the blowing agent is emitted during the production of polyol systems in drums for shipping to foaming companies.

Assuming an available supply of CFC-11 for spray, the most emissive type of rigid polyurethane foam application, that hypothetically could reach more than 50% of net values of emission (depending on level of blowing agent, reactivity of foam, elevation of site on processing, etc.). These scenarios would require production of large volumes of foams, including, in many cases, production of CFC-11 that would be greater than 50,000 tonnes to support CFC-11 emissions of 13,000 tonnes per year. Examples of simulations with CFC-11 polyurethane blown foams, rigids for domestic appliances and spray, as well as flexible foam that would result in 13,000 tonnes of emissions follow.

Preliminary examples of CFC-11 utilization in foam applications are described in the Table A4.4 and Table A4.5 which provides a high level, preliminary analysis based on formulations from the 1980s. These are not definitive and only meant to be examples.

Table A4.4²⁴⁰ Examples of CFC-11 formulations in PU rigid foams

Simulation of CFC-11 Release during foaming for typical polyurethane formulation (Examples)				
Components	PU Rigid- Insulation (*)		PU Rigid- Spray (#)	
	Example	Blown with	Example	Blown with
	CFC-11	CFC-11 Wt %	CFC-11	CFC-11 Wt %
Polyol	100,00	38,17	100,00	41,67
CFC-11	32,00	12,21	20,00	8,33
Isocyanate, PMDI	130,00	49,62	120,00	50,00
Isocyanate, TDI				
Isocyanate, Modified				
Total	262,00	100,00	240,00	100,00
CFC-11 Released during foaming , %	15	15	25	25
CFC-11 Total Released, pbw	4,80	1,83	5,00	2,08
Foam and CFC-11 required to release 13 Gg per application (only during foaming)				
Components	PU Rigid - Therm Insulation		PU Rigid - Spray	
	Pbw, MT	Wt %	Pbw, MT	Wt %
Polyol	270833	38,17	260000	41,67
Required CFC-11	86667	12,21	52000	8,33
Isocyanate, PMDI	352083	49,62	312000	50,00
Total Foam Required, MT	709583	100,00	624000	100,00
CFC-11 Released during foaming , %	15		25	
CFC-11 Total Released, pbw (MT)	13000		13000	

(*), (#)
Emission of Blowing Agent during foaming 15_25% Rentz et al
CHEMICALS PRODUCTS MANUFACT PROCESSING (Emission of Blowing agent during foaming 15_25%)
Modeling Emissions of High GWP Gases (EPA Vintaging model paper - Gowin emission 4-6%)
CFC-11 Emissions Review & Data A MacCulloch, P Ashford (10%)

²⁴⁰ Note that the tables A4.3, A4.4, A4.5, and A4.5 in the preliminary report have been replaced by new tables A4.3 and A4.5 to clarify them and to eliminate errors.

Table A4.5 shows examples of the use of CFC-11 in polyurethane foams for flexible slab used mainly in comfort applications. The other example is flexible molded foam used for comfort, automotive seats and office furniture.

Table A4.5 Examples of CFC-11 formulations in PU flexible foam area

Simulation of CFC-11 Release during foaming for typical polyurethane formulation (Examples)				
Components	PU Flexible - Slab (§)		PU Flexible - Molded (‡)	
	Example CFC-11 PBW	Blown with CFC-11 Wt %	Example CFC-11 PBW	Blown with CFC-11 Wt %
Polyol	100,00	65,36	100,00	90,91
CFC-11	3,00	1,96	10,00	9,09
Isocyanate, PMDI				
Isocyanate, TDI	50,00	32,68		
Isocyanate, Modified			75,00	68,18
Total	153,00	100,00	110,00	100,00
CFC-11 Released during foaming , %	98	98	95	95
CFC-11 Total Released, pbw	2,94	1,92	9,50	8,64
Foam and CFC-11 required to release 13 Gg per application (only during foaming)				
Components	PU Flexible - Slab		PU Flexible - Molded	
	Pbw, MT	Wt %	Pbw, MT	Wt %
Polyol	442177	65,36	136842	54,05
Required CFC-11	13265	1,96	13684	5,41
Isocyanate, PMDI				
Isocyanate, TDI	221088	32,68		
Isocyanate, Modified			102632	40,54
Total Foam Required, MT	676531	100,00	253158	59,46
CFC-11 Released during foaming , %	98		95	
CFC-11 Total Released, pbw MT	13000		13000	
(§), (‡)				
Example usage 3-10% CFC-11 Flexible Foam EP 0239704 A2				
Example usage 3-10% CFC-11 Flexible Molded Foam EP 0239704 B1				

Marketing of CFC-11

There are indications of CFC-11 marketing into foams use. The Foams Technical Options Committee was provided with a substantiated copy of an offer for sale of CFC-11 for 2200 USD/tonne through distribution, has seen offers for sale on internet websites, and has learned more through industry discussions.

This is sample of the advertisement on the website in May 2018. The link to the site did not work in July 2018. It is followed by an offer for sale to a distributor.

https://www.alibaba.com/trade/search?fsb=y&IndexArea=product_en&CatId=&SearchText=11+refrigerant&viewtype=

 	<p>China Suppliers For Sale Refrigerant R11 Gas</p> <p>US \$10.00-\$50.00 / Piece</p> <p>1150 Pieces (Min. Order)</p>	  <p>Nanjing JLHB Environmental Technolo... China (Mainland) </p> <p>Response Rate </p>
 	<p>R11 Refrigerant Gas Cold media</p> <p>US \$10.00-\$50.00 / Unit</p> <p>1150 Units (Min. Order)</p>	  <p>Guangzhou Zhigao Freeze Equipment ... China (Mainland) </p> <p>Transaction Level:  </p> <p>Response Rate</p>
  	<p>E-COOL refrigerant R11 gas</p> <p>US \$1.00-\$45.00 / Piece</p> <p>1140 Pieces (Min. Order)</p>	  <p>Lin'an E-COOL Zhi Leng She Bei Co., Ltd. China (Mainland) </p> <p>Transaction Level:  </p> <p>Response Rate</p>
	<p>Refrigerant Gas R11</p> <p>100 Pieces (Min. Order)</p>	 <p>AL WALEED REFRIGERANT GAS INDUSTRY L.L.C United Arab Emirates</p>

From May of 2018, note minimum order quantity of 15.504 tonnes.



99.8% purity CFC-11 refrigerant gas

US \$15 / Piece

Min. Order 15504 Kilograms

CFC-11 Offer for Sale

From [REDACTED]
Sent: Tuesday, 9 January 2018 1:10 PM
Subject: cfc-11 for rigid pu foam

Dears,
how are you?
I am very glad to have had some communications with you via linkedin.

As told you we are the manufacturer and supplier of blowing agent CFC-11 and HCFC-141b for rigid pu foam.I have been exporting hcfc-141b since 2009.Of course,the Middle East is the main market,including Singapore.Though CFC-11 is mainly for domestic market,yet i want to expand the exportation of cfc-11.I recommended CFC-11,which has much better blowing effect than 141b.And it is much cheaper.

The price based on CFR Singapore for CFC-11 is USD2200/mt now.

Any problem,do not hesitate to let me know.

[REDACTED]
Sales manager
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]

HCFC-141b pricing for comparison

hcfc 141b for Freezer Insulation Foam

FOB Reference Price: [Get Latest Price](#)

\$1.90 - \$2.50 / Kilograms | 800 Kilogram/Kilograms (Min. Order)

Lead Time:	Quantity(Kilograms)	1 - 10000	>10000
	Est. Time(days)	2	Negotiable

[Contact Supplier](#)

Leave Messages

Seller Support: Trade Assurance
- To protect your orders from payment to delivery

Payment:
More ▾

Shipping: Alibaba.com Ocean Shipping Service from China to U.S.
[Get shipping quote](#)

[Add to Compare](#) [Share](#)

https://www.alibaba.com/product-detail/hcfc-141b-for-Freezer-Insulation-Foam_62088741628.html

high quality and good price refrigerant gas R245FA...	HCFC- 141b refrigerant gas 250KG	Air Condition High Purity HCFC R141B New...	Direct factory Dichlorofluoroethane Hcf...	High quality hcfc 141b polyurethane foam resin...
US \$8-15 / Kilogram 10000 Kilograms (Min.)	US \$1-100 / Kilogram 7752 Kilograms (Min.)	US \$20-50 / Piece 100 Packs (Min. Order)	US \$3.5-3.7 / Kilogram 250000 Kilograms (Min.)	US \$2000-3000 / Ton 1 Ton (Min. Order)
8 yrs Beijing Starget ... ✓ 1 3 3 1 71.6%	10 yrs Zhejiang MR ... 1 1 1 1 79.0%	8 yrs Ningbo Sanhen... 1 1 1 1 6.8%	3 yrs Guangzhou Ch... 1 1 1 1 54.9%	4 yrs Shandong High... 1 1 1 1 88.3%
Contact Supplier	Contact Supplier	Contact Supplier	Contact Supplier	Contact Supplier

hcfc 141b for Freezer Insulation Foam	HCFC 141b Refrigerant Gas	HCFC 141B Refrigerant Gas Cylinder	hcfc- 141b for pu spray foam closed cell	HCFC R141B
US \$1.9-2.5 / Kilogram 800 Kilograms (Min. Order)	US \$20-50 / Piece 100 Pieces (Min. Order)	US \$15-50 / Piece 20 Square Feet (Min. Order)	US \$1.9-2.5 / Kilogram 800 Kilograms (Min. Order)	MASTER REFRIGERANTS
4 yrs Zhongshan BA... 1 1 1 1 89.3%	8 yrs Ningbo Sanhen... 1 1 1 1 6.8% "Received on time" (1)	8 yrs Ningbo Sanhen... 1 1 1 1 6.8%	4 yrs Zhongshan BA... 1 1 1 1 89.3%	Contact Supplier
Contact Supplier	Contact Supplier	Contact Supplier	Contact Supplier	Contact Supplier

<https://www.alibaba.com/showroom/hcfc-141b.html>

Pricing of dichloromethane

Dichloromethane pricing for comparison:

 Chemicals Organic Intermediate CAS NO.: 75...	 Methylene Chloride	 China high purity 99.99% 75-09-2 methylene chloride	 Industrial Grade Methylene chloride	 99% Methylene Chloride with best price
US \$360-700 / Ton 20 Tons (Min. Order)	US \$550-700 / Ton 21.6 Tons (Min. Order)	US \$560-580 / Ton 21.6 Tons (Min. Order)	US \$400-450 / Ton 20 Tons (Min. Order)	US \$580-600 / Ton 21.6 Tons (Min. Order)
11 yrs Guangzhou Z...	7 yrs Dongying City ...	4 yrs Dongying Rich ...	9 yrs Shandong Jinh...	4 yrs Shandong S-Sa...

<https://www.alibaba.com/showroom/methylene-chloride.html>

Additional ODS enforcement and related information

Additional ozone-depleting substances (ODS) enforcement was documented for the final report. The following table includes examples from a number of parties where attempts were made to sell illegal ODS products but were intercepted by various government agencies.

Table A4.6 Additional ODS enforcement and related information

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
Argentina	<p>In 2009, the Ozone Programme Office of the Ministry of Environment and Sustainable Development and the Customs Service of the Ministry of Finance of Argentina seized 1,150 cylinders of HCFC-22 mis-labelled as HFC-134a. The case was prosecuted and heavily fined, and the next step is the final disposal of the seized refrigerants.</p>	https://www.unenvironment.org/news-and-stories/story/environmental-authorities-and-customs-join-forces-against-environmental
Botswana	<p>The Botswana Unified Revenue Services (BURS) and Ministry of Environment Natural Resources Conservation and Tourism (MENT) have partnered to fight illegal importation of Ozone Depleting Substances (ODS).</p> <p>The Ministry, through the Department of Meteorological Services (DMS) handed over, eight refrigerant identifiers to the BURS which will be used at ports of entry to test gases imported into the country in order to combat illegal trade of prohibited ODS which may be disguised as ozone friendly.</p> <p>The purchasing of the gadgets is a step in the implementation of the requirements of the Montreal Protocol of 1987, that controls the production and consumption of ODS. Botswana became party to the protocol in 1992.</p>	http://www.sundaystandard.info/botswana-fights-importation-illegal-ozone-depleting-substances
Lesovo, Bulgaria	Bulgarian customs officials seized 24,000kg (1000 cylinders) transported by a truck from Turkey.	https://www.coolingpost.com/world-news/bulgarian-customs-stop-more-contraband-refrigerant/

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
Bulgaria	Macedonian national received a suspended six month prison sentence and a fine of around €500.00 for attempting to import 40 13.6kg cylinders of R22 .	https://www.coolingpost.com/world-news/suspended-sentence-for-illegally-importing-r22/
Vrushka Chuka, Bulgaria	<p>On 21 Aug 2017, Bulgarian customs officers at the Bulgarian-Serbian border stopped the illegal import of 300 cylinders of HCFC-22 marked as HC-600a.</p> <p>The customs officers were instructed to destroy in the cylinders in facilities recommended by the law. Bulgaria sanctioned the driver of the truck and investigated the consignee company on possible criminal action.</p>	http://conf.montreal-protocol.org/meeting/mop/mop30/presentation/Information-Documents/MOP-30-INF5.docx
Hangzhou, China	<p>In October 2013, local law enforcement authorities raided Hangzhou Sporlan facilities and seized 300 cylinders of counterfeit R-134A.</p> <p>Hangzhou Sporlan was required to pay damages to DuPont for the crime committed. In addition, Hangzhou Sporlan agreed to cease to use, advertise or otherwise infringe on the DuPont, SUVA and ISCEON trademarks and word marks. In addition, the agreement required that Hangzhou Sporlan reveal all their suppliers and information associated with bulk refrigerants, cylinders and carton packages of counterfeit goods so subsequent investigations can be pursued.</p>	https://www.coolingpost.com/world-news/dupont-seizes-r134a-counterfeits-in-china/
Colombia	Colombia rejected the export of 4,704 kg of HCFC-22 after being contacted by China notifying the Ozone Technical Unit of the Ministry of Environment and Sustainable Development of Colombia that the export permit request made in China did not match with the import license issued by the Colombian authorities.	http://wedocs.unep.org/bitstream/handle/20.500.11822/29760/OzN20190830.pdf?sequence=1&isAllowed=true

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
Costa Rica	The Costa Rica National Customs Service seized 412 cylinders of hydrochlorofluorocarbon (HCFC-22 or R-22) in 2014. Due to effective post-control measures, it managed to identify past illegal traffic and confiscate these goods.	https://www.unenvironment.org/news-and-stories/story/environmental-authorities-and-customs-join-forces-against-environmental
Dominican Republic	In 2017, the Ozone National Programme of the Ministry of Environment and Natural Resources and the General Directorate of Customs of the Dominican Republic reported 6,700 cylinders of CFC-12 mislabeled as HFC-134a in 2017. The company was charged a fine and the cylinders are to be returned to the country of origin.	https://www.unenvironment.org/news-and-stories/story/environmental-authorities-and-customs-join-forces-against-environmental
EU	The European Producers Trade Association (EFCTC) has launched a programme to help fight against this illegal trade. One of its features include an “Action Line” that will permit any individual to report alleged suspect HFC offerings confidentially to a trusted and independent contractor.	https://efctc.integrityline.org/
Vaalimaa, Finland Finland-Russia border	On 27 Feb 2011, A truck coming from Latvia tried to cross—allegedly by accident - the Vaalimaa Customs checkpoint in Eastern Finland which is the primary customs and border-crossing between the European Union and the Russian Federation. Because of the suspicious behavior of the driver, the truck was scanned (see photo) and 1150 refrigerant cylinders of 13.6 kg each were detected—in total 15.64 tons. The cylinders and their packaging were labeled R22 and hidden behind a cover cargo of glass- and ceramic ornaments and other decorative products. The R22 cylinders were mis-declared and did not have any serial numbers.	http://www.unep.fr/ozonaction/information/mmcfiles/7559-e-Monitoring_trade_in_HCFCs.pdf http://www.envirosecurity.org/ecocide/nov2012/Presentation_Julian_Newman.pdf

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
	The goods have been seized and will eventually be destroyed. Investigations concerning the origin of the chemicals and the people involved in this smuggling case are ongoing.	
Hamburg, Germany	In over 105 seizures between September 2012 and April 2014, the German authorities seized 715 refrigerators and air-conditioning units, about 6,500 cooling compressors and 52 second-hand trucks with refrigeration or air-conditioning units. These equipment were intended for Nigeria, Burkina Faso, Ghana and Pakistan. All seized goods were destroyed.	http://www.unep.fr/ozonaction/information/mmcfiles/7711-e-ECA_OzoneProtectionAward2014InfoNote_2015.pdf
Greece	The Greek Special Secretariat of Financial and Economic Crime Unit (SDOE) uncovered 1,939 illegal disposable containers of HFC refrigerant. The SDOE has not revealed the types of refrigerants that were confiscated, but photos indicate the presence of R407C and R404A .	https://www.tanea.gr/2019/09/11/greece/sdoe-katasxethikan-pano-apo-23-tonoi-freon-apo-tin-kina/
Honduras	Between 2015 and 2018, the Ozone Technical Unit, Secretariat of Natural Resources and Environment of Honduras and the Executive Directorate of Revenue Customs Office of Puerto Cortes seized milk tanks and air conditioners containing HCFC-22 . The confiscated equipment was retrofitted to alternative refrigerants before it was donated to public institutions.	https://www.coolingpost.com/world-news/awards-for-seizures-of-illegal-refrigerants/
Gujarat, India	On 1 Mar 2013, the Indian Directorate of Revenue Intelligence / Customs seized 182901.6 metric kg of R22 which were stored in 5 ISO tanks as well as 354 empty disposable cylinders on 1 March 2013.	http://www.unep.fr/ozonaction/information/mmcfiles/7711-e-ECA_OzoneProtectionAward2014InfoNote_2015.pdf

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
JNPT Nhava Sheva	<p>The goods originated from China, with shipment papers indicating that they were intended for re-export under an Export Oriented Unit (EOU) scheme. The EOU was misused and the goods were diverted for use within India.</p> <p>The total fines and penalties amounted to INR 1,363,652 (~\$ 22,730 (US)), excluding the personal penalties of approximately \$ 170 (US) for each the 5 persons involved.</p>	
Tughlakabad India Pipavav Port	<p>On 25 Jul 2013, the Indian Directorate of Revenue Intelligence / Customs seized 1,100 cylinders of HCFC-22, weighing 13.6 kg each. They originated from China, were not declared in the bill of lading, and were concealed behind furniture.</p> <p>The government issued a show cause order to which the importer, a Delhi-based firm, has a right to reply. The firm also has a right to personal hearing before a penalty can be imposed. No further action could be taken until the show cause order was adjudicated.</p>	http://www.unep.fr/ozonaction/information/mmcfiles/7711-e-ECA_OzoneProtectionAward2014InfoNote_2015.pdf
Chennai, India	<p>On 23 Jun 2015, Directorate of Revenue Intelligence officials seized 80,000 kg of R22 worth more than 1 crore (around USD210,000). The ODS were imported from China by T. Anil Jain, managing director of Refex Refrigerants, which has a factory on the outskirts of Chennai. He was filling smaller cans with R-22 gas and selling them as R134a.</p> <p>The businessman was importing dichlorodifluoromethane.</p>	https://www.coolingpost.com/world-news/indian-customs-seize-80-tonnes-of-r22/ https://timesofindia.indiatimes.com/city/chennai/DRI-seizes-ozone-depleting-gas/articleshow/46073465.cms

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
		<p>https://timesofindia.indiatimes.com/city/chennai/Chennai-businessman-held-for-importing-banned-gas-worth-Rs-1-crore/articleshow/47021713.cms</p> <p>http://mopia.ca/wp-content/media/OzoNews-Vol-XV-30April2015.pdf</p>
Netherlands	In March 2019, Dutch authorities confiscated 1600kg of illegal R134a (123 13.6kg cylinders). The authorities are seeking for a further 477 cylinders supplied by the same trader.	https://www.coolingpost.com/world-news/dutch-authorities-intercept-illegal-r134a-refrigerant/
Karachi, Pakistan	<p>On 7 Nov 2018, customs authorities confiscated 18,000 kilogrammes of the smuggled refrigerant at Karachi Port.</p> <p>The business responsible for the shipment, M/S Cool Corporation, claimed to be importing R-32 gas (also known as HFC-32), but customs agent Asim Awan noticed that the container was not classified for R-32. The tank was pasted with large stickers declaring its contents as R-32 and flammable, which R-22 is not.</p> <p>Pakistani customs have now confiscated the tank and authorities are preparing to take further necessary actions</p>	https://www.unenvironment.org/news-and-stories/story/pakistan-customs-seize-massive-smuggled-shipment-ozone-depleting-gas

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
Puerto Fenix, Paraguay	On 31 Mar 2015, Paraguay confiscated over 2000 illegal air conditioning units containing HCFC-22 . The Environment Secretariat has not indicated the origin of the shipment but photographs suggest the units were from China.	http://www.unep.fr/ozonaction/information/mmcfiles/7711-e-ECA_OzoneProtectionAward2014InfoNote_2015.pdf
Paraguay	Over three seizures, the General Directorate of Customs of Paraguay confiscated 1,150 cylinders of mainly HCFC-22 in 2010, and 27,000 split air-conditioning units that use HCFC-22 gas, in 2015.	https://www.unenvironment.org/news-and-stories/story/environmental-authorities-and-customs-join-forces-against-environmental
Cebu, Philippines	<p>In 2014, the Bureau of Customs – Port of Cebu seized 110 tanks of CFC-12, labelled as HFC-143A, weighing 13 kg each. The shipment came from China.</p> <p>Because CFC-12 is a prohibited substance, the Philippines has the option of confiscating it for destruction or returning it to China. Contrastingly, HFC-143A is a regulated substance. Thus, the Philippines can auction it to accredited importers.</p>	https://www.pressreader.com/
Manila, Philippines	<p>In 2012, DuPont initiated an investigation against T.A. Fresco, a Philippine company. T.A. Fresco was suspected of supplying refrigerants to a shipping company.</p> <p>The investigation revealed that T.A. Fresco was selling CFC-12 falsely labelled as DuPont's Suva 134-A (HFC-134A). DuPont settled the case in 2014. The agreement T.A. Fresco to issue a public apology to DuPont in a national Philippine</p>	https://www.coolingpost.com/world-news/dupont-settles-with-filipino-fraudsters/

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
	newspaper full compensation for the destruction of the counterfeit refrigerant, and monetary compensation for the illegal distribution of this product.	
Radauti, Suceava, Romania	<p>On June 2014, the Ministry of Environment and Climate Change of Romania was informed by the European Commission of an email correspondence advertising refrigerant cylinders containing R12, R22, R404A, R407C, R410A and R134a refrigerants for sale.</p> <p>Enforcement officers seized 244.8 kg of ODS, including ten cylinders of R12 (136 kg) and 8 cylinders of R22 (108.8 kg).</p>	https://wedocs.unep.org/bitstream/handle/20.500.11822/26555/7810-e-iPIC_ECASeizuresReport.pdf?sequence=1&isAllowed=true http://smeitss.mycpanel.rs/bilten/eca-network/ECA%20Ozone%20Protection%20Award%202016%20seizure%20summary%20English.pdf
St. Petersburg, Russia	<p>The shipment originated from China and was intended for Moscow. The shipment papers indicated ethylene-glycol instead of CFC-11 and HFC-134a instead of the other substances because neither is regulated by the Montreal Protocol at the time.</p> <p>In 2014, Russia launched a major operation for detention and arrest of organizers and perpetrators of a large-scale smuggling scheme for ozone-depleting substances illegally entering its territory. The operation resulted in the seizure of 1,500 cylinders containing various ODS:</p> <ul style="list-style-type: none"> - HCFC-22 – 6.8 MT - CFC-113 – 2.04 MT 	http://www.unep.fr/ozonaction/information/mmcfiles/7711-e-ECA_OzoneProtectionAward2014InfoNote_2015.pdf

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
	<ul style="list-style-type: none"> - CFC-12 – 4.08 MT - HFC-141b – 2.7 MT - CFC-11 – 18.8 MT <p>All the substances except for CFC-113 were seized and will be destroyed after completion of the cases. CFC-113 was stored in St. Petersburg for destruction.</p>	
Valencia, Spain	<p>The Nature Protection Service of the Spanish Civil Guard, coordinated by the specialised Environment and Urban Planning Unit of the Spanish Public Prosecutor's Office, discovered that a company in Spain was involved in smuggling 10 tons of HCFC-22 without a legal license. The operation generated € 500,000 to €1,000,000 for a criminal gang.</p> <p>The investigation further discovered that the HCFC-22 was exported to Panama as regenerated HCFC-22 refrigerant liquids. The total amount of HCFC-22 exported was 10,000 kg.</p>	https://www.europol.europa.eu/newsroom/news/how-company-earned-to-%E2%82%AC1-million-illegally-trading-ten-tons-of-ozone-depleting-substances
Spain	<p>In 2014, the SEPRONA unit of the Civil Guard of Spain investigated illegal trade activities in Spanish harbors. HCFC-22 refrigerants have been seized from fishing vessels in the past.</p> <p>The investigation revealed that the company in question had been trading in HCFC-22 illegally with companies based in Spain and other EU countries. The company also traded in non-EU countries without obtaining a valid trade license</p>	https://wedocs.unep.org/bitstream/handle/20.500.11822/26555/7810-e-iPIC_ECASeizuresReport.pdf?sequence=1&isAllowed=y https://ecodiario.eleconomista.es/sociedad/noticias/7613390/06/16/Incautados-37000-kilos-de-gas-R22-para-barcos-

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
	<p>and without properly stating in the customs declaration form that it was shipping ozone depleting refrigerants.</p> <p>The Civil Guard confiscated 37,000 kg of HCFC-22.</p>	prohibido-por-ser-perjudicial-para-el-ozono.html
Valencia, Spain	<p>In April 2019, Spanish police stopped illegal trade in refrigerant R22 being carried out by a Valencia-based company, which is thought to have netted up to €1m. Ten people were allegedly involved in the illegal export of 10 tons of R-22 to Panama.</p>	https://www.youtube.com/watch?v=pM8cb5h-mDg https://www.coolingpost.com/world-news/valecia-company-investigated-over-illegal-r22-exports/
Antalya, Turkey	<p>On 4 Jun 2014, a Turkish company that was not registered as an ODS importer attempted to import 3,100 cylinders of HCFC-22 labelled as HFC-404, HFC-410, and HFC-134A. The cylinders arrived from China by ship.</p>	https://wedocs.unep.org/bitstream/handle/20.500.11822/26555/7810-e-iPIC_ECASeizuresReport.pdf?sequence=1&isAllowed=y
Uzbekistan	<p>On 2 Aug. 2014, customs officers discovered an illegal shipment of 3,100 cylinders containing refrigerants in the railway container of the freight train, arriving at the railway station.</p> <p>"Savay", en route from UAE to Kyrgyzstan. It contained:</p> <ul style="list-style-type: none"> - 100 cylinders of R12 (1360 kg), 	https://wedocs.unep.org/bitstream/handle/20.500.11822/26555/7810-e-iPIC_ECASeizuresReport.pdf?sequence=1&isAllowed=y http://smeitss.mycpanel.rs/bilten/eca-network/ECA%20Ozone%20Protectio

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
	<ul style="list-style-type: none"> - 440 cylinders of different sizes from 1 to 13.6 kg of R22 (2110 kg), - 2520 cylinders of different sizes from 0.32 to 13.6 kg of R134a (3280 kg), - 111 cylinders of R404A containing 800g or 10,9 kg of the substance (603,9 kg) and - 19 cylinders of R407C (214,7kg). <p>The shipment was accompanied by an invoice with incorrect details on the type of refrigerants, quantity and harmonized system (HS) codes.</p>	n%20Award%202016%20seizure%20summary%20English.pdf
Uzbekistan	<p>In a series of 7 seizures from 21 February 2014 to 4 August 2015, the government confiscated 1,361.16 kg of ODS from Uzbekistani nationals smuggling ODS in cylinders and cans hidden in baggage compartments of private cars. The breakdown of substances are as follows:</p> <ul style="list-style-type: none"> - CFC-12 – 971.76 kg - HFC-134A – 210 kg - HC600a – 121.4 kg - HCFC-22 – 58 kg 	https://wedocs.unep.org/bitstream/handle/20.500.11822/26555/7810-e-iPIC_ECASeizuresReport.pdf?sequence=1&isAllowed=y

Jurisdiction (for enforcement or inspection activity)	English-reference summaries or excerpts of announcement content	URLs and scans of website content
	The cans containing CFC-12 were destroyed while the rest were sold in the domestic market. The individuals were fined 5 million Uzbekistani Som (~\$ 582.75 US)	
Vietnam	May 8, 2019 - Vietnam's Ministry of Industry and Trade included the granting of import license for ODS among the administrative procedures that are processed online. (Allowing for more transparent access to shipment information for ODS, facilitating enforcement and inspection activities.)	https://en.vietnamplus.vn/moit-goes-online-for-administrative-procedures/153341.vnp

Appendix 5: Supporting analyses for “bottom-up” emissions model and sensitivity analysis

The Task Force examined historic and current data and assumptions (e.g., production, consumption, banks, emissions, etc.) to better understand potential sources of the unexplained CFC-11 emissions. Several methodologies were employed including the development of a new “bottom-up” emissions model followed by a “sensitivity analysis”²⁴¹ to evaluate the importance of uncertainties of specific parameters in forecasting derived atmospheric emissions. This was then compared to the derived atmospheric emissions to see if modifying a particular variable might better describe the derived emissions. After assumptions were varied one at a time, the Task Force modified multiple variables in an attempt to better describe the source of the unexplained emissions of CFC-11 from previous production and banks.

In the 2006 TEAP report, the composition of the market and total production from AFEAS²⁴² is calculated and compared to the production reported to UNEP.²⁴³ In 1993, AFEAS data only accounted for less than 85% of UNEP reported production as the majority of production shifted to Article 5 parties. As the TEAP 2006 report²⁴⁴ points out, the discrepancy between AFEAS sales data and UNEP production data increases as early as 1989. To avoid introducing this error into the analysis, this model utilizes UNEP data starting in 1989. The dataset also includes production in the Soviet Union from 1968 to 1985 using literature-based estimates.^{245,246}

In building the “bottom-up” model several assumptions need to be made. One important parameter for which there is significant uncertainty, is the release rate from banks. The bank release rate depends on several factors which include, but are not limited to, the composition of the bank (R/AC, foams, etc.), the environmental conditions and the method of disposal. To obtain a more holistic understanding of the bank emissions rate profile over time, two different approaches were employed. In both cases a combination of atmospheric measurements and “bottom-up” production data yielded estimates about the annual global bank emission rate. The first analysis was based on atmospheric measurements from Western Europe and may be considered as a proxy emission after CFC-11 is banned. The second analysis used atmospheric burden data starting in 1978.

²⁴¹ A sensitivity analysis is used to determine the importance of specific independent variables in a resulting dependent variable.

²⁴² AFEAS data is digitally available only on third party websites, including the following:
<https://agage.mit.edu/data/afeas-data>. Accessed May 2019.

²⁴³ Table 3.3, page 17, TEAP, 2006. *Technology and Economic Assessment Panel Task Force on Emissions Discrepancies Report*.

²⁴⁴ TEAP, 2006. *Technology and Economic Assessment Panel Task Force on Emissions Discrepancies Report*.

²⁴⁵ McCulloch, Archie, *et al.*, Releases of Refrigerant Gases (CFC-12, HCFC-22 and HFC-134a) to the Atmosphere, *Atmospheric Environment*, 2003, **37** (7), 889–902.

²⁴⁶ Hurst, D. F., *et al.*, Emissions of ozone-depleting substances in Russia during 2001, *Journal of Geophysical Research*, 2004, **109** (D14). <https://doi.org/10.1029/2004JD004633>.

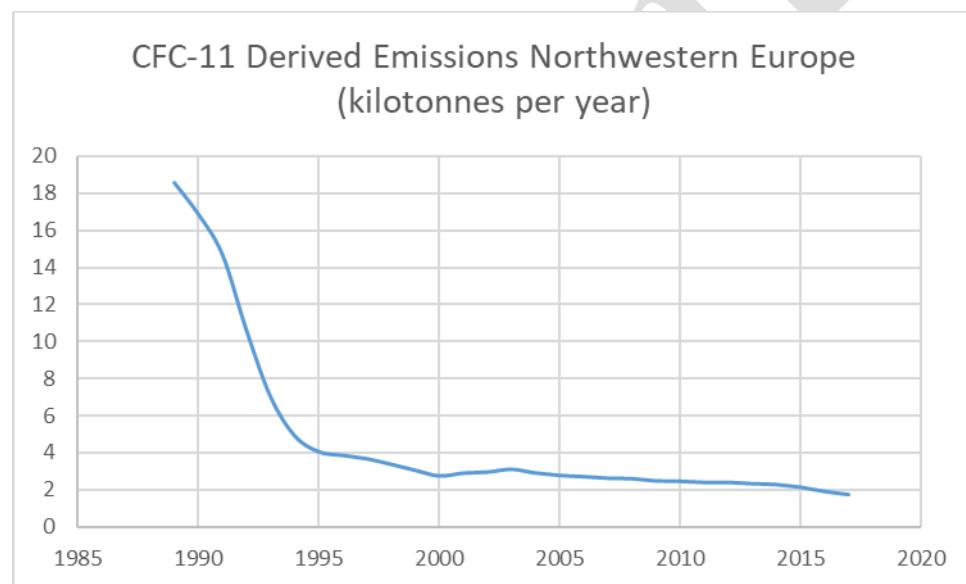
Estimating total CFC-11 banks and emissions rates

Approach 1: Estimating release rates from banks using “top-down” regional emissions estimates

Long term atmospheric emissions, presumed to be from banks (e.g., from installed insulating foams, chillers, refrigerator foams insulation, landfills, etc.) were explored to better understand the expected emissions globally as a comparison to the recent unexpected emissions. The hypothesis under consideration is that emissions rates over time from a location where no new CFC-11 has been “consumed” (as defined by the Montreal Protocol) for 20 years might provide a proxy for background emissions rates that might be anticipated from banks globally and from eastern Asia when adjusted to 2010 which is the year that “consumption” ended in eastern Asia and globally.

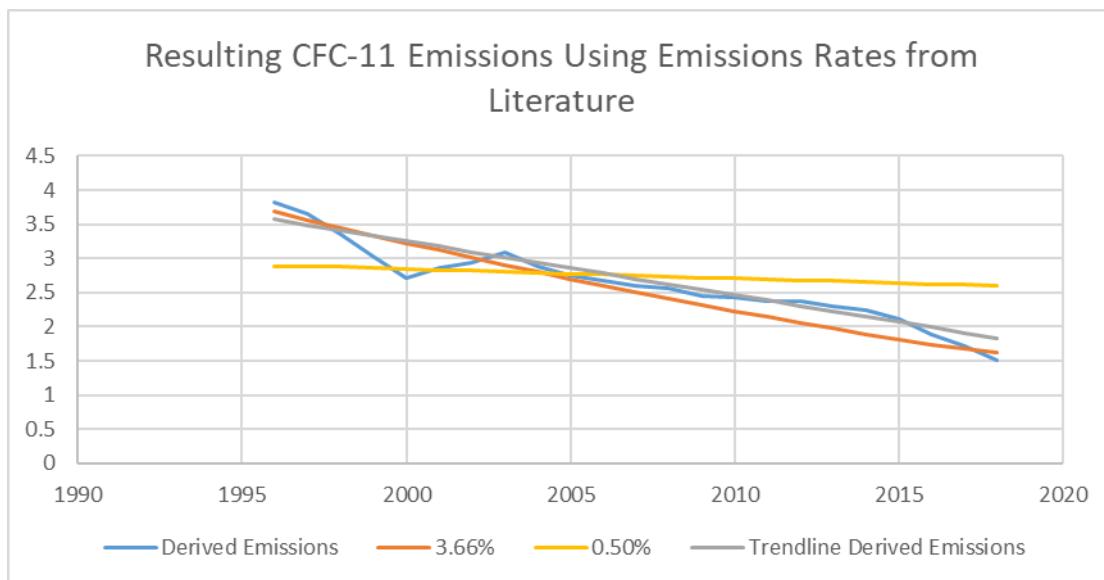
Concentrations of CFC-11 from Northwestern Europe are monitored in Mace Head Ireland and used to derive emissions rates. The derived emissions rates have been generally stable to declining since 1997. The emissions levels have been generally declining since before 1990 as shown in Figure A5.1. The steep decline from 1990 through 1996 is likely a result of the transition from CFC-11 to other alternatives in anticipation of the ban in 1996.

Figure A5.1 CFC-11 atmospheric emissions in Northwestern Europe (kilotonnes)



A range of emissions rates from literature (e.g., UNFCCC reports, AFEAS, FTOC reports and other sources) were used to explore a potential bank volume associated with those emissions rates that might result in emissions that would align with the derived emissions from Western Europe. The emissions rates used ranged from 0.5% to 4%. The necessary bank volume to support those emissions and minimize the difference between calculated emissions and the derived emissions from Western Europe was estimated. Examples of those estimates of emissions from banks (A5.2) and bank volumes (A5.3) are shown in the next figures.

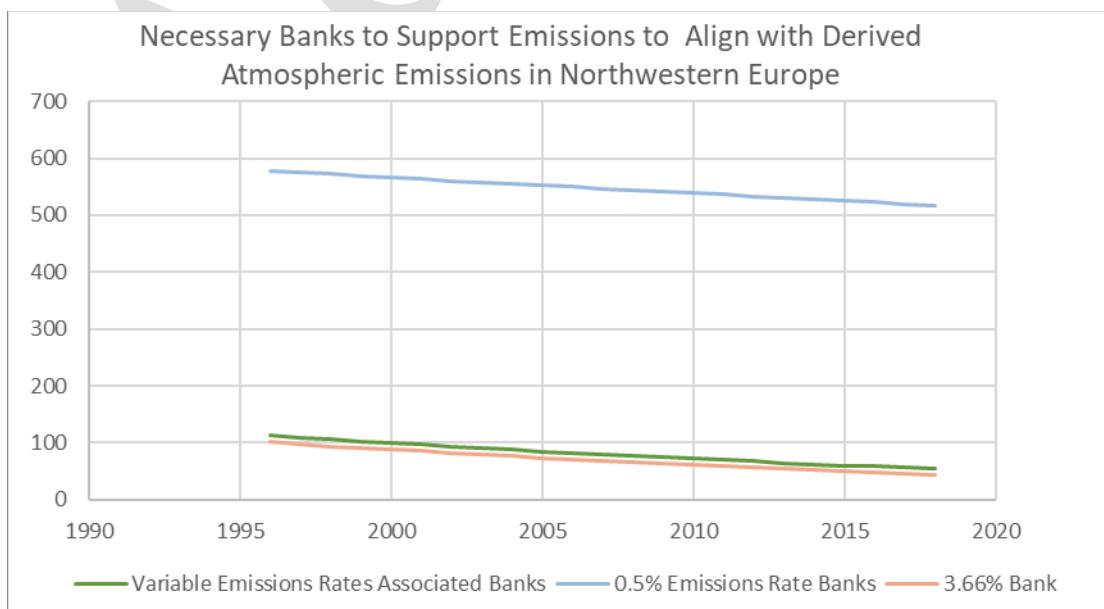
Figure A5.2 Resulting CFC-11 emissions using emissions rates found in the literature (kilotonnes)



The associated banks necessary to support the emissions are shown in Figure A5.3. The seemingly small range of emissions rates significantly impacts the calculated volume of CFC-11 necessary to support it.

Variable emissions rates were also used to attempt to more closely align with the derived emissions. The necessary bank to support those rates is also included in the chart below.

Figure A5.3 Resulting CFC-11 banks using literature emissions rates that are necessary to align with derived atmospheric emissions in Northwestern Europe (kilotonnes)



The emissions rates with the closest statistical correlation to the derived emissions ranged from 3 to 4% per year. These emissions rates are consistent with previous analyses of emissions rates.²⁴⁷ The associated banks to support those emissions rates were between 100 and 125 kilotonnes. It is important to note that this work is very preliminary and additional refinement is needed. However, it does highlight the importance in better understanding emissions rates in calculating remaining banks. The Task Force intends to further refine its study of emissions rates from banks.

Approach 2: Emissions rates utilising atmospheric burden data between 1978-2016

To determine the rate of CFC-11 released from installed banks as a function of time, a simple model of CFC-11 emissions was used to estimate these values based on the assumption that emissions happen at production, application, and from the installed banks. To constrain the model to simulate bank emissions rates, several sources of data are combined. The data used in the analysis described in this section sources are as follows:

- Production from the AFEAS database and the data reported to UNEP
- Sectoral breakdowns of use as reported to AFEAS
- Annual emissions as derived from Montzka *et al.* (2018)²⁴⁸
- Atmospheric concentration in 1978 as derived by Rigby *et al.* (2013)²⁴⁹

For simplification, an assumption is made that in 1978, the first year of repeated CFC-11 atmospheric concentration measurements, all the CFC-11 ever produced resided either in the atmosphere or in the installed banks or has been destroyed. In this instance, the model assumes that there had been no atmospheric destruction in the 44 years since the first CFCs were produced. This assumption leads to an estimate of the maximum bank size. Summing the total CFC-11 production reported to AFEAS through 1978 (~4.3 million tonnes) and subtracting the total measurement-derived atmospheric CFC-11 burden (~3.2 million tonnes) indicates the size of the 1978 CFC-11 installed bank (~1.1 million tonnes) for this model.

To solve for the total annual bank emissions, we can compare the derived total emissions to the expected production and application emissions from the total amount of produced CFC-11 each year. This approach is corroborated by comparing total emissions before 1978 to the derived atmospheric CFC-11 burden in that year. Assuming reasonable constant production and application emissions factors for the three CFC-11 using sectors (refrigeration, close-cell foams, and emissive uses), the sum of pre-1978 emissions (~3.3 million tonnes) is comparable to the total atmospheric burden (~3.2 million tonnes). The sectoral composition of CFC-11 use is provided by AFEAS data.

²⁴⁷ Ashford *et al.* 1999, *Development of a global emission function for blowing agents used in closed cell foam*, Final Report to AFEAS, and also what Montzka *et al.*, (2018) derived on a global scale considering reported production for the mid-2000s.

²⁴⁸ Montzka, S. *et al.*, An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, **557**, 413–417 (2018). <https://doi.org/10.1038/s41586-018-0106-2>.

²⁴⁹ Rigby, M. *et al.*, Re-evaluation of the lifetimes of the major CFCs and CH₃CCl₃ using atmospheric trends, *Atmospheric Chemistry and Physics, Atmos. Chem. Phys.*, 2013, **13**, 2691–2702. <https://doi.org/10.5194/acp-13-2691-2013>.

Figure A5.4 Bank emissions rate as derived from the atmospheric burden measurements for 1996-2015

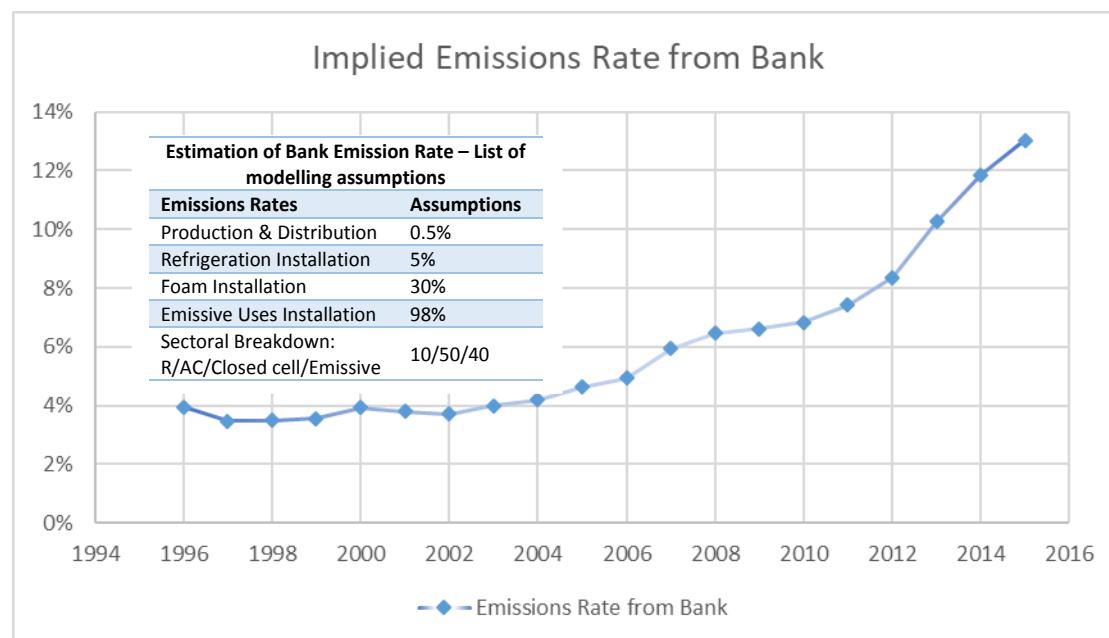
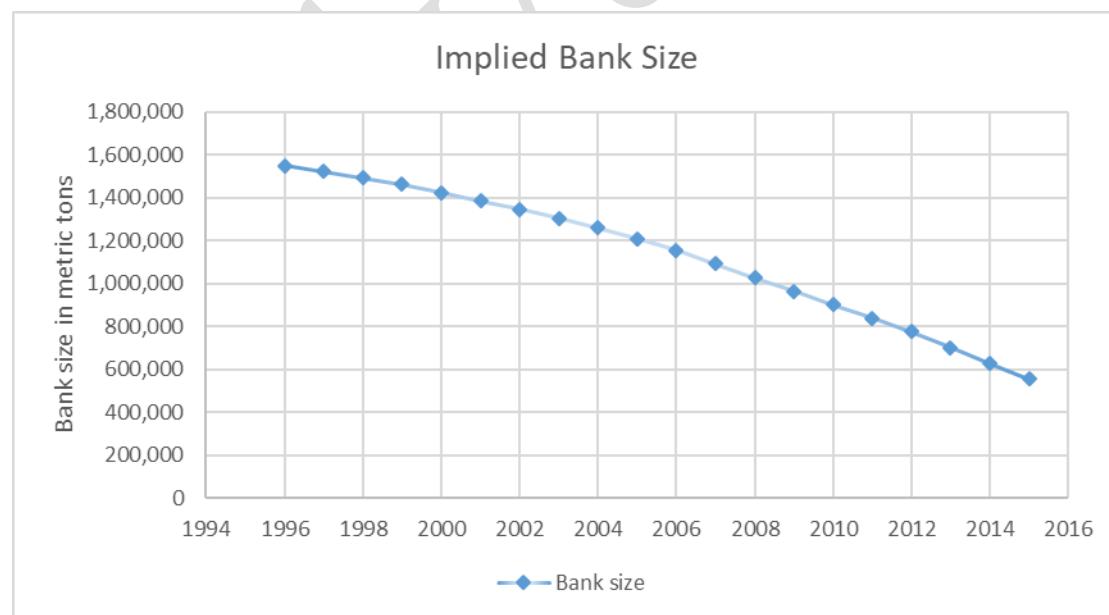


Figure A5.5 Bank size as derived from the atmospheric burden measurements for 1996-2015 (tonnes)



With reliable assumptions for the emissions rates from production and application, and AFEAS's market composition data, total annual emissions are correlated to emissions from the installed bank: any CFC-11 emissions not emitted during production or application must be emitted from the bank.

The final step in calculating the annual bank emission rate is therefore determining the size of the installed bank each year, shown in Figure A5.5. Using the prescribed method, the installed bank figure for 1978 can be propagated forward in time by a method of accounting for all the production in a given year. Any CFC-11 produced in a given year that is not emitted (known from the derived emissions) must be added to the bank. More precisely, the change to the installed bank size in a given year is the difference between new production and total emissions. The annual emissions from banks and the total bank size were used to calculate the annual bank emissions rates, shown in Figure A5.4. The implied bank emission rate from 1996-2002 was 3.7% on average, which agrees with the results of the “Estimated emissions rates from banks using “top-down” regional emissions estimates” (above).

The bank emissions profile starts deviating starting in 2002, as do the derived emissions this analysis is built upon. The results also indicate that if the atmospherically derived emissions were to have originated from a sudden change in bank emissions rates, then the bank emissions rates would have to gradually increase from 3.7% in 2002 to 13% in 2016, which is highly unlikely.

“Bottom-up” model sensitivities for the preliminary report

The model’s sensitivity to an array of parameters (Table A5.1) was analyzed to provide a realistic range of expected emissions and bank size. Understanding the sensitivity of the model indicates how critical specific assumptions are to the analysis. The most critical parameters may then be further refined, and less effort is needed to refine parameters that do not impact the analysis significantly.

A broad range of parameters were used in this sensitivity analysis to explore any possibility that previous production and banks might explain the unexpected emissions of CFC-11. By varying the sector-specific emission rates occurring from installation and banks, as well as the emission rate of production the model produces an emission curve that harmonized with that derived from atmospheric measurements up to 2002. However, there was no scenario under which the behavior of the curve post-2002 followed that of the observed atmospheric concentrations. Under any circumstances, the emissions are expected to continue to fall as banks are being depleted and no addition to the bank or the atmosphere is expected since production ceased globally in 2010.

Bank emissions

The model’s sensitivity to bank emissions rates was tested using an array of different scenarios and assumptions based on what we know to be realistically possible and probable. Low, medium and high scenarios are shown in Figures 6 and 7. There were no scenarios for which the “bottom-up” emissions profile followed the behavior of the atmospherically derived emissions after 2002. In addition, the emissions profile from non-Article 5 parties (Western Europe) where the vast majority of the bank resides, shows generally declining emissions after the ban in 1996 onwards.

Figure A5.6 “Bottom-up” emissions sensitivity to bank emissions rates (kilotonnes)

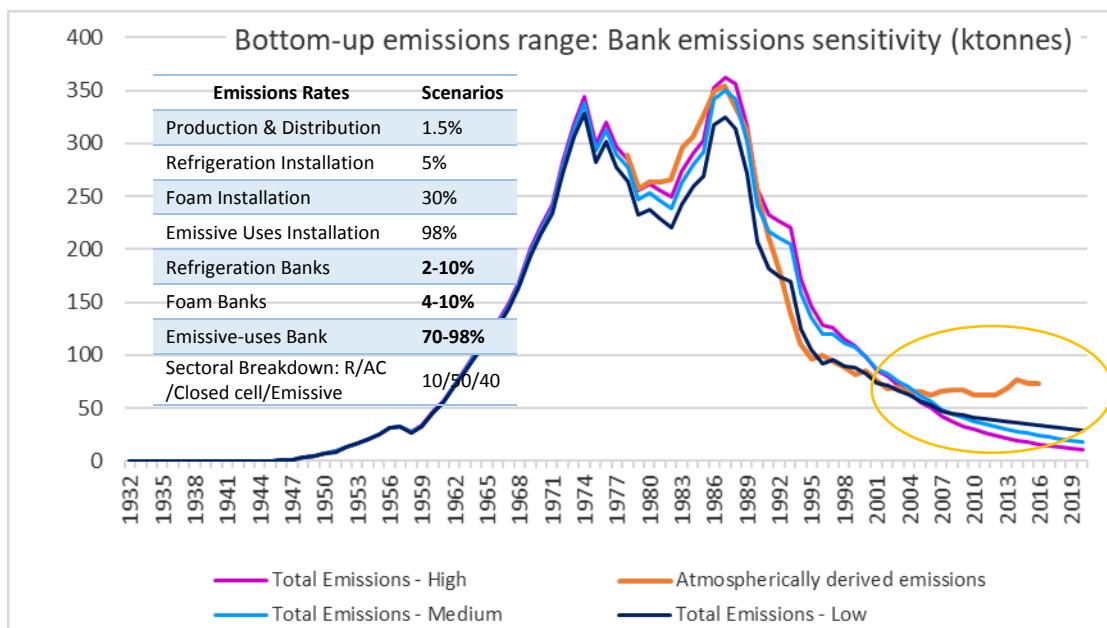
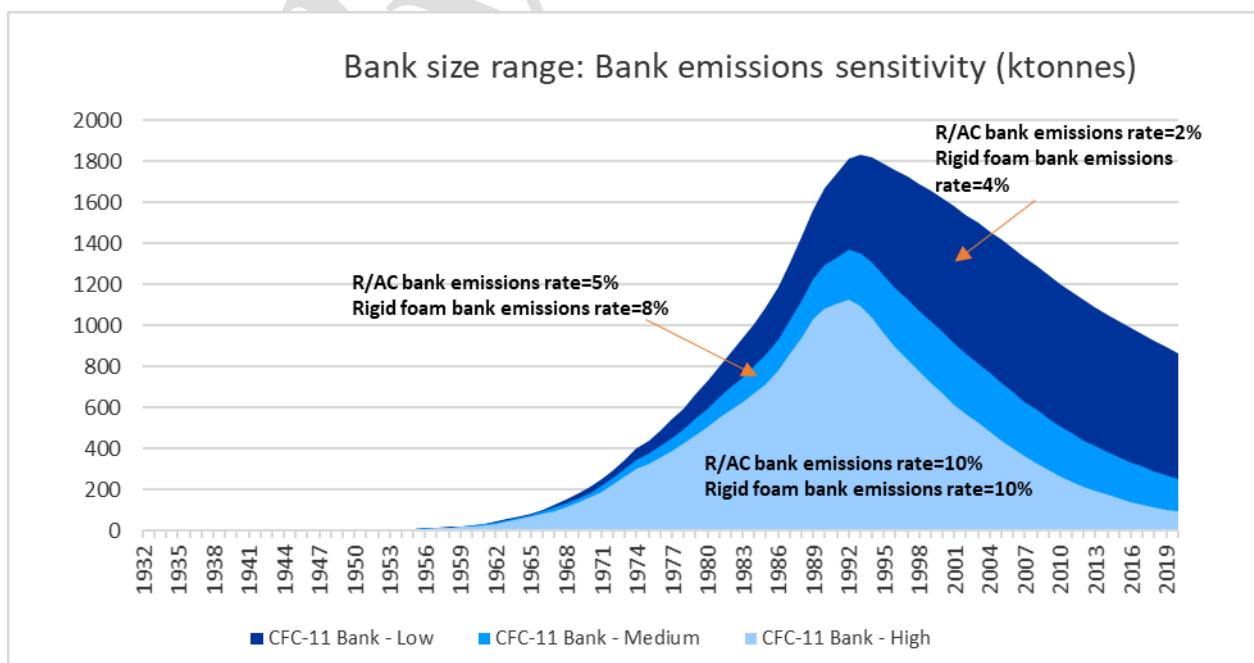


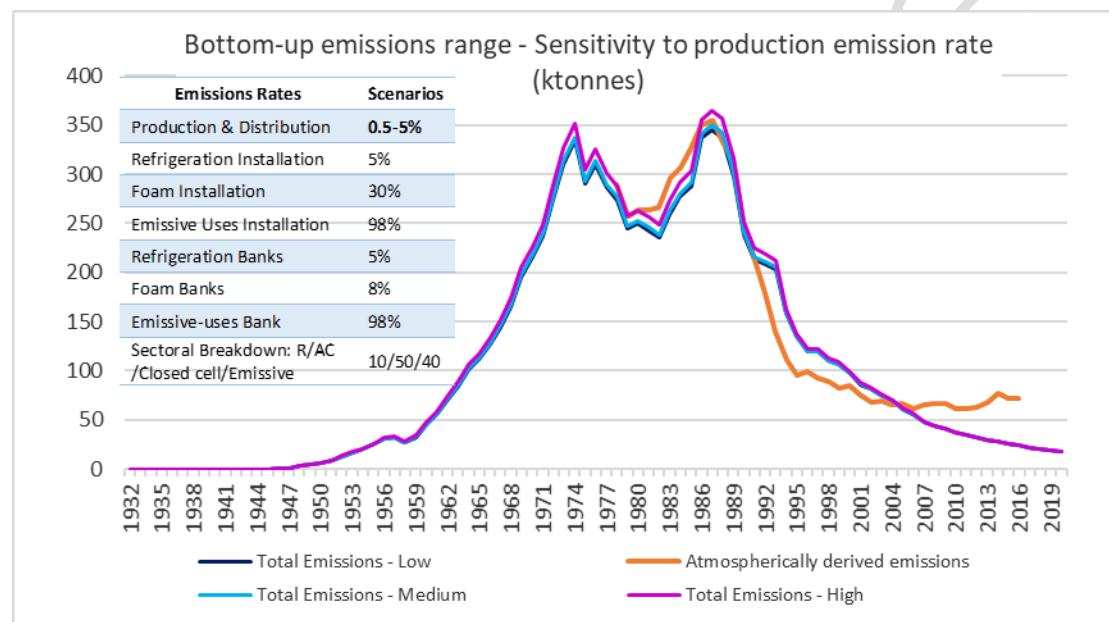
Figure A5.7 Area graph of the “bottom-up” bank size for different bank emissions scenarios (kilotonnes)



Production emissions

Emissions during production of CFC-11 vary depending on the level of sophistication of the production facility. The IPCC guidelines suggest a production emissions rate of 0.5%. However, it is possible that a rate of 1.5% may more closely resemble realistic conditions. Additional emissions in the supply chain (e.g., loading cylinders, etc.) may add 1-3% emissions. The model's sensitivity was tested for a range of 0.5-5% production emissions rates. Higher values were also considered but are not presented here. Increased production emissions rates do not have a significant impact on the emissions profile post-1992 because the dominant emissions contributor is the bank built mostly in non-Article 5 parties.

Figure A5.8 “Bottom-up” emissions sensitivity to production emissions rates (kilotonnes)



Note: The rate of emissions during the CFC-11 production process does not affect the size of the banks since these emissions happen prior to the chemical being sold.

Refrigeration and air-conditioning

The model is not sensitive to the rate of emissions during installation of CFC-11 in refrigeration and air-conditioning equipment (R/AC), as seen in the figures below. R/AC accounts for less than 10% of CFC-11 use from the 1940s onwards and therefore the emissions rate during installation of R/AC equipment has no significant impact on the overall emissions profile.

Figure A5.9 “Bottom-up” emissions sensitivity to emissions rates during installation of R/AC equipment (kilotonnes)

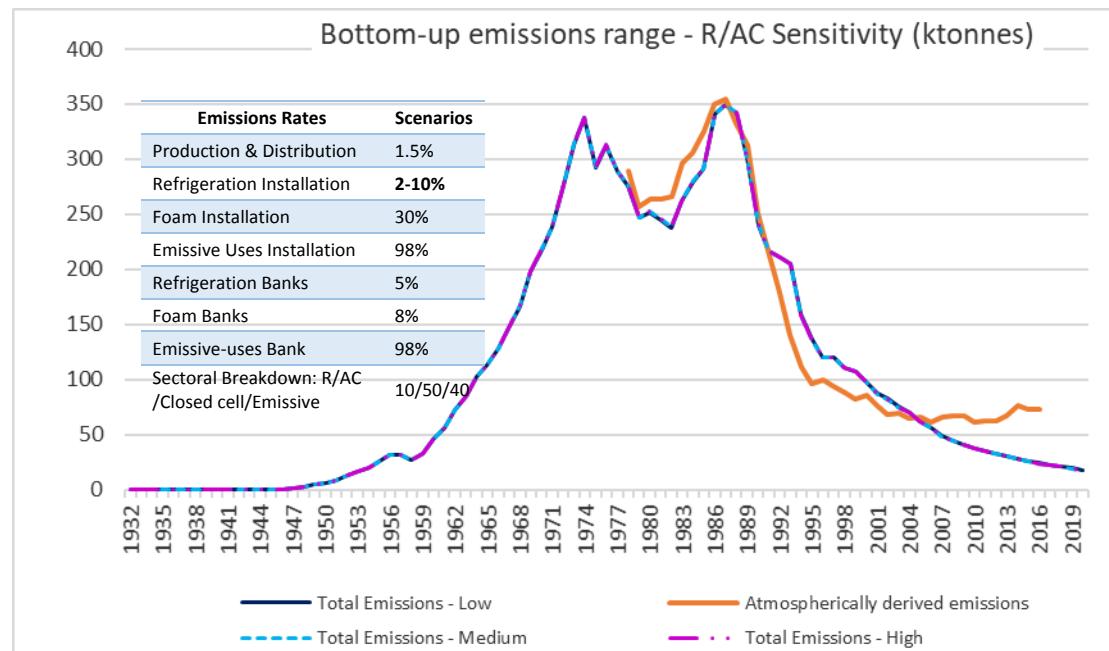
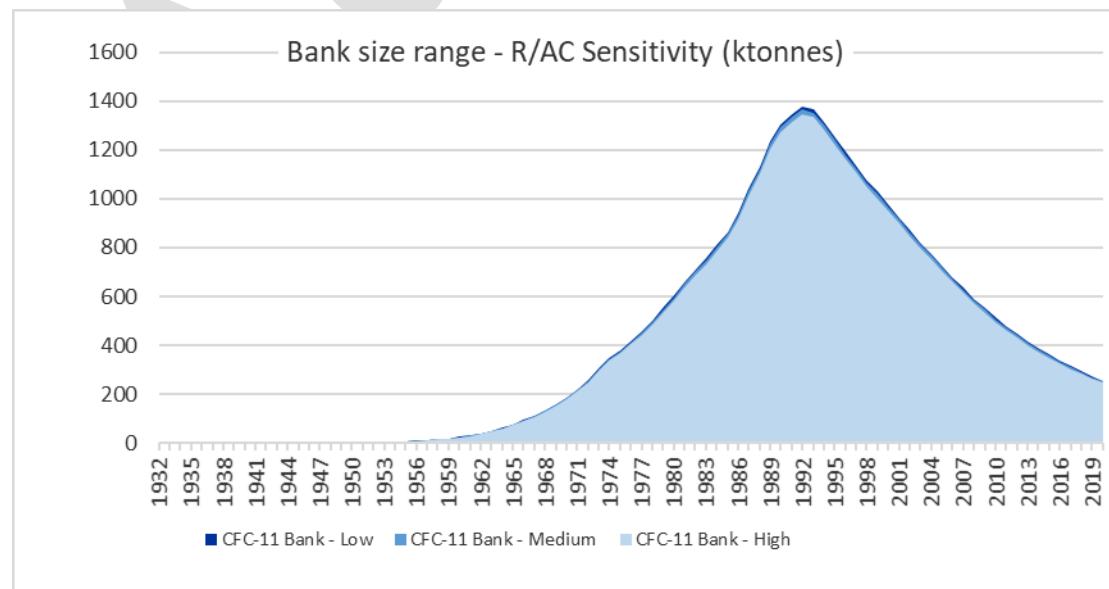


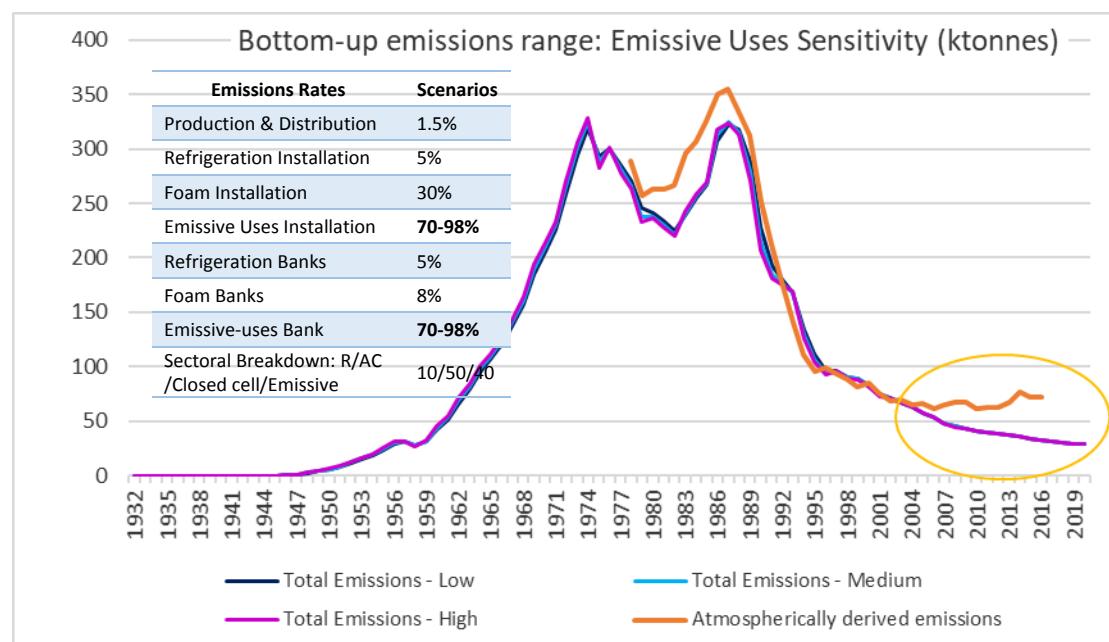
Figure A5.10 Range of bank size for different emissions rates during installation of R/AC equipment (kilotonnes)



Emissive-uses

Emissive-uses include the use of CFC-11 as an aerosol, as a solvent or in flexible (open cell) foams. Most of the CFC-11 is emitted directly during use in these applications and therefore they do not substantially contribute to the banks. Emissive-uses dominated the market in the 1950s, 60s and 70s and continued to account for more than 30% of the CFC-11 market. However, the analysis has shown that the assumptions on the emission rate of these applications does not significantly impact the emissions profile.

Figure A5.11 “Bottom-up” emissions sensitivity to emissions rates during application of emissive uses (kilotonnes)



Note: None of the scenarios follow the profile of the atmospherically derived emissions after 2002. The emissions rate of emissive uses such as aerosols, solvents and flexible foams does not have a significant impact on the overall emissions profile and cannot explain the unexpected behavior after 2002.

Figure A5.12 Range of bank size for different emissions rates during application of emissive uses (kilotonnes)

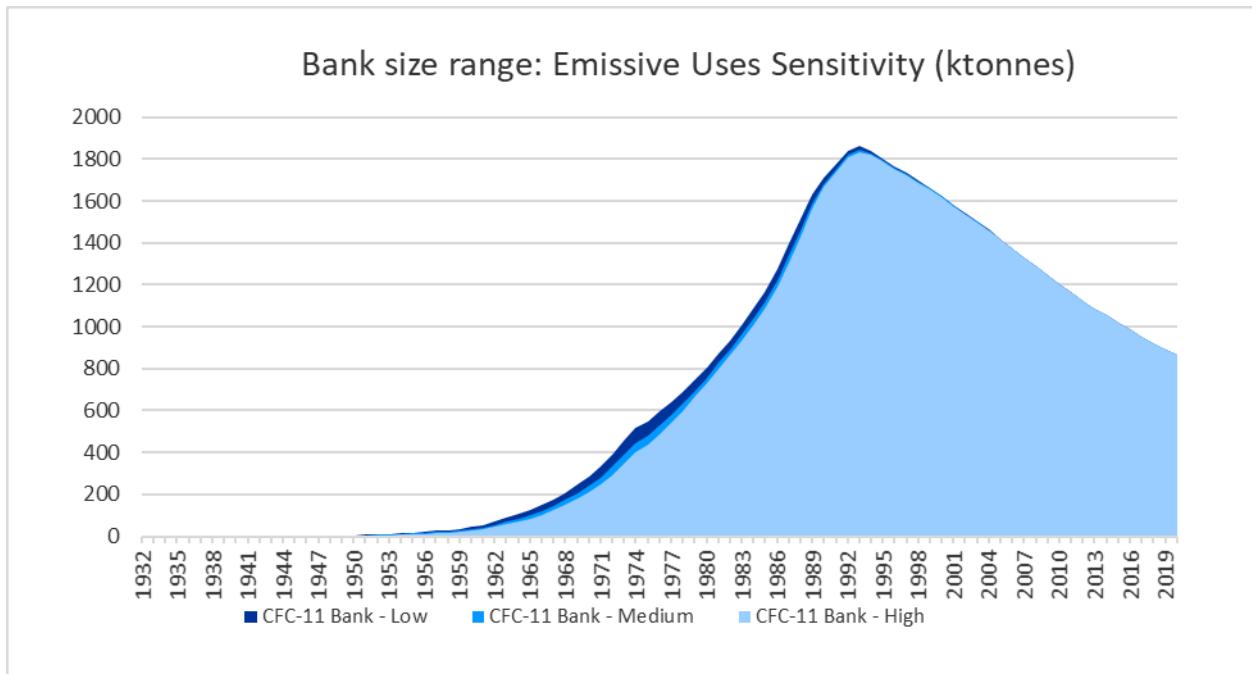
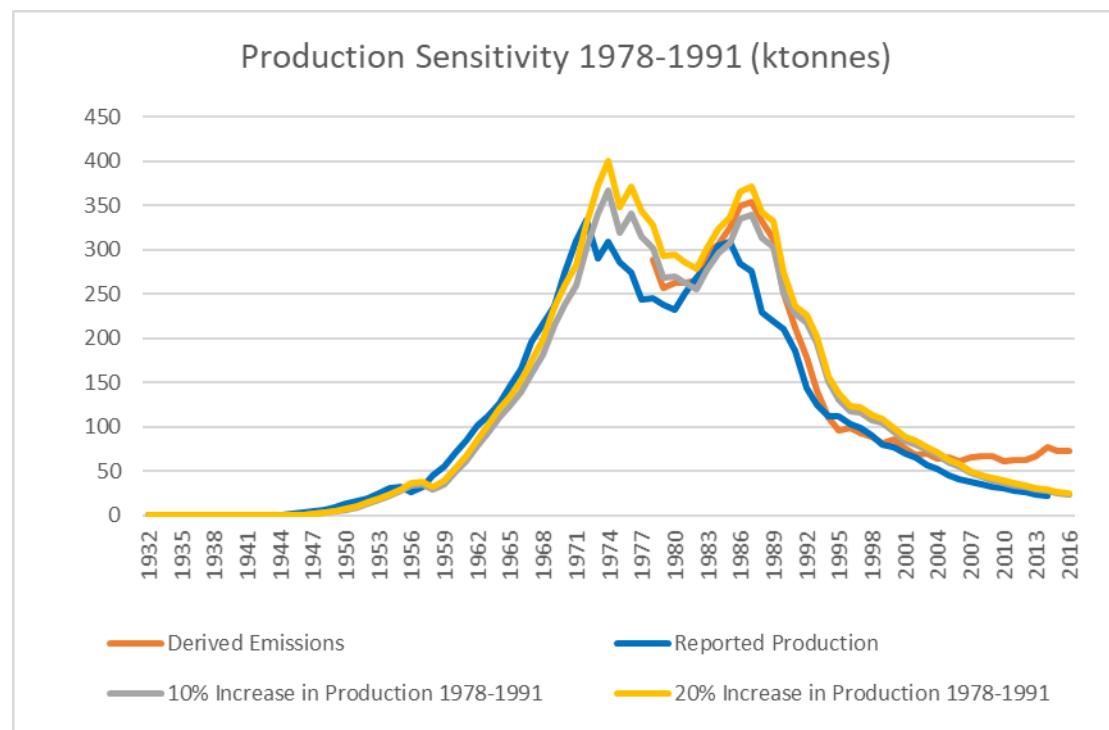


Figure A5.12. Area graph showing “bottom-up” calculation of bank size for a range of emissive-use emissions rates. As expected, the emissions rate of emissive-uses has minimal impact on the bank size.

Production under-reporting

Another scenario that was explored was that of potential under-reported production, in an attempt to clarify how the emissions profile would be affected by a reporting error. The production data reported through AFEAS and UNEP were increased by 10% and 20% separately. There was alignment with the derived emissions through 1991, but then deviated into higher emissions rates. The scenario was then changed to remove the increase in the data reported to UNEP and the deviation was delayed until 1992.

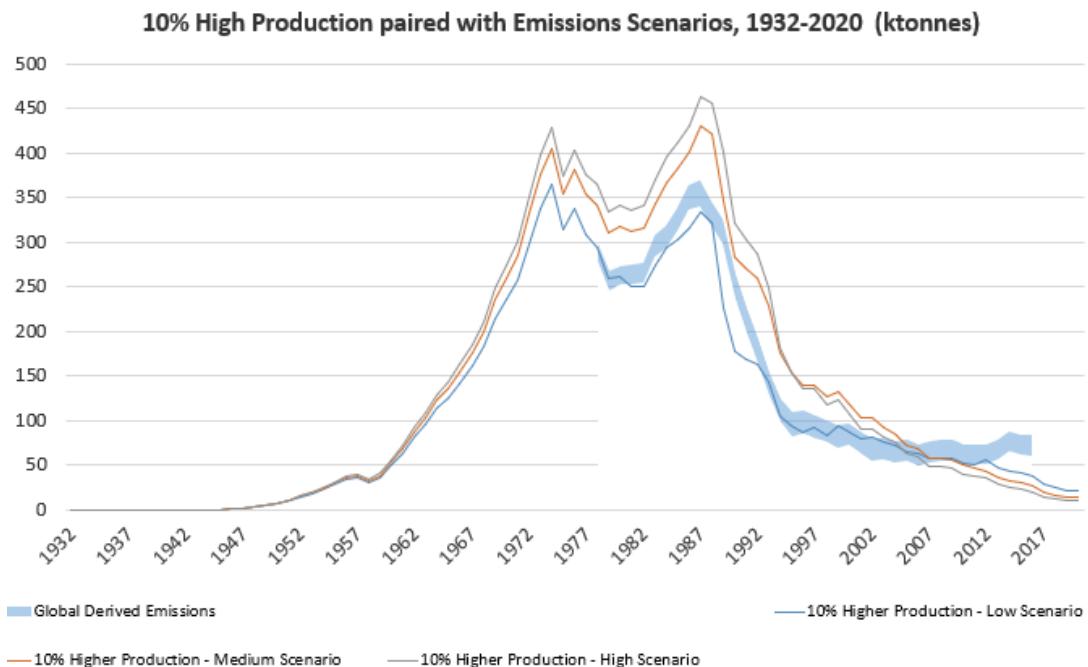
Figure A5.13 “Bottom-up” emissions sensitivity to changes in reported production for the period between 1978-1991 (kilotonnes)



Note: None of the scenarios follow the profile of the atmospherically derived emissions after 2002.

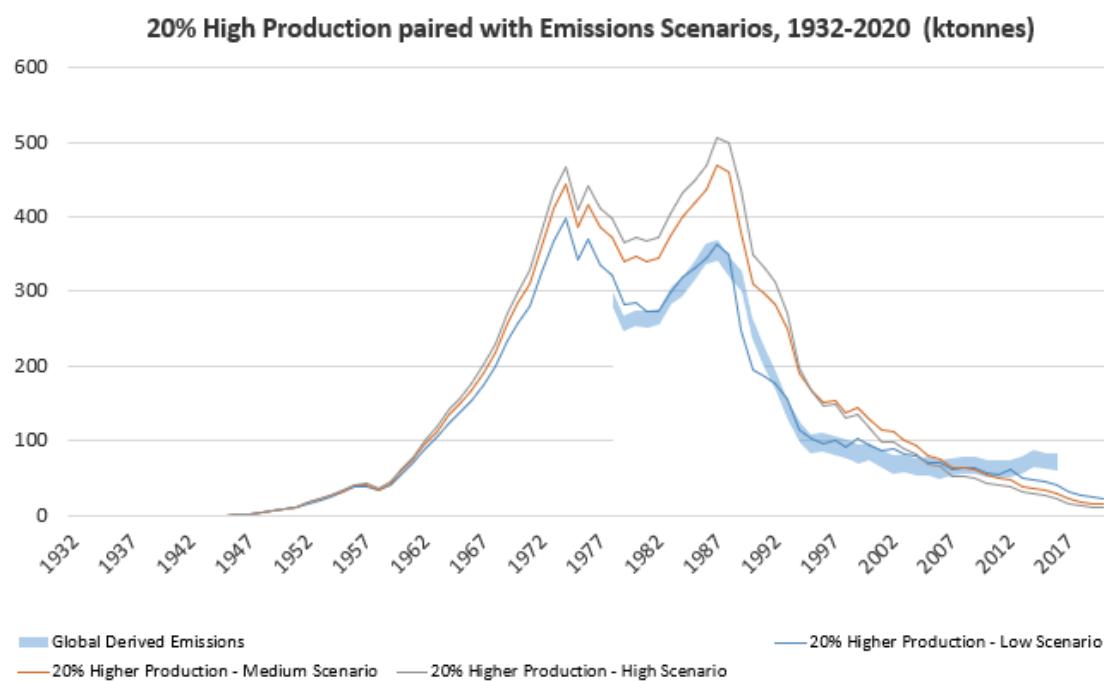
For the final report, the high production test for 10%, 20% and 40% increased production was paired with the revised emissions scenarios shown in Table 6.2. The resulting emissions are shown in Figures A5.14-16.

Figure A5.14²⁵⁰ “Bottom-up” emissions range assuming 10% higher production than reported (kilotonnes)



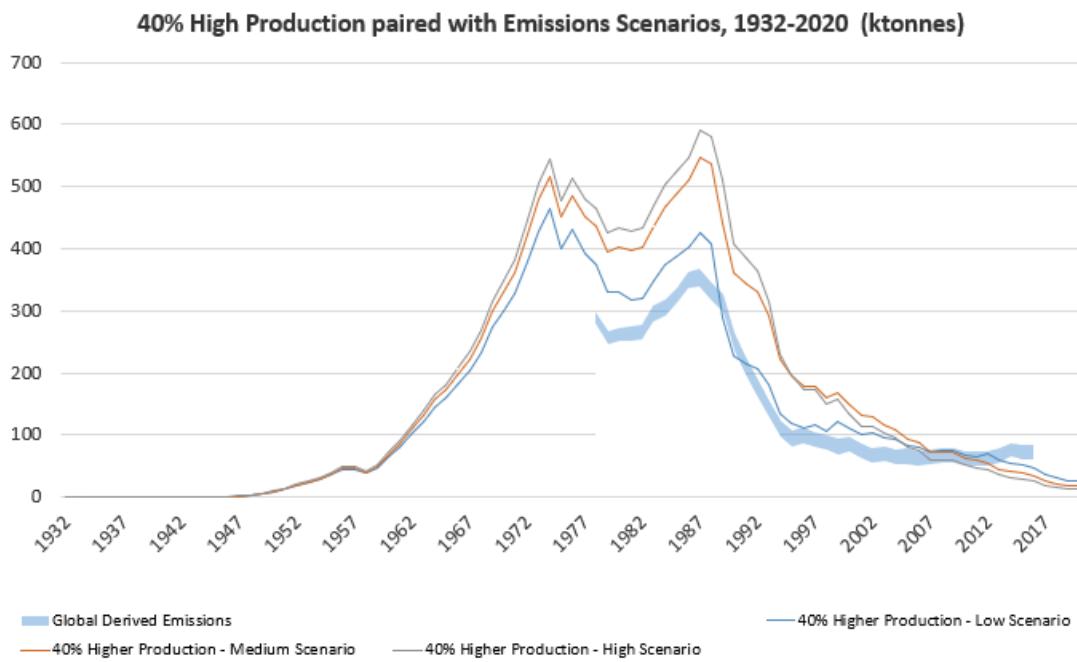
²⁵⁰ Replaces Figure A5.14 in preliminary report

Figure A5.15²⁵¹ “Bottom-up” emissions range assuming 20% higher production than reported (kilotonnes)



²⁵¹ Replaces Figure A5.15 in preliminary report.

Figure A5.16²⁵² “Bottom-up” emissions range assuming 40% higher production than reported (kilotonnes)



The model indicates that pairing the high production test with the low emissions rates scenario (shown in Table 6.2) delivers emissions that resemble the atmospheric-derived emissions. However, based on industry knowledge it seems highly unlikely that the emissions rates used in the low emissions scenario accurately depict reality. Industry experts suggest that the average emissions rates are in fact higher than the rates indicated by literature.

In addition, even though there might have been isolated cases of under-reported production, the Task Force finds it unlikely that companies and parties were consistently grossly under-reporting to both AFEAS and UNEP. A 10-20% discrepancy in reported versus actual production may be expected, but the Task Force believes that anything more than that is not to be reasonably expected. However, based on the current modeling, the Task Force cannot effectively rule out the possibility that a combination of under-reporting and varying emissions factors may have led to larger banks and subsequent bank emissions than was previously believed.

²⁵² Replaces Figure A5.16 in preliminary report

The Task Force included a range of scenarios. The highest and lowest emissions scenarios and largest and smallest bank scenarios are included here based on learnings from the Sensitivity Analysis which showed that the model was most sensitive to production rates and emissions from production and foams. All of the other scenarios examined fell into the range of these scenarios. These combine highest production rates with highest and lowest emissions rates and separately lowest production rates with highest and lowest emissions rates. The outcomes of these scenarios are noted below.

Figure A5.17 Range of Emissions Scenarios

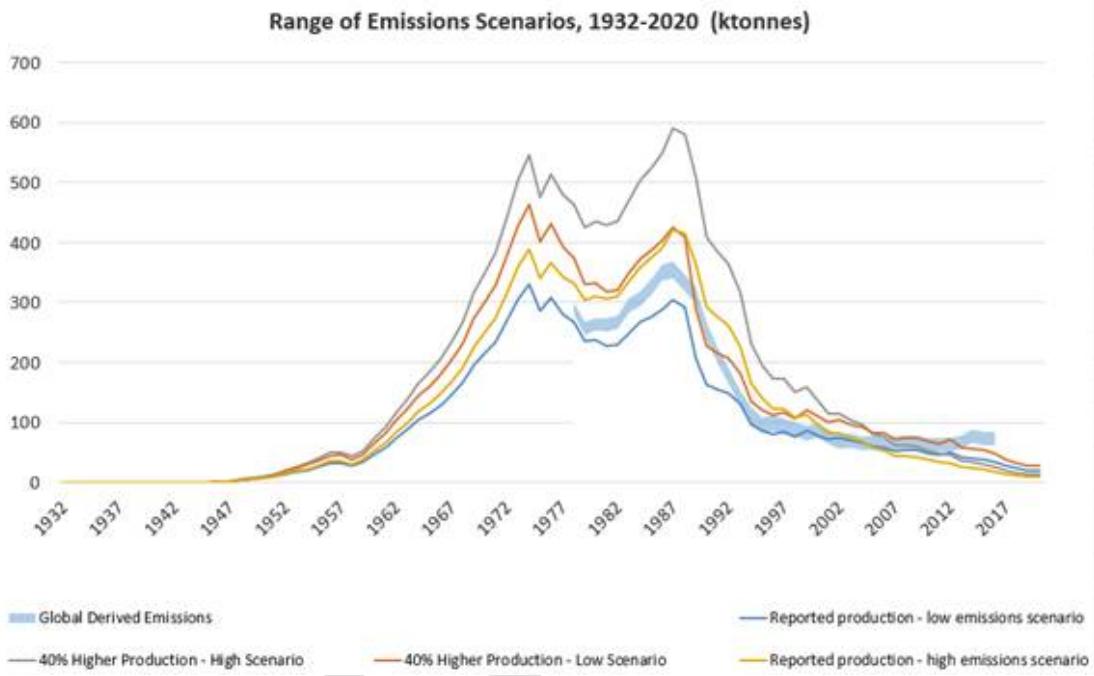
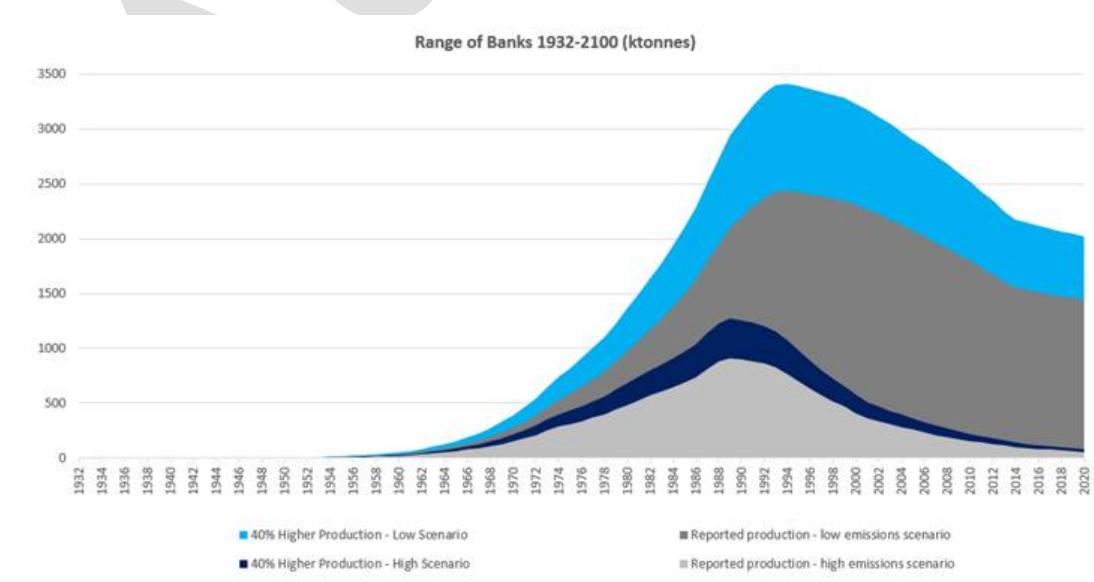


Figure A5.18 Range of banks scenarios



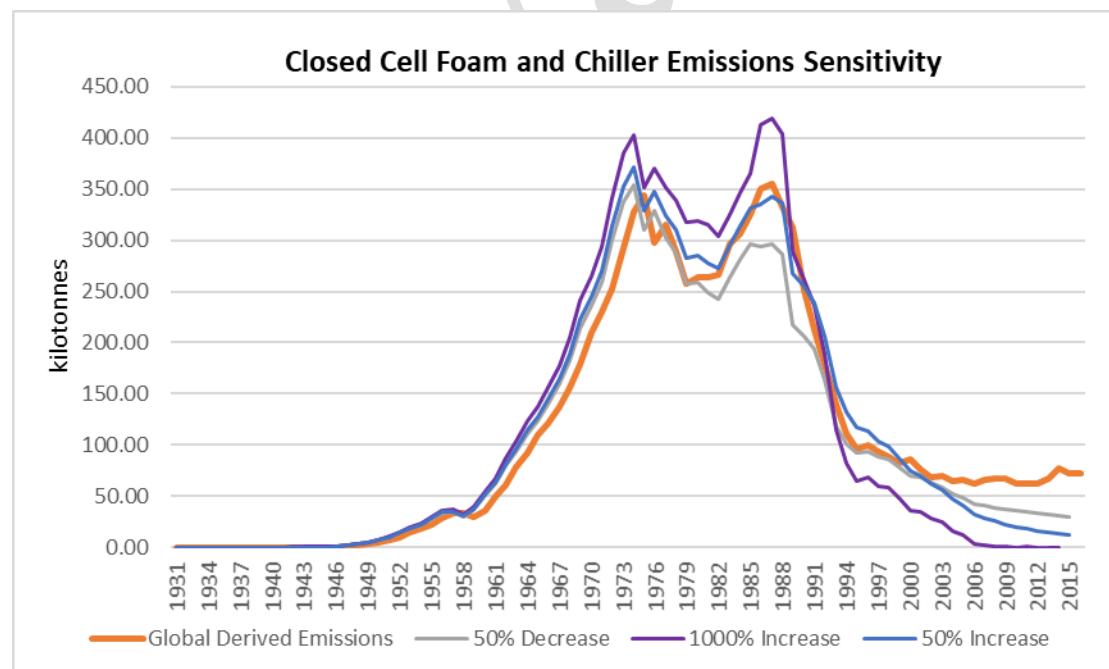
Duplicating the derived emissions

The sensitivity analysis did not provide any scenarios that explained the unexpected emissions. Possible scenarios were then considered beyond the range of the sensitivity analysis in an attempt to find a solution that might align with the derived atmospheric emissions

Initially, emissions rates were varied in an attempt to duplicate derived emissions. Using 10% production emissions, and an increased bank emissions rate of 150% the previous assumption, the deviation in “bottom-up” and derived emissions was delayed until 2006, but the difference increased in later years as bank levels dropped further due to higher emissions rates. An exaggerated example of 1000% of the previous assumption better showing the differences.

As shown in the figure below increasing the emissions rates from the refrigerant and closed-cell foam sector by 50% and even 1000% did not align with the derived emissions. This was followed with a scenario decreasing the emissions rates by 50%. In all cases, the derived atmospheric emissions in the period from 1976 through 1994 could not reproduce the derived atmospheric emissions. In all cases, emissions were lower than the atmospheric derived emissions after 2003. In the cases where the emissions rates from the banks were increased, the banks were too small to support the derived atmospheric emissions, and when the emissions rates were increased the emissions rates were too low to reach the derived emissions.

Figure A5.19 “Bottom-up” extreme scenarios, in which the emissions rates from the R/AC and closed-cell foam sector were increased by 50% and 1000%, and decreased by 50% (kilotonnes)



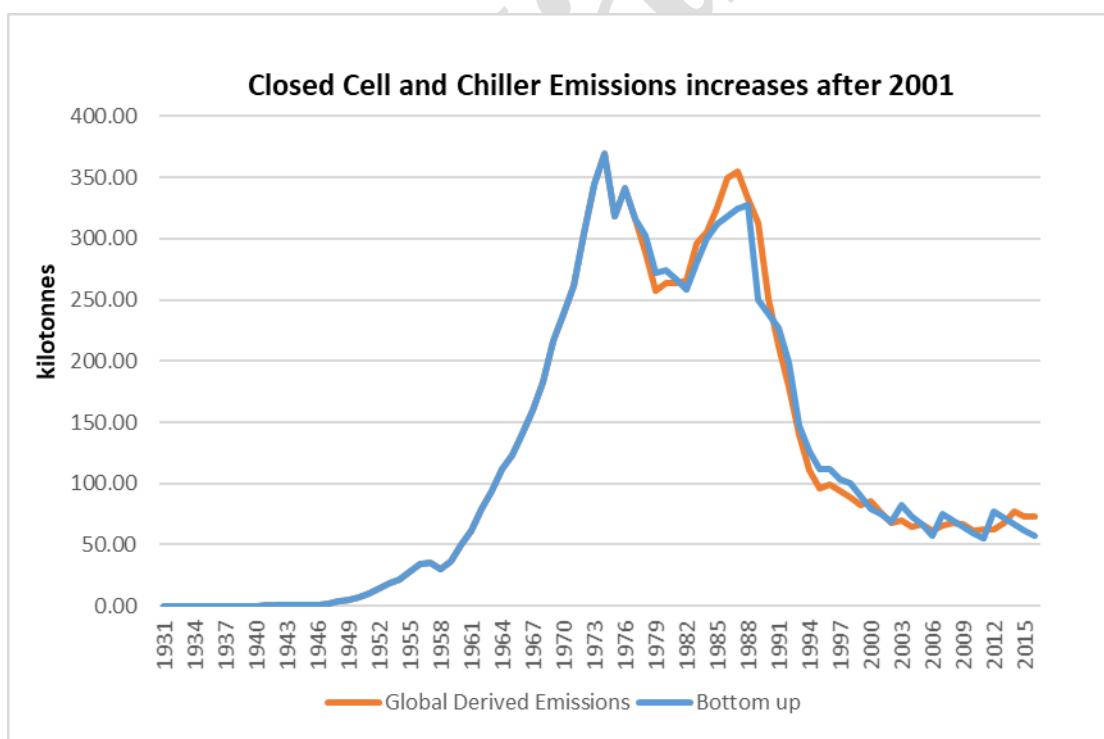
In an attempt to align with the derived emissions, modeled bank emissions rates were then changed as in the table below. The emissions rate from the chiller and foam banks were increased to 24% of the overall banks to align with the derived atmospheric emissions as

shown in the figure below. The Task Force knows of no practical reason that nearly one quarter of the banked CFC-11 in foams and as a refrigerant would be released in a single year four years in a row. This issue is further exacerbated by the fact that much of the foam blowing agent is maintained in the foam matrix and difficult to emit as noted in the TEAP Task Force Report on Foam destruction.

Table A5.1 Modelled bank emissions rates tested

Years	Refrigerant	Foam
1934 to 2002	5.00%	8.00%
2003 to 2006	7.00%	11.20%
2007 to 2011	10.00%	16.0%
2012 to end	15.0%	24.00%

Figure A5.20 “Bottom-up” emissions, when emissions rate from the chiller and foam banks were increased to 24% of the overall banks to align with the derived atmospheric emissions (kilotonnes)

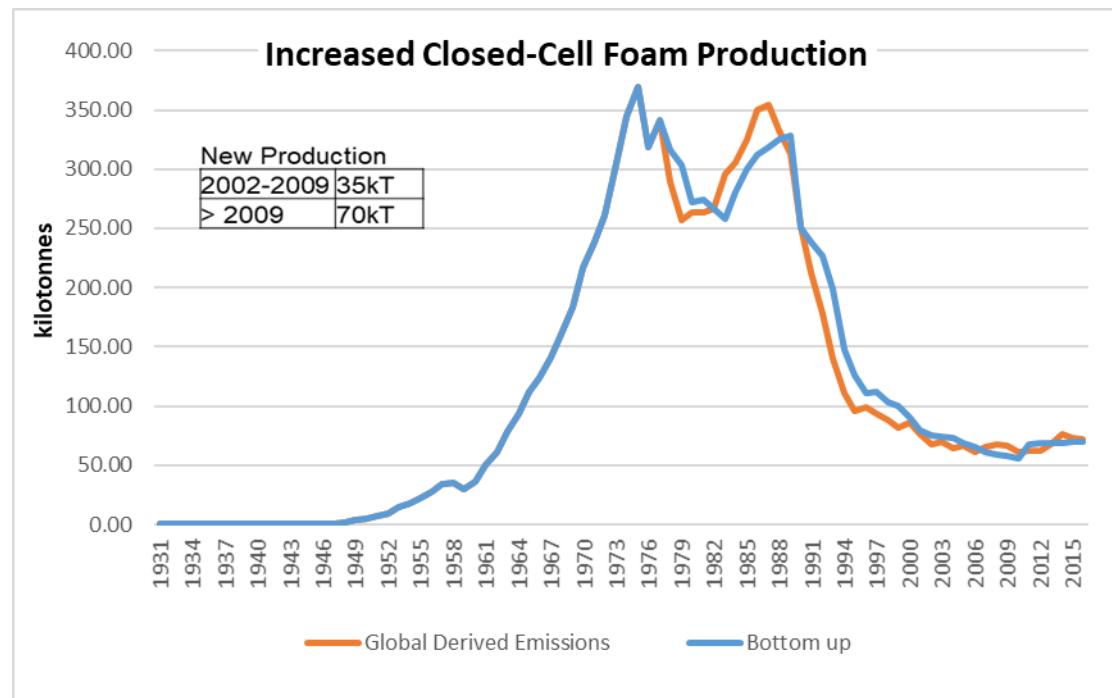


A scenario was then developed with 20 kilotonnes additional production from 2002 through 2009 and 50 kilotonnes production from 2009 through 2015 with results that were aligned to the derived emissions model. The production was then used in closed cell and emissive uses

like open cell foams (50%, sold into each sector). A similar scenario was created with 10% use in chillers, but it did not significantly change the harmonization with the derived emissions; although, it did increase the banks notably.

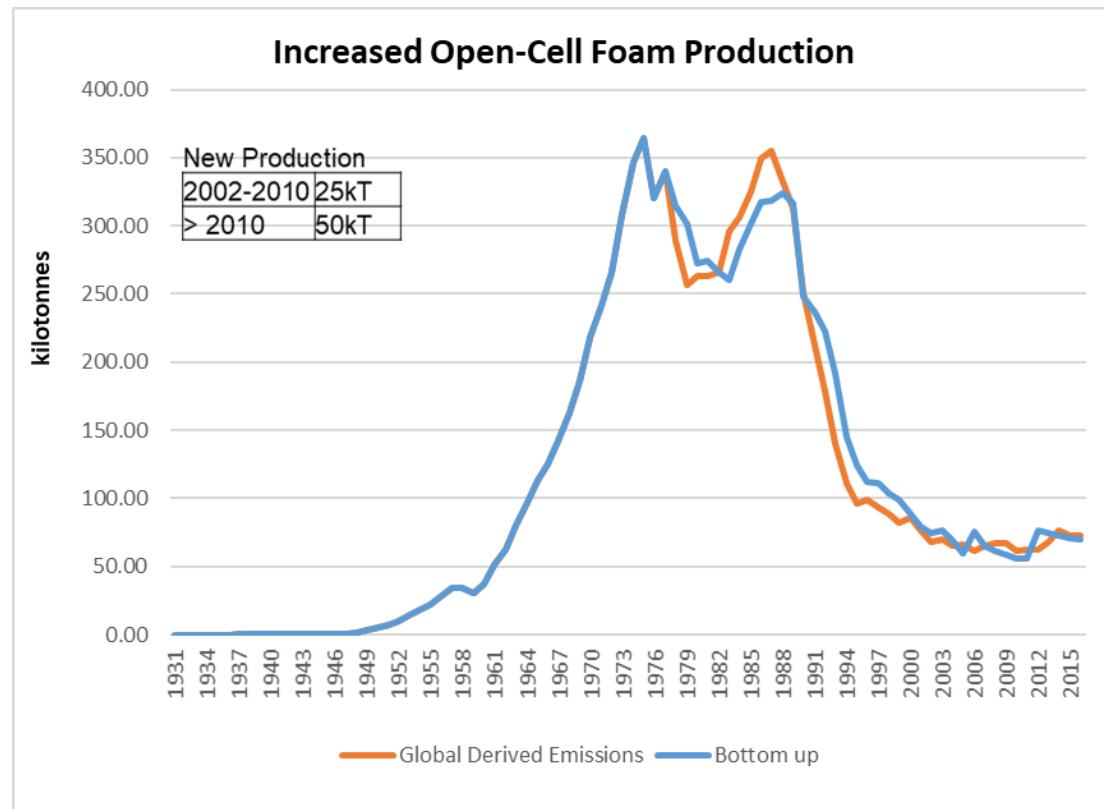
Similarly, a scenario was developed with production of CFC-11 of 35 kilotonnes from 2002–2009 and 70 kilotonnes from 2009 – 2016 used in closed cell foams only with the following results.

Figure A5.21 “Bottom-up” emissions for increased production of closed cell foams from 2002 through 2016 (kilotonnes)



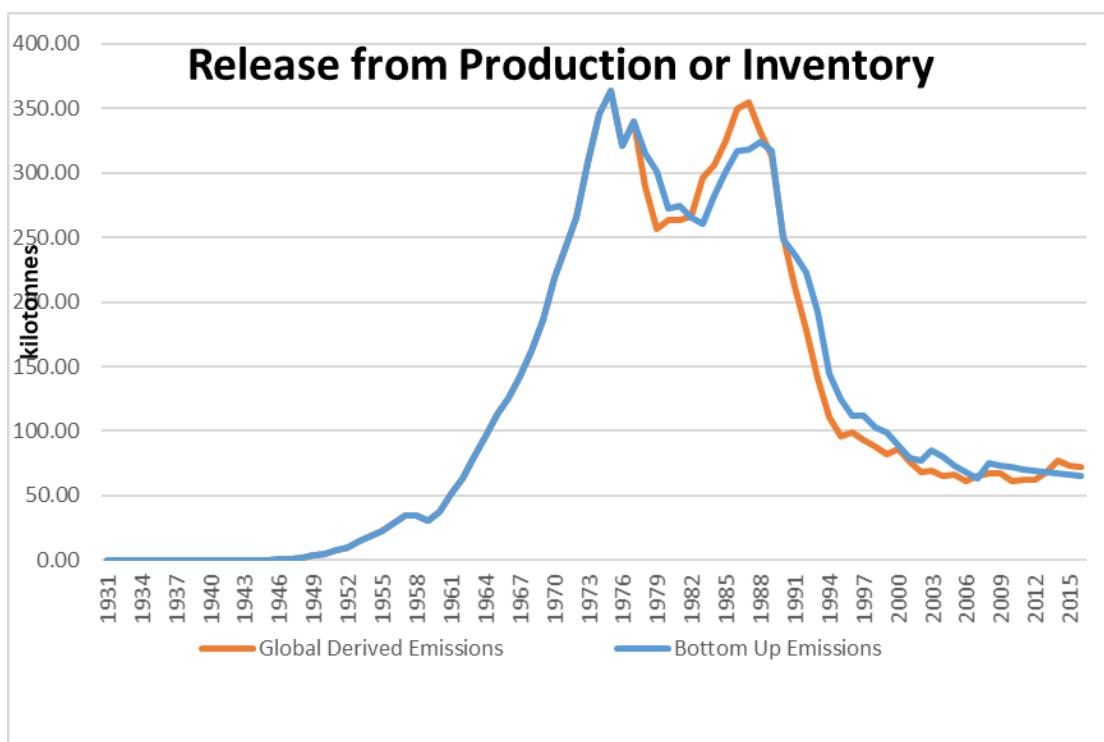
A scenario was developed with additional production of CFC-11 of 25 kilotonnes from 2005–2010 and 50 kilotonnes from 2011–2016 used solely in open cell foams with the following results.

Figure A5.21 “Bottom-up” emissions for additional production used in open-celled foams (kilotonnes)



A scenario was developed with additional production of CFC-11 of 25 kilotonnes from 2005-2010 and 50 kilotonnes from 2011-2016 that was emitted from production with the following results. It seems unlikely that large quantities would be produced and merely released from an economic perspective.

Figure A5.22 “Bottom-up” emissions assuming additional production CFC-11 released to atmosphere (kilotonnes)



Regional CFC-11 emissions from closed-cell foams

In an attempt to better quantify the unexpected emissions of CFC-11, the Task Force has evaluated expected emissions from banks so that they might be differentiated from total emissions. The key focus of this effort has been related to foam banks as banks from other uses have largely been released. For reference, banks related to emissive uses such as aerosols, propellants and open-celled foams have been estimated to have been very small as they are largely emitted during manufacturing or use, and any remaining solvents would have been either recycled or emitted. CFC-11 used in chillers has been carefully contained and remaining CFC-11 used as a refrigerant has largely been reclaimed, recycled or destroyed. Also, as noted in the chapter on refrigerants in the preliminary report, less than 35,000 tonnes of CFC-11 remained in the chiller bank as of 2008. In contrast, CFC-11 used in closed-cell foams is emitted throughout the product lifecycle: during the foam manufacture process (manufacture and installation of foam in a refrigerator or building), while the foam is in use, during the dismantling process and from landfills (unless the foam or blowing agent is collected and destroyed).

In the 2006 Rigid and Flexible Foams Assessment Report, a detailed breakdown was developed of the use of blowing agents in foams by global sub-region and foam type. This has

been used as the basis for this methodology evaluating CFC-11 foam emissions and banks for this final report. These numbers were used from 1980 through 1996.

Note that in 1986, Article 5 parties produced only 4% of the total production of CFC-11. Because Article 5 parties produced and consumed very small quantities of CFC-11 prior to 1981, the model has been simplified assuming that no CFC-11 was used in Article 5 parties prior to 1981. By 1996, CFC-11 was banned from use in non-Article 5 parties. For the periods of time prior to significant use by Article 5 parties and after the ban for non-Article 5 parties, the distribution by foam type and region has been normalized to the total production for non-Article 5 and Article 5 parties respectively. It is also important to note that no allowance has been made for the legal export of goods containing CFC-11 from Article 5 parties to non-Article 5 parties in appliances and other finished products such as refrigerated containers. This will bias the banks and emissions from those banks to be higher in Article 5 parties that are large exporters of those finished products such as China, Thailand, South Korea, Brazil, Mexico and other locations.

Documented emissions rates from a number of sources were considered including the Flexible and Rigid Foams Technical Options Committee (FTOC) as well as the 2007 IPCC report for a number of types of foams in this analysis. The FTOC included the latest research related to emissions by product type as well as handling losses in their emissions rates. There is a limited body of information related to emissions rates from landfills. It was largely assumed that emissions rates from landfills would be approximately equivalent to the emissions rates from products taking into consideration that the foam would not be encapsulated as they are during use (coated or in an appliance, etc.), but conservatively there would be some cover of the landfill. Conservative emissions rates were used to maximize the size of the banks for this analysis during later years so that the maximum possible emissions would be described as “expected”.

The regional emissions and banks approximations follow using the “most likely” scenarios as the basis for the total use of CFC-11 in closed cell foams.

Figure A5.23 Global banks and emissions related to closed-cell foams



Figure A5.24 CFC-11 banked in foams in Europe over time using 2006 FTOC Assessment Report foam manufacturing estimates

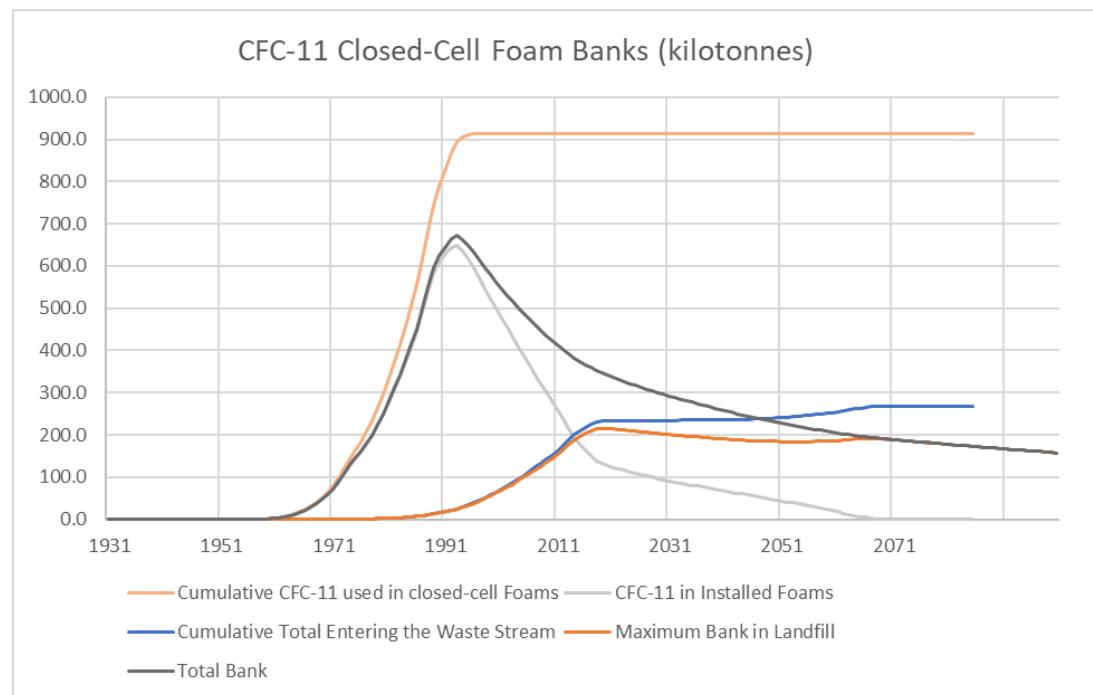


Figure A5.25 CFC-11 banked in foams in Europe over time using 2006 FTOC Assessment Report foam manufacturing estimates 50% of the CFC-11 is destroyed

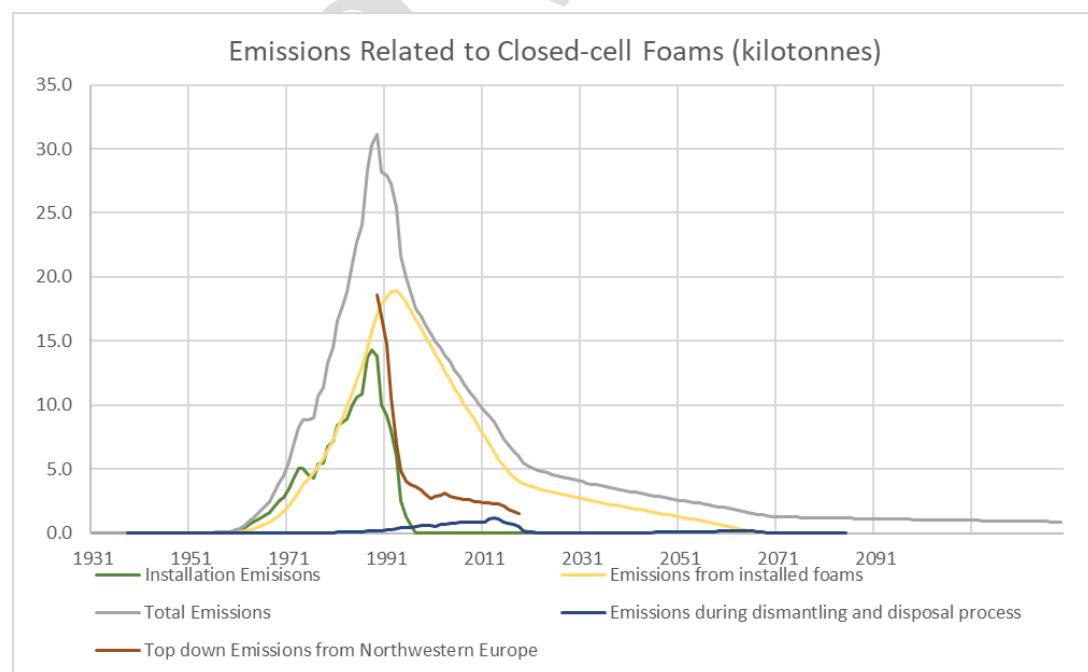


Figure A5.26 North America banks and emissions related to closed-cell foams



Figure A5.27 Japan banks and emissions related to closed-cell foams

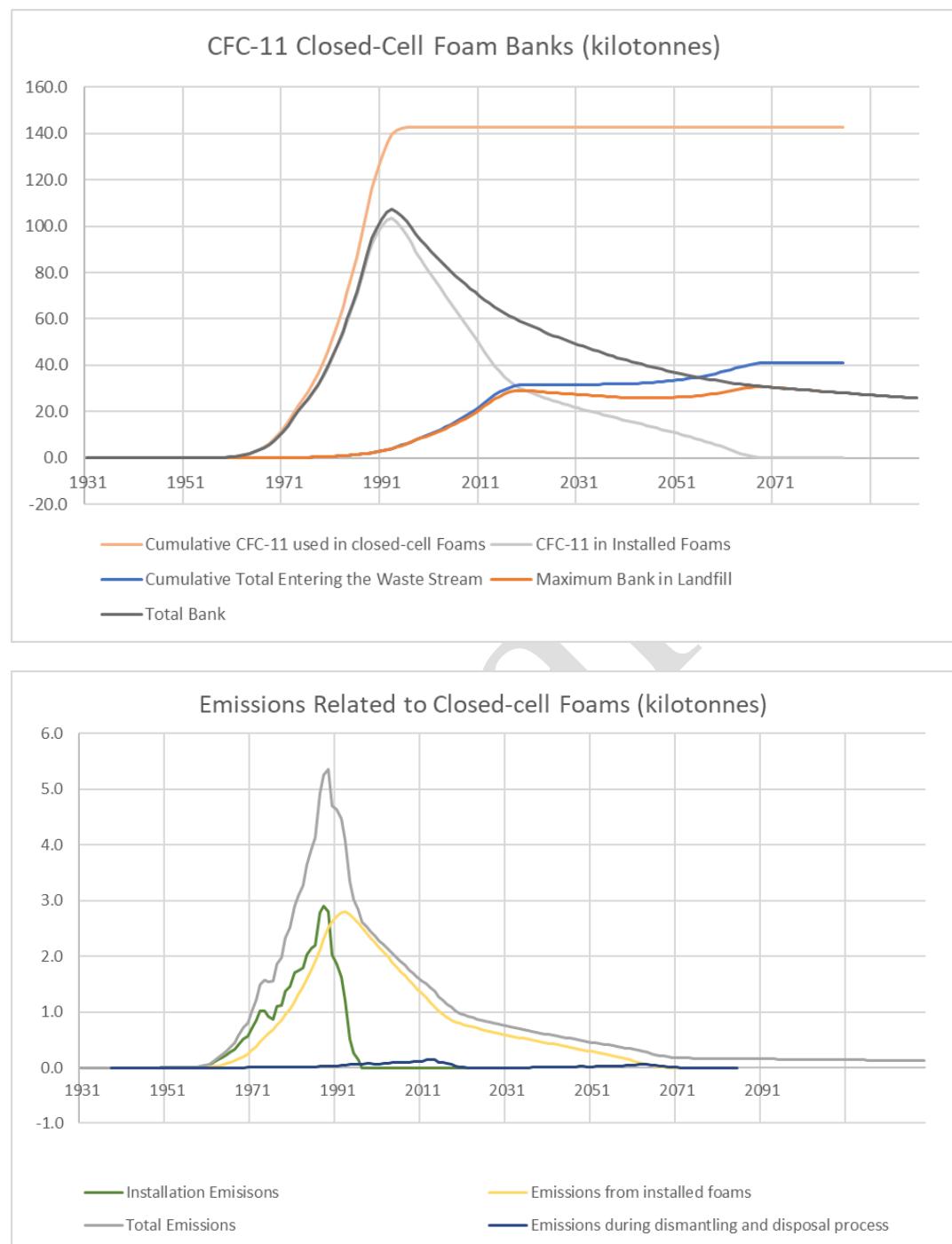


Figure A5.28 Non-Article 5 Other banks and emissions related to closed-cell foams

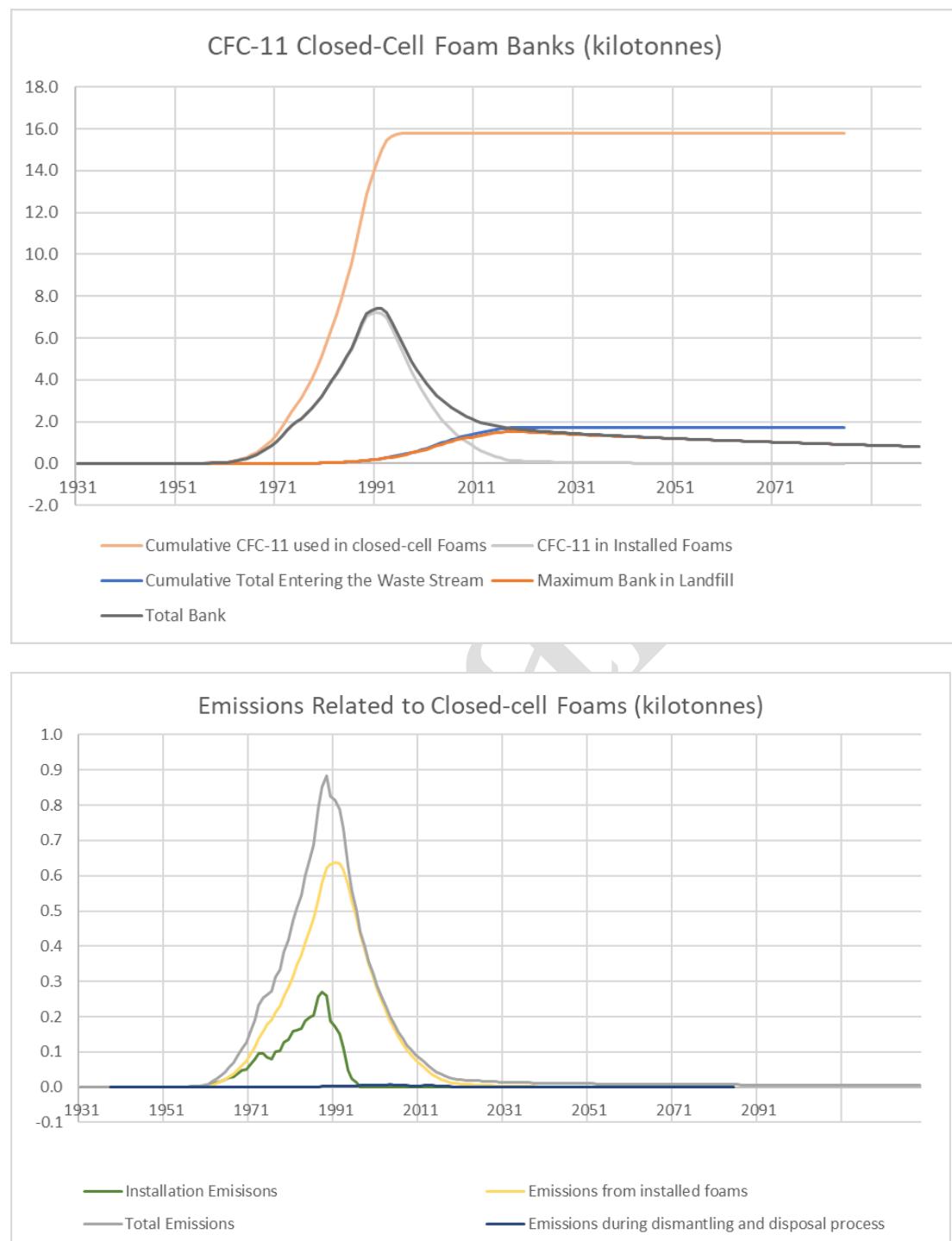


Figure A5.29 Northeast Asia “most likely” CFC-11 emissions from closed-cell foam scenario

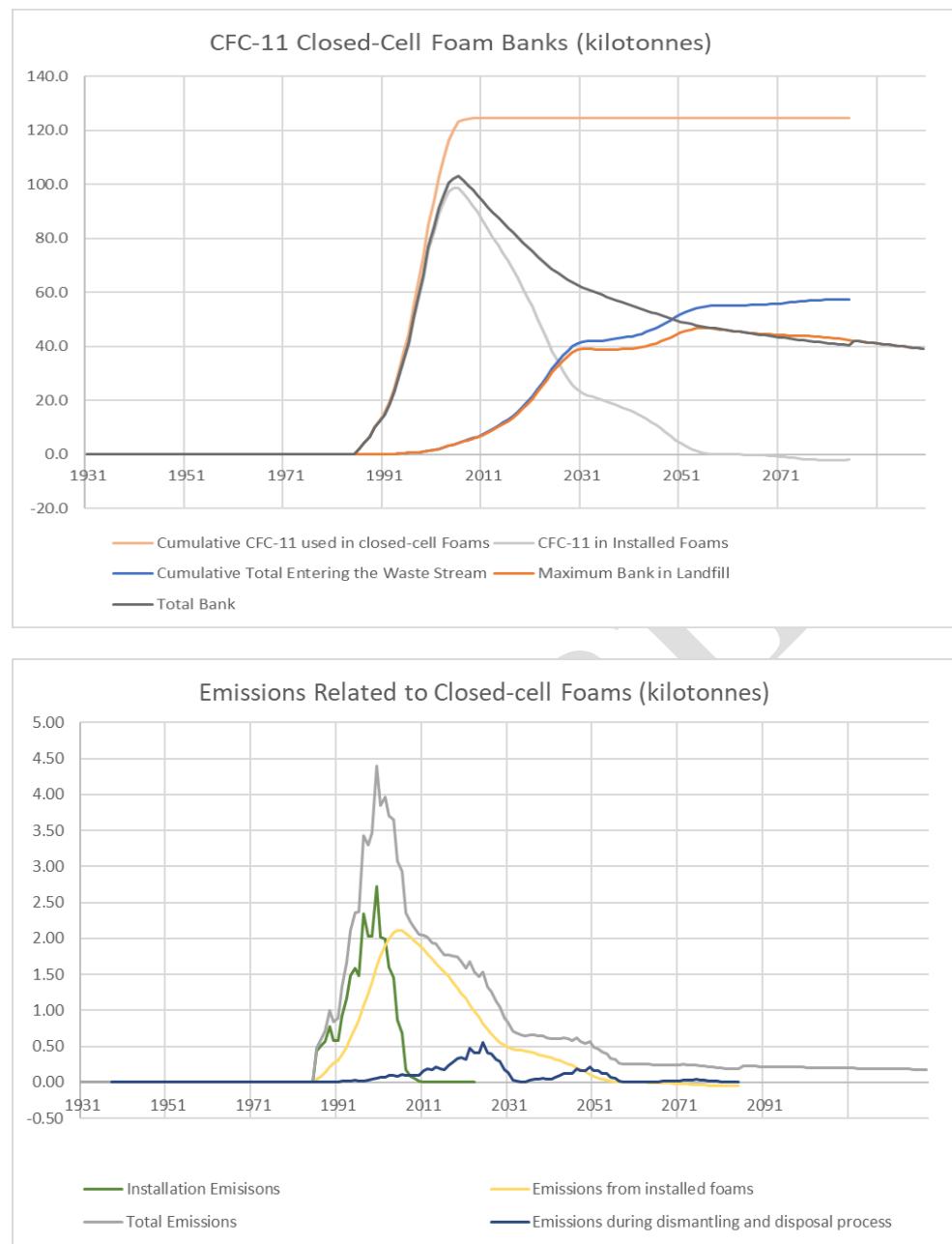


Figure A5.30 CEIT “most likely” CFC-11 emissions from closed-cell foam scenario

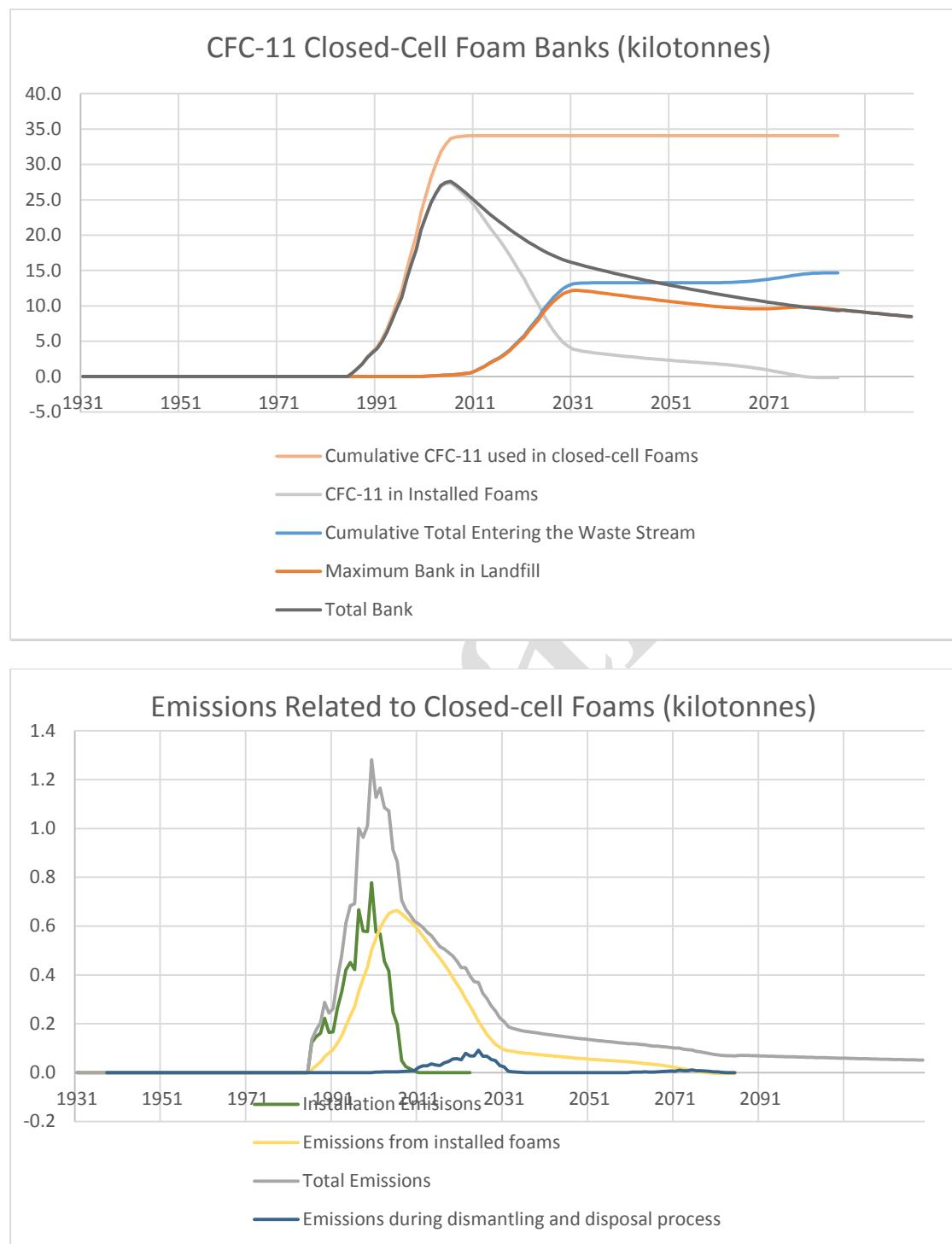


Figure A5.31 SE AP “most likely” CFC-11 emissions from closed-cell foam scenario

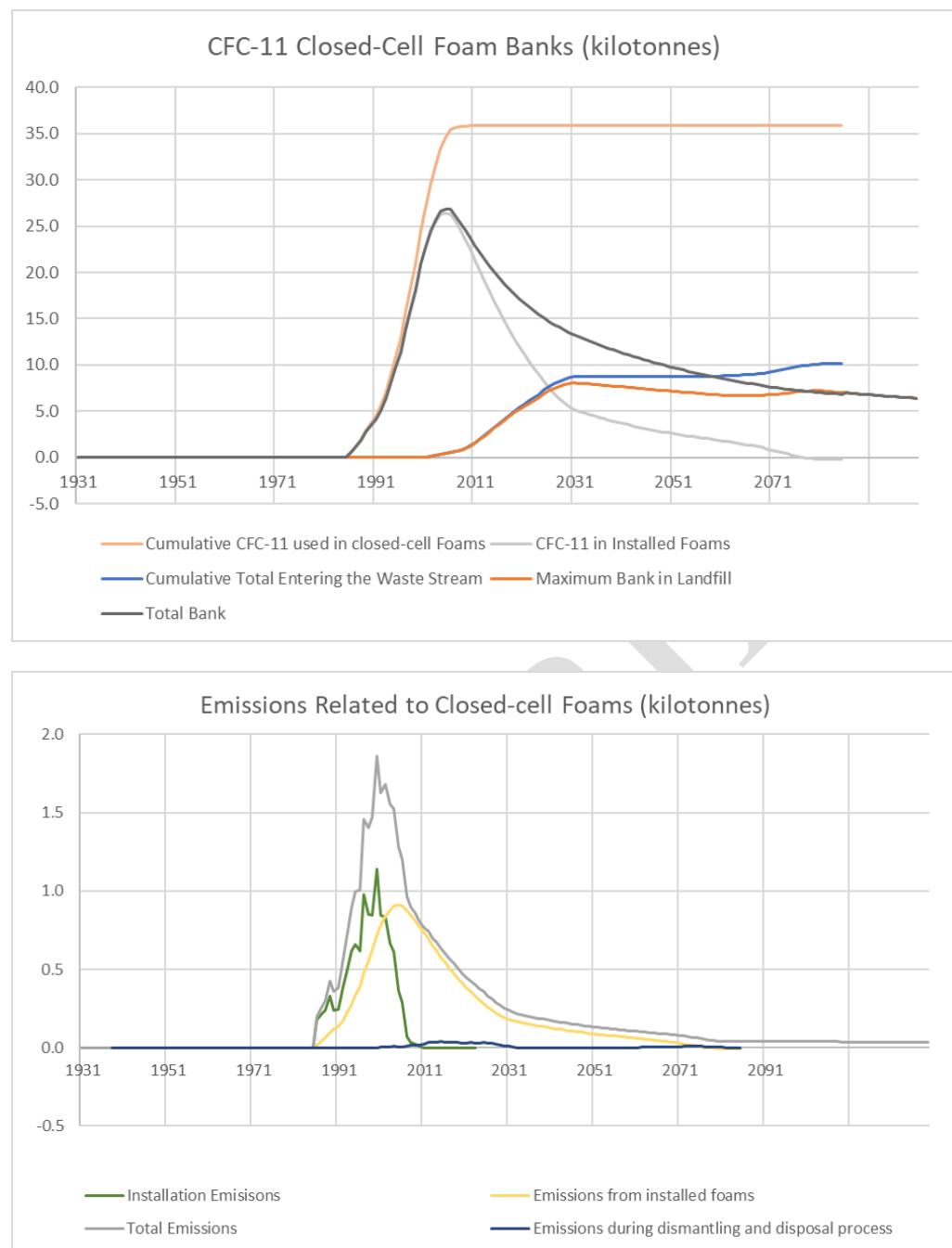


Figure A5.32 South AP “most likely” CFC-11 emissions from closed-cell foam scenario

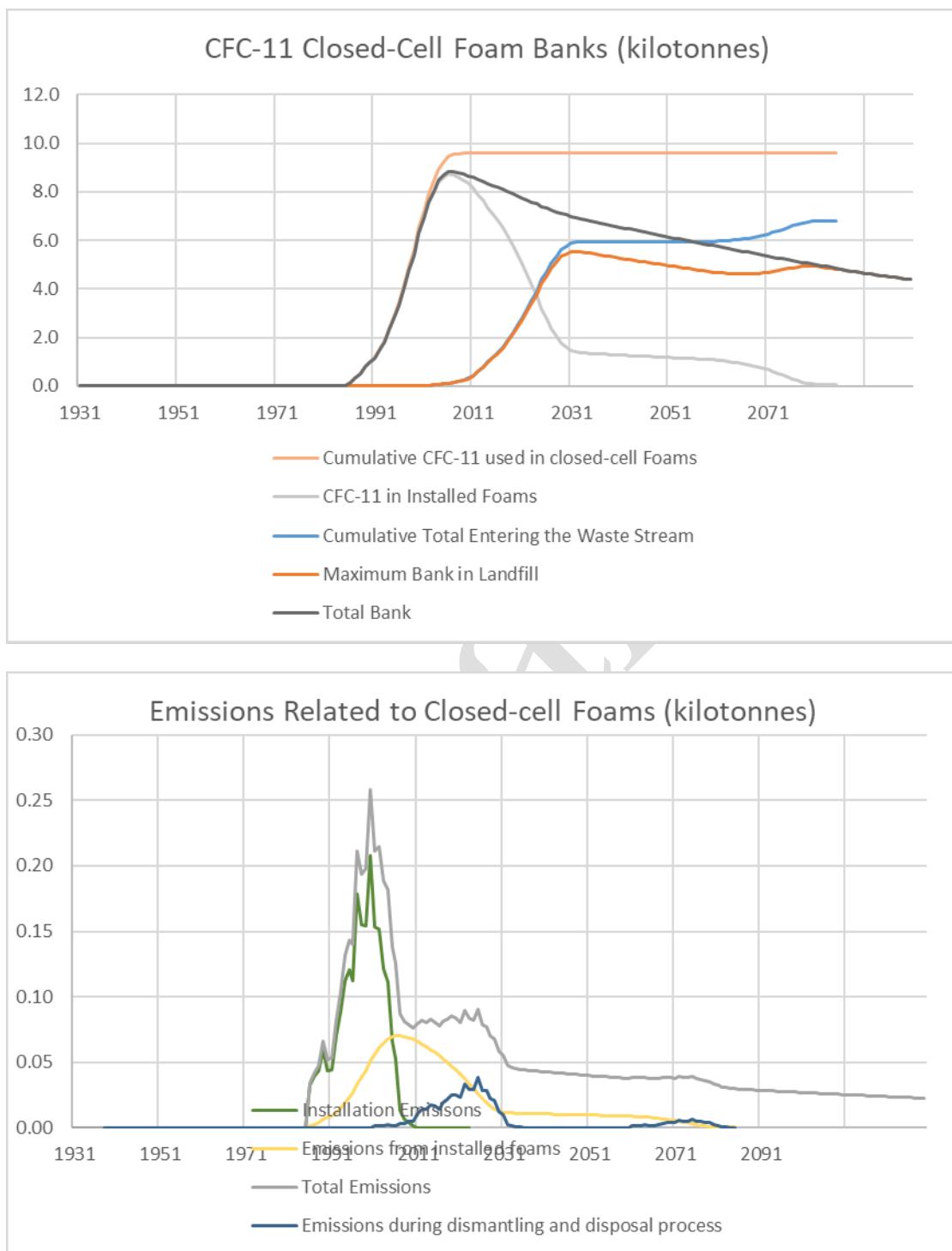


Figure A5.33 Sub-Saharan Africa “most likely” CFC-11 emissions from closed-cell foam scenario

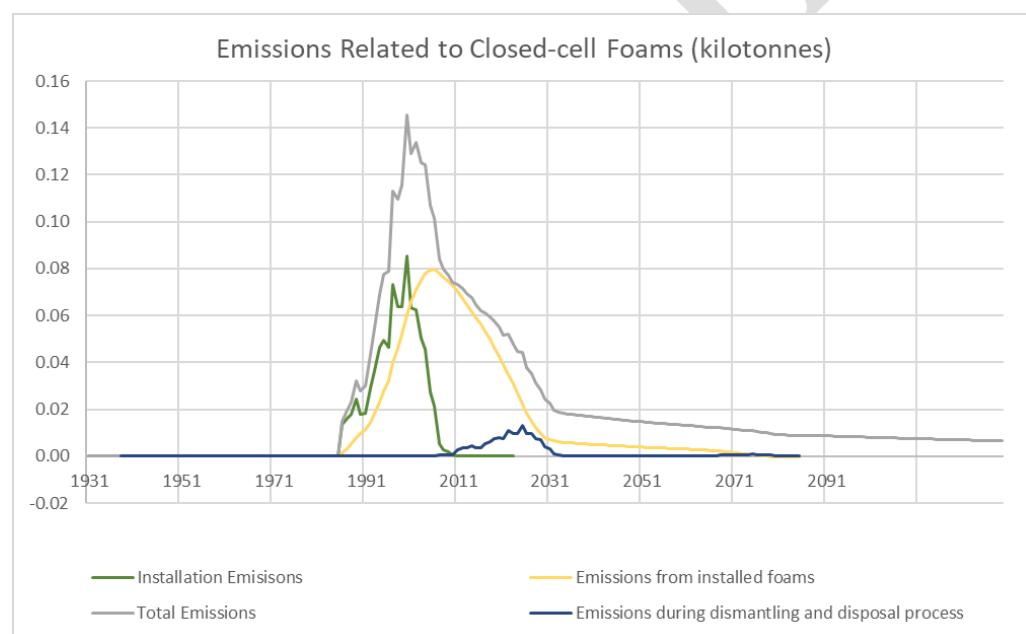
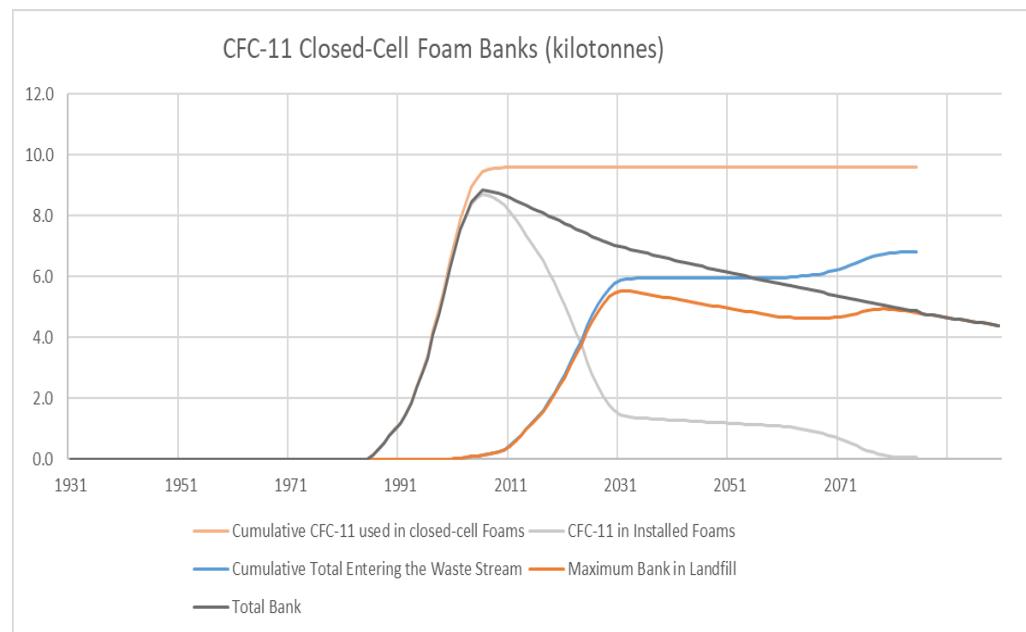


Figure A5.34 Middle East, North Africa “most likely” CFC-11 emissions from closed-cell foam scenario

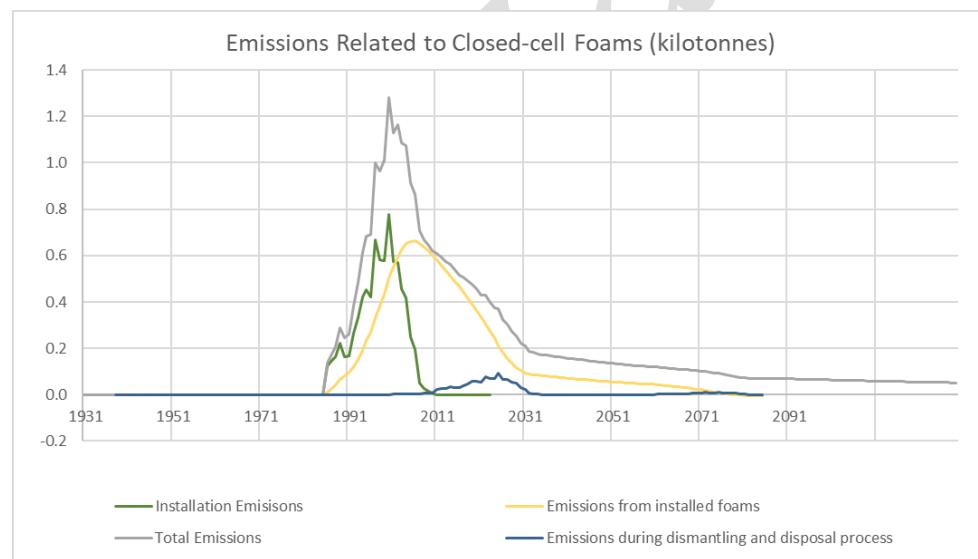
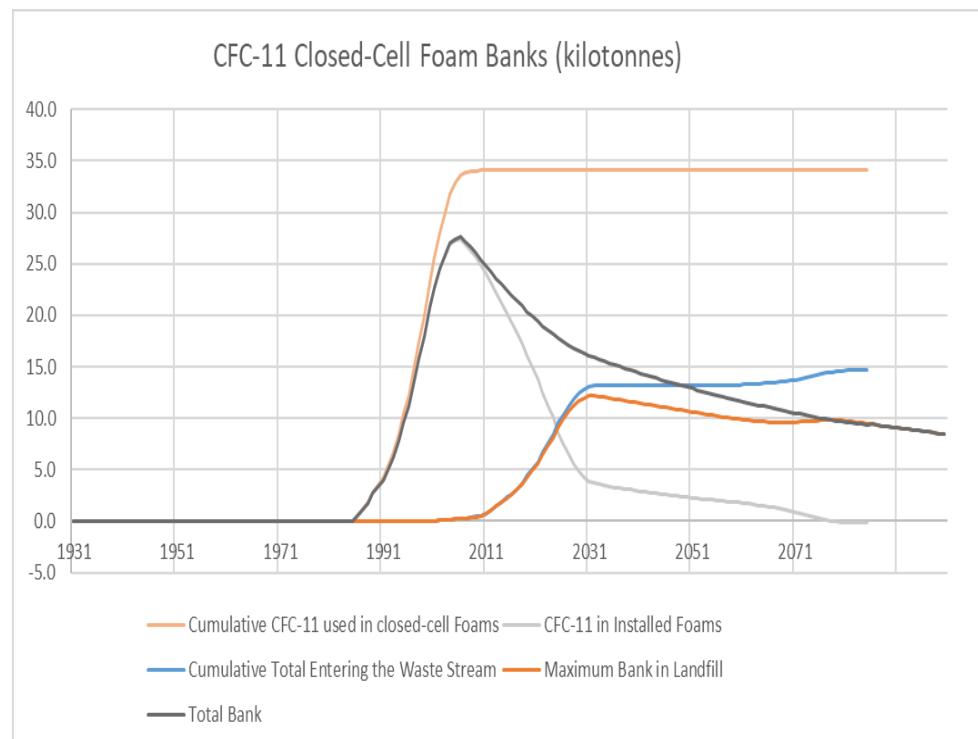
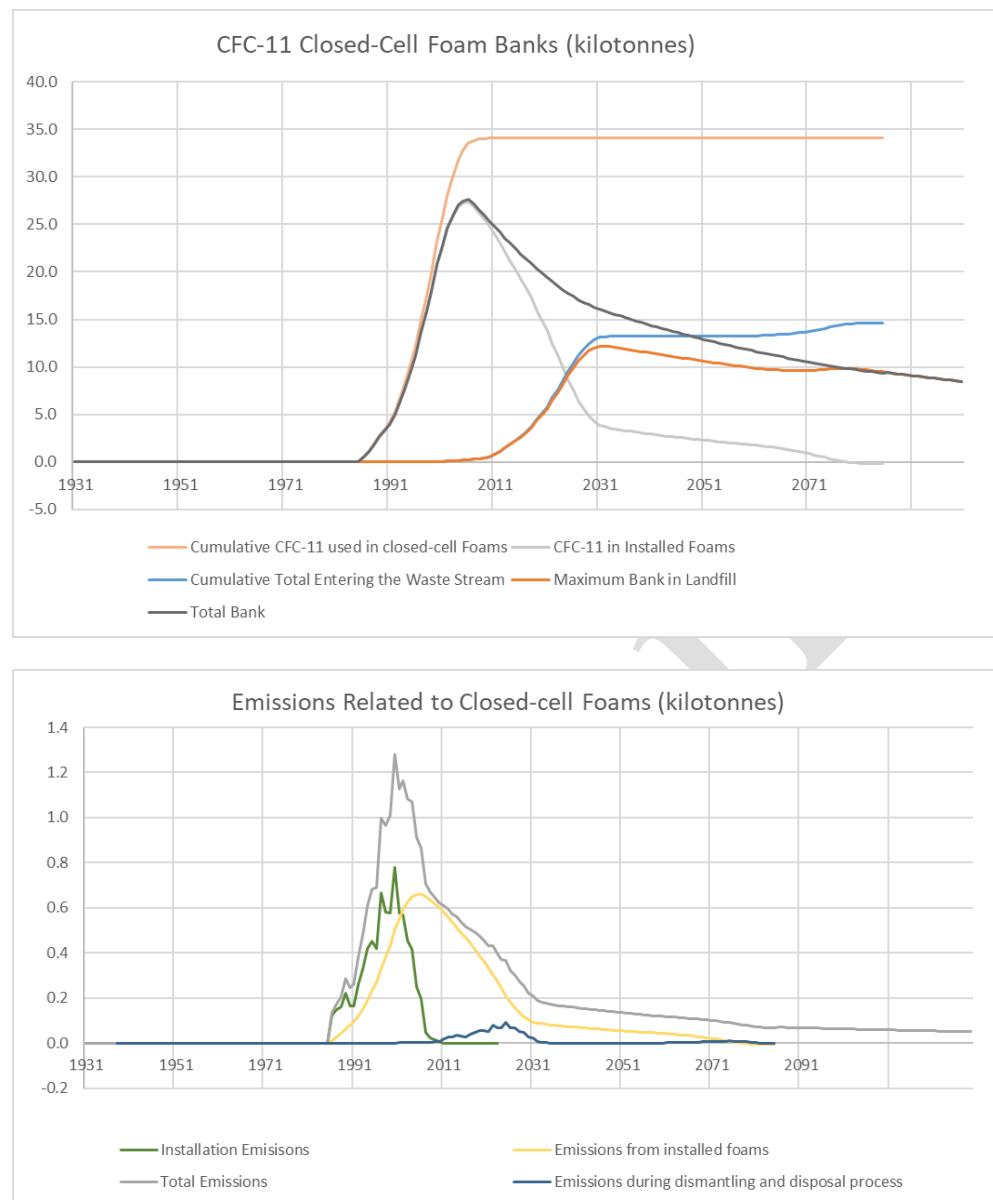


Figure A5.35 Latin America “most likely” CFC-11 emissions from closed-cell foam scenario



Appendix 6: Emissions considerations based on the SROC 2005 report values

A6.1 Introduction

Appendix 6 investigates the emissions from “bottom-up” calculations in Special Report on Ozone and Climate (SROC)²⁵³ for the period 2002-2012 and compares them with emissions derived from atmospheric measurements.

For this Task Force report, the BAU banks and emission values from the SROC report have been used for CFC-11, but for the reasons mentioned in Section 6.3, the size of the CFC-11 banks were underestimated because of the assumption of full release at end-of-life unless recovery was already established (e.g. in refrigerators). With some CFC-11 used in 2002 in refrigeration and AC, implying a bank and emissions, this use was expected to disappear after 2019-2025 (see section 4). The main emphasis in this CFC-11 Emissions Task Force Report is on CFC-11 emissions from foam banks.

The size of existing and future banks of blowing agent in the appliance and transport sectors was estimated, but for the reasons mentioned above, the size of the CFC-11 banks may have been underestimated because of the assumption of full release at end-of-life unless recovery was already established (e.g., in refrigerators). The baseline scenario already takes into account the recovery activity taking place in Europe and Japan, so bank sizes were assumed to not automatically equate to future emissions.²⁵⁴

Based on the quantities and types of usage in developed countries reported by AFEAS until 1987-1990, approximately 8% of the CFC-11 production was used for refrigeration, 30% was used for closed cell foam, and 62% was used in open cell foams, aerosol propellants, solvents, and other emissive uses. In developed countries, with decreasing amounts of CFC-11 produced, the percentage of CFC-11 used for closed cell foam production increased to more than 60% in the period from 1990 to 1995. For a more conservative assumption for the banks, a similar percentage for closed cell foam production for the period after 1995 in the total developing country CFC-11 production was used. Foam production is the most important consideration in determining the CFC-11 bank. While open cell foam, solvents, aerosols, etc.,

²⁵³ This chapter references:

IPCC/TEAP Special Report on Ozone and Climate (SROC), 2005. *Special Report, Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbon and Perfluorocarbons*, Intergovernmental Panel on Climate Change and Technology and Economic Assessment Panel, Cambridge University Press, 2005, ISBN 100-521-68206-1 (Report and Supplementary Material);

TEAP, 2005. *Supplement to the IPCC/TEAP Report*, Technology and Economic Assessment Panel, November 2005, ISBN 92-807-2733-8;

Montzka, S. et al., An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, 2018, **557**, 413–417. <https://doi.org/10.1038/s41586-018-0106-2>;

SPARC, 2013. *Lifetimes of Stratospheric Ozone-Depleting Substances, Their Replacements, and Related Species*, SPARC Report No. 6, WCRP-15/2013, December 2013.

²⁵⁴ A conclusion drawn in 2015 was that, with technology proven and the cost of recovery from refrigerators currently estimated at 10-50 USD/tCO₂-eq, it would appear reasonable to assume that all refrigerator foams could be managed at end-of-life by 2015 if the investment in plants to do so were geographically spread appropriately. This would, however, involve investment in developing as well as developed countries. One scenario evaluated in this report looks at the potential impact of all appliances being processed at end-of-life with anticipated recovery levels in excess of 80% of the original blowing agent loading.

are essentially 100% emissive, closed cell foam is less emissive during manufacturing. CFC-11 use in refrigeration and AC is assumed to be for servicing to compensate for leaks. The percentage used for servicing is dependent on installation due to new manufacturing of CFC-11 equipment, which applies to the developing countries until about 2004 (See chapter 4).

Using these assumptions, the SROC report estimated that 97% of the total bank was held in closed cell foams in 2002²⁵⁵, and 2.8% remained in R/AC equipment bank, plus some other small stockpiles (i.e., MDIs). Although there is some uncertainty, it was estimated that approximately 35-40% of total CFC-11 cumulative production through 2010 would remain in foam banks, whereas this percentage is in the order of only 5% for the banks in the R/AC sector. This is mainly for CFC-11 chillers for air conditioning and for some industrial refrigeration purposes. The rest (~55-60%) of cumulative production through 2010 had already been emitted. Tables A6.1 and A6.2 show the banks and emissions values for CFC-11 for a BAU case for non-Article 5 and Article 5 parties for the separate years 2002 and 2015.

Table A6.1 CFC-11 Business as Usual (BAU) 2002 and 2015 banks for non-Article 5 and Article 5 parties

2002 BAU Banks for CFC-11										Total SROC
	Refrigeration, Stationary AC, Mobile AC	Domestic refrigeration	Commercial refrigeration	Transport refrigeration	Industrial refrigeration	Stationary AC	Mobile AC	Foams	Medical Aerosols	
		t	t	t	t	t	t	t	t	kt
Non-Article 5	30,856	0	0	0	901	29,955	0	1,230,618	2,100	1263.6
Article 5	14,588	0	0	0	167	14,421	0	407,679	700	423.0
Global	45,444	0	0	0	1,067	44,376	0	1,638,297	2,800	1686.5

2015 BAU Banks for CFC-11										Total SROC
	Refrigeration, Stationary AC, Mobile AC	Domestic refrigeration	Commercial refrigeration	Transport refrigeration	Industrial refrigeration	Stationary AC	Mobile AC	Foams	Medical Aerosols	
		t	t	t	t	t	t	t	t	kt
Non-Article 5	8,751	0	0	0	430	8,321	0	915,934	0	924.7
Article 5	5,287	0	0	0	99	5,188	0	194,292	700	200.3
Global	14,037	0	0	0	529	13,508	0	1,110,226	700	1125.0

²⁵⁵ It was assumed for the SROC model that blowing agent was totally released at product end of life as a ‘worst-case’ assumption. This assumption was addressed in later work when greater consideration was given to foam banks in the waste stream (e.g., landfills). This is important, since the reduction in total bank size in the period between 2002 and 2015 would be exaggerated when applying that ‘worst case’ assumption.

Table A6.2 Business as Usual (BAU) 2002 and 2015 emissions for non-Article 5 and Article 5 parties

2002 BAU Emissions for CFC-11												
	Refrigeration, Stationary AC, Mobile AC	Domestic refrigeration	Commercial refrigeration	Transport refrigeration	Industrial refrigeration	Stationary AC	Mobile AC	Foams	Medical Aerosols	Total SROC		
	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	kt yr-1		
Non-Article 5	4,652	0	0	0	202	4,450	0	13,884	2,100	20.6		
Article 5	2,455	0	0	0	34	2,421	0	6,018	700	9.2		
Global	7,106	0	0	0	236	6,870	0	19,902	2,800	29.8		

2015 BAU Emissions for CFC-11												
	Refrigeration, Stationary AC, Mobile AC	Domestic refrigeration	Commercial refrigeration	Transport refrigeration	Industrial refrigeration	Stationary AC	Mobile AC	Foams	Medical Aerosols	Total SROC		
	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	t yr-1	kt yr-1		
Non-Article 5	2,134	0	0	0	68	2,066	0	10,140	0	12.3		
Article 5	1,342	0	0	0	17	1,326	0	4,338	700	6.4		
Global	3,476	0	0	0	84	3,391	0	14,478	700	18.7		

A6.2 Bank and emission values for CFC-11 from the SROC report, put in scenarios and compared with atmospheric derived emission values

Manufacturing of refrigeration equipment using CFC-11 (centrifugal chillers for AC and industrial refrigeration) ended in non-Article 5 parties in the early 1990s, and in Article 5 parties in the early 2000s (see chapter 4). Based on the average lifetime of chillers, it is likely that there are still a small number of chillers in operation since 2015 and will be until 2020 through 2025 (provided they can be serviced with CFC-11 from e.g., stored or reclaimed CFC-11). Since the equipment lifetime is limited to about 20-30 years (following statistics, some chillers will have longer lifetimes), it seems unlikely that the R/AC chiller sub-sector is contributing significantly (only ~1%) to any bank of CFC-11 after the period 2015-2018 (see chapter 4, compare also the percentages given above).

The SROC report estimated that the CFC-11 bank mainly consists of CFC-11 in closed cell foams, with small emissions (assumed to be in the order of 1.5-2.5% per year of the total CFC-11 content) during foam use (which can be 15-20 years for (cooling and heating) equipment and can be 40-50 years or more in the case of building insulation). CFC-11 emissions could be larger than a few percent of the bank if a significant quantity of foam were shredded and the CFC-11 were vented. This could also be the case if significant quantities of CFC-11 containing foam were removed from buildings that are demolished or renovated, depending, to some degree, on whether certain amounts of CFC-11 from large foam pieces were extracted and collected in a facility and subsequently destroyed).²⁵⁶ Finally, CFC-11 emissions could also be larger than a few percent of the bank if new production were emitted through foam manufacture. However, the assumption made for SROC was complete release of the blowing agent at the end-of-life and that nothing remained in the bank (or a waste bank).

²⁵⁶ However, building foam is not assumed to play a role until after 2020 because of its estimated 40 to 50-year lifetime (SROC, 2005).

The foam bank modelling (results as given in SROC takes different types of emissions into account. Calculated values for the CFC-11 global foam bank were estimated in the SROC report at 1,638 kilotonnes in 2002, and extrapolated to a value of 1,110 kilotonnes for the year 2015. These values are higher than the results shown in Section 6.4 above.

In the SROC analysis, uncertainties in the lifetime of foam products are skewed toward longer than “normal” use. They are estimated to be -5%/+15% longer. These assumptions were applied to both the 2002 and 2015 bank estimates. When these uncertainties are taken into account, the 2002 foam bank emitting CFC-11 is estimated to be 1,556-1,884 kilotonnes (2002), and the bank for 2015 is estimated to be 1,055-1,277 kilotonnes.²⁵⁷ Using the SROC analysis assumptions, these numbers could continue to be used since not many PU foam products using CFC-11 as a blowing agent have been added to the global bank after the year 2003-2004 (with exception of a small amount of foam products in Article 5 parties).

The CFC-11 foams emissions are calculated in SROC to be 19.9 kilotonnes for the year 2002 and have been estimated at 14.5 kilotonnes for the year 2015, based upon the bank sizes and a small increase in the release rate from 1.2 to 1.3%). Adding the same uncertainties of -5%/+15% here results in 18.9-22.9 kilotonnes of emissions for the year 2002, and 13.8-16.7 kilotonnes of emissions for the year 2015 (however, it should be noted that this does not probe the full range of possible uncertainty including other factors such as unreported production⁴).

SROC also calculates a bank for R/AC equipment (together with MDIs) at 48.2 and 14.7 kilotonnes for the years 2002 and 2015 and emissions at 9.9 and 4.2 kilotonnes for the same years, respectively (with MDI emissions of 2.8 and 0.7 kilotonnes, respectively). These emissions include both leaks during operation and emissions at end of life (i.e., emissions when the chiller is dismantled).

Adding the banked amounts for R/AC equipment (and for MDIs) to the foam bank yields 1604-1932 kilotonnes for the year 2002 and 1,070-1,292 kilotonnes for the year 2015. As a result, the drop in bank size is then 534-640 kilotonnes. This equals an annual drop in the CFC-11 bank of about 44-45 kilotonnes per year²⁵⁸⁾²⁵⁹ (the bank values decrease because they assume emissions in the year of end of life). This is impacted by the treatment of foams at end-of-life. All values can be found in Tables A6.1 and A6.2.

Based on the 2002 and 2015 bank estimates, the total R/AC and foam emissions for the year 2002 were calculated to be in the range of 28.4-32.4 kilotonnes per year. For the year 2015, the emissions are estimated to be in the range of 18.0-20.9 kilotonnes per year. As average values, 30.4 and 19.5 kilotonnes per year are selected here for the years 2002 and 2015, respectively. The (annual) emissions calculated from the bank (using certain release rates) are substantially smaller than the (annual) bank decrease, mentioned in the paragraph above (due to the fact that a portion of the bank disappears each year that represents CFC-11 contained in products reaching end-of-life).

²⁵⁷ The Montzka *et al.* (2018) paper mentions a bank of about 1,420 kilotonnes in the year 2008, which is simply an interpolation of the “bottom-up” values for 2002 and 2015 from SROC (2005).

²⁵⁸ Full range is 38-45 kilotonnes per year

²⁵⁹ The Montzka *et al.* (2018) paper mentions a bank of about 1,420 kilotonnes in the year 2008, which is simply an interpolation of the “bottom-up” values for 2002 and 2015 from SROC (2005).

Globally, not much of the CFC-11 that is released from the bank is assumed to be reclaimed or collected and destroyed.²⁶⁰ Based on the estimates in the SROC report, the bank decrease includes any direct emissions of CFC-11 from production, refrigerant charging and the foaming process plus the emissions that would be produced in case products are dismantled and shredded, plus all emissions assumed to gradually occur at end of life. The bank decrease values would therefore represent a hypothetical maximum in emissions.

Emissions scenarios were considered using the SROC values and other methodologies to calculate the differences in the (annual) bank decrease compared to the atmospheric derived emissions:

1. Emissions calculated from a linear bank decrease;
2. Emissions calculated from an exponential bank decrease, in which bank values in 2002 and 2015 are the same as in (1) (1,638 and 1,110 kilotonnes), but the emissions are calculated as a fraction of the bank size, using a certain release factor (in this case the total emissions over the period 2002-2015 should be the same as in case 1);
3. Direct emission values described in the SROC report calculated from release rates for the years 2002 and 2015 using a linear decrease for the years in between. (These results are not much different from an exponential decrease over this period);²⁶¹
4. An average scenario from the scenarios 2 and 3 (a bank decrease and direct emissions calculated from release rates).

Taking into account that it would be desirable to study three different types of scenarios, cases 1, 2 and 3 are elaborated upon. Values are given in Table A6.3.

Table A6.3 CFC-11 emissions following a number of scenarios for 2002-2008 and 2015 (kilotonnes per year)

Calculated emissions for scenarios 1-3	2002	2008	2015
Scenario 1, linear bank decrease	44.5	44.5	44.5
Scenario 2, exponential bank decrease	49.7	45.4	40.7
Scenario 3, direct emissions	30.4	25.4	19.5
Average (of scenarios 2 and 3)	40.1	35.4	30.1

For clarity, the emission values given in Table A6.2 are based on emissions calculated from the CFC-11 totals for foams, R/AC and MDIs. The 2002-2015 decrease is assumed for the sum of all sectors, even though the decrease in R/AC and MDIs may be substantially different from a linear one.

From scenario 1, the total maximum emission over the 2002-2015 period is assumed to be the difference between the banks in the two years, at 579 kilotonnes, a value taken from the range of 534-640 kilotonnes given above. The difference in calculated emissions between 2002 and

²⁶⁰ Although there are some foam shredding facilities that capture the blowing agent, this is not assumed to be a major source for reducing emissions.

²⁶¹ Note that cases 1 and 2 include bank decreases assuming release at end-of-life. Case 3 only looks at emissions from product still in use.

2015 is (only) 359.5 kilotonnes which is about 55% of the value calculated for the total bank decrease.

From a practical perspective, banks decrease when products reach their end-of-life (e.g., destruction through incineration) or by emissions of refrigerants or blowing agents to the atmosphere.

- When products, such as foams, are landfilled, it is more accurate to assume that they continue to emit (maybe at slightly different, lower release rates) rather than assuming that the remaining load of CFC-11 is emitted [immediately] as soon as the product enters the waste stream. In the SROC analysis, it was assumed that products at the end-of-life would no longer emit CFC-11. It would be more accurate to assume that the CFC-11 foam products landfilled prior to 2002, would continue to emit during 2002-2015 and thereafter. If the SROC model were to continue to be used, it may be helpful to correct this assumption. However, there is no reason to expect a sharp increase in such emissions after 2012, so it would be unable to explain Montzka's observations.
- In Europe, regulations require (see also above) that foam be removed and shredded with the blowing agent recovered and destroyed along with any residual foam yielding very small quantities of emissions at the end-of-life. This procedure is being applied in many European (all EU) countries. It is not the policy in the US where was the other major market for polyurethane foams, although some utilities and retailers voluntarily destroy foam blowing agent.²⁶² It is not clear what percentage of products this would apply to globally.

In conclusion, the direct emissions from release rates in the SROC report (at 1.5-2.5% release rate annually) are much lower than “top-down” calculated CFC-11 emissions for the period before 2012.

A6.3 CFC-11 emissions calculations from the atmosphere

Concentration measurements are performed many times per year at many monitoring stations located all over the globe. Average global concentrations and how they change per year can be estimated from these measurements with the help of simple box models (3-/12 box). CFC-11 abundances continue to decrease because the annual stratospheric destruction of CFC-11 is larger than ongoing emissions. The destruction can be estimated from the CFC-11 lifetime in the atmosphere, which is estimated to be 52 years.²⁶³ This implies that an amount in the order of almost 2% of the CFC-11 in the atmosphere is destroyed each year, due to the natural break-down processes, in the absence of emissions. If the measured decrease is smaller than this 2% per year value, ongoing emissions are implied, and one can derive the global emission amount that would have to be added to yield the measured CFC-11 decline. For the time interval $n+1$ and n the following would apply for the total amount A (the *atmospheric abundance*) in the atmosphere:

$$A_{n+1} = A_n * e^{-(1 / \text{lifetime})} + \sum \text{emissions (year } n+1\text{)}$$

Emissions derived in this way are dependent on an accurate estimate of the CFC-11 lifetime (which includes all relevant atmospheric processes that have an impact on its breakdown or

²⁶² epa.gov/rad

²⁶³ This implies that after 52 years, 63.3% of the original global atmospheric CFC-11 content will have disappeared, following a $(1/e)$ decrease, i.e., the decrease during one lifetime and after two lifetimes 86.5%, etc.

removal from the atmosphere). The SPARC (2013) report recommends a lifetime of 52 years with an uncertainty range of 43 to 67 years. The longer the CFC-11 lifetime, the smaller the emissions that would be required to sustain the same concentration in the atmosphere.

Table A6.4 CFC-11 emissions derived (in Gg or kilotonnes) from atmospheric measurements during 1994-2016, considering a 57.5-year lifetime (Montzka²⁶⁴)*

Year	Emission (Gg)	Year	Emission (Gg)	Year	Emission (Gg)
1994	103.9	2002	54.4	2010	51.1
1995	92.0	2003	56.5	2011	53.2
1996	89.0	2004	56.9	2012	50.9
1997	75.8	2005	54.4	2013	58.7
1998	81.7	2006	50.8	2014	68.9
1999	69.5	2007	51.6	2015	64.0
2000	67.3	2008	54.9	2016	68.0
2001	67.7	2009	57.4	2017*	~70.0

*Note: The 2017 value given is an approximate value that was not reported in this 2018 paper

These are assumed to be the emissions derived from atmospheric calculations and should represent the total of emissions from all banks, processes, etc. In Montzka *et al.*²⁶⁵, the emission quantities (as given in Table A6.4) have been determined with a 3-box model²⁶⁶ atmospheric simulation of the measured CFC-11 concentration and its change over time and a 57.5-year lifetime for CFC-11. Note that consideration of a shorter atmospheric lifetime (e.g., 52 year) would imply even larger global emissions to sustain the measured atmospheric concentrations than those appearing in Table A6.4.

As of 2002, the “top-down” emissions derived from the atmospheric observations and a 57.5-year lifetime are within the range of 50.8-57.4 kilotonnes (Gg), see Table A6.5, with an average of 53.9 (± 3) kilotonnes) per year over the period 2002-12. This results in the measured global decline of the CFC-11 atmospheric concentration from 2002 through 2012.

²⁶⁴ Ibid., Montzka, S. *et al.*, 2018.

²⁶⁵ Ibid., Montzka, S. *et al.*, 2018.

²⁶⁶ Montzka *et al.* noted that differences with a 12-box model were shown to be marginal.

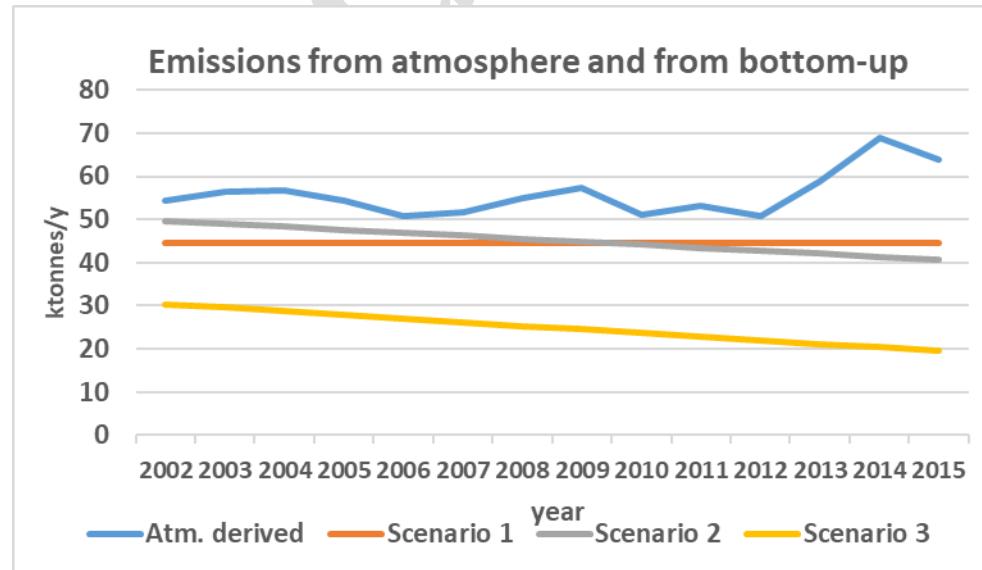
Table A6.5 “Top-down” CFC-11 emissions calculated (in kilotonnes per year) from the atmosphere and a 57.5-year lifetime (first column), also given in Table A6.4, compared to those estimated from “bottom-up” calculations under various scenarios as given in Table A6.3, for the period 2002-2015

Year	Atmosphere	Scenario 1	Scenario 2	Scenario 3	Average scenario 2-3
2002	54.4	44.5	49.7	30.4	40.1
2003	56.5	44.5	48.9	29.5	39.2
2004	56.9	44.5	48.2	28.7	38.4
2005	54.4	44.5	47.5	27.8	37.6
2006	50.8	44.5	46.8	27.1	36.8
2007	51.6	44.5	46.1	26.2	36.1
2008	54.9	44.5	45.4	25.4	35.4
2009	57.4	44.5	44.8	24.6	34.6
2010	51.1	44.5	44.1	23.8	33.7
2011	53.2	44.5	43.4	22.9	33.0
2012	50.9	44.5	42.7	22.0	32.2
2013	58.7	44.5	42.0	21.2	31.5
2014	68.9	44.5	41.3	20.4	30.8
2015	64.0	44.5	40.7	19.5	30.1

A6.4 Observations and conclusions

Figure A6.1 below shows the sizes of emissions reported in Montzka *et al.*²⁶⁷ versus the emissions calculated for the scenarios 1 through 3 (Table A6.5).

Figure A6.1 CFC-11 emissions calculated (in kilotonnes per year) from the atmospheric measurements, plus “bottom-up” emissions calculated under various scenarios (Table A6.5)



²⁶⁷ Ibid., Montzka, S. *et al.*, 2018.

Based on the emissions derived from the measured atmospheric changes (Table A6.4) and the calculated CFC-11 bank values from SROC, it can be concluded that between 3.5 and 5% of the CFC-11 bank escaped to the atmosphere each year up to the year 2012 (which is higher than the SROC assumption for the release rate). Looking at the scenario 1 in Table A6.5 above, the release rate would be in the range 2.6-3.9%. In the case of scenario 2, the release rate would be 2.9-3.5%, for the emissions scenario 3 it would be 1.66-1.76% (almost constant at 1.7%). Release rates are high in the case of scenarios 1 and 2 because they take into account more than just the CFC-11 release from banks. The release values noted by Montzka *et al.*²⁶⁸ are the ratio of the emissions derived and the average bank size (at 1,420 kilotonnes).

1. The linear bank decrease (assuming constant emissions per year) provides a reasonable proxy when the bank is large. It does not include an assumption that emissions are gradually decreasing as the bank sizes diminish and may be more apparent when the bank is small. A linear bank decrease would also result in increasing release rates (emissions per bank unit), which is not conform reality. Between 2002 and 2015, the SROC bank is calculated to decrease by 33%. The nature of emissions from banks over time will be considered further in the final report.
2. The global emissions determined by Montzka *et al.*²⁶⁹ are fairly steady over a period of 10 years (from the 2002-2012). The steady emissions may indicate additional emissions from other sources than from the bank as described in the SROC report (e.g., waste emissions, emissions from new (illegal) foam production, etc.).
3. In Montzka *et al.*²⁷⁰, the emissions derived from atmospheric measurements for the period 2002-2012 (with release rates of 3.2-4.2%, in relation to an average bank size of 1,420 kilotonnes) are consistently higher than the “bottom-up” emissions calculated --based on an average bank release rate of about 1.7%-- of 19.9 (for 2002) and 14.5 kilotonnes (for 2015), as in the SROC report.
4. There are more emissions from R/AC (chillers) and MDIs in earlier years, 2002-2008, since more products are assumed to emit in these years. However, this does not significantly impact the emissions given in Table A6.5 and Figure A6.1 due to the much smaller banks for these products. A sensitivity analysis could be conducted to further refine this analysis.
5. Additional exploration of CFC-11 emissions from waste and dismantling activities as well as from new production will be helpful in future analyses, in particular to better quantify the unexpected CFC-11 emissions after 2012.

The sudden increase (13 ± 5 kilotonnes) in emissions as described by Montzka *et al.*²⁷¹ cannot be explained by a similar, sudden increases in bank emissions.

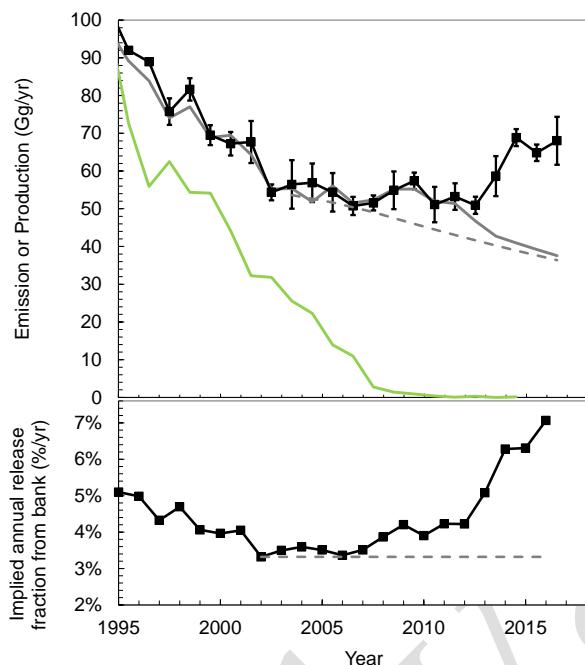
²⁶⁸ Ibid., Montzka, S. *et al.*, 2018.

²⁶⁹ Ibid., Montzka, S. *et al.*, 2018.

²⁷⁰ Ibid., Montzka, S. *et al.*, 2018.

²⁷¹ Ibid., Montzka, S. *et al.*, 2018.

Figure A6.2 Figure showing the emissions derived from atmospheric measurements, and a possible decreasing emission curve from banks emissions 2004-2016 (the release fraction from an assumed average bank size (1,420 kilotonnes is also given) (the green line gives the CFC-11 production as reported by parties) (Montzka *et al.*²⁷²)



Even a large increase in the foam bank size may result in changes to emission estimates, but these would never occur as sudden as the unexpected emissions derived after 2012. If the emission increase were to be related to the CFC-11 banks (in particular the foam bank), it can only be related to changes in the handling of portions of foam that are removed from the bank (handling the waste stream, products that are being dismantled and shredded with CFC-11 being vented). It is difficult to imagine that such changes would occur within a period of two years, which is the period derived from atmospheric measurements. Furthermore, this would require that during several years a huge amount of foam would be destroyed in this manner.

²⁷² Ibid., Montzka, S. *et al.*, 2018.

Annex 1: Submission by China in response to decision XXX/3(3)

China

Decision XXX/3 of the Montreal Protocol on Substances that Deplete the Ozone Layer which concerns the unexpected emissions of trichlorofluoromethane (CFC-11) requires parties to submit to the Ozone Secretariat by 1 March 2019 relevant scientific and technical information to assist the Scientific Assessment Panel (SAP) and the Technology and Economic Assessment Panel (TEAP) in conducting relevant scientific research.

We attach great importance to the issue of unexpected emissions of CFC-11 and have carefully reviewed the action we have taken to fulfill MP, and conducted the surveys and research on the market consumption of CFC-11 substitutes. The following information is thereby submitted to the Ozone Secretariat by China for the consideration by SAP and TEAP while conducting their studies.

China joined the Vienna Convention on the Protection of the Ozone Layer in 1989 and the Montreal Protocol on Substances that Deplete the Ozone Layer (hereinafter referred to as the Montreal Protocol) in 1991. As a party, we are committed jointly with other countries to ozone layer protection and other global environmental actions. After nearly 30 years of unremitting efforts, China has fulfilled its international obligations under the Convention and the Protocol, and has completely ceased the production and consumption of five major categories of ozone-depleting substances (ODS) for their controlled uses, namely CFCs, halons, carbon tetrachloride (CTC), methyl chloroform (TCA) and methyl bromide (MBr), over-fulfilled the phase-out target of HCFCs Stage I, and abide by the provisions of the Protocol as scheduled. A total of roughly 280,000 MT of ODS have been phased out, accounting for more than half of the amount phased out in developing countries, therefore making important contributions to the successful implementation of the Convention and Protocol. Of the amount of ODS phased out, CFCs accounted for about 108,000 MT.

Before the ban of ODS use, CFC-11 was mainly used in the polyurethane (PU) foam, industrial and commercial refrigeration, tobacco and aerosol sectors in China. Among them, PU foam used to be the largest consuming sector for CFC-11. Therefore, regarding the unexpected CFC-11 emission, we conducted market analysis on the production of foam products and the use of various blowing agents since the ban of CFC-11.

The main subsectors using PU rigid foam in China currently include household appliance (insulation), solar water heater (water tank), building material (insulation material), cold storage, refrigerated transportation (reefer container and refrigerated vehicle, square cabin, etc.), petrochemical (pipe), automobile (integral skin foam such as steering wheel, seat, ceiling, etc.), aerospace, furniture manufacturing, etc., a small amount is used for non-insulation purpose such as shoe-making, floating body, etc.

The blowing agents used include HCFC-141b, hydrocarbon (cyclopentane, etc.), HFC-245fa/365mfc, HFOs, water and methyl formate. The ratio of various blowing agents in pre-blended polyols is shown in Table 1, and consumption of various blowing agents and production of PU foams as a result of market research are shown in Table 2.

Table 1: Ratio of various blowing agents in pre-blended polyols

Blowing agent	Ratio in pre-blended polyols
HCFC-141b	19-25%, maximum distribution 20%
water	2.5-8%, maximum distribution 4%
cyclopentane	10-12.5%, maximum distribution 11.5%
HFC-245fa/365mfc	10-12.5% (compared with CFC/HCFC system, more water is needed) , maximum distribution 11.5%
HFO	Around 20%, more HFO would be added than HFCs, in consideration of cost reduction, 15% is used for calculation

Table 2: Estimation of various foaming agent consumption and PU foam production (tonnes)

Year	2011	2012	2013	2014	2015	2016	2017
HCFC-141b consumption, T	63570	59109	46338	46864	34202	34821	36439
hydrocarbon (cyclopentane, etc.) consumption,T	25500	28500	34000	34500	36500	38000	40200
HFC consumption, T	1840	3200	4770	6980	8220	7200	7500
HFO consumption, T					1200	1400	1600
Water consumption, T	2900	3000	5200	5200	6100	6600	6800
methyl formate and other blowing agents consumption, T	300	350	350	250	250	250	250
PU foam production, 10,000 T	134.98	139.50	152.11	158.36	158.54	164.42	173.39

Note: HCFC-141b consumption is reported to the Multilateral Fund Secretariat every year. Cyclopentane consumption is based on the sales data of cyclopentane producers and the consumption data of refrigerator and freezer manufacturers. HFCs and HFO consumptions are from the sales data of HFCs producers and PU foam users. Water consumption is based on the output of polyurethane products using water as blowing agent, taking into account the production process and formulation ratio.

We hope the above information would be useful for our SAP and TEAP experts to better understand the country's consumption situation. We are ready to work continuously with the Secretariat and Assessment Panels on this important issue.