MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

MAY 2012

VOLUME 2

DECISION XXIII/9 TASK FORCE REPORT
ADDITIONAL INFORMATION ON ALTERNATIVES TO
OZONE-DEPLETING SUBSTANCES

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The opinions expressed are those of the Panel and its Task Force and do not necessarily reflect the reviews of any sponsoring or supporting organisation.

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Foreword

The May 2012 TEAP Report

The May 2012 TEAP Report consists of three volumes:

Volume 1: May 2012 TEAP Progress Report

Volume 2: May 2012 TEAP XXIII/9 Task Force Report

Volume 3: May 2012 TEAP XXIII/10 Task Force Report

Volume 1
Volume 1 contains the MTOC essential use report, progress reports, the MB CUN report, and TEAP-TOC issues as requested by Decision XXIII/10.

Volume 2
Volume 2 is the Assessment Report of the TEAP XXIII/9 Task Force on additional information on alternatives to ozone-depleting substances (this report).

Volume 3
The separate Volume 3 of the TEAP Progress Report contains the report of the Task Force responding to Decision XXIII/10.

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ES Executive Summary

ES.1 Mandate

Consistent with Decision XXIII/9 of the Twenty Third Meeting of the Parties, the Technology and Economic Assessment Panel (TEAP) has prepared a report on additional information on alternatives to ODS for submission to the Open-ended Working Group at its 32nd meeting in 2012. The report deals in four chapters with (a) refrigeration and air conditioning, (b) foams, (c) fire protection and (d) solvents.

ES.2 Refrigeration and air conditioning

Refrigerant demand and banks
The refrigerant demand includes refrigerant charged into new equipment and refrigerant used for servicing the installed base of equipment. Refrigerant banks are in fact the cumulated quantities of refrigerant contained in the refrigeration and AC systems of all vintages. The two main sectors both in terms of quantities of refrigerant banked, in particular HCFC-22, are commercial refrigeration and stationary air conditioning. The lifetime of the equipment varies from 10 to 30 years; therefore, there is significant inertia when changing from one refrigerant to another. This means that certain trends are visible earlier in the various refrigerants used (the demand) than in the various refrigerants banked. The trends are different in Article 5 and Non-Article 5 countries, owing to the different HCFC phase-down schedules and the different economic growth rates, which can be significant in certain Article 5 countries.

In 2015, the global HCFC-22 demand is estimated to be in the range of 500,000 tonnes for the commercial refrigeration and stationary air conditioning sectors. The growth in HFC demand will remain substantial for air conditioning, in particular in Article 5 countries. The uptake of low-GWP refrigerants has begun, but growth rates are rather uncertain. The HCFC banks are forecast to further increase in Article 5 countries in stationary refrigeration during 2010-2015. In stationary AC the HCFC banks started to decrease in 2005 in Non-Article 5 countries. In Article 5 countries, where they are even larger, they are forecast to decrease as of 2015. HFC banks are increasing in all sectors globally. In 2015 they are forecast to be larger than 100,000 tonnes in commercial refrigeration and larger than 400,000 tonnes in stationary AC in both Non-Article 5 and Article 5 countries.

Refrigerant options
The assessment of the technical, economic and environmental feasibility of options in Refrigeration and Air Conditioning considered the following aspects: energy efficiency of the equipment, toxicity and flammability of alternative refrigerants; greenhouse gas emissions, and direct and societal costs (presented for some options). Considering that the present RAC technology, using the vapour compression cycle, will be dominant for the next decades, the main options regarding the replacement of HCFCs are represented by alternative refrigerants.

The refrigerant options for HCFC replacement are categorised as low GWP and medium/high GWP alternatives. The refrigerants deemed to fall into the set of low GWP alternatives which are broadly suitable for replacement of HCFC-22 are: HFC-152a, HFC-161, HC-290, HC-1270, R-717, R-744, HFC-1234yf, HFC-1234ze. The refrigerants considered to fall into the set of medium/high GWP alternatives are: HFC-134a, R-410A, R-404A and HFC-32, although there are a variety of other mixtures of HFCs, which also fall into this category. According to toxicity, flammability, and compatibility with materials, the refrigerant options were classified in 7 groups (4 for low and 3 for medium/high GWP).

Other than vapour-compression refrigeration, technologies that could be used for HCFC phase-out are: absorption cycle, desiccant cooling systems, Stirling systems, thermoelectric and a number of other thermodynamic cycles. Most of these technologies are not close to commercial viability for air-cooled air conditioning applications. While these alternative cycles are feasible they have thus far not been proven to be economically viable. Therefore, it is unlikely that they will significantly penetrate these markets, other than for potential niche applications (such as absorption cycle), during the next decade. Alternative technologies will therefore have a minimal impact on the HCFC-22 phase-out.

For each HCFC RAC application, the current and longer term refrigerant options for new equipment are described. Throughout, consideration is only given to new systems and not conversion or retro-fit of existing systems. Whilst some of the refrigerants are broadly available, several options are not fully mature at present and their application cannot be achieved immediately (such as HFC-161, HFC-1234yf and other unsaturated HFCs and blends). For some currently available refrigerants their application in certain types of systems is still under development.

A comprehensive description of the refrigerant technology options can be found in the 2010 UNEP RTOC Assessment report.

Cost elements

The costs associated with adopting alternative refrigerants should be assessed against some baseline, and the commonly used HCFC-22 has been chosen.

Costs may be broken down into specific categories. The first category is direct RAC product costs, which are fixed by system manufacturers and suppliers, with the most significant being research and development, refrigerant cost/ price during manufacturing system components/ materials, installation costs and production line conversion. The second category is societal costs, which are peripheral to the product itself, primarily comprising technician training, technician tooling, service and maintenance costs (which mainly involves refrigerant cost/price) and disposal costs.

Several of these individual costs are normally grouped into the conventional Incremental Capital Costs (ICC) (including research and development and production line conversion) and Incremental Operating Costs (IOC) (including refrigerant, components and installation costs).

It is essential to recognise the difference between actual cost implications arising from the characteristics of the refrigerants themselves and the so-called “market introduction” costs associated with the introduction of any new technology.

Considering both the variety of different refrigerants and different applications, the individual costs vary widely. Therefore, where possible, the report offers a range of values for these individual costs, whilst in some cases, only a qualitative indication is given. It has not been possible to quantify aggregated costs for a refrigerant-application matrix. However, a summary of the incremental costs for a number of low GWP alternatives obtained from a recent EU study is provided.

High ambient temperatures

High ambient temperatures generate more stringent conditions to reach high energy efficiency and lead also to more restrictive conditions in terms of refrigerant choices. HCFC-22 has been the refrigerant of choice for the two dominant applications (1) stationary air conditioning and (2) commercial refrigeration.

- *Stationary air conditioning at high ambient temperatures*
  The primary global replacement, especially for the dominant air-cooled equipment designs, is R-410A, a blend of hydro-fluorocarbon (HFC) refrigerants of which the critical temperature (71.4 °C) is significantly lower than the one of HCFC-22 (96.1 °C). In case condensing temperatures approach the critical temperature, the cooling capacity as well as the energy efficiency are declining sharply. Small, packaged equipment in common usage world-wide for comfort air conditioning, are mass produced and the refrigerant choice needs to consider a series of criteria: cooling capacity at high outdoor temperatures, energy efficiency, required input power, refrigerant GWP, safety and costs. Moreover, the availability of the refrigerant for servicing has to be included as a criterion for all types of countries. The choice of a unique refrigerant is part of the standardisation process and is assumed to lower costs. Currently, several options are open, the RTOC 2010 Assessment Report mentions that HFC-134a, R-407C, R-410A, HFC-32, HFC-152a, HFC-161, HFC-1234yf, HFC-1234yf based blends and HC-290 (propane) are possible replacement options for HCFC-22. The list will be shortened in the coming years dependent on the emphasis put on the criteria considered.
- *Commercial refrigeration at high ambient temperatures*
  The refrigerant choices for commercial refrigeration depend on the cooling capacity and the levels of evaporation temperature. HFC-134a, which has a relatively low volumetric capacity, has been and is still the preferred refrigerant choice in small equipment (stand-alone equipment and some condensing units) whereas HCFC-22 or R-404A, with a larger refrigeration capacity, are used in large commercial systems but also in small systems for low evaporation temperatures. Hot climates imply high condensing temperatures and pressures and lead to the choice of "medium pressure" refrigerants such as HFC-134a or HFC-1234yf for low capacity single stage systems. With the exception of HC-290 (and its limitation for large systems due to safety concerns), there is a lack of low GWP refrigerants with a large refrigeration capacity to replace R-404A or HCFC-22 in single stage refrigeration systems. Cascading systems with CO_2 used at the low temperature level and refrigerants such as HFC-1234yf or HC-290 at the high temperature level turn out to be energy efficient designs in hot climates.

ES.3 Foams

The following points summarise the conclusions of the assessment of the technical, economic and environmental feasibility of the different options for blowing agents in foams:

- The main market segments currently using HCFCs are rigid polyurethane (PU), including polyisocyanurate (PIR), insulating foams and extruded polystyrene (XPS) foam.
- Hydrocarbons (HCs), mainly pentanes, are the preferred choice for HCFC replacement in rigid PU foams in medium/large enterprises. For some very stringent applications such as appliances they are currently blended with saturated HFCs to enhance the foam thermal performance.
- Saturated HFCs, HFC-245fa, HFC-365mfc/HFC-227ea, HFC-134a are used in significant amounts in developed countries, particularly in North America, for rigid PU foam. However, this well-proven technology has two drawbacks, high incremental operating cost because of the blowing agent cost and high GWP.

- There are current and emerging low GWP options to replace HCFCs in the different foam market segments.
- The capital conversion costs for the safe use of HCs in SMEs is prohibitive/not cost effective. This constitutes a barrier to the conversion away from HCFCs in the required timeframe.
- Small quantities of Oxygenated Hydrocarbons (HCOs), specifically, methyl formate, and carbon dioxide (water), both low GWP options, are being used in integral skin foam and some rigid PU foam applications with a penalty compared to HCFC-141b in operational cost and thermal performance.
- Recent evaluations of unsaturated HFCs and HCFCs, commercially known as HFOs (actually HFOs and HCFOs), done in a commercial household refrigerator/freezer line, showed an improved thermal performance compared to saturated HFCs. These substances that exhibit GWP values lower than 10, will be commercially available in 2013.

ES.4 Fire protection

HCFCs and their blends were one of several options introduced into the market as alternatives to halon 1301 and halon 1211 for total flooding and local/streaming applications respectively. It has been estimated that Clean Agent alternatives, i.e. those agents that leave no residue, comprise approximately 51% of the former halon market. Of this, HCFCs are used in approximately 1% of the applications, and thus it is clear that the use of HCFCs in fire protection is very small compared to other alternatives. This is primarily due to tradition, market forces, and cost compared with carbon dioxide and not-in-kind alternatives.

As with the halons, the use of HCFCs in fire protection is driven by the fire protection application, which can be summarized as total flood applications, and local/streaming applications.

Total flood applications: Only HCFC Blend A is still produced and its use today is primarily for recharge of existing systems, and even this is diminishing because of changes in national regulations in the countries where it is accepted. Clean agent alternatives to this agent include inert gases (nitrogen, argon or blends of these two, sometimes incorporating carbon dioxide as a third component), HFCs, and a fluoroketone (FK). The inert gas systems have no environmental impact as a replacement for HCFC Blend A and FK 5-1-12 has almost negligible environmental impact. However, the system costs of these alternatives are significantly higher than the two closest HFC alternatives, and the footprint of the cylinders necessary for the inert gases is three times that of its competitors because of the amount of agent required for extinguishment.

Local/streaming applications: Only HCFC Blend B is marketed in both non-A5 and A5 countries, with a market ratio of 4 to 1 respectively. Limited quantities of HCFC-123 and HCFC Blend E are still marketed in portable extinguishers in some A5 countries such as India and Indonesia. HCFC-123 is the primary component of the HCFC clean agents commercialized for use in streaming applications. When comparing the costs of portable extinguishers, one has to take into account their fire rating – a measure of extinguisher performance – and the clean agent options, HCFC-123 based and HFC-236fa, are significantly more expensive than traditional options, e.g. multipurpose dry powder, water, and carbon dioxide. Thus they are only used where users consider cleanliness a necessity. The ODP of HFC-236fa is 0 and that of HCFC-123 0.02. However, HFC-236fa has a 100-year integrated Global Warming Potential (GWP) of 9,810, which is much more than the value of 77 for HCFC-123, although the HCFC Blend B formulation also contains a small percentage of CF_4, a high GWP gas. Nevertheless, according to

(Wuebbles, 2009), the small CF_4 content means that one could emit over 40 times the amount of HCFC Blend B before one would have the same impact on climate as using HFC-236fa. Finally, it should be noted that an unsaturated hydrobromofluorocarbon (HBFC), 3,3,3-trifluoro-2-bromo-prop-1-ene (2-BTP), has completed fire testing and many of the toxicity tests required for commercialization. Should it receive final approvals, it would be an effective substitute for HCFC Blend B, although it may be more expensive.

Development and testing of alternatives to ODS in fire protection continues and Chapter 2.0 of the 2010 Report of the Halons Technical Options Committee (HTOC) describes in detail the attributes of the alternatives to ODS.

With the exception of aircraft cargo bays, fire extinguishing agent alternatives to ODSs, in the form of non-ozone depleting gases, gas-powder blends, powders and other not-in-kind technologies (i.e., non-gaseous agents) are now available for virtually every fire and explosion protection application once served by ODSs. However, retrofit of existing systems that use ODS may not always be technically and/or economically feasible.

ES.5 Solvents

Among the ODSs controlled by the Montreal Protocol, CFC-113 and 1,1,1-trichloroethane (TCA) were used primarily for precision and metal cleaning.

Over 90% of the ODS solvent use had been reduced through conservation and substitution with not-in-kind technologies by 1999. The remaining less than 10% of the solvent uses are shared by several organic solvent alternatives, which include chlorinated solvents, a brominated solvent, and fluorinated solvents. Fluorinated solvents are essentially used as alternatives to CFC-113, and HCFCs are included in this category as well as HFCs and HFEs (hydrofluoroethers).

The elimination of HCFCs from solvent applications still leaves many options available and they have found various levels of acceptance. However, no single option seems well suited to replace HCFCs completely.

Recently, unsaturated fluorochemical HFOs (hydrofluoroolefins) with zero ODP and HCFOs (hydrochlorofluoroolefins) with negligibly small ODP were stated to be under development. They have ultra low GWP (<10) and are expected to replace high-GWP HFC and low or moderate GWP HFE solvents. They also could be candidates to replace HCFCs in certain solvent applications.

1 Introduction

1.1 Terms of Reference

Decision XXIII/9 of the Twenty-third Meeting of the Parties requested the Technology and Economic Assessment Panel (TEAP) to prepare this report for consideration by the Open-ended Working Group at its 32nd meeting.

1.2 Scope and Coverage

The text of Decision XXIII/9 is as follows:

To request the Technology and Economic Assessment Panel to prepare a report in consultation with the other scientific experts, if necessary, for consideration by the Open-ended Working Group at its thirty-second meeting containing information on, among other things:

(a) The cost of alternatives to hydrochlorofluorocarbons that are technically proven, economically viable and environmentally benign;
(b) Alternatives to hydrochlorofluorocarbons that are technically proven, economically viable, environmentally benign and suitable for use in high ambient temperatures, including how such temperatures may affect efficiency or other factors;
(c) Quantities and types of alternatives already and projected to be phased in as replacements for hydrochlorofluorocarbons, disaggregated by application, both in parties operating under paragraph 1 of Article 5 of the Montreal Protocol and parties not so operating;
(d) An assessment of the technical, economic and environmental feasibility of options in consultation with scientific experts

1.3 Composition of the Task Force

The TEAP established a XXIII/9 Task Force (RTF) to prepare this report to respond to Decision XXIII/9. The composition of the Task Force is as follows:

- Lambert Kuijpers (The Netherlands, co-chair TEAP, co-chair RTOC);
- Miguel Quintero (Colombia, co-chair FTOC);
- Dave Catchpole (UK, co-chair HTOC)
- Denis Clodic (France, member RTOC)
- Daniel Colbourne (UK, member RTOC)
- Sukumar Devotta (India, member RTOC)
- Martin Dieryckx (Belgium, member RTOC)
- Mike Jeffs (UK, member FTOC)
- Fred J. Keller (USA, member RTOC);
- Roberto Peixoto (Brazil, co-chair RTOC);
- Keiichi Ohnishi (Japan, co-chair CTOC);
- Francesca Pignagnoli (Italy, member FTOC);
- Enshan Sheng (China, member FTOC);
- David J. Williams (USA, member FTOC);
- Allen Zhang (China, member FTOC).

The XXIII/9 Task Force was co-chaired by Lambert Kuijpers and Miguel Quintero.

A preliminary draft of the report was discussed by the TEAP during its meeting in Berlin, Germany, 26-30 March 2012. Suggestions for the finalisation of the report were given and a final draft was circulated by email to the XXIII/9 Task Force and the TEAP for endorsement.

1.5 The Structure of the XXIII/9 Report

The structure of the TEAP XXIII/9 Task Force Report is as follows:

The Executive Summary is presented first in this report, with separate parts referring to the separate chapters.

Chapter 1, "Introduction", presents the Terms of Reference, establishment of the Task Force and the consultative processes used to prepare this report.

Chapter 2, "Considerations on definitions used" describes how the terms environmentally benign, technically feasible, environmentally feasible, technically proven etc. have been used.

Chapter 3, "Refrigeration and air-conditioning", describes the global, non-Article 5 and Article 5 banks of HCFC chemicals and their alternatives (as they can be found in equipment). It then describes options following clause (d) followed by cost analysis as requested in clause (a). An update of the 2010 TEAP/RTOC report on alternatives to HCFCs for high ambient temperatures is given in an annex to the chapter.

Chapter 4, "Foams", describes the global, non-Article 5 and Article 5 use of HCFC chemicals and their alternatives. It then describes options following clause (d) followed by cost analysis as requested in clause (a).

Chapter 5, "Fire protection", describes the global, non-Article 5 and Article 5 use of HCFC chemicals and their alternatives. It starts with an analysis of costs following clause (a) and then describes options following clause (d).

Chapter 6, "Solvents", describes the global, non-Article 5 and Article 5 use of HCFC chemicals and their alternatives. It then describes options following clause (d) and gives some consideration on clause (a).

2 Considerations on definitions used

2.1 Environmentally benign and environmentally feasible

"Environmentally benign" as a term is used in this Decision XXIII/9 for the first time, characterising alternatives to HCFCs or alternative equipment to HCFC equipment. One could say that its meaning goes wider than just GWP or ODP. However, one should remember that CFCs would have been considered 'environmentally benign' in the 1930s because nobody knew about ozone depletion (or climate impacts) caused by these substances. There may be an "ozone depletion" equivalent "environmental impact" waiting for substances that we think are environmentally benign today, so this term is never an absolute one.

"Environmentally feasible" could be considered a risk assessment term and relates then to "hazard plus emissions", and one can say that here the application is as important as the substance (the HCFC alternative or alternative option). In this light there is no need to have one GWP limit across all sectors and sub-sectors, but what is required here is a maximum limit on "environmental damage in a given period", which will have to be defined across each sector.

In summary, it is not possible to define environmentally benign, in the context of technical feasibility and commercial availability without a wide range of interpretations. "Environmentally benign" cannot therefore be the sole guiding principle for assessing alternatives to HCFCs and HCFC equipment.

The Task Force therefore decided that each of the sectors should deal with clauses (a) and (d) in a "consistent" manner, without putting "environmentally benign" as the overruling criterion for both clauses.[1] A more suitable criterion is "environmentally feasible", which takes into account the wider environment and relates to "hazard plus emissions".[2] However, since other environmental aspects (such as flammability etc.) have to be considered it turns quickly into an environmental acceptability issue.

The assessment of costs of alternatives (technically proven and economically viable) could then be done for a number of alternatives with certain characteristics (including GWP). However, it should be done against a baseline of HCFCs or HCFC based equipment; furthermore application of high GWP alternatives that are technically proven (and probably economically viable) should be assessed for comparative reasons.

2.2 Technical and economic feasibility

Technical feasibility addresses whether particular alternatives work, can be made to work, and where/how they can be applied.

[1] This means that one can list the fluids that are considered to be environmentally benign at the start of the response without giving a definitive reason for their inclusion.

[2] This would imply that non-emissive applications would remain environmentally feasible even if they would apply ultra high GWP gases such as SF6, provided there are no emissions throughout the lifecycle.

Economic feasibility should discuss how those costs for certain alternatives may change in the future (e.g., lower costs as production volumes increase, higher or lower electricity costs, potential influence of factors such as policy measures. Analysis of the factors that influence costs and how the costs may go up or down over the next 3-7 years would be valuable, but it is doubtful whether this can be applied to all alternatives considered.

2.3 Low GWP

One can say that low GWP alternatives are ones that have a GWP below a certain limit, e.g., 1000, 300, 100, 25. However, what is the environmental impact if, for example, more foam has to be used to realise certain properties, or if manufacturing or end of life treatments would add less benign aspects?

In discussions the TEWI, LCA and LCCP have so far not been acknowledged since they are too complicated to draw conclusions compared to the ones one can draw using the simple GWP parameter. It quickly raises the question whether the GWP is a clear criterion if one starts to vary the time horizon to be considered from 100 to 20 years or so. Furthermore there are huge differences between sectors on usage patterns (also related to emissions, which are quite different in foams versus e.g. leaking RAC equipment).

For refrigeration and AC certain limits for a (low) GWP have been proposed (300 by TEAP in 2010) (the value of 150 is also often used, which comes from the European MAC regulation). In the text of this report, a number of interpretations have been used:

- certain experts in RAC want to see several alternatives investigated, below GWP 1000, or even including higher GWP ones such as R-410A or HFC-134a
- certain experts in the fire protection community see environmental impact as of a less priority if only high GWP alternatives are available
- certain experts express as their opinion that not only the GWP should be taken into account but also the amount emitted, giving a total amount of carbon dioxide equivalent, which is a measure for climate impact (which brings one back to a TEWI discussion)
- foam experts are of the opinion that the term environmentally benign should be broken down into specific components such as ODP, GWP, toxicity, etc., and some measure comparable to the LCCP. In foams the LCCP calculation gets very complex, so that the foam thermal conductivity is actually the best energy performance indicator. In terms of the GWP for foam applications, foam experts are of the opinion that one can define a substance as "low GWP" if its GWP value is less than 25.

2.4 Considerations on how the report was put together

The Task Force has extensively deliberated on how to put the report together. Looking at the decision, clause (d) should give the proper information on the key options and can go beyond what is in clause (a-c), not limiting it to HCFC alternatives, but alternatives in general, including technical, economic and environmental feasibility as well as market availability.

In principle one could first do an assessment of existing solutions, then the innovative and new solutions that could come to market within a 3-7 years timeframe. After these considerations the cost element could be considered

Where it concerns the composition of the report, the Task Force concluded that it was too difficult to consider clauses (a) and (d) via cross sectorial elements and therefore the report assesses costs, market demand, use and banks as well as the feasibility of options in a chapter per subsector (for all HCFC consuming sectors, i.e., refrigeration and AC, foams, fire protection and solvents). This also implies that there are small differences per subsector how the clauses (a) and (d) have been dealt with and in which sequence.

In some cases the environmentally benign issue is looked at more from a pure GWP point of view, with differences in understanding what should be considered low-GWP, in other cases the "environmentally benign-environmental feasible" issue is looked at from an environmental feasibility perspective.

In all cases costs have been considered, wherever possible, for options that are technically proven or have been demonstrated regarding feasibility, with more or less emphasis on the "economically feasible" argument.

3 Refrigeration and air conditioning

3.1 Banks in Refrigeration and AC equipment in Non-Article 5 and Article 5 countries

Decision XXIII/9 requests in clause (c) the TEAP to report on quantities and types of alternatives already and projected to be phased in as replacements for hydrochlorofluorocarbons, disaggregated by application, both in parties operating under paragraph 1 of Article 5 of the Montreal Protocol and parties not so operating.

The data on refrigerant inventories (banks) are based on the Tier 2a methodology as defined in the Revised Guidelines for Greenhouse Gas Inventories (IPCC, 2006) . Several reports have been published by Clodic and co-workers from the Center of Energy and Processes (CEP) (Clodic, 2005; Clodic 2010; Clodic, 2011). The results of (Clodic, 2005) have been the basis for the refrigerant inventories given in the IPCC-TEAP report (IPCC, 2005) and the results of (Clodic, 2010) have been published in Annex 2 of the RTOC 2010 Assessment Report (RTOC, 2010). The calculation method and all assumptions used in the calculations are presented in those documents. For the projections from 2010 to 2015, the assumptions made for near term refrigerant choices are presented in (Clodic, 2011) for the developed countries. These assumptions have also been thoroughly discussed with a number of experts from global manufacturing companies specialized in stationary air conditioning and commercial refrigeration. First, the data on refrigerant banks for commercial refrigeration and stationary air conditioning have been derived for a number of large Non-Article 5 and Article 5 countries as well as several regions. These have then been added up with totals assigned to one of two groups, Non-Article 5 and Article 5. For the year 2015, the data on HCFC replacements as in the approvals by the Multilateral Fund have also been used.

The refrigerant demand includes refrigerant charges for new equipment and refrigerant quantities used for servicing the installed bases of equipment. Some information on demand is included here. Imported refrigerant quantities are included in the demand; they are taken into account through annual equipment sales.

A first graph for each of the two subsectors shows the demand in Non-Article 5 and Article 5 countries. Each of the subsequent series of four figures in this subchapter consists of four pie charts showing the percentages of the different refrigerants in the bank: CFCs, HCFCs, HFCs and others (CO_2, ammonia and hydrocarbons) for the years 2000, 2005, 2010 and 2015. A fifth graph in these figures shows the trends of the growth and decrease of the banks for the four groups of refrigerants.

3.1.1 Commercial refrigeration

3.1.1.1 Commercial refrigeration in Non-Article 5 countries

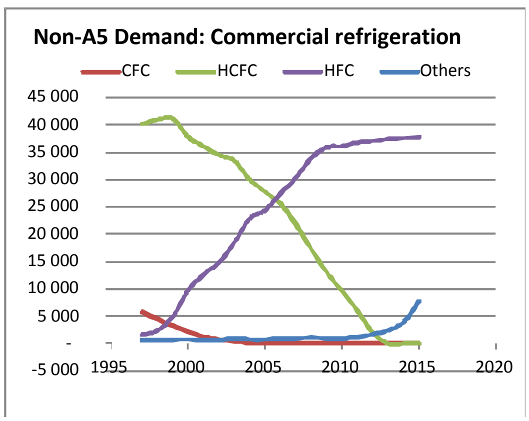
The phase-out of HCFCs in Non-Article 5 countries has been different in Europe, in the US and in Japan. Europe decided to accelerate the phase-out schedule by strong regulatory measures: HCFCs have been banned from new refrigeration equipment as of the year 2000 for all RAC applications except heat pumps. The USA has only capped HCFC sales following the Montreal Protocol schedule for Non-Article 5 countries. Japan has accelerated the refrigerant changes following an intermediate regulatory schedule.

In Non-Article 5 countries, the refrigerants charged in large commercial refrigeration systems represent about 40% of the total commercial refrigeration bank. The remaining 60% is located in all small and medium size systems installed in hotels, restaurants, convenience stores, food specialty shops, gas and train stations etc.

Commercial refrigeration demand in Non-Article 5 countries

The demand for commercial refrigeration in Non-Article 5 countries is given in Fig. 3-1. It shows that the demand for HCFCs is expected to approach zero by 2015, the demand for HFCs is expected to slowly grow after a period of steep increase (1999-2009). The demand for other refrigerants (HC-290, R-717, R-744) is expected to be in the order of 17% of the total in tonnes; this can be translated in a larger percentage of equipment because of the lower charge used for hydrocarbons.

Fig. 3-1: Demand for commercial refrigeration in Non-Article 5 countries



Commercial refrigeration banks in Non-Article 5 countries

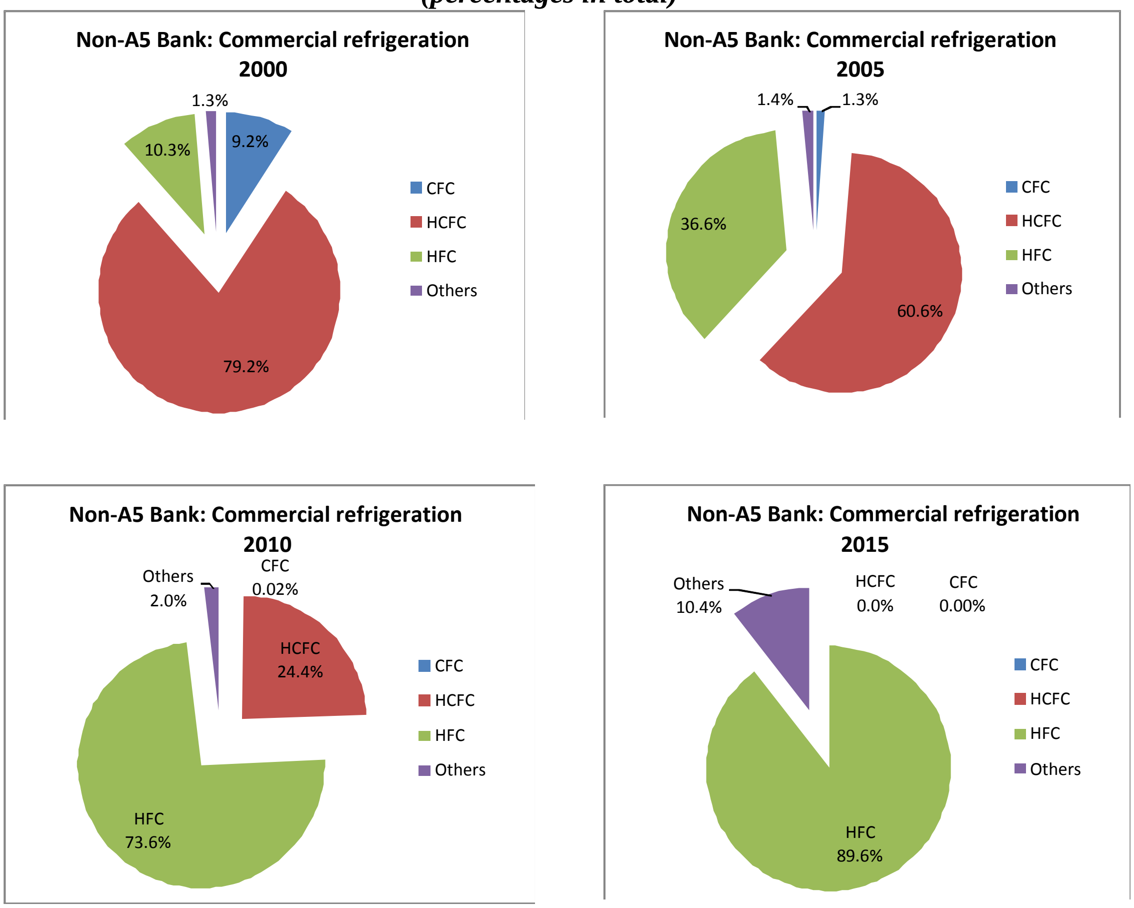
Table 3-1 below shows the following trends:

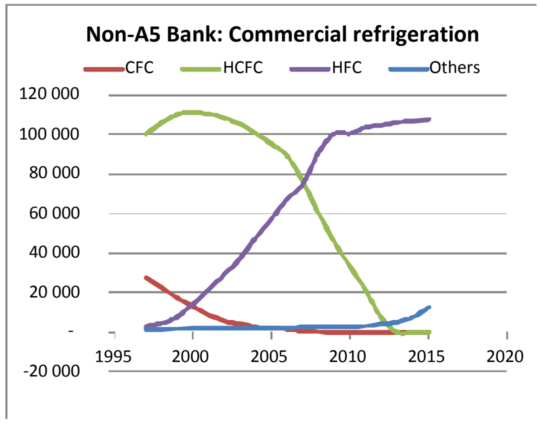
- A rapid phase-out of CFCs due to the relative short lifetime of commercial refrigeration equipment (between 7 and 15 years)
- A limited success of HCFC refrigerant blends to replace R-502 (the blend of CFC-115 and HCFC-22) by R-408A and R-401A
- A quick increase in the banks of R-404A because of the lack of other, low GWP options
- A limited uptake of ammonia and propane due to safety issues in sales areas
- A possible rapid development of low GWP HFC refrigerant equipment (bank) associated with the use of CO2 at low temperature.

Moreover, a decrease of refrigerant charges is forecast due to the implementation of secondary systems and lower energy consumption due to the introduction of doors on display cases even at the medium temperature level.

Table 3-1: Commercial Refrigeration – Refrigerant banks in Non-A5 Countries (tonnes)							
Year	CFC-12	HCFC-22	HCFC-blends (R-408A, 401A)	HFC-134a	R-404A/ R-507A	HFC-blends (R-422D, 427A, new)	Other (HC-290, R-717, R-744)
2000	9,500	98,300	13, 000	4,000	10,300	0	0
2005	1,800	84,000	11,400	7,400	50,000	0	0
2010	30	28,500	5,000	26,000	75,000	0	0
2015	0	0	0	28,000	80,000	20,000	14,500

Figure 3-2: Banks in commercial refrigeration in Non-Article 5 countries (percentages in total)





3.1.1.2 Commercial Refrigeration in Article 5 countries

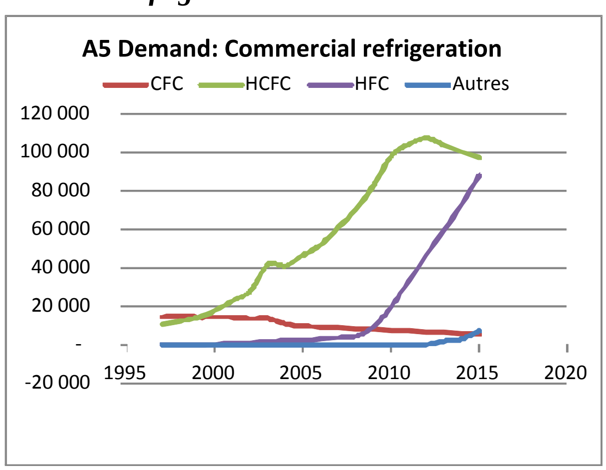
The fast development of countries such as Brazil, China and India, as well as the fast urbanization in all Article 5 countries has led to a fast and substantial development of the cold chain and especially commercial refrigeration. In 2010, the refrigerant bank in all Article 5 countries was more than twice the refrigerant bank in non-Article 5 countries.

Figure 3-2 with the four pie charts shows that HCFC-22 is the dominant refrigerant and that it will still be the dominant refrigerant in 2015.

In developing countries, refrigerants charged in large commercial refrigeration systems represent only 10 to 20% of the total commercial refrigeration bank depending on the development of supermarkets. The remaining 80 to 90 % are found in small and medium size systems found in hotels, restaurants, convenience stores, food specialists, gas and train stations etc. It should be noted that the lower the GDP of the country the lower the share of centralized systems. The cold chain in small stores begins usually by equipment very close to domestic freezers and refrigerators.

Commercial refrigeration demand in Article 5 countries

Figure 3-3: Commercial refrigeration demand in Article 5 countries



The demand for commercial refrigeration in Article 5 countries is given in Fig. 3-3. It shows that the demand for HCFCs is expected to decrease after 2010-2011, the demand for HFCs began to steeply increase from 2008-2009. The demand for other refrigerants (HC-290, R-717, R-744) is expected to be in the order of 6% of the total in tonnes; this can be translated in a larger percentage of equipment because of the lower charge used for hydrocarbons.

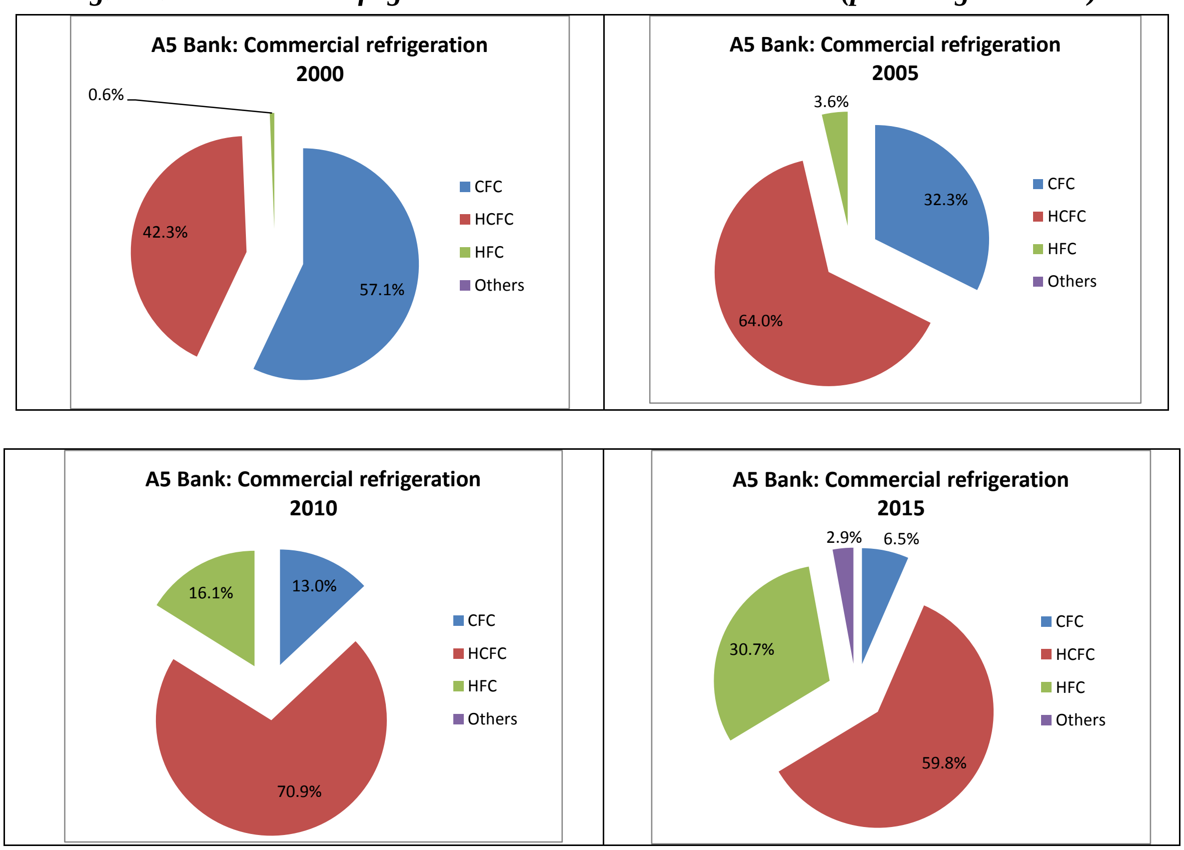
Table 3-2 clearly shows that:

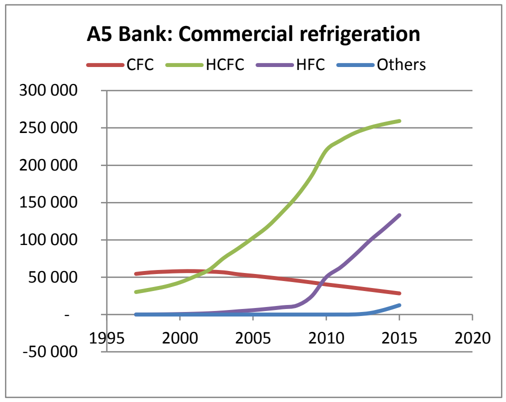
- CFCs are decreasing but will still be in use in 2015 due to the longer lifetime of small commercial refrigeration equipment in Article 5 countries
- HCFC-22 has seen a very strong increase in use due to both the phase-out of CFCs in new equipment and the increase of food preservation in urban areas
- The increase of use of R-404A is forecast because many refrigeration systems have been developed for this refrigerant and only require a few adaptations for HCFC-22 equipment even if R-404A cannot be considered a drop-in refrigerant for HCFC-22.

Table 3-2: Commercial Refrigeration – Refrigerant banks in Article 5 countries (tonnes)

Year	CFCs	HCFC-22	HCFC blends	HFC-134a	R-404A	Other (HC-290 and R-717)
2000	58,000	40,000	3,000	600	100	0
2005	52,000	100,000	3,000	3,000	3,000	0
2010	40,000	217,000	3,000	9,000	40,000	0
2015	28,000	255,000	5,000	24,000	100,000	12,500

Fig. 3-4: Commercial refrigeration banks in Article 5 countries (percentages in total)





3.1.2 Stationary AC

3.1.2.1 Stationary AC in Non-Article 5 countries

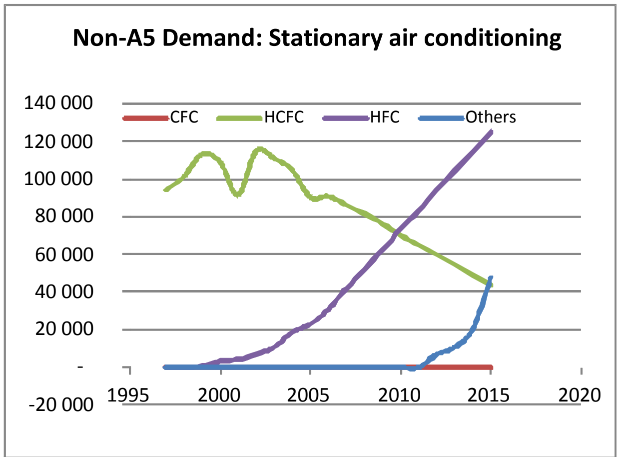
Stationary AC does not include chillers but includes many different types of equipment where cooling capacity varies from 1.5 kW up to several hundreds. All those systems are mass-produced and the market experiences strong competition on prices and energy efficiency. It has to be underlined that Stationary AC represents about 50% of the total refrigerant bank.

As shown in the following figures HCFC-22 has been and is still the dominant refrigerant in Non-Article 5 countries. Even though Europe organized a rapid phase-out of HCFC-22 as of the year 2000, its market share for air conditioning is relatively small, i.e., it has about 15% of the global refrigerant bank. In 2010 the HCFC-22 bank was about 545,000 tonnes and represents a share of more than 60% of the total. One has to keep in mind that the US started shifting away from HCFC-22 in 1998, however, the use in new products was outlawed not earlier than in 2010.

Refrigerant demand for stationary air conditioning in Non-Article 5 countries

The demand for stationary AC in Non-Article 5 countries is given in Fig. 3-5. It shows that the demand for HCFCs is decreasing as of 2000; this decrease is expected to continue after 2010-2012. The demand for HFCs is expected to steeply increase beyond the year 2015; this increase started when the demand for HCFCs started to decrease. The demand for other refrigerants (HC-290, R-717, R-744) is expected to be in the order of 22% of the total in tonnes; this can be translated in a larger percentage of equipment because of the lower charge used for hydrocarbons.

Fig. 3-5: Refrigerant demand for stationary air conditioning in Non-Article 5 countries



Refrigerant banks for stationary air conditioning in Non-Article 5 countries

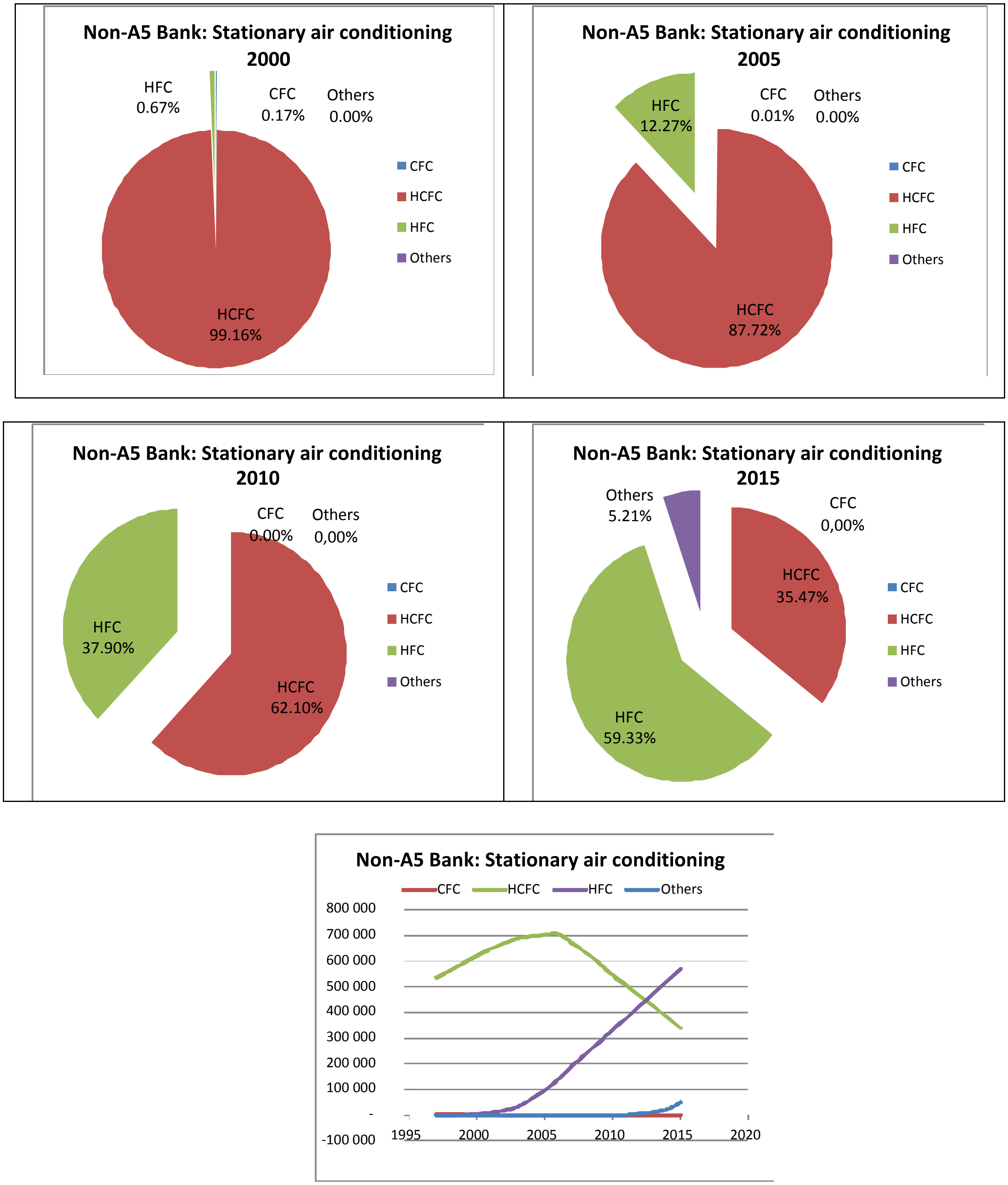
Table 3-3 indicates that:

- The phase-out of CFCs has been relatively fast
- The uptake of HFC-134a is relatively small because of the better price and performances ratio of HCFC-22 AC equipment
- R-410A is the preferred substitute for new equipment due to a higher refrigeration capacity and consequently a lower cost for compressor plus system compared to R-407C
- R-407C still has a market share because the same compressors as those developed for HCFC-22 can be used provided a change from alkyl-benzene to POE lubricants is made
- An uptake of HFC-32 and new low GWP blends is forecast in order to lower the GWP of refrigerant emissions.

Table 3-3: Stationary AC - Refrigerant banks for Non-Article 5 countries (tonnes)

Year	CFC-12	HCFC-22	HFC-134a	R-407C	R-410A	HFC-32 & new HFC blends	Other (HC-290)
2000	1100	622,000	1,600	700	1,900	0	0
2005	100	703,300	6,200	37,900	54,300	0	0
2010	5	545,000	21,100	98,000	213,700	0	0
2015	0	341,000	35,000	170,000	345,000	20,000	5,000

Fig. 3-6: Stationary AC - Refrigerant banks for Non-Article 5 countries (percentages in total)



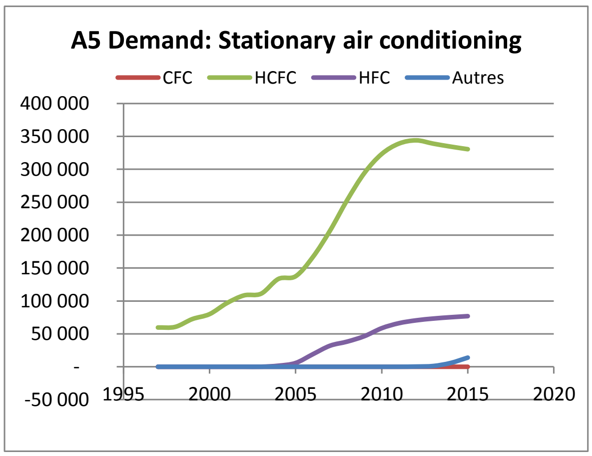
3.1.2.2 Stationary AC in Article 5 countries

Since 2010, the refrigerant bank of stationary AC in developing countries has become larger than that situated in Non-Article 5 countries. The dominant refrigerant in 2010 was HCFC-22 with a 973,000 tonnes bank, representing about 85% of the stationary refrigerant bank in Article 5 countries.

Refrigerant demand for stationary air conditioning in Non-Article 5 countries

The demand for stationary AC in Non-Article 5 countries is given in Fig. 3-7. It shows that the demand for HCFCs is expected to slightly decrease during 2011-2015. The demand for HFCs is expected to steeply increase far beyond the year 2015; the growth in HFC demand already started during 2005-2007. The demand for other refrigerants (HC-290, R-717, R-744) is expected to be in the order of 3% of the total in tonnes; this can be translated in a larger percentage of equipment because of the lower charge used for hydrocarbons.

Fig. 3-7: Stationary air conditioning demand in Article 5 Countries



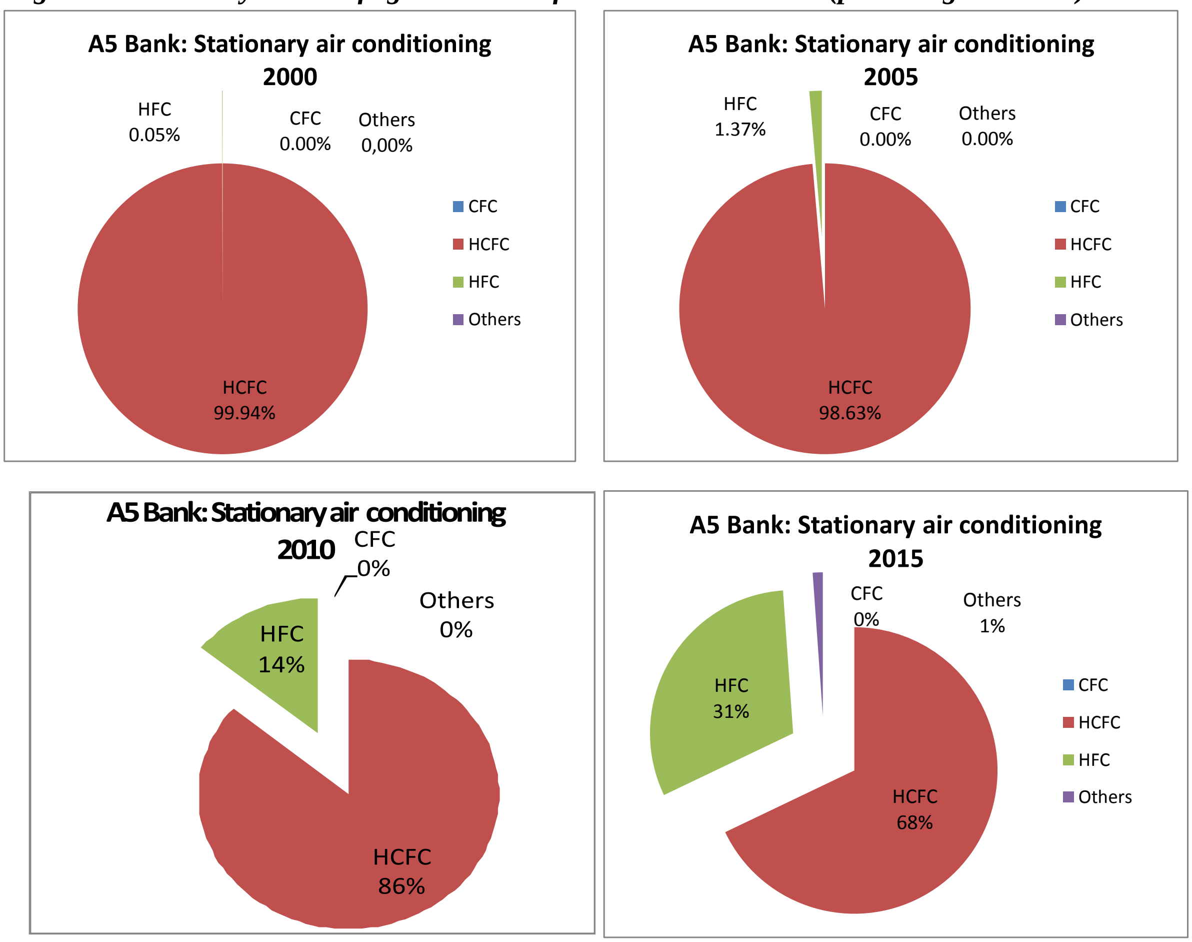
Refrigerant banks for stationary air conditioning in Non-Article 5 countries

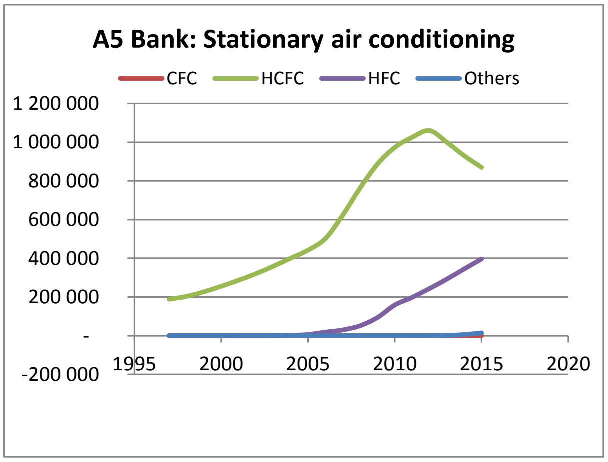
Table 3-4 shows that:

- For the year 2015 the forecast is that HCFC-22 will still represent 2/3rds of the stationary AC bank
- The development of HC equipment and the consequent increase in HC banks is limited due to the safety issues involved and global companies are not expected to generalize their use
- HFC-134a will have a limited share of the market owing to a better cost/ performance ratio of large capacity refrigerants
- The use of R-410A is likely to increase rapidly in China owing to the dedicated export policy of Chinese companies and due to the fact that Chinese chemical companies dominate the production of both HFC-125 and HFC-32.

Table 3-4: Stationary AC – Refrigerant banks for Article 5 countries (tonnes)							
Year	CFC-12	HCFC-22	HFC-134a	R-407C	R-410A	HFC-32 & new HFC blends	Other (HC-290)
2000	0	255,000	135	0	0	0	0
2005	0	442,000	700	4,700	800	0	0
2010	0	973,000	4,100	16,400	138,000	0	0
2015	0	870,000	11,000	41,000	345,000	7,000	14,500

Fig. 3-8: Stationary AC - Refrigerant banks for Article 5 countries (percentages in total)





3.2 Assessment of options in refrigeration and air conditioning

The assessment of the technical, economic and environmental feasibility of options considered the following aspects:

- Technical feasibility: energy efficiency of the equipment, and aspects related to toxicity, flammability;
- Economic feasibility: investment costs, operating/ongoing cost (clause (a) presented in 3.4);
- Environmental feasibility: energy efficiency of the equipment and greenhouse gas emissions[3].

HCFC-22, HCFC-123, HCFC-142b and HCFC-124 are HCFC refrigerants used in refrigeration and air conditioning applications, with HCFC-22 being by far the most important in Article 5 countries. Considering that the present RAC technology, using the vapour compression cycle, will be dominant for the coming decades, the main options regarding the replacement of HCFCs are represented by alternative refrigerants as working fluids for this technology. In the case of supermarket refrigeration it involves also changes in the system configuration (indirect, cascade and hybrid systems). Options related to the use of other technologies ("not in kind"), such as absorption and Stirling cycles, magnetic, thermoacoustic and thermoelectric processes, are in different degrees of development and application. For each HCFC RAC application, the current and longer[4] term refrigerant options for new equipment are presented, as well as the current situation of "not in kind" technologies.

The options for HCFC replacements are categorised as low GWP and medium/high GWP alternatives. The refrigerants deemed to fall into the set of low GWP alternatives which are broadly suitable for replacement of HCFC-22 are: HFC-152a, HFC-161, HC-290, HC-1270, R-717, R-744, HFC-1234yf, HFC-1234ze.

[3] A more comprehensive evaluation should also look at water use, raw material use, solid waste, wastewater, other air emissions, noise, odours and dust.

[4] The technology options mentioned below are identified as "current", meaning that they are applied at the present time or in some cases their introduction is imminent, whereas "longer term" implies that the technology is anticipated to be available within the next 3 – 5 years.

These refrigerants are grouped according to common characteristics (Table 3-5).

The refrigerants deemed to fall into the set of medium/high GWP alternatives are: HFC-134a, R-410A, R-404A and HFC-32, although there are a variety of other mixtures of HFCs, which also fall into this category.

These refrigerants are grouped according to common characteristics (see Table 3-5).

Table 3-5: Groupings of low GWP alternatives

Group	Refrigerants	Characteristics
Group 1	HFC-152a, HFC-161*, HC-290, HC-1270	Medium or high flammability, low toxicity, similar vapour pressure to HCFC-22, similar material compatibility to HCFC-22
Group 2	HFC-1234yf, HFC-1234ze	Low flammability, low toxicity, lower vapour pressure than HCFC-22, similar material compatibility to HCFC-22
Group 3	R-744	Non-flammable, low toxicity, significantly higher pressure than HCFC-22, similar material compatibility to HCFC-22
Group 4	R-717	Low flammability, high toxicity, similar vapour pressure to HCFC-22, different material compatibility to HCFC-22

* It is noted that HFC-161 to date has not yet received a final safety (toxicity) classification under ISO 817

Table 3-6: Groupings of medium/high GWP alternatives

Group	Refrigerants	Characteristics
Group 5	HFC-134a, R-404A, R-410A	Non-flammable, low toxicity
Group 6	HFC-32	Low flammability, low toxicity, higher vapour pressure than HCFC-22

The HCFC alternatives for each RAC application described below are for new systems and not conversion or retrofit of existing systems. A comprehensive description of the refrigerant technology options can be found in the 2010 UNEP RTOC report (UNEP, 2010).

Commercial refrigeration – condensing units

Condensing units are compressor/condenser assemblies that are normally connected on-site to an evaporator with additional interconnecting pipework. They are typically installed in bakeries, butcher shops, convenience stores and small supermarkets. The technology can be considered as a mass production one with usually hermetic compressors, sometimes semi-hermetic ones. Condensing unit is a widely used option in Article 5 countries.

Low GWP alternatives
In terms of low-GWP alternatives, HCs are currently available, but further development is required for "safety-optimisation" of larger capacity systems. R-744 is deemed viable in cool and moderate climates but the equipment is not yet widely available for all capacities. HFC-1234yf and other unsaturated HFCs and (as yet, undisclosed) blends of these, including blends with saturated HFCs (or just HFCs), may also be suitable, however neither refrigerants nor hardware are currently available.

Medium/High GWP alternatives
HFC-134a, R-404A, R-410A and other mixtures of HFCs are currently used in condensing units but it is also feasible to use HFC-32 in such systems.

Commercial refrigeration – centralised systems

Centralised systems are those normally used within supermarkets; they are direct expansion systems comprising one or more racks of a series of compressors installed in a machinery room with refrigerant piping distributed to display cabinets and coldrooms throughout the store. Compressor rack may be applied to two temperature levels (fresh food and frozen food) and either a common condenser or a condenser for each temperature level is normally positioned outside. HCFC-22 is still a dominant option for all Article 5 countries because the cost of HCFC-22 technology is the cheapest and compressors are available on the global or local market.

Low GWP alternatives
Current low GWP option for HCFC-22 and HFC-404A replacement in cool and moderate climates is R744 in direct expansion systems in a trans-critical / sub-critical cycle depending on the ambient temperature. Other low GWP refrigerant options result in alternative system designs, such as:

- Indirect systems; use of a heat transfer fluid such as a glycol, brine with HC-290, HC-1270, R-717 or any of the refrigerants for a direct system being used as the primary refrigerant
- Evaporating secondary systems; use of pumped R744 undergoing partial phase-change with HC-290, HC-1270, R-717 or any of the refrigerants for a direct system being used as the primary refrigerant
- Cascade systems; HC-290, HC-1270, R-717 or any of the refrigerants for a direct system being used in the high stage and R-744 being used in the low temperature stage
- Indirect distributed system; HC-290, HC-1270, R-717 or any of the refrigerants for a direct system used in a chiller from which chilled water is circulated to water-cooled condensing units on each cabinet and cold room
- Hybrid systems; involving a combination of any of the above

HFC-1234yf and other unsaturated HFCs and (as yet, undisclosed) blends of these, including blends with HFCs, may also be suitable longer term options, however, neither refrigerants nor hardware are currently available.

Medium/High GWP alternatives
HFC-134a, R-404A, R-410A and other mixtures of HFCs are currently used in centralised systems but it is also feasible to use HFC-32 in systems based on the concepts listed above for low-GWP alternatives. Under hot climates, R-404A exhibits lower energy efficiency compared to HCFC-22 due to its lower critical temperature (72 °C) compared to HCFC-22 (86.5 °C).

Air-to-air air conditioning

Air-to-Air air conditioners consist of a broad range of product configurations and generally fall into four distinct categories, based primarily on capacity or application: small self-contained air conditioners (window-mounted and through-the-wall air conditioners); non-ducted split residential and commercial air conditioners; ducted, split residential air conditioners; multi-split air conditioners (covered in the next section); and ducted commercial split and packaged air conditioners. In each of these categories, the term "air conditioner" includes systems that directly cool or heat the conditioned air.

Low GWP alternatives
The only currently available long term low GWP option is HC-290. The longer-term options being considered to replace HCFC-22 in these applications include HFC-152a, unsaturated HFC blends (HFC-1234yf, HFC-1234ze or other unsaturated HFCs blended with other HFCs or HCs), R-744 (CO_2) and HFC-161.

Medium/High GWP alternatives
HFC-134a and R-410A and other mixtures of HFCs are currently used in air conditioning but it is also feasible to use HFC-32.

Air conditioning – multi-split

Non-ducted products can be sub-divided into two sub-categories: single-split and multi-split. With multi-split systems, a single outdoor condensing unit is connected to two or more indoor fan coils. These products typically have much higher refrigerant charge levels than single-split non-ducted units. In addition, variable refrigerant flow (VRF), systems, are a further sub-category of multi-split non-ducted air conditioning systems.

VRF systems are typically used in commercial applications and are distinguished from regular multi-split systems by their ability to modulate the refrigerant flow in response to the system demand. VRF systems normally consist of a several indoor air-handling units connected to a single outdoor unit. The outdoor unit modulates the total refrigerant flow using various compressor capacity control systems.

Low GWP alternatives
There are no low-GWP current options, except for R744 in certain circumstances, although longer term options include unsaturated HFC blends and blends with HFCs.

Medium/High GWP alternatives
R-410A and other mixtures of HFCs are currently used in condensing units but it is also feasible to use HFC-32 in such systems.

Positive displacement chillers

Comfort air conditioning in large commercial buildings and building complexes (including hotels, offices, hospitals, universities, and other central systems) is commonly provided by chillers. Chillers cool water or other heat transfer fluid (such as a water-antifreeze mixture) that is pumped through heat exchangers in air handlers or fan-coil units for cooling and dehumidifying the air. Chillers also are used for process cooling in commercial and industrial facilities

Positive displacement chillers are comprised of one or more compressors (mainly reciprocating, screw, and scroll), an evaporator that cools a heat transfer fluid (water, brine, glycol, etc), displacing heat to the surroundings either via an air-cooled or evaporative condenser or via a water-cooled condenser/cooling tower arrangement. Some chillers may also operate in reverse cycle mode to provide heating functionality.

In addition to air conditioning, a proportion of chillers are also used for commercial, industrial and food processing refrigeration purposes.

Low GWP alternatives
Low GWP long term refrigerant options for chillers currently available include R-717, HC-290 and HC-1270 and also R744 for cool and moderate climates. Other longer term options are likely to include HFC-161, HFC-1234ze, HFC-1234yf and other unsaturated HFCs and (as yet, undisclosed) blends of these, including blends with HFCs.

Medium/High GWP alternatives
HFC-134a, R-404A, R-410A and other mixtures of HFCs are currently used in chillers but it is also feasible to use HFC-32 in such systems.

Heating-only heat pumps

Heat pump water heaters are designed especially for heating service hot water (including domestic water) to a temperature between 55 and 90 ºC.

Heating-only heat pumps normally take heat from water, ground or air sources, and then transfer it to a water circuit for either space heating, hot water heating or both. These systems are normally applied to domestic and small commercial situations.

Low GWP alternatives
Heat pumps are currently available using R-744 and HC-290. Longer term options are likely to include HFC-152a, HFC-161, HFC-1234ze, HFC-1234yf and other unsaturated HFCs and (as yet, undisclosed) blends of these.

Medium/High GWP alternatives
HFC-134a, R-404A, R-410A and other mixtures of HFCs are currently used in heat pumps units but it is also feasible to use HFC-32 in such systems.

The various alternatives discussed above are summarised in Table 3-7 and Table 3-8.

Table 3-7: Indication of possible application of "low GWP alternatives" to HCFC-22

Refrigerant	Comm refrig – cond units	Comm refrig – central systems	Industr. refrig	Air cond and heat pumps – air-to-air	Air cond – multi-split	Chillers	Heating only heat pumps
HFC-152a				×		×	×
HFC-161		[chillers]		×		×	×
HC-290	×	[chillers]		×		×	×
HC-1270	×	[chillers]		×		×	
R-717	×	[chillers]	×			×	
R-744		×	×	×	×	×	×
HFC-1234yf	×	×		×	×	×	×
HFC-1234ze	×	×		×	×	×	×

Table 3-8: Indication of possible application of "medium/high GWP alternatives" to HCFC-22

Refrigerant	Comm refrig – cond units	Comm refrig – central systems	Industr. refrig	Air cond and heat pumps – air-to-air	Air cond – multi-split	Chillers	Heating only heat pumps
HFC-134a	×	×	×			×	×
R-410A	×	×	×	×	×	×	×
R-404A	×	×	×	×	×	×	×
HFC-32	×	×	×	×	×	×	×

3.2.1 Special considerations for refrigerant options

Certain refrigerants require special considerations, which apply to the various applications where they are used. Typically, these special considerations have cost implications associated with them.

Flammability
The refrigerants HFC-161, HC-290, HC-1270, HFC-32, R-717 and HFC-1234yf are all flammable refrigerants. Safety standards (such as EN 378, IEC 60335-2-40, etc) limit the quantity of refrigerant that can be used in certain situations and also demand special construction features, including elimination of potential sources of ignition. HFC-161 and hydrocarbons have higher flammability, whereas HFC-32, R-717 and HFC-1234yf have lower flammability.

Toxicity
The refrigerant R-717 is a higher toxicity refrigerant. Safety standards (such as EN 378, ASHRAE-15, etc) limit the use of higher toxicity refrigerants within occupied spaces and also demand special construction features, including for machinery rooms.

Efficiency
Generally, most of the options described for the various sub-sectors will achieve the same efficiency as HCFC-22 within ±5%. Some refrigerants have particularly favourable thermo-physical properties, which through their exploitation by careful system design and optimisation enable a greater improvement in efficiency or equal efficiency with significant reductions in equipment size (due to a decrease in the heat exchanger area). On the other hand, for cooling applications (i.e., not heat pump cycles) one refrigerant, R-744, exhibits an increasing drop in

efficiency as the ambient temperature exceeds 30-35ºC (depending upon the application), although this can be offset if heat recovery is applied.

Maturity
Whilst some of the refrigerants are broadly available, several options are not fully mature at present and their application cannot be achieved immediately (such as HFC-161, HFC-1234yf and other unsaturated HFCs and blends). For some refrigerants that are currently available, their application in certain types of systems is still under development.

Further discussion of the challenges associated with various options is provided in the 2010 UNEP RTOC report.

Table 3-9: Summary of the technical, economic and environmental characteristics of the HCFC replacement options

	GWP	*Application*	*Current Status*	*Efficiency*	*Flammability*	*Toxicity*
R-404A	3700	CR, HP	CA	as HCFC-22		
R-410A	2100	AC, HP, CH	CA	as HCFC-22		
HFC-134a	1370	CR, CH, HP	CA	as HCFC-22		
HFC-152a	133	HP, AC	CA	as HCFC-22	++	
R-407C	1700	AC, CR, CH	CA	as HCFC-22		
R-744	1	CR, HP, CH	CA	as HCFC-22		
R-717	<1	CR, AC, CH, HP	CA	as HCFC-22	+	++
HC-290	<20	CR, AC, CH, HP	CA	as HCFC-22	+++	
HC-1270	<20	CR, AC, CH, HP	CA	as HCFC-22	+++	
HFC-32	716	AC, CH, HP, CR	PT	as HCFC-22	+	
HFC-161	12	AC, CH, HP, CR	PT	as HCFC-22	+++	
Unsat HFC (HFC-1234yf, etc)	<4.4	HP, CH, CR	PT	as HCFC-22	+	
Unsat. HFC/HFC blends		AC, CR, HP, CH	PT	Probably as HCFC-22		
"Not in kind" Technologies						
Sorption cycle		CH, AC	CA	poor	(+)	(+++)
Desiccant cooling systems		AC	CA	good		
Stirling cycle		CR, AC	PT			
Thermoelectric		CR, AC	CA	poor		
Thermoacustic		CR, AC	PD	poor		
Magnetic		CR, AC	PD	good		

CR – Commercial refrigeration
AC – Air conditioning
HP – Heat pump
CH – Chiller
CA – Commercially available
PT – Prototype testing

3.3 Cost aspects

The cost implications of introducing alternative refrigerants may be considered in two different categories:

- Direct product costs
- Societal costs

When considering costs associated with an alternative refrigerant, the baseline refrigerant is HCFC-22 since it is the most commonly used in Article 5 countries.

Generally for a new technology, "market introduction" costs are normally incurred due to the smaller initial output of components, materials and so on. Since these are not necessarily related to the refrigerant characteristics, they are neglected.

Patents exist related to production, use and system/component designs for different refrigerants. Owing to the complexity of this issue, the costs associated with these are not addressed here, but should be allowed for when considering several of the alternative refrigerants.

The conventional cost categories under the MLF include only incremental capital costs (ICC) and incremental operating costs (IOC), which are typically allocated to production line equipment and differences in system parts and components, respectively. For clarity, see Table 3-10, where each cost is categorised as ICC, IOC or "other".

Table 3-10: Indication of which costs are assigned as ICC, IOC or others

Cost	**ICC**	**IOC**	**Other**
Refrigerant cost (price) – manufacturing		×	
Refrigerant cost (price) – service/ maintenance			×
System components (materials)		×	
Installation costs		×	
Production line conversion	×		
Technician training			×
Technician tooling			×
Service and maintenance costs			×
Disposal costs			×

3.3.1 Direct product costs

These are costs incurred in the design, construction, production and installation of a system. They therefore comprise the research and development costs associated with integration of the refrigerant, refrigerant price, differences in cost for components arising from necessary changes for the refrigerant, additional requirements during on-site installation or construction of the system and purchase of alternative equipment for the production line.

Refrigerant cost (price)

The price of the refrigerant varies widely according to country, particular distributor, size of cylinder, etc. For newer refrigerants, there is often a 'market introduction' cost inherent within the price. As such, it is found that the price per unit mass of refrigerants varies widely.

A document published by the MLF (MLF, 2010) provided a survey of refrigerant prices globally but mainly comprised data for common CFCs, HCFCs and HFCs; of the substances of interest, the only ones for which values were provided were HFC-134a, R404A, R410A and R290. For other refrigerants of concern within this report, a number of refrigerant suppliers in different countries were consulted. For some refrigerants which are particularly new (i.e., R1234yf and R1234ze) and not in wide commercial use, typical retail price is not well known; despite this certain producers have provided an indication. Based on these sources a range of prices is indicated in Table 3-12.

Table 3-12: Refrigerant price ranges

Refrigerant	Price range (manufacture) (US$ per kg)	Price range (service) (US$ per kg)
HFC-152a	3 – 4	3 – [20]
HFC-161	3 – 4	3 – [20]
HC-290	2 – 6	7 – 20
HC-1270	2 – 5	3 – [20]
R-717	0.5 – 2	[1 – 4]
R-744	0.5 – 2	5 – 7
HFC-1234yf	45 – 65*	[45 – 80]*
HFC-1234ze	[30 – 50]*	[30 – 65]*
HFC-134a	7 – 9	4 – 24
R-404A	8 – 10	6 – 35
R-410A	8 – 10	8 – 45
HFC-32	7 – 9	[30 – 50]

NOTE: Values in parentheses [ ] are estimated

* Prices are current estimates; they may fall as these HFCs come into more widespread use

By comparison, the price for HCFC-22 is normally US $2 – $4 per kg for manufacturing quantities and US $2 – $20 per kg for servicing.

Since refrigerants have different densities, the quantity of refrigerant required for a system of a given cooling capacity varies. Consequently, the expenditure on refrigerant would be adjusted accordingly and the results of calculations are shown in Table 3-13. Through circuit design, the refrigerant charge may be increased or reduced in order to optimise efficiency; however, this is not accounted for here as it is not necessarily directly linked to the refrigerant properties.

Table 3-13: Ratio of refrigerant liquid density to R22 liquid density

Refrigerant	Charge size ratio	Charge-adjusted price range (manufacture) (US$ / kg HCFC-22-eq)	Charge-adjusted price range (service) (US$ / kg HCFC-22-eq)
HFC-152a	76%	2 - 3	2 - 15
HFC-161	61%	2 - 2	2 - 12
HC-290	41%	1 - 2	3 - 8
HC-1270	42%	1 - 2	1 - 8
R-717	51%	0.3 - 1	1 - 2
R-744	52%	0.3 - 1	3 - 4
HFC-1234yf	92%	41 - 60	41 - 73
HFC-1234ze	98%	29 - 49	29 - 64
HFC-134a	102%	7 - 9	4 - 24
R404A	86%	7 - 9	5 - 30
R410A	87%	7 - 9	7 - 39
HFC-32	80%	6 - 7	24 - 40

System components

Refrigerant choice affects the material costs of several types of components. The components are grouped according to:

- Compressors
- Heat exchangers (evaporator, condenser)
- Piping and valves
- Safety features

The variation in compressor cost is primarily related to the differences in compressor size, which is linked to the required displacement of the refrigerant. R-717, material costs are often comparatively higher because of addressing compatibility issues through use of different metals or using open type compressors.

Materials for heat exchangers mainly differ due to the requirements in tube diameter and surface area in order to compensate for lower or higher pressure, pressure drop and heat transfer coefficients.

For most HFC and HC refrigerants, the variation in material cost for piping and valves also arises from equivalent pressure loss of the refrigerant and operating pressure. In the case of R-717 and R-744 stainless steel tends to be employed, which has higher costs associated with it, but these should be considered with respect to potential improvements in efficiency and longevity of systems.

Safety features differ according to the refrigerant. For flammable refrigerants, these may include sealed electrical enclosures and in larger systems, gas detection and extract ventilation equipment. For R-717, gas detection and extract ventilation is required in most systems to address higher toxicity issues.

Table 3-15 provides a range of system costs for the different component groups. In most cases, the costs are rather sensitive to the specific approach taken by system producers, in terms of circuit design, heat exchanger design and safety strategy. Note that the costs considered within Table 3-15 do not account for the non-system parts, such as casing, wiring, aesthetics, etc.

Table 3-15 Variation in selected system component material costs

Refrigerant	**Typical variation of overall system material costs**			
	Compressor	**Heat exchangers (evaporator, condenser)***	**Piping and valves**	**Safety features**
HFC-152a	+1% – +2%	-5% – 0%	-2% – 0%	+1 – +5%
HFC-161	+1% – +2%	-10% – 0%	-2% – 0%	+1 – +5%
HC-290	+1% – +2%	-10% – 0%	-2% – 0%	+1 – +5%
HC-1270	0%	-10% – 0%	-2% – 0%	+1 – +5%
R-717	+5% – +15% (??)	-5 – +5% (??)	+5 – +20% (??)	+1 – +15%
R-744	+5% – +15% (??)	-5 – +5% (??)	+5 – +20% (??)	0% – +1%
HFC-1234yf	+3% – +5%	0% – +15%	0% – +2%	+1% – +3%
HFC-1234ze	+3% – +5%	0% – +15%	0% – +2%	+1% – +3%
HFC-134a	+3% – +5%	0% – +15%	0% – +2%	0%
R-404A	0%	0%	0%	0%
R-410A	-2% – -4%	-5% – 2%	-2% – 2%	0%
HFC-32	-2% – -4%	-5% – 2%	-2% – 2%	+1% – +3%

* If mini-channel heat exchangers are used, the cost variation would be different

As a means of comparison, the approximate distribution of the total material cost is according to Table 3-16.

Table 3-16: Approximate distribution of material costs

	Integral	**Split**	**Centralised**
Compressor(s)	50%	50%	40%
Refrigerant	10%	10%	20%
Piping and valves	10%	10%	20%
Heat exchangers	30%	30%	20%

It is important to be aware that the variation in component and material costs can differ widely especially in centralised systems where a large number of design options are in current use (see section 3-2).

Installation costs

- Installation costs as a result of alternative refrigerant use can affect the following:
- Installation of refrigerant piping
- Installation of main refrigeration machinery (compressors, condensers, evaporators, valves)
- System preparation; pressure/strength testing, evacuation, charging and leak (tightness) checking
- Installation of necessary safety equipment
- System commissioning

For self-contained systems, the installation costs are fairly similar for all alternatives, whereas for site-installed systems, there can be a significant variation in installation costs.

Table 3-17: Variation in system installation costs compared to HCFC-22 systems

Refrigerant group	System type	Aspect				
		Refrigerant piping	**Main refrigeration machinery**	**System preparation**	**Safety equipment**	**System comm**
Group 1 152a, 161, 290, 1270	Integral	n/a	Neg.	n/a	Small incr.	Neg.
	Split	Neg.	Neg.	Neg.	Neg.	Neg.
	Central [in chillers]	n/a	Neg.	n/a	Small incr.	Neg.
Group 2 HFC-1234yf, HFC-1234ze	Integral	n/a	Neg.	n/a	Neg.	Neg.
	Split	Neg.	Neg.	Neg.	Neg.	Neg.
	Central	Neg.	Neg.	Neg.	Neg.	Neg.
Group 3 R-744	Integral	n/a	Neg.	n/a	n/a	Neg.
	Split	Small incr.	Neg.	Neg.	n/a	Neg.
	Central	Medium incr.	Neg.	Neg.	n/a	Neg.
Group 4 R-717	Integral	n/a	Neg.	n/a	Small incr.	Neg.
	Split	Small incr.	Neg.	Neg.	Small incr.	Neg.
	Central	Medium incr.	Neg.	Neg.	Small incr.	Neg.
Group 5 R-410A, R-404A	Integral	n/a	Neg.	n/a	Neg.	Neg.
	Split	Neg.	Neg.	Neg.	Neg.	Neg.
	Central	Neg.	Neg.	Neg.	Neg.	Neg.
Group 6 HFC-32	Integral	n/a	Neg.	n/a	Neg.	Neg.
	Split	Neg.	Neg.	Neg.	Neg.	Neg.
	Central	Neg.	Neg.	Neg.	Neg.	Neg.

n/a: not applicable
Neg.: difference is negligible
Small incr.: a small increase in overall installation time
Medium incr.: a medium increase in overall installation time

Where differences are applicable, the additional time required (and thus cost) for the various installation activities are negligible for the majority of cases. In general specific values are difficult to give because of the wide variation in system designs and conditions that result in a correspondingly wide variation in relative costs.

Production line conversion

With a change in refrigerant for factory produced and charged systems, a number of production line equipment changes need to be considered. For example, new refrigerant containers, supply lines and pumps may be required; the refrigerant may be flammable requiring extractor fans; it may require higher pressures, upgraded vacuum pumps, helium type leak tightness testing, and changes to heat exchanger tube diameters etc.

Apart from the characteristics of the refrigerant, the cost of production line conversion depends upon the type and size of systems and the annual production run. A range for typical costs of equipment (including installation and commissioning) is provided (Table 3-18). Two categories of production type are considered:

- Medium scale; producing large systems (chillers, rack systems, VRF, etc) with 5000 systems per year
- Large scale; producing small systems (split ACs, condensing units, etc) with 200,000 systems per year

It is acknowledged that in certain cases several different types of systems may be produced in the same production line, but for the purposes of the discussion, they are assumed to operate independently.

Table 3-18: Cost range for conversion of production line - medium and large

Refrig-erant	Producti on type	Equipment costs ($)					
		Refrigerant system *	Charging machines *	Tightness checking	Safety system *	Ultrasonic welding †	Exchanger tooling †
Group 1	Medium	15,000	30,000		10,000		
	Large	40,000	60,000	110,000	60,000	[80,000]	[700,000]
Group 2	Medium	15,000	30,000		4,000		
	Large	40,000	60,000	110,000	20,000	[80,000]	[700,000]
Group 3	Medium	15,000	30,000				
	Large	40,000	60,000	110,000			[700,000]
Group 4	Medium	15,000	30,000		10,000		
	Large						
Group 5	Medium	15,000	30,000				
	Large	40,000	60,000	110,000			[700,000]
Group 6	Medium	15,000	30,000		4,000		
	Large	40,000	60,000	110,000	20,000	[80,000]	[700,000]

* Where systems are not pre-charged, these items are not required.

† Costs indicated in parentheses imply that they may or may not be required depending upon the particular production methods within an organisation.

scale

Given the range of different prices of equipment from different suppliers and the differences in equipment requirements according to the specific production line arrangements, the costs in Table 3-18 can be considered to vary by up to ±50%.

3.3.2 Societal costs

These are costs associated with enabling organisations and enterprises with the design, specification and handling of systems, which use alternative refrigerants. They therefore primarily comprise the time required for technician training, differences in tooling for technicians, changes to the time required for service and maintenance of systems, the requirements for disposal at end of life as well as the formation of necessary rules for applying and handling alternatives.

Technician training

This covers training of technicians to assist them with becoming competent with the use of the refrigerant during equipment installation, maintenance, servicing and disposal. The following describes the costs associated with additional knowledge to what they would need to know about with regards to HCFC-22 (Table 3-19).

Table 3-19: Additional training topics and estimated time requirements

Group	Additional training	Time requirements
Group 1	Handling flammability	3 days
Group 2	Awareness of flammability	1 day
Group 3	Handling high pressure Alternative system design	3 days
Group 4	Awareness of flammability Handling higher toxicity Addressing material compatibility	4 days

Technician tooling

For technicians to suitably install and service equipment using the alternative refrigerants there is sometimes a need to procure new tools and equipment. From a systematic consideration of all possible tools and equipment that a technician may use, few items were identified which would have to be replaced solely as a result of a change in refrigerant.

Table 3-20: Key tools and equipment changes for different refrigerant groups

Tools and equipment	Group 1	Group 2	Group 3	Group 4
	HFC-152a, HFC-161, HC-290, HC-1270	HFC-1234yf, HFC-1234ze	R-744	R-717
Manifold gauge	Y *	Y/N *	Y	Y
Gas detector	Y	Y/N	Y	Y
Recovery machine	Y	Y/N	N	Y

* An alternative option is to use a comparator (slide rule)

It is noted that some of the alternatives are more susceptible to system contaminants, so it could be argued that the importance of using a vacuum pump and vacuum gauge is heightened in some cases. Similarly, because of the comparatively smaller charge sizes for certain options, there may be a need for more accurate electronic charging balances.

Service and maintenance costs

Service and maintenance costs are mainly associated with refrigerant price. Otherwise, some differences in the amount of time (and thus cost) may occur, such as recovery duration or longer evacuation periods (arising from the use of synthetic oils or high solubility of the refrigerant within the oil), etc. However, these are difficult to quantify and probably have a small variation compared to other influences (such as local practice, etc.). For flammable and higher toxicity refrigerants, additional time for safety checks may be necessary, but again, this is normally minor compared to the remaining site activities. Therefore, given the variations in practices, there is not considered to be any significant variation in service and maintenance costs amongst different refrigerants, except for that imposed by the refrigerant price itself.

Disposal costs

Disposal costs are primarily sensitive to national regulations. In most Article 5 countries, it is not prohibited to vent common refrigerants. However, in some countries there are regulations relating to the emissions of fluorinated substances, so it is not clear what the specific requirements would be for HFC-152a, HFC-161, HFC-1234yf and HFC-1234ze. In all countries it is anticipated that R717 must be recovered and recycled or disposed of.

If currently available equipment is not suitable for use with existing refrigerants (such as HCFC-22) then additional expenditure may be necessary for recovery machines and recovery cylinders. It is expected that a collection/ transportation/ delivery infrastructure for recovered refrigerants would already be in place due to CFC/HCFC legislation.

3.3.3 Summary of findings from EU study

The recent EU Study (Schwartz, 2011) to accompany the revision of the fluorinated gas regulation contained an assessment of costs of different alternative technologies. Since this is the only recent source containing such information, it is mentioned here.

The costs are broadly separated into ICCs and IOCs, although the definition did not necessarily match that of ICC and IOC within the Montreal Protocol context. The baseline for the calculations is the use of HCFC-22.

For commercial refrigeration, incremental costs are indicated on a time basis, this implying that the immediate additional cost (2015) includes for market introduction costs, whereas the eventual costs (e.g., by 2020 or 2030) represent the differences in material and additional labour costs only. For other types of systems, the market introduction costs are not included since it is assumed that the large number of systems built within a short period enables these introduction costs to be rapidly overcome.

The ICC values are calculated by averaging the investment cost over a ten year period.

Table 3-21: Cost impacts of alternative technologies from the EU F-gas study

Applica-tion	System type	HC-290/ HC-1270		R-744		R-717		HFC-1234yf	
		ICC	IOC	ICC	IOC	ICC	IOC	ICC	IOC
Comm refrig – cond units	Direct	+1%	+20% → 5% (2030)	+1%	+35% → 0% (2030)	n/a	n/a	+1%	35% → 0% (2030)
	Indirect	+1%	+35% → 0% (2030)	n/a	n/a	n/a	n/a	n/a	n/a
Comm refrig – central systems	Direct/ transcrit	n/a	n/a	Neg.	+25% → 0% (2030)	n/a	n/a	n/a	n/a
	Indirect (small)	Neg.	+30% → 0% (2030)	n/a	n/a	n/a	n/a	n/a	n/a
	Indirect (large)	Neg.	+15% → 0% (2020)	n/a	n/a	n/a	n/a	n/a	n/a
	CO2 sec (small)	Neg.	+50% → 0% (2030)	n/a	n/a	n/a	n/a	Neg.	+50% → 0% (2030)
	CO2 sec (large)	Neg.	+20% → 0% (2020)	n/a	n/a	n/a	n/a	Neg.	+20% → 0% (2020)
Industrial refrig	General	n/a	n/a	n/a		Neg.	+50%	n/a	
Air cond and heat pumps	Factory sealed	+0.5%	-1%	+0.5%	+20%	n/a	n/a	+0.5%	+6%
	air-to-air	+0.5%	-2%	+0.5%	+25%	n/a	n/a	+0.5%	+8%
	VRF	n/a	n/a	+1%	+20%	n/a	n/a	+1%	+12%
	ducted	n/a	n/a	+1%	+15%	n/a	n/a	+1%	+12%
Chillers	Small	+1 - +5%	+5%	+5 - +20%	+25%	+10 - +50%	+40%	+1 – 5%	+1%
	Large (incl centrif)	+1%	0%	++5%	+20%	+3 - +7%	+20%	+15%	+5%
Heat pumps	Heating only	+1%	+5%	+2%	+10%	n/a	n/a	+1%	+5%

3.3.4 Concluding remarks

This section breaks down the various cost elements for applying alternative refrigerants to different types of systems.

There are important variables associated with the estimation of costs for a given refrigerant option. These include:

- Size of the enterprise
- Extent of product development within an enterprise
- Maturity of the product and option
- Extent of spread and maturity of the technology throughout an industry

- Status of patents and technology licences
- Range of models and system capacities
- Refrigerant charge quantity of existing models
- Whether the enterprise produces heat exchangers internally or sources externally
- Country/geographical location

It is therefore difficult to provide precise costs for most systems because of the contribution of these factors in addition to the wide variation in production methods and system designs.

Annex to chapter 3

HCFC alternatives under high ambient temperature conditions

A3.1 Introduction

Decision XXIII/9 mentions in clause (b) that TEAP (and its RTOC) should give information on "Alternatives to HCFCs that are technically proven, economically viable, environmentally benign and suitable for use in high ambient temperatures, including how such temperatures may affect efficiency or other factors"

The 2010 TEAP Progress Report (UNEP, 2010) gave an extensive description of the selection of alternatives under high ambient temperature conditions. Since then, no new studies on this issue have been published. This annex provides a summary of the information as well as results of calculations varying several important parameters.

A3.1.1 HCFC-22 and its substitutes

HCFC-22 is the most widely used refrigerant in refrigeration and air-conditioning equipment (RTOC, 2010). Owing to the accelerated phase-out schedule for Article 5 Parties, the performance of alternatives and replacements to HCFC-22 under extreme weather conditions --as occur in many Article 5 countries and some non-Article 5 countries-- has become an important issue for unitary air conditioning equipment and commercial refrigeration.

HCFC-22 has been chosen in many refrigeration and air conditioning (RAC) applications, because its thermodynamic properties have led to some interesting compromises between the initial costs for the equipment and operational costs, which are mainly driven by energy efficiency. For RAC systems operating at high ambient temperatures, the most efficient choice is a refrigerant with a critical temperature higher than 80°C in order to condense under energy efficient conditions and with heat exchange areas at competitive costs. HCFC-22 has a critical temperature of 96°C and thus performs well in hot climates. However, the critical temperature is not the only refrigerant characteristic, which must be considered when selecting refrigerants for hot climates. HCFC substitutes have to fulfil a number of contradictory criteria, which lead to different choices dependent on the application. For example, HCFC-22 will have a different substitute refrigerant in large supermarket applications than it would have in air to air AC systems. For mass-produced systems such as air conditioning, initial costs, reliability (including safety) and energy performance are key elements that will define a series of options. For field erected systems, such as centralized commercial refrigeration systems, initial costs, the reputation of the brand name and reliability are the drivers for the refrigerant choice.

A3.2 Refrigerants for high ambient temperature air conditioning

Air conditioning is generally done using either unitary (air-to-air) equipment or liquid chillers, which are indirectly cooling air in water-to-air heat exchangers. For large centrifugal chillers, the refrigerant choices are HCFC-123 (which has replaced CFC-11) and HFC-134a (which has replaced CFC-12). Both refrigerants perform well at higher condensing temperatures. Currently HFC-1234ze is being tested as a replacement. HCFC-22 is widely used in non-centrifugal chillers, which vary largely in terms of cooling capacity and compressor types.

A3.2.1 Air to air AC system design and refrigerant choices for high ambient temperatures

High ambient conditions (above 40°C) impact both cooling capacity and energy efficiency (COP). The governing thermodynamic properties result in a declining capacity and efficiency for all refrigerants as the heat-rejection (refrigerant condensing) temperature increases.

The two main HFC refrigerant blend substitutes for HCFC-22 are R-407C and R-410A. For all small systems with a capacity lower than 20 kW the preferred choice is R-410A. R-407C is selected in many cases to keep the same (compressor) technology as the one used for HCFC-22. Hydrocarbons are also being used in some low refrigerant-charge applications.

In order to understand the different technical compromises, table A3-1 gives a series of thermodynamic characteristics, which have a direct impact on either initial cost or on energy efficiency or equipment reliability.

The first generic property of a refrigerant is its critical temperature. The higher the critical temperature the easier the refrigerant can be used under high ambient conditions. The table shows that R-410A is not the best option to replace HCFC-22 (comparing their critical temperatures of 71.4 °C and 96.1 °C); at equivalent equipment design the energy performance is about 15% lower at 60°C condensing temperature. This implies that extra design efforts have to be made in order to achieve comparable energy efficiency.

Table A3-1: Important thermodynamic characteristics of refrigerants for high ambient temperature conditions

Refrigerant	Tc (°C)	P_{cond} (60°C) (Mpa)	P_{evap} (10°C) (MPa)	ρ_{asp} (kg/m^3)	Q_{ov} (kJ/m^3)	$T_{discharge}$ (°C)	COP (*)
HCFC-22	96.1	2.42	0.68	24.7	3760	100	2.8
R-410A	71.4	3.83	1.08	35.7	4830	96	2.3
R-407C	86.0	2.76	0.77	23.2	3250	64	2.8
HC-290	96.7	2.11	0.63	11.9	2985	79	2.6
HFC-32	78.1	3.92	1.10	25.8	5870	117	2.6
R-717	132.3	2.60	0.61	4.1	4750	162	3.1
HFC-134a	101.1	1.67	0.41	19.6	2290	80	2.7
HFC-1234yf	94.7	1.63	0.44	20.6	2030	69	2.4
HFC-1234ze	109.4	1.27	0.30	13.9	1740	72	2.6
HC-1270	91.1	2.52	0.77	16.3	3490	87	2.6
HFC-161	102.2	2.17	0.60	14.1	3600	88	2.9

Note: Shown are critical temperature, condensation and evaporation pressures, density, volumetric capacity, discharge temperature and coefficient of performance (COP)

Note: The COP is calculated for 5 K superheat, an overall compressor efficiency of 0.7 for all refrigerants, a condensing temperature of 60°C and an evaporating temperature of 10°C

When analyzing the refrigerant with the highest critical temperature (R-717, critical temperature 132.3 °C), it shows the highest COP, but due to the very low molar mass (17 g/mole) the discharge temperature at the compressor outlet (162 °C) is not acceptable for reliability. It would require liquid injection to keep this temperature at a level lower than 130 °C.

At high ambient temperatures, propane (HC-290) appears to have a low discharge temperature, a relatively good energy efficiency but a 20 % lower volumetric capacity (Q_{0v}) compared to HCFC-22. This drawback is not essential. HC-290 is obviously thermodynamically well suited for high ambient conditions. The main limitation of use is related to its flammability, which limits its use to small refrigerant charges and requires also safety precautions which implies higher costs.

A3.2.2 Overview of refrigerants

The current refrigerants of choice for unitary air conditioning are HCFC-22, R-407C and R-410A (see section 3.2). R-410A is the dominant choice for HCFC-22 in many countries. Many refrigerants have already been analysed in the 2010 TEAP report (TEAP, 2010). Some highlights and extra information can be found below.

HC-290 has performance characteristics similar to HCFC-22; its GWP is around 20. Its thermodynamic characteristics are close enough to HCFC-22 so that the current products that employ HCFC-22 could be re-engineered to employ HC-290. HC-290 has successfully been commercialised as an HCFC-22 replacement in low charge, room and portable air-conditioner applications of less than 5 kW. Safely and cost effectively applying hydrocarbons to larger unitary systems will be a significant technical challenge.

HFC-32 (GWP 717) is not only considered as an alternative to HCFC-22, but also as an alternative to R-410A. HFC-32 is not a drop-in substitute to HCFC-22, and some adaptations are also necessary to switch from R-410A to HFC-32. HFC-32 is moderately flammable classified as A2L refrigerant (L meaning low), so much larger charges can be used compared to HC-290. IEC-235-2-40 as well as EN-378 standards prescribe the maximum allowable charge with reference to the room volume. HFC-32 will have higher capacity at high ambient temperatures. HFC-32 with its critical temperature is less efficient than HCFC-22 at high temperature at equivalent design, but its performance is slightly higher than R-410A at high condensing temperatures (above 60°C). The discharge temperature of HFC-32 is high which needs to be considered when applying it at high ambient conditions.

HFC-134a seems attractive from the point of view that it has better energy performance compared to HCFC-22 at high ambient temperatures. However, it is a low pressure refrigerant, therefore extensive redesign of the base system components would be required. Design changes would include larger displacement compressors, increased heat exchanger areas and increases in piping sizes used in heat exchangers and inter-connecting tubing. All of these changes would lead to substantial increases in the product cost. Its GWP is classified as high.

HFC-152a and HFC-161 are two low GWP HFCs (GWP equal to 133 and 12, respectively). Both are flammable (the safety classification of HFC-161 is not yet been established) and have performance characteristics similar to HFC-134a. The design of HFC-152a equipment should follow the requirements of relevant safety standards such as IEC 60335-2-40, which requires limited refrigerant charges or (under certain circumstances) the use of indirect systems. In addition, significant redesign of existing HCFC-22 equipment would be required to utilise HFC-152a. The necessary system design changes are similar to those described for HC-290.

HFC-161 is a flammable, low GWP alternative, and also being evaluated as a replacement for HCFC-22 in air conditioning systems. Studies comparing HCFC-22 and HFC-161 are just beginning to appear in literature; much of the current research is being conducted in China. As with all flammable refrigerants, HFC-161 would need to be applied using an appropriate safety standard such as IEC-60335-2-40.

Due to low volumetric capacities, the low GWP refrigerants R-1234yf as well as R-1234ze require design changes. These include larger displacement compressors, increased heat exchanger areas and larger diameter interconnecting tubing. The changes are similar to the changes described for HFC-134a. HFC-1234yf has an A2L flammability rating and would need to be applied using appropriate safety standards. In general, these have about a 50% lower volumetric capacity than HCFC-22 and are not considered as substitutes for HCFC-22 for air to air AC systems (Minor, 2008). The cooling capacity has to be much larger (> 150 kW) to make these low GWP refrigerants competitive to HCFC-22.

A3.2.3 Concluding remarks

A number of low GWP alternatives to HFC refrigerants are currently under development. However, because these refrigerants are in the early stages of development it is premature to list them as options to the current HCFC alternatives.

However, in the longer term, as non-ODP and low-GWP technologies are developed to replace current HCFC-22, R-407C and R-410A products, equipment designed to operate with acceptable efficiency and capacities at the extreme environment conditions should become available in both Non-Article 5 and Article 5 countries.

A3.3 Refrigerants for high ambient temperature commercial refrigeration

Commercial refrigeration covers a wide variety of equipment, and can be classified in three categories: stand-alone equipment, condensing units, and centralized systems. According to the type of system, the refrigerant charge varies from hundreds of grams to a thousand kilograms. Moreover, depending on the system type, the refrigerant choice is different. Usual choices have been: HFC-134a with a relatively low volumetric capacity is used in small equipment (most stand-alone equipment and some condensing units) and preferably at the medium level of the evaporating temperature. Refrigerants such as HCFC-22 or R-404A, with a larger volumetric capacity, are used in large centralized systems for all levels of evaporating temperatures.

The phase-out of HCFC-22 (as occurred in Europe) has caused an extension of the range of refrigerant options to be considered. Refrigerants as diverse as hydrocarbons (HC-600a, HC-290, HC-1270), CO_2 (R-744), intermediate blends (R-422D or 427A) for drop-in or nearly drop-in replacement of HCFC-22 and the usual HFC-134a and R-404A are in use depending on the emphasis set on GWP, safety and energy efficiency for HCFC-22 replacement. Moreover, new refrigerant options were proposed using HFC-1234yf either as pure refrigerant or as component of new blends.

For centralized systems, the cascading system is currently having market-share in supermarkets, with CO_2 applied at the low-temperature level and a variety of refrigerants at the high-temperature level, including ammonia, propane (HC-290), propylene (HC-1270), as well as R-404A.

A3.3.1 Small commercial refrigeration

Stand-alone equipment encompasses a wide variety of equipment types: vending machines, ice machines, ice cream freezers, water fountains, glass door bottle coolers, and plug-in display cabinets. For evaporating temperatures varying from -15°C to 0°C and cooling capacities varying from tens of Watts to 200 W, lower volumetric capacity refrigerants such as HFC-134a or HC-600a are the preferred choice; nevertheless HCFC-22 had a small share of the market in this family of equipment. For hot climate conditions the preferred choice is HFC-134a for those systems, which have been designed based on a single-stage system and the refrigerants have been chosen based on this type of system.

For evaporating temperatures varying from -35°C to -20°C, HCFC-22, R-404A or HC-290 are being used. Exceptions exist, some companies are choosing R-744, even if this refrigerant is not energy efficient at high ambient temperatures.

Table A3-2: Properties of refrigerants and small commercial refrigeration equipment

	CFC-12	HFC-134a	HC-600a	HC-290	HFC-1234yf	R-744
ODP	1	0	0	0	0	0
GWP	10900	1370	20	20	4	1
Molecular mass (g/mol)	120.9	102	58.12	44.1	114	44.01
Normal boiling point (°C)	-29.8	-26.1	-11.7	-42	-29	-78 (frosting)
Critical pressure (MPa)	4.13	4.06	3.64	4.25	3.27	7.38
Critical temperature (°C)	112	101.1	134.7	96.9	95	30.98

The significant introduction of the low GWP refrigerant HC-600a in refrigerators has also led to its use in small commercial equipment such as water fountains, and in equipment having a refrigerant charge lower than 150 g. For ice-cream freezers, stand-alone display cases, ice makers, propane (HC-290) has been significantly introduced in Europe. Owing to their relatively high critical temperatures, HFC-134a, HC-600a and HC-290 are well suited to hot climate applications. The limitation for the use of hydrocarbons is the refrigerant charge, for safety purpose.

For larger refrigerant charges (in the range of several hundreds grams), owing to flammability risks, some global companies have decided to develop the use of CO_2 (R-744) for vending machines. Owing to the low critical temperature of this refrigerant (31°C), those systems experience very high pressure (above 10 MPa) and there is no longer support condensation at the high-pressure side (there is the trans critical cycle). The efficiency of such a trans-critical cycle is relatively low. In summary, CO_2 is not the most suitable fluid for high ambient temperatures, mainly due to relatively poor energy efficiency.

As mentioned above, the thermodynamic properties of low GWP HFC-1234yf are very close to those of HFC-134a (see Table A3-1). Although not directly within the context of this report, it makes this refrigerant a suitable option to replace HFC-134a in hot climates with small adaptation of capillary tubes. It has to be noted that, because this refrigerant has a larger molecule (and heat capacity) than HFC-134a, its discharge temperature is significantly lower (and it would therefore be even more suitable for hot climates).

In summary, for hot climates, four possible refrigerant options can be used in the current low capacity refrigeration technology: HFC-134a, HC-600a, HC-290 and HFC-1234yf.

A3.3.2 Large centralised systems (supermarket refrigeration)

Conservation of frozen food at -18°C requires evaporation temperatures in the range of -35°C to -38°C or even lower for ice creams. Even in moderate climates, those evaporating temperatures have led to a excessively high compressor discharge temperatures when using HCFC-22 (therefore R-502, with lower discharge temperatures, replaced HCFC-22 in European systems). R-404A and R-507 have been formulated in order to replace R-502 and have high molecular weight molecules in order to lower discharge temperatures. Intermediate blends as R-422D or R-427A have been designed to replace HCFC-22 as drop-in options. However, their GWPs are high attractive and their critical temperatures do not imply any gains for high ambient temperature conditions.

Table A3-3: Properties of refrigerants and large commercial refrigeration equipment

	HCFC-22	HC-290	R-404A(1)	R-422D(2)	R-427A(3)	R-744
ODP	0.05	0	0	0	0	0
GWP	1810	20	3900	2700	2300	1
Molecular mass (g/mol)	96.47	44.1	97.6	109.9	106.7	44.01
Boiling point (°C)	-40.8	-42.1	-46.2	-43.2	-39.1	-78.4
Critical pressure (MPa)	4.99	4.25	3.73	3.9	4.02	7.38
Critical temperature (°C)	96.1	96.7	72	79.7	90.2	30.98

Blend compositions, with weight percentages in brackets : (1) R-125/143a/134a (44/52/4) (2)R-125/134a /600a (65.1/31.5/3.4) (3)R32/125/143a/134a (15/25//10/50)

Hot climates imply high condensing temperatures and, for the usual refrigerants, high condensing pressures. High pressures and temperatures have several consequences:

- The energy penalty for a single-stage system is about 1.5% per K of higher condensing temperature, meaning that COPs of medium and low-temperature commercial systems are lower by 15 to 25% in hot climates compared to moderate ones
- For low-temperature applications (frozen food), the discharge temperatures of the compressor with HCFC-22 are so high that liquid injection is necessary either at the suction port or at an intermediate stage if the compressor design allows such an injection.

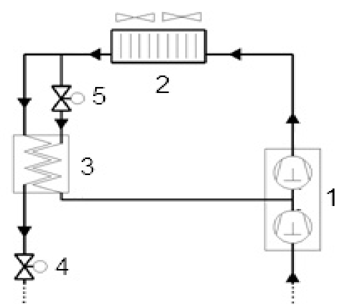
High temperatures at the compressor discharge line imply energy losses and possible decomposition of the lubricant when temperatures become higher than 140°C. As indicated above, HCFC-22 is not the best refrigerant to be used in a direct expansion system for low-temperature applications (evaporating temperature below –35°C) with a condensing temperature above 50°C. The consequence is that single stage systems have to be improved leading to more complex designs.

Several designs have been developed over time in order to improve energy efficiency of low-temperature applications and also to limit the discharge temperature at the compressor discharge port. Those options have been developed over many years in the industrial food sector and these advanced ones are being used in certain regions (so far limited to Northern Europe but not necessarily). The main options are as follows.

- Option 1: liquid injection of refrigerant at the suction port of the compressor; it is the cheapest option, the gain is the temperature control at the discharge port of the compressor, but there is no gain in terms of energy efficiency. This option has been developed for HCFC-22 at high ambient conditions.
- Option 2: sub-cooling of the liquid phase of the main refrigerant flow by an economizer (3) (see Figure A3-1), which requires a compressor (1) capable of sucking at an intermediate pressure the vapor coming from the evaporation, the secondary refrigerant mass flow rate coming from the economizer.

- Option 3: the cascade system (see Figure A3-2) where two different refrigerants are used in two separated refrigeration systems connected by an evaporator-condenser (5). The cascade system allows choosing the most adapted refrigerant for the high temperature level.

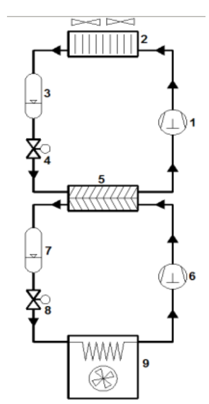
Figure A3-1: Economiser principle



1: compressor, 2: air condenser, 3: economizer, 4 and 5: Expansion valves

Only screw and scroll compressors are capable of compressing two flows at two different pressures. Screw compressors are used in industrial refrigeration but rarely in large supermarkets. Scroll compressors are gaining market share but mostly for condensing units. The main technical option for compressors in supermarkets is the reciprocating technology, the reason why this option is not widely spread.

Figure A3-2: Cascade system



1: high temperature compressor, 6: low temperature compressor, 2: air condenser, 3 and 7: refrigerant receivers, 4 and 8: Expansion valves, 9: low temperature evaporator, 5: evaporator-condenser

The cascading system design is gaining market-share in supermarkets (so far in Europe), with R-744 used at the low-temperature level and a variety of refrigerants at the high-temperature level, among which are: the low GWP refrigerants R-717, HC-290, HC-1270 (propylene), as well as the high GWP R-404A. This design is more costly than the simple one-stage systems, however, in terms of energy efficiency it is much better, with energy efficiency gains in the range to 15 to 30% compared to the single-stage system and can also operate well at high ambient conditions.

A3.3.3 Overview of refrigerants

Intermediate HFC blends such as R-422D or R-427A have been developed in order to make a retrofit from HCFC-22 to HFC based blends easy. These blends as well as R-404A (one component being HFC-125) have lower discharge temperatures compared to HCFC-22, but all have high GWPs.

It is clear that a "free" sub-cooling of the refrigerant is available when supermarkets are air-conditioned and where the refrigerant leaves the high-pressure receiver at, for example, 50°C or above. The long liquid lines (about 100 m or more) are installed in the sales area, where the temperature is about 25°C, and so the refrigerant enters the expansion valve at about 30°C. This temperature decrease leads to better energy efficiency for the refrigeration system, but energy savings in the refrigeration system are offset by increased energy consumption of the AC system ("option 3" above).

Some equipment manufacturers have developed refrigeration systems using hydrocarbons, either HC-290 (propane) or HC-1270 (propylene). Two different types of equipment have to be distinguished:

- Condensing units with refrigerant charge up to several kg in direct expansion systems where either R-404A or R-290 with safety rules defined in the safety standard EN-378.
- Centralized indirect systems with HC-290 or R-404A as primary refrigerants and an indirect system using a heat transfer fluid (HTF) to deliver cooling capacity in the sales area.

  R-744 is proposed in cascading systems for low temperature with R-744 at the low temperature and a refrigerant as HFC-134a at the medium temperature level. This for cold and temperate climates with a small number of hours at temperatures higher than 30°C.

Indirect systems consist of a primary circuit installed in a machinery room where a heat transfer fluid (HTF) is cooled in a primary heat exchanger and then circulates in the heat exchangers (formerly evaporators) of the display cases (RTOC, 2010). This design allows for reducing the refrigerant charge by more than 50%. The refrigerant could be an HFC (R-404A), an HC (R-290, R-1270), or ammonia (R-717), depending on local regulations on the use of flammable or toxic refrigerants.

A3.3.4 Concluding remarks

For high ambient temperatures following conclusions can be drawn:

- For stand-alone equipment, four possible refrigerants can be easily used with the current refrigeration technologies: HFC-134a, HC-600a, HC-290, and HFC-1234yf.

- R-744 can be used in a cascading system at the low level of temperature and requires a high critical temperature refrigerant in the high temperature level. The refrigerants typically being used in the high temperature level are: HFC-134a, but also HC-290 or ammonia depending on the weight put on safety and environmental criteria. Low GWP refrigerants HFC-1234yf or HFC-1234ze may be used in future.

- For centralised systems, owing to the large refrigerant charge and the number of fittings when some hundreds of evaporators are installed in the sales area, it is impossible to use direct expansion systems with flammable refrigerants. For this reason, indirect systems have been used in commercial refrigeration for more than ten years.

HCs such as HC-290 and HC-1270 can be used in hot climates and they exhibit relatively low discharge temperatures compared to HCFC-22. Nevertheless, refrigerant quantities have to be limited and direct expansion systems should have a circuit that is almost completely welded in order to limit refrigerant leaks. Thorough safety precautions have to be taken, one of the most relevant ones being charge reduction by using the indirect system concept. Owing to the development of HFC-1234yf, new blends with low GWP can be expected in the next years. In order to mitigate environmental impact, safety, and energy efficiency, those new blends will possibly be used in indirect systems (for medium temperature applications) or in cascading systems, with CO_2 at the low temperature level.

One important comment should be made here. This would apply to commercial refrigeration -- but also to larger capacity air conditioning systems.

Apart from looking at the direct replacement of the refrigerant HCFC-22 by low GWP refrigerants, it is extremely important to also consider design changes to the overall system environment. These changes should improve system conditions and lower condensation temperatures (operation control strategies during day and night, condensers put in a cold storage area, which is cooled during night-hours etc.) leading to efficient operation.

4 Foams

4.1 Key issues

The following points summarize the current situation in the foam market on HCFC replacement:

- The main market segments currently using HCFCs are rigid polyurethane (PU), including polyisocyanurate (PIR), insulating foams and extruded polystyrene (XPS) foam.
- Hydrocarbons (HCs), mainly pentanes, are the preferred choice for HCFC replacement in rigid PU foams in medium/large enterprises. For some very stringent applications such as appliances they are currently blended with saturated HFCs to enhance the foam thermal performance.
- Saturated HFCs, HFC-245fa, HFC-365mfc/HFC-227ea, HFC-134a are used in significant amounts in developed countries, particularly in North America, for rigid PU foam. However, this well proven technology has two drawbacks, high incremental operating cost because of the blowing agent cost and high GWP.
- There are current and emerging low GWP options to replace HCFCs in the different foam market segments.
- The capital conversion costs for the safe use of HCs in SMEs is prohibitive/not cost effective. This constitutes a barrier to the conversion away from HCFCs in the required timeframe.
- Small quantities of Oxygenated Hydrocarbons (HCOs), specifically, methyl formate, and carbon dioxide (water), both low GWP options, are being used in integral skin foam and some rigid PU foam applications with a penalty compared to HCFC-141b in operational cost and thermal performance.
- Recent evaluations of unsaturated HFCs and HCFCs, commercially known as HFOs, done in a commercial household refrigerator/freezer line, showed an improved thermal performance compared to saturated HFCs. These substances that exhibit GWP values lower than 10, will be commercially available in 2013.

4.2 Market segments using HCFCs

The main foam market segments using HCFCs are:

- Rigid PU and/or PIR insulating foams (collectively referred to as PU foams in this report) and
- XPS foam.

There is one additional segment where HCFCs are being used: PU integral skin foams for automotive and furniture applications. However, usage is much less than in insulating foams per unit of foam because of higher foam density plus the overall market is much less than for insulating foams.

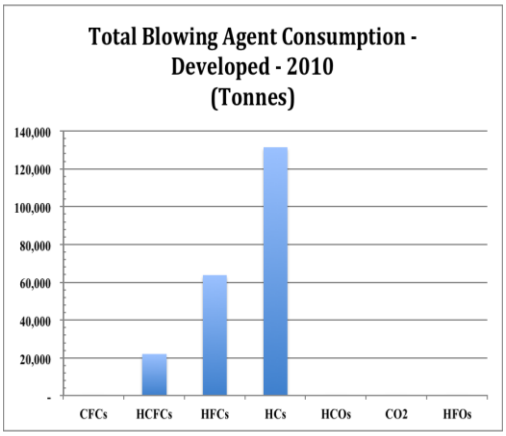
On the contrary, several foam sectors, particularly those such as flexible PU foams used for upholstered furniture and mattresses and for various foams, including those based on polystyrene or PU, for packaging applications, did not use HCFCs to replace CFCs.

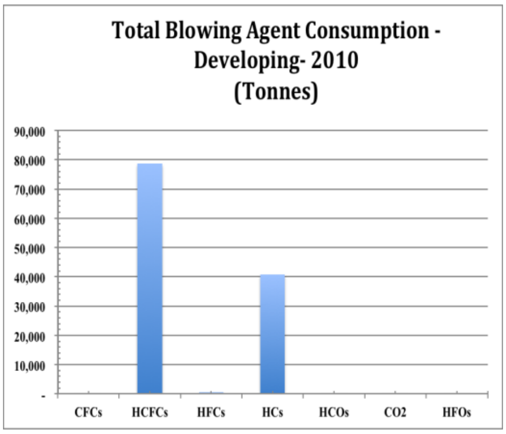
As described in Table 4-1, for PU foams the HCFC of choice to replace CFCs has been HCFC-141b. This was almost a “drop-in” for CFC-11 and has been particularly suitable for the small and medium sized enterprises where it was not economical to retrofit to allow the safe use of hydrocarbons (HCs). For XPS board foams HCFC-22 alone or in blends with

HCFC-142b was the blowing agent of choice and growth in its use has been driven by the growing number of XPS plants in operation in China, Kuwait, Saudi Arabia, Brazil, Turkey and others.

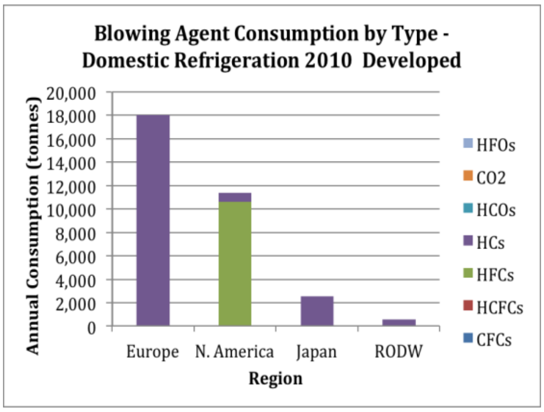
Table 4-1: Foams sectors where HCFCs are currently used	
Sector	**HCFCs Currently Used**
XPS Board	HCFC-22/HCFC142b (blends), HCFC-22, HCFC-142b
PU Insulating Foams	
Domestic refrigerators/freezers	HCFC-141b, minor use of HCFC-141b/HCFC-22
Commercial refrigerators/freezers	HCFC-141b
Refrigerated trucks & reefers	HCFC-141b, minor use of HCFC-141b/HCFC-22
Sandwich panels – continuous	HCFC-141b
Sandwich panels – discontinuous	HCFC-141b
Spray foam	HCFC-141b
Insulated pipes	HCFC-141b
Block foams	HCFC-141b
One Component Foams	HCFC-22
Integral skin foams	HCFC-141b

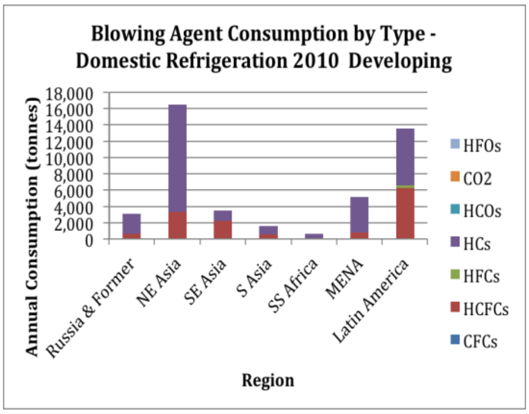
The worldwide 2010 consumption of blowing agent for these applications, extrapolated from the data presented in the FTOC 2010 Assessment (FTOC, 2011), is estimated as 338,000 tonnes, 253,000 in PU and the rest in XPS. From the total of 338,000 tonnes, around 218,000 are used in developed countries and 120,000 in developing countries. The following graphs illustrates the consumption by substance in Article 5 and non-Article 5 Parties:

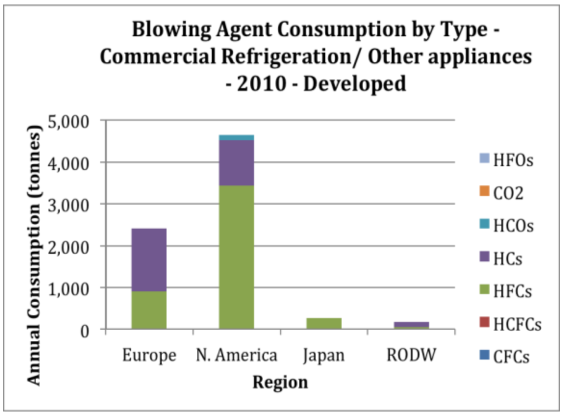


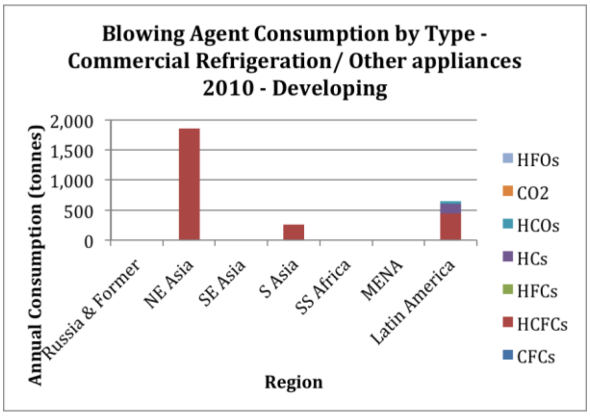


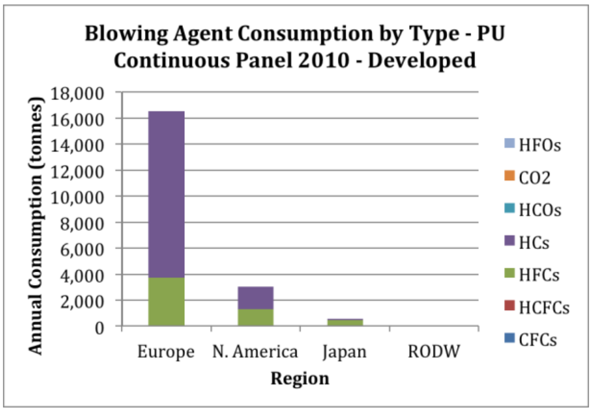
The estimated amount of the different substances used as blowing agents in 2010 in the most relevant applications of Table 4-1 are graphically described as follows:

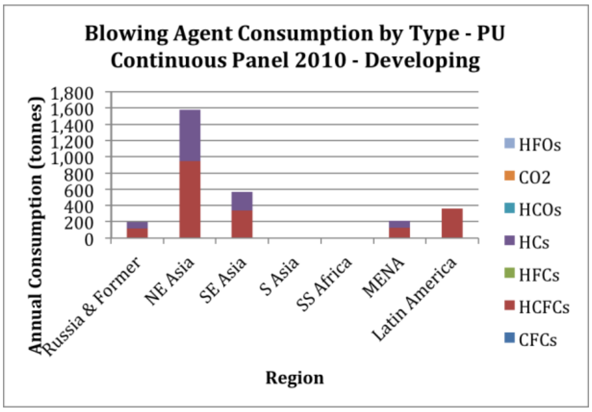

Blowing Agent Consumption by Type - Domestic Refrigeration 2010 Developed
Annual Consumption (tonnes)
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
20,000
Europe
N. America
Japan
RODW
Region
HFOs
CO2
HCOs
HCs
HFCs
HCFCs
CFCs

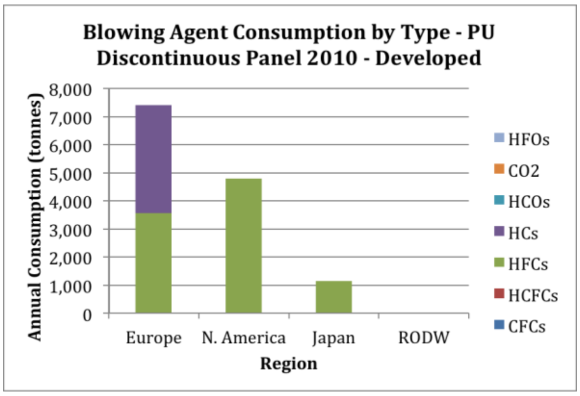

Blowing Agent Consumption by Type - Domestic Refrigeration 2010 Developing
Annual Consumption (tonnes)
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
Russia & Former
NE Asia
SE Asia
S Asia
SS Africa
MENA
Latin America
Region
HFOs
CO2
HCOs
HCs
HFCs
HCFCs
CFCs

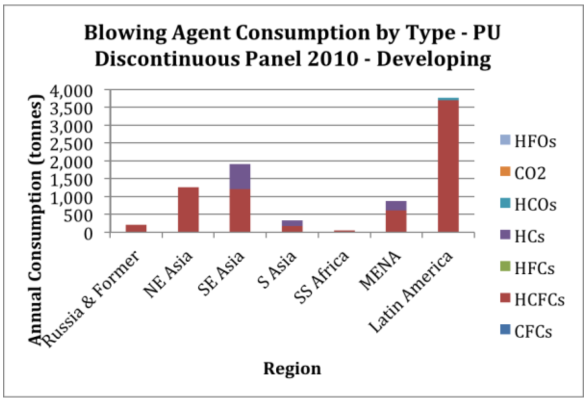

Blowing Agent Consumption by Type - Commercial Refrigeration/ Other appliances - 2010 - Developed
Annual Consumption (tonnes)
0
1,000
2,000
3,000
4,000
5,000
Europe
N. America
Japan
RODW
Region
HFOs
CO2
HCOs
HCs
HFCs
HCFCs
CFCs

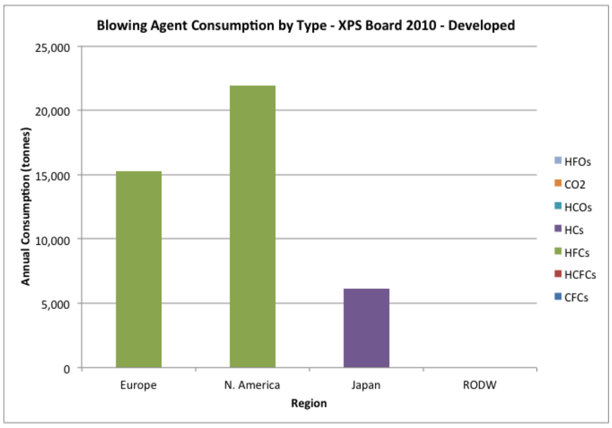

Blowing Agent Consumption by Type - Commercial Refrigeration/ Other appliances 2010 - Developing
Annual Consumption (tonnes)
0
500
1,000
1,500
2,000
Russia & Former
NE Asia
SE Asia
S Asia
SS Africa
MENA
Latin America
Region
HFOs
CO2
HCOs
HCs
HFCs
HCFCs
CFCs

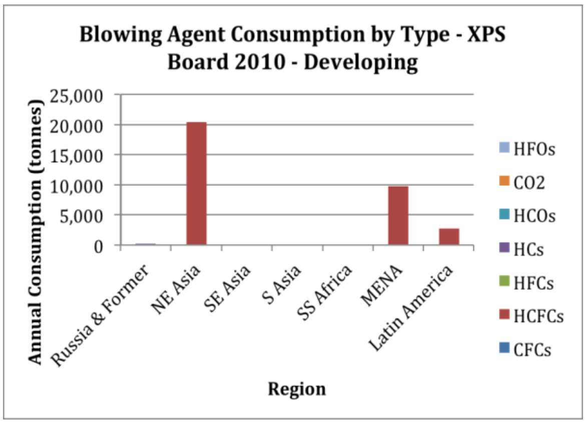

Blowing Agent Consumption by Type - PU Continuous Panel 2010 - Developed
Annual Consumption (tonnes)
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
Europe
N. America
Japan
RODW
Region
HFOs
CO2
HCOs
HCs
HFCs
HCFCs
CFCs


Blowing Agent Consumption by Type - PU Continuous Panel 2010 - Developing
Annual Consumption (tonnes)
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
Russia & Former
NE Asia
SE Asia
S Asia
SS Africa
MENA
Latin America
Region
HFOs
CO2
HCOs
HCs
HFCs
HCFCs
CFCs


Blowing Agent Consumption by Type - PU Discontinuous Panel 2010 - Developed
Annual Consumption (tonnes)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Europe
N. America
Japan
RODW
Region
HFOs
CO2
HCOs
HCs
HFCs
HCFCs
CFCs


Blowing Agent Consumption by Type - PU Discontinuous Panel 2010 - Developing
Annual Consumption (tonnes)
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Russia & Former
NE Asia
SE Asia
S Asia
SS Africa
MENA
Latin America
Region
HFOs
CO2
HCOs
HCs
HFCs
HCFCs
CFCs





4.3 General overview of blowing agents

Several reports that describe in detail the different options for HCFC replacement have been recently published: (World Bank, 2009, World Bank 2011), (UNEP DTIE, 2010), (Proklima, 2009) and (FTOC, 2011). Based on these sources this section provides an updated overview of the alternatives.

In foams, the blowing agent has two principal functions:

1. The **physical expansion** of the foaming mixture to produce the desired foam density. The foam expansion is normally achieved by the combination of two mechanisms:

- The generation of CO_2 as a consequence of the water/isocyanate reaction, and
- The evaporation and expansion of the blowing agent by the exothermic reaction mixture.

The boiling point of the blowing agent and catalysis of the foam formulation influences the relative rate at which these two mechanisms occur, which strongly affects the foam ability to flow. In general, the lower the boiling point, the better the flow. Immediately after the foam is produced there are usually two gases simultaneously present in the cells: carbon dioxide and the selected blowing agent (HCFC-141b, HFC-245fa, cyclopentane, etc.).

2. Contribution to the **thermal insulating performance** of the foam (in insulating foams). The blowing agent should remain in the closed cell foam and have a low gaseous thermal conductivity plus a lower rate of diffusion through the foam (polymer matrix) compared to air or carbon dioxide so that the good insulating properties are retained over time.

Classical publications (Oertel, 1994), (Huntsman, 2002), (Gum & Ulrich, 1992) highlighted the desirable characteristics for a blowing agent. In addition to the need to minimise the impact of the foam on ozone depletion and climate change, the list included the following:

- Physiologically non hazardous (low toxicity)
- Non flammable
- Chemically/physically stable
- Advantageous boiling point for ease of handling and optimum performance in the intended application
- Good solubility in polyols (for polyurethane systems)
- Commercially available, and
- Economically viable.
- As an additional set of characteristics for thermally insulating foams, the following were deemed as advantageous:
- Low gaseous thermal conductivity.
- Appropriate boiling point range to minimize condensation of the blowing agent in the final foam at operational temperatures in low temperature applications, but high enough to maximise yields of the blowing agent and to minimize vapour pressure in tanks and containers when shipping blends.
- Low solubility in the foam polymer to avoid matrix plasticisation that can cause dimensional stability problems.
- Low diffusion rate through the polymer matrix.

In its 2010 assessment report the FTOC introduced the concept that there is a need for "proven" blowing agent options. For example, in the critical case of rigid foam applications, it is suggested that a testing programme includes:

- Environmental and toxicology testing (ODP, GWP, VOC, toxicology)
- Processing characteristics:
  - Stability in polyol blends
  - Miscibility with polyols
  - Flow properties (flow index, minimum fill density)
  - Reaction times including jig dwell times ("demould time")
  - Atmospheric concentrations during processing and comparison with flammable limits in air
  - Effects on equipment – seals and metal parts
- Physical & Fire properties:
  - Closed cell content
  - Density/strength (compression strength) relationships
  - Dimensional stability versus temperature and ageing using accepted accelerated methods
  - Thermal conductivity versus temperature and ageing using accepted accelerated methods
  - Foam friability
  - Adhesion to different substrates
  - Fire code testing for construction industry foam-based components
  - Other testing specific to the intended application

- Trials under commercial production conditions and long term testing of articles

The major blowing agents being commercially used as substitutes for HCFCs in the foam sector, or being considered for commercial introduction in the short-term, are shown in the sections that follow. While the impact of ODS regulations is well known, it might be useful to note, for example, that other environmental factors, such as GWP impact and classification as volatile organic compounds (VOCs) may have a bearing on local acceptance. It is therefore encouraged to make a full evaluation of the national and local circumstances when choosing blowing agent options.

4.3.1 Substances currently used as blowing agents

4.3.1.1 Hydrocarbons (both directly added and pre-blended with polyol)

Table 4-2: Hydrocarbons

	Cyclo-Pentane	**n-Pentane**	**Iso-Pentane**	**Iso-Butane**	**n-Butane**
Chemical Formula	(C_5H_{10})	$CH_3(CH_2)_3CH_3$	$CH_3CH(CH_3)CHCH_3$	$CH_3CH(CH_3)CH_3$	$CH_3CH_2CH_2CH_3$
Molecular Weight	70.1	72.1	72.1	58.1	58.1
Boiling Point (^{0}C)	49	36.1	28	-11.7	-0.45
Gas Conductivity (mW/mK @ 10^{0}C)	11.0	14.0	13.0	15.9	13.6^
Flammable Limits in Air (vol.%)	1.5-8.7	1.4-8.0	1.4-8.3	1.8-8.4	1.8-8.5
TLV or OEL (ppm) (USA)	600	610	1000	800	800
GWP (100 yr time horizon)	<25*	<25*	<25*	<25*	<25*

Ref: FTOC 2010 assessment report. ^ Measured at 0^{0}C * Precise figure varies according to local atmospheric conditions

Table 4-2 reports the primary hydrocarbon alternatives used in the foam sector. The boiling point range is sufficiently wide to allow for gaseous blowing agent processes such as extruded polystyrene and one-component polyurethane systems to be served by C_4 hydrocarbons (butanes), while the higher boiling point, liquid applications can be served by C_5 hydrocarbons (pentanes).

A significant advantage of the hydrocarbon family is that they can easily be blended to provide a combination of properties. For example, it has always been known that cyclopentane offered better thermal performance (lower gaseous conductivity) than other hydrocarbons, but its boiling point is relatively high leading to lower cell gas pressures and higher foam densities. This led to the use of blends of cyclopentane with isopentane to retain the overall thermal properties while lowering the overall boiling point and reducing the foam density. In addition, the cost of isopentane is generally lower than for cyclopentane and cost savings could be achieved.

As stated in (FTOC, 2011), the major drawback of the hydrocarbon family is their flammability. This has a strong impact on both the capital costs for processing to ensure that safety is properly engineered and on product handling, which is particularly problematic for smaller enterprises. Efforts have been made to reduce costs at the foam manufacturers by pre-blending hydrocarbons into polyols at systems houses. The challenge is to develop a long-term stable formulation with no phase separation. A successful industrial case has been reported in Northern Europe where a system house, for some years, has been delivering formulated polyols containing cyclopentane in one-tonne containers and 200 l drums to different industries in Eastern and North-Eastern Europe (Proklima, 2009). This approach allows reduced investments on the user's side without compromising the insulating efficiency and the long-term dimensional stability performance. This experience shows that investment in one blending facility may make it possible to reduce investments in manufacturing plants. While the cost of hydrocarbon storage tanks, pumps and premixing stations can be avoided; the safety modifications for the polyol blend storage and foaming line and the installation of proper monitoring and ventilation systems will still be required. It is estimated that savings in increased capital cost (ICC) for the end user are in the order of 25 to 35%.

On the other hand, in this scenario, the topic of investing to handle flammability of hydrocarbons is extended to a larger number of players, a supplier would have to invest to handle hydrocarbons in its operation, with added costs that will reflect in higher material cost. As well a UNDP demonstration project on third stream addition of pentane at the manufacturer plant has been completed in Egypt in 2011, proving the viability of this option in particular for small producers with simple factory layouts. This is currently estimated to be the least capital cost demanding option to handle hydrocarbons.

4.3.1.2. Saturated HFCs

The following table illustrates the characteristics of the commonly available saturated HFCs and indicates that the range of boiling points is sufficient to meet most of the requirements of the foam manufacturing industry.

Table 4-3: Saturated HFCs

	HFC-134a	**HFC-152a**	**HFC-245fa**	**HFC-365mfc**	**HFC-227ea**
Chemical Formula	CH_2FCF_3	CHF_2CH_3	CF_3CH_2 CHF_2	CF_3CH_2 CF_2 CH_3	CF_3CHF CF_3
Molecular Weight	102	66	134	148	170
Boiling Point (^{0}C)	-26.2	-25	15.3	40.2	-16.5
Gas Conductivity (mW/mK @ 10^{0}C)	12.4	14.3*	12.5*	10.6*	11.6
Flammable Limits in Air (vol.%)	None	3.9-16.9	None	3.8-13.3	None
TLV or OEL (ppm) (USA)	1000	1000	300	1000	1000
GWP (100 yr time horizon)^	1430	124	1030	794	3220

Ref: (FTOC, 2011). * Measured at 24-25^{0}C. ^ (IPCC, 2007)

HFC-227ea is usually co-blended with HFC-365mfc at varying levels, usually 7 or 13%, to reduce the flammability characteristics of the latter. Similarly, HFC-152a is sometimes used as a co-blowing agent with HFC-134a in order to enhance blowing efficiency. Its flammability and high cell wall permeability make it less suitable as a blowing agent on its own. HFC-134a is also used neat in PU foams and blended with HFC-245fa in US.

In polyurethane foam sectors HFC based foams are usually co-blown with CO_2 (water) by taking advantage of the isocyanate/water reaction. This can offset the increased cost of HFCs. In addition, the co-blowing strategy does reduce the potential GWP impact of the direct emissions of blowing agent from the foam.

4.3.1.3 Carbon dioxide

In PU, carbon dioxide, derived from the isocyanate-water reaction, has been used as an alternative to HCFCs (and CFCs in the past).

Foams based on this option tend to have poorer insulating properties compared to other blowing agent technologies. Since CO_2 is a small molecule it tends to migrate from the foam cells rapidly. Where no other blowing agent is present this can result in loss of cell gas pressure and potential foam shrinkage. To compensate for this, higher foam densities are required. Despite these hurdles, some formulation suppliers have successfully developed specific water blown technologies for commercial refrigeration applications, including sandwich panels and commercial appliances.

Fully water blown solutions can be adopted in some applications to address specific environmental regulations without entering into significant equipment changes investments, leaving the opening to be converted later on into co-blowing with physical blowing agents by the time when new proven low ODP low GWP non- flammable solutions will be available.

The addition of formic acid as a chemical blowing agent can provide technical advantages compared to full water-blown technology, providing excellent foam aesthetics, improved processability and good performance (e.g. flow, density distribution and adhesion), in particular at low mould temperature. However, some drawbacks have been identified with this approach mainly linked to potential corrosion and shelf life issues.

Liquid CO_2 has found widespread use, particularly in Europe, in the extruded polystyrene sector. The attraction of using CO_2 is its relative inertness and also its low global warming potential (GWP=1). In PU foam liquid CO_2 has found limited usage --in combination with gaseous CO_2-- for spray applications, particularly in Japan.

4.3.1.4. Oxygenated hydrocarbons (Methyl Formate, Methylal and Dimethyl Ether)

As the industry driven by Decision XIX/6 has searched for cost-effective solutions to HCFC substitution, the potential for using oxygenated hydrocarbons has emerged. These had not been used in any significant way in non-Article 5 countries because the economies of scale were sufficient to allow the direct use of hydrocarbons.

Table 4-4: Oxygenated hydrocarbons (HCOs)

	Methylal	**Methyl Formate**	**Di-methyl Ether**
Chemical Formula	$CH_3\,OCH_2OCH_3$	$CH_3(HCOO)$	CH_3OCH_3
Molecular Weight	76.1	60.0	46.07
Boiling Point (^{0}C)	42	31.5	-24.8
Gas Conductivity (mW/mK @ 15^{0}C)	Not available	10.7 (@ 25^{0}C)	15.5
Flammable Limits in Air (vol.%)	2.2-19.9	5.0-23.0	3.0-18.6
TLV or OEL (ppm) (USA)	1000	100	1000
GWP (100 yr time horizon)	“Negligible”	“Negligible”	1^

Ref: (FTOC, 2011), ^ (IPCC, 2007)

Although flammable some oxygenated hydrocarbons, particularly methylal and methyl formate exhibit flash points higher than hydrocarbons and, when mixed with polyols at right proportions, can produce non-flammable blends resulting in reduced conversion costs. These products, methylal and methyl formate, have been the subject of Multilateral Fund supported pilot projects to explore the capabilities of these materials.

The properties of dimethyl ether limits its use to the gaseous blowing agent market in view of its boiling point. The product is already used as a propellant/blowing agent in one-component foams and is also being evaluated for extruded polystyrene.

4.3.2 Emerging substances

4.3.2.1. Unsaturated HFCs and HCFCs

These compounds represent an emerging group of blowing agents that exhibit a number of the characteristics also displayed by saturated HFCs, but have considerably lower GWPs (< 15). The prime reason for these lower values relates to the shorter lifetime of the molecules in the atmosphere caused by the presence of a double bond between adjacent carbon atoms.

Since these compounds are still in the state of development and early commercialisation, there is often incomplete information available. The most advanced, in terms of commercialisation and disclosure, is HFO-1234ze(E) which has already been introduced into the European market as a replacement option for HFC-134a in the PU one-component foam (OCF) market and, more generally, for HFC-134a in XPS foams

Recent evaluations in a commercial household refrigerator/freezer line showed up a 4 % improvement in energy efficiency performance of HFO (HCFO)-1233zd(E) based formulations over the baseline HFC-245fa (Bowman, 2011).

Table 4-5: Unsaturated HFCs (HFOs)

Trade Name	**Solstice™ Gas BA**	**Formacel® 1100**	**Solstice™ Liquid BA**	**AFA-L1**
Common name	1234ze(E)	1336mzzm(Z)	1233zd(E)	Undisclosed
Chemical Formula	Trans- $CF_3CH=CHF$	Cis- CF_3-CH=CH-CF_3	Trans- ClCH=CH-CF_3	Undisclosed
Molecular Weight	114	164	130.5	<134
Boiling Point (^{0}C)	-19	33	19	10.0<T<30.0
Gas Conductivity (mW/mK@ 10^{o}C)	13.0	10.7	10.6 (25^{o}C)	9.0
Flammable Limits in Air (vol.%)	None to 28^{o}C^	None	None	None
TLV or OEL (ppm) (USA)	Unpublished	500[a]	300***	Undisclosed
GWP (100 yr time horizon)	<6	8.9	<7**	<15
Producer	Honeywell	DuPont	Honeywell	Arkema

Ref: (FTOC, 2011). ^ Flame limits of 7.0-9.5 at 30^{o}C are quoted. (a) DuPont Allowable Exposure Limits (8-12 hr. TWA)
*** Preliminary Honeywell OEL (occupational exposure limit). **(Anderson, 2008)

Cost prediction is similar to saturated HFCs. Provided that the evaluation results in the HFOs being proven for these applications then it is likely that they will be considered as "drop-in" alternatives to HFCs and capable for implementation with no additional capital costs. The first commercial manufacture of a liquid HFO is estimated by 2013.

The main characteristics of these products are presented in Table 4-5.

4.3.3 Technical feasibility of HCFC replacement options by sub-sectors

The technical feasibility of a blowing agent technology will depend on a number of factors which include the chemistry of the foam formulation being processed, the existing (or future) foam processing equipment being proposed, the quantity of foam being manufactured and sold each year (size of enterprise), the local standards pertaining, the experience already gained by others both internationally and locally in similar processes and applications, and overall the foam application of the foam.

Based on a recent report (World Bank, 2011) with additional input, particularly for XPS foams, tables that describe the pros and cons of each HCFC-replacement option for each sub-sector were updated and included in the annex.

4.3.4 Environmental impact and safety issues

Three parameters contribute to the overall impact of the HCFC replacement options as it relates to the climate criterion. These are:

- Embodied energy
- Direct emissions of greenhouse gases used as blowing agents
- Indirect emissions of CO_2 related to the energy consumption of buildings or products (where the energy saved by a foam can reduce those emissions)

In addition to the climate impact there can be a number of other environmental considerations that include, inter alia, the effect on low-level ozone formation usually associated with Volatile Organic Compounds (VOCs) and the environmental (or human) toxicity of atmospheric breakdown products.

4.3.4.1 Climate impact of emissions

To make relatively precise estimates of the climate impact of emissions two variables should be known:

- The initial content of the blowing agent in the foam. In PU rigid foams very often, if not always, the blowing agent (hydrocarbons, saturated HFCs, etc.) is co-blown with CO_2 derived from the water-isocyanate reaction. The proportion of a given blowing agent in the gas cells depends on the specific formulation (type and nature of polyols, catalysts, surfactants, etc.).
- The likely emissions profile of the substance through the lifecycle of the manufactured product/equipment

Table 4-6 shows an example of the emission profile for two HFCs in different foam sub-sectors.

Table 4-6: Emission profiles for HFC-134a and HFC-152a uses				
Sub-Sector	**Product Life in years**	**First Year Loss %**	**Annual Loss %**	**Maximum Potentia End-of-Life Loss %**
Polyurethane – Integral Skin	12	95	2.5	0
Polyurethane – Continuous Panel	50	10	0.5	65
Polyurethane – Discontinuous Panel	50	12.5	0.5	62.5
Polyurethane – Appliance	15	7	0.5	85.5
Polyurethane – Injected	15	12.5	0.5	80
Polyurethane – Spray	50	25	1.5	0
One Component Foam (OCF)	50	95	2.5	0
Extruded Polystyrene (XPS) - HFC-134a	50	25	0.75	37.5
Extruded Polystyrene (XPS) - HFC-152a	50	50	25	0
Extruded Polyethylene (PE)	50	40	3	0

Ref: (UNEP DTIE, 2010)

However, even where the focus of attention is only on direct emissions of blowing agents, care must be taken to ensure that the comparisons are appropriate. The following items are relevant to ensure this:

1. The influence of the boiling points, solubility, and other properties of the respective alternative blowing agents on the losses in production.
2. The impact of the blowing efficiencies of different technology options.
3. The rate of permeation (Solubility x Diffusivity) of blowing agent through the cell walls.
4. Permeability of the facings /liners utilized in specific applications
5. Different lifetime in the different applications
6. Constraints from the technology choice that would prevent recovery at end of life.

When no adjustments are made for items above, the choice of blowing agent from a climate perspective is directly linked to its GWP. A simple approach to consider the GWP and the impact of the blowing efficiency of different options is to apply the perfect gas law, which states that a mole of gas independent of its nature will occupy a fixed given volume at constant pressure and temperature conditions.

This means that 70.1 kg of cyclo-pentane will approximately generate the same foam volume than 117.0 kg of HCFC-141b. Table 4-7 shows the climate impact of the different blowing agents based on this approach. It is noted that all the options with GWP < 25 have the same relative impact compared to HCFC-141b on climate change. The formula used was:

Delta GWP = -((Option's MW/HCFC-141b's MW) x Option's GWP - HCFC-141b's GWP)

Table 4-7: Emissions impact based on GWP and blowing efficiency			
Baseline: 1 ton of HCFC-141b			
Blowing Agent	**GWP**	**MW**	**Delta GWP**
			Reduction of Emissions (tons of equiv. CO2)
HCFC-141b	725	117	Base Line ("0")
HFC-245fa	1,030	134	(455)
HFC-365mfc	794	148	(279)
HFC-277ea	3,220	170	(3,954)
HFC-134a	1,430	102	(522)
Cyclo-Pentane	<25	70	>710
n-Pentane	<25	72	>710
Carbon dioxide	1	44	725
Methyl formate	-	60	725
Methylal	-	76	725
AFA-L1	<15	<134	>708
Formacel® 1100	9	164	713
Solstice LBA	7	131	717
Solstice GBA	6	114	719

4.3.4.2 Impact of HCFC option on energy consumption

Perhaps the most relevant benefit of thermal insulation is that, once installed in energy-saving applications such as refrigerators and freezers or in buildings, it avoids CO_2-equivalent emissions through reduced combustion of fossil fuels to meet heating and cooling requirements throughout its lifetime.

The blowing agent plays a key role in the insulating foam performance and so the HCFC replacement has to take into account any change in the energy efficiency performance of the foam in the final product (refrigeration unit, buildings, etc.). In many cases this effect will offset the direct emissions from blowing agent release.

However, the level to which this is the case will depend largely on the sensitivity of energy efficiency to such choices, which will in turn depend on the configuration of the appliance or building or other insulated article and the levels of insulation used and the assumed lifetime of the article. In practice, it is often the case that energy efficiency is only partially influenced by these technology choices and, in such situations the comparative process reverts largely to a comparison of direct emissions only.

There is some concern that the above-mentioned approach (exemplified by Table 4.7), focused solely on the GWP of the blowing agent and quantities used (i.e. blowing efficiency), over-simplifies the climate impact issue. Although it is recognised that specifying the life-cycle energy impacts by available methods (LCA, TEWI or LCCP) can be difficult when the end uses of the foams in question are uncertain, it is viewed that a constant thermal performance model would allow for the inclusion of other factors, such as thermal efficiency and density and thereby give a more reliable and balanced comparison of options. For applications in countries where there are energy efficiency requirements (e.g. domestic appliances in India), life-cycle energy impacts by currently used methods.

The most common parameter to evaluate the foam thermal performance is its thermal conductivity that depends in part on the gaseous thermal conductivity of the blowing agent. Other important factors that affect the foam conductivity are the gas composition in the cells (amount of blowing agent versus CO_2) and the cell morphology (isotropy, size and distribution). It should be emphasised that the thermal performance of a PU foam blown with a given blowing agent largely depends on the formulation used (polyol types, proportion, catalysts, surfactants, etc.).

In Tables 4-8 and 4-9 values for thermal conductivity are given for foams for the various applications for some of the HCFC alternatives. In many applications, where the foam is faced with gas permeable facing materials (or none in many cases with XPS) the “aged” thermal conductivity is quoted. This gives a good indication of the long-term performance in, for example, the insulation of a building.

The difference in the gas conductivities can be partially offset by improvements in foam structures (such as smaller cells to reduce radiative heat transfer), by design improvements in the end article or building by, for example, increasing the foam thickness, or by adding R-value enhancement additives (XPS foam). The gas phase thermal conductivity of the blowing agent, then, is not necessarily a good predictor of the thermal conductivity of the final foam.

Table 4-8: Comparison of foam insulation values for XPS		
Blowing Agent	**Aged λ-Value (mW/mK, 10°C)**	**Comments**
HCFC-142b/ HCFC-22	28-30	Widely used in China and other A5 countries – the industry norm before HCFC phase-out
CO_2	32-40	Poor solubility and processability, high diffusivity and increased thermal conductivity
CO_2/Ethanol	32-40	Ethanol improves processability, but increased flammability and VOC concerns.
CO_2/Butane	30-38	Improved processability with HCs, but increased flammability and VOC concerns. Some thermal conductivity improvement is possible with certain hydrocarbons
HFC-134a	28-30	Needed for lowest foam thermal conductivity. Solubility is worse than that of HCFCs.
HFC-152a	30-38	Flammability issues. Has low initial thermal conductivity and good solubility, but high diffusivity may lead to a rapid "ageing" in thermal conductivity
Solstice GBA	25-30	Based on commercially produced product from an EU producer.

Ref. (World Bank, 2011)

For XPS foams, if achieving the lowest thermal conductivity is necessary or if local market considerations warrant, HFC-134a or HFC-152a become viable options. If cost is the only driver, then CO_2 based systems may be a preferred option. There is, however, significant capital required to convert an XPS manufacturing option to liquid CO_2 technology, and there may be limitations on thickness of XPS foams.

In many PU applications, a gas impermeable facing material that is, usually, applied "in-situ" during the manufacturing process, covers the foam. In these cases, there is little or no significant difference between the "initial" and "aged" foam thermal conductivities. These applications are marked by* in Table 4-9 below. Initial and aged thermal conductivity values are displayed in the table for spray foam. There is no data included for integral skin foams, which are not used as high-performance insulating applications.

Table 4-9: Comparison of foam insulation values for PU			
Sector	**Blowing Agent**	**Foam Thermal Conductivity (mW/mK, 10°C)**	**Comments**
Domestic refrigerators/freezers*	HCFC-141b	18-19	Baseline
	HFC-134a	22-23	
	HFC-245fa	17-19	Bowman & Sinaga [2011] reported that lambda for 245fa foam is as low as 17 at 10ºC
	Solstice LBA	16-17	Bowman & Sinaga [2011] reported that lambda for LBA foam is as low as 16 at 10ºC
	Cyclo and Cyclo/iso pentane	19-20	Result of intensive system optimisation, actual values down to 18.7 mW/mK
Commercial refrigerators/freezers*	HFC-245fa	20-21	
	Pentanes	21-22	
	CO_2 (water)	24 (initial)	Ageing dependant on construction/design
Refrigerated trucks & reefers*	HFC-245fa	20-22	Static mixer required
	HFC-365mfc/HFC-227ea	20-22	
	Cyclopentane	20-22	
Sandwich panels* (Continuous)	HFC-365mfc/HFC-227ea	21-23	
	Solstice LBA	19-21	Bowman & Sinaga [2011]
	Solstice GBA	22-24	Bowman & Sinaga [2011]
	Cyclopentane	19-20	Results of on-going system optimisation
Sandwich panels* (Discontinuous)	HFC-365mfc/HFC-227ea	21-23	
	HFC-245fa	20-21	
	Cyclopentane	20-22	
PU Spray	HCFC-141b	21 (initial), 26 (aged)	Baseline
	HFC-245fa	23 (initial), 28 (aged)	
	Solstice LBA	20 (initial) 25 (aged)	Honeywell CPI 2011 paper
	CO_2 (water)	24 (initial) 32 (aged)	
Pipes*	HFC-365mfc	21-23	
	Cyclopentane	21-23	
Blocks	HFC-245fa HFC-365mfc Pentane	21-23	

Source: (World Bank, 2009)

4.3.4.3 Safety considerations

Evaluating safety is a complex issue and involves the assessment of risk, as defined by the intrinsic hazard of a chemical and the statistical likelihood of exposure. Even hazardous chemicals can be handled safely where the solution can be engineered to avoid exposure. A close example would be the handling of isocyanate during the foam injection or spraying process. However, for foam, the fact that many blowing agents remain in the foam after manufacture and slowly diffuse during the use phase, means that having intrinsically hazardous substances as blowing agents is not tolerable. Toxicity testing, in particular, is therefore a high priority for potential blowing agents and enterprises would be cautioned against choosing a technology where the toxicity of the blowing agent has not already been fully characterised. The Occupational Exposure Limits (OEL) value of the different HCFC options is provided in Tables 4.2 - 4.5.

4.4 Cost effectiveness

The assessment of cost effectiveness of the HCFC options should involve two factors:

- The incremental capital cost (ICC)
- The incremental operating cost (IOC)

4.4.1 The Incremental Capital Cost (ICC)

Because of its flammability, the well-proven hydrocarbons are the HCFC replacement options that require the highest ICC. The following Table 4-10 on costs (World Bank, 2009) gives an indication of the ICC for a typical foam manufacturing facility consuming 25-50 tonnes of blowing agent per year:

Table 4-10: Incremental Capital Cost (ICC) for a typical foam manufacturing facility

Equipment	**Costs One Dispenser (US $ '000)***	**Costs Two Dispensers (US $ '000)***	**Comments**
Storage tank, piping	Up to 270	Up to 400	
Pre-blending station	120	240	Optional 1 pre-mixer for 2 dispensers
Day tanks	15	30	Optional 1 day tank for 2 dispensers
Metering unit retrofit	15-55	30-110	Assuming high pressure machines installed
Safety sensors	30-37	37-56	
Exhaust	15-40	15-40	
Moulds/ fixtures retrofitting	20-40	20-40	
Grounding	7-15	7-15	
Civil work	7-15	15-30	Strongly dependant on factory location and layout
Installation & commissioning	27-80	27-80	
Totals ($ '000)	**250-680**	**410-1,035**	

*Conversion rate €1 = US $1.34

Ref. Modified from (World Bank, 2009) and (World Bank, 2011)

The pentane storage tank is major element of the costs and, in certain circumstances, could be replaced by a drum handling storage area. The second largest elements are the pre-blending stations. The above costs assume that the enterprises already have high pressure metering units. If this is not the case, then high pressure-metering units costing up to US$150,000 to US$ 200,000 each would be required. There may be additional expenditure to cover the provision of nitrogen for the blanketing of storage tanks and other tanks and pipes. The cost will depend on the level of facilities already installed. Another relevant consideration is the location of the factory, whether or not it is adjacent to a residential area.

For XPS foam there is the need for modification to the foam extruder and associated equipment for use with flammable blowing agents, such as hydrocarbons, and for high-pressure operation while using low solubility blowing agents, such as carbon dioxide.

The use of HFC-245fa in PU rigid foam manufacture requires some measures to counteract its comparatively low boiling point of 15.3°C. A static mixer can be used to blend the blowing agent into the polyol formulation. Alternatively, the chemicals, blowing agent and polyol formulation, can be cooled to about 10°C before blending or the blending can be done in a closed vessel capable of handling the vapour pressure of the HFC-245fa. The miscibility of HFC-245fa is very good in the polyol formulation with stability of several days to several months in systems designed for longer term storage, like spray foam systems.

For the flammable emerging options (methyl formate, methylal) safety measures may be necessary to handle their flammability depending on the blowing agent content in the formulated polyol. For formic acid some provision could be required to manage the eventual corrosiveness. In the case of methyl formate the technology proprietor emphasize that, provided stabilized systems are used, no special considerations are needed for equipment. The leading equipment suppliers have designed special kits with a cost per dispenser between 10 and 20 thousand dollars.

In addition, consideration must be given as to their capability to be “drop-in” replacements for saturated and unsaturated HFCs, that is, to be capable of use without additional capital expenditure.

4.4.2 The Incremental Operating Cost (IOC)

The calculation of the Incremental Operating Cost (IOC) should take into account, inter alia, the following factors:

- The cost ($/kg) at plant of the blowing agent
- The cost ($/kg) at plant of the other raw materials in the PU system (formulated polyol and isocyanate)
- The usage level of blowing agent and any co-blowing agents (e.g. CO_2 (water)) in the formulation
- The ratio between the different components in the formulation
- The annual usage of the PU foam
- Any changes in density required to achieve the same functionality

Table 4-11 gives an example of the IOC for a PU domestic refrigeration operation when a typical HCFC-141b based formulation is converted to cyclopentane. The IOC could vary from US$ 46.0 to US$ 365.6 per ton of PU system depending on the density of the cyclopentane based foam and the prices of HCFC-141b, cyclopentane and the rest of raw materials (formulated polyol and isocyanate). The following factors are taken into consideration:

- Factory produced foam with HCFC-141b has an average foam core density of about 32 kg/m^3. To assure the adequate dimensional stability when blowing with cyclopentane the average foam core density is needed to increase up to 33-34 kg/m^3.

- The prices at plant of the raw materials other than blowing agent do not change when HCFC-141b is replaced by cyclopentane but there is a significant change in the proportion of the chemicals owing to the different blowing efficiency of pentane
- Typical prices ranges for the blowing agents and raw materials are used.

Table 4-11: ICC per ton of PU system for pentane conversion

	Chemical	Current Formulations	Consumption	Unit	US$/unit	Total cost consumption (US$)	
Before:							
Foam density (kg/m3)	**32**						
	HCFC - 141 b	94.0	94.0	Kg	3.5 - 2.4	329.0 - 225.6	
	Polyol A	367.5	367.5	Kg	2.5 - 3.5	918.8 - 1,286.3	
	Polymeric MDI	538.5	538.5	Kg	2.5 -3.5	1,346.5 - 1,885.1	
		1000.0	1,000.0			**Total**	**2,594.3 - 3,397.0**
After:							
Foam density (kg/m3)	**33 - 34**						
	Cyclopentane	56.2	60.2 - 62.1	Kg	2.0 - 4.2	120.5 - 260.8	
	Polyol B	367.5	393.9 - 405.8	Kg	2.5 - 3.5	984.6 - 1,420.3	
	Polymeric MDI	538.6	577.2 - 594.7	Kg	2.5 - 3.5	1,443.1 - 2,081.5	
		962.3	1,031.3 - 1,062.6			**Total**	**2,548.2 - 3,762.6**
Incremental Operating Costs/ton of PU system (US$)							**46.0 - 365.6**
Incremental Operating Costs/ton of PU system (%)							**1.77 - 10.76**

Tables 4-12 to 4-14 provide information on the price of the different HCFC options along with the foam densities currently used.

Table 4-12: Price range of blowing agents

Price	**US $/kg CIF**
Cyclopentane	2 - 4
HFC-245fa	9 – 13
HFC-365mfc	8 – 12
HFC-134a	6 – 13
Methyl Formate	2 - 4
Methylal	1.4 - 1.7
AFA-L1	11 - 17
Formacel® 1100	11 - 17
Solstice Gas BA	11 - 17
Solstice Liquid BA	11 - 17

Table 4-13: Densities for XPS foams		
Density with HCFC-142b/ HCFC-22 (kg/m^3)	**Alternative technology**	**Density (kg/m^3) (Δ-change %)**
25-45	CO2	34-48 (6)
	CO2/Ethanol	32-45
	CO2/ hydrocarbon	32-45
	HFC-134a (blends)	33-45
	HFC-152a	25-45
	HFC-134a/HFC-152a blend	32-45
	Solstice LBA	25-45

Ref: (World Bank, 2011)

Table 4-14: Densities for PU rigid foams				
Segment	**Sub-Segment**	**Density with HCFC-141b (kg/m^3)**	**Alternative technology**	**Density (kg/m^3) (Δ-change %)**
Domestic Refrigerator/ Freezers		33-35	Cyclopentane Cyclo/isopentane HFC-245fa HFC-134a Solstice LBA	34-36 (3) 34-35 (1) 32-34 (- 3) 32-34 (-3)
Commercial refrigerators/ freezers	Vending machines	35-37	HFC-245fa	32-34 (- 3)
	Display cases	37-39	HFC-245fa	32-34 (- 3)
	Chest freezers	37-39	HFC-245fa	32-34 (- 3)
Reefers		40-45	Cyclopentane HFC-365mfc HFC-245fa HFC-134a	40-45 (0) 40-45 (0)
Sandwich panels continuous		40-42	Pentane, HFC-365mfc	40-42 (0) 40-42 (0)
Sandwich panels discontinuous		41-44	Pentane, HFC-365mfc HFC-134a	41-44 (0) 41-44 (0)
Spray foams	Walls, Pipes & tanks	33-36	HFC-245fa HFC-365mfc HFC-134a Solstice LBA	32-34 (-3) 32-36(- 3) 32-34 (-3)
	Roofs	48-50	HFC-245fa HFC-365mfc	48-50 (0)
Pipe-in-pipe		70-80	Cyclopentane HFC-365mfc	70-80 (0) 70-80 (0)
Blocks	Pipe sections	34-36	Pentane HFC-365mfc	34-36 (0)

Ref: (World Bank, 2009)

Annex to chapter 4:

Pros and Cons of HCFC replacements by sub-sector

Based on a recent World Bank report published (World Bank, 2011) the following tables that describe the pros and cons of each HCFC-replacement option for each sub-sector were updated and included in the annex. Following the classification used by the FTOC in its progress reports, Table A-6 groups the domestic and commercial appliance sub-sectors and Table A-7 groups the sub-sectors, which form the building/construction sector.

TABLE A-1: HCFC REPLACEMENT OPTIONS FOR APPLIANCES (DOMESTIC & COMMERCIAL), TRUCKS & REEFERS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Domestic refrigerators/freezers			
Cyclopentane & cyclo/iso blends	*Low GWP*	*Highly flammable*	*High incremental capital costs but most enterprises in sub-sector are large*
	Low operating costs		*Global industry standard*
	Good foam properties		
Saturated HFCs (HFC-245fa)	*Non-flammable*	*High GWP*	*Low incremental capital costs*
	High operating costs		*Improved insulation (cf. HC)*
	Good foam properties		*Well proven technology*
Unsaturated HFC/HCFCs (HFOs)	*Low GWP*	*High operating costs*	*Successful commercial trials; first expected commercialization in 2013*
	Non-flammable		*Promising energy efficiency performance: equal or better than saturated HFCs*
			Low incremental capital cost
Commercial refrigerators/freezers plus vending equipment			
Cyclopentane & cyclo/iso blends	*Low GWP*	*Highly flammable*	*High incremental capital cost, may be uneconomic for SMEs*
	Low operating costs		*Well proven technology*
	Good foam properties		
HFC-245fa, HFC-365mfc/227ea	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	*Improved insulation (cf. HC)*

CO_2 (water)	*Low GWP*	*Moderate foam properties – high thermal conductivity & high foam density*	*Low incremental capital cost*
	Non-flammable	*High operating costs*	*Improved formulations (second generation) claim no need for density increase vs HFC co-blown*
Methyl Formate	*Low GWP*	*Moderate foam properties -high thermal conductivity & high foam density-*	*Moderate incremental capital cost (corrosion protection recommended)*
	Flammable although blends with polyols may not be flammable	*High operating costs*	
Liquid Unsaturated HFC/HCFCs (HFOs)	*Low GWP*	*High operating costs*	*First expected commercialization in 2013*
	Non-flammable		*Promising energy efficiency performance: equal or better than saturated HFCs*
			Low incremental capital cost
Refrigerated trucks & reefers			
Cyclopentane & cyclo/iso blends	*Low GWP*	*Highly flammable*	*High incremental capital cost, may be uneconomic for SMEs*
	Low operating costs		
	Good foam properties		
HFC-245fa, HFC-365mfc /227ea	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	*Improved insulation (cf. HC)*
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity & high foam density-*	*Low incremental capital cost*
	Non-flammable	*High operating costs*	*Not used in reefers*
Liquid Unsaturated HFC/HCFCs (HFOs)	*Low GWP*	*High operating costs*	*First expected commercialization in 2013*
	Non-flammable		*Promising energy efficiency performance: equal or better than saturated HFCs*
			Low incremental capital cost

Ref: (World Bank, 2011), (UNDP, 2010)

TABLE A-2: HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Boardstock & Sandwich panels – continuously produced			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*High incremental capital costs but most enterprises in sub-sector are large*
	Low operating costs		*Industry standard*
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	
			Improved insulation (cf. HC)
Liquid Unsaturated HFC/HCFCs (HFOs	*Low GWP*	*High operating costs*	*First expected commercialization in 2013*
	Non-flammable		*Trials in progress*
			Low incremental capital cost
Sandwich panels – discontinuous			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*High incremental capital cost, may be uneconomic for SMEs*
	Low operating costs		
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea, HFC-134a	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	*Improved insulation (cf. HC)*
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity-*	*Low incremental capital cost*
	Non-flammable		
Methyl Formate	*Low GWP*	*Moderate foam properties - high thermal conductivity-*	*Moderate incremental capital cost (corrosion protection recommended)*
	Flammable although blends with polyols may not be flammable		

Liquid Unsaturated HFC/HCFCs (HFOs	*Low GWP*	*High operating costs*	*First expected commercialization in 2013*
	Non-flammable		*Trials in progress*
			Low incremental capital cost
Spray foam			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*Unsafe to use in this application*
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	*Industry standard*
	Good foam properties	*High operating costs but improved by using mixed HFC/ CO_2 (water)*	
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity & high density-*	*Extra thickness leading to a cost penalty*
	Non-flammable		
Methyl Formate	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*Safety concerns when used for this application*
Liquid Unsaturated HFC/HCFCs (HFOs	*Low GWP*	*High operating costs but improved by using mixed HFC/ CO_2 (water)*	*First expected commercialization from 2013*
	Non-flammable		*Trials in progress*
			Low incremental capital cost
Insulated pipes (pipe-in-pipe for district central heating systems)			
Cyclopentane	*Low GWP*	*Highly flammable*	*High incremental capital cost*
	Low operating costs		*Industry standard*
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	
	Good foam properties	*High operating costs*	
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity-*	
	Non flammable		

Block foams for various applications including panels, pipe insulation section, etc			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*High conversion costs, may be uneconomic for SMEs*
	Low operating costs		*Well proven technology*
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	*Low conversion costs*
	Good foam properties	*High operating costs but improved by using mixed HFC/ CO_2 (water)*	
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity & poor ageing-*	*Extra thickness leading to a cost penalty*
	Non flammable		
Liquid Unsaturated HFC/HCFCs (HFOs	*Low GWP*	*High operating costs*	*Trials in progress*
	Non-flammable		
One Component Foams			
Butane, propane, DME	*Low GWP*	*Highly flammable*	*Industry standard*
	Low operating costs		
	Acceptable foam properties		*Well proven in application*
HFC-134a, HFC-152a	*Non-flammable*	*High GWP*	*Low conversion costs*
		High operating costs	*High operating costs but improved by using mixed HFC/CO_2 (water)*
Gaseous unsaturated HFCs (HFOs)	*Low GWP*		*Proven in this application*

Ref: (World Bank, 2011), (UNDP, 2010)

TABLE A-3: HCFC REPLACEMENT OPTIONS FOR INTEGRAL SKIN PU FOAMS FOR TRANSPORT & FURNITURE APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Integral skin foams			
CO_2 (water)	*Low GWP*	*Poor skin quality*	*Suitable skin may require* in-mould-coating – *added expense*
	Low conversion costs		*Well proven in application if skin acceptable*
n-Pentane	*Low GWP*	*Highly flammable*	*High conversion costs, may be uneconomic for SMEs*
	Low operating costs		*Low operating costs*
	Good skin quality		*Well proven in application*
Methyl formate	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*Moderate conversion costs*
	Good skin quality	*Moderate operating costs*	*Newly proven in application*
Methylal	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*High conversion costs, may be uneconomic for SMEs*
	Good skin quality	*Moderate operating costs*	*No industrial experience*
Shoe-soles			
CO_2 (water)	*Low GWP*		*Well proven in application with polyester polyol technology*
	Low conversion costs		
	Skin quality suitable for sports shoe mid-soles		
HFC-134a	*Used to give required skin in town shoes*	*High GWP*	
Methyl formate	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*Moderate conversion costs*
	Good skin quality	*Moderate operating costs*	*Newly proven in application*
Methylal	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*High conversion costs, may be uneconomic for SMEs*
	Good skin quality	*Moderate operating costs*	*No industrial experience*

TABLE 4-4: HCFC REPLACEMENT OPTIONS FOR XPS FOAM			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Butane	*Low GWP*	Highly flammable	
	Low operating costs		
HFC-134a	*Non-flammable*	*High GWP*	
	Good foam properties, especially thermal performance	*Medium/high operating costs*	
Gaseous unsaturated HFCs (HFOs)	*Low GWP*	*High unit cost*	*Semi-commercial availability – under evaluation*
CO_2 /Ethanol/DME	*Low GWP, low unit cost*	*Small operation window*	*Difficult to process especially for more than 50mm thickness board*
	Non-flammable	*Flammable co-blowing agent*	*Need ethanol and DME as co-blowing agent*

Ref: (World Bank, 2011)

5 Fire protection

5.1 The use (market) of HCFCs in Fire Protection

Several reports that describe the use of HCFCs in fire protection have been published in the past. These include the IPCC TEAP Special Report, the TEAP Decision XX/8 Task Force Report, and the Assessment Reports of the Halons Technical Options Committee. Based on these sources, and in consultation with technical experts, this section provides an updated overview of the current use of HCFCs in fire protection.

HCFCs and their blends were one of several options introduced into the market as alternatives to halon 1301 and halon 1211 for total flooding and streaming applications respectively. In the three years since the publication of the TEAP Decision XX/8 Task Force Report, there have been only minor changes in the use patterns for the alternatives to these two halons. This was not unexpected owing to the long lead times for testing, approval, and market acceptance of new fire protection equipment and agents. However, no new alternatives based on HCFCs have been introduced in that period.

As of 1999, it was estimated that only 4% of the former halon market still required halon in new systems and extinguishers. Applications with halon had successfully shifted to new systems with many different alternative agents and approaches. Currently, that value could probably be reduced by more than half since, with the exception of some applications in civil aviation, there are virtually no applications that cannot use alternative fire protection materials and/or methods. The TEAP Decision XX/8 Task Force estimated the breakdown of the former halon market to be:

- Not-In-Kind (non-gaseous) Agents: 49%
- Clean Agents: 51%
    - *carbon dioxide and inert gases 24%*
    - *halons 4%*
    - *PFCs >0%*
    - *FK 2%*
    - *Iodinated FCs >0%*
    - *HFCs 20%*
  - *HCFCs 1%*

It is clear from the above, that the use of HCFCs in fire protection is very small compared to other alternatives. This is primarily due to tradition, market forces, and cost compared with carbon dioxide and not-in-kind alternatives.

In the United States (US), the phase out of halons and other ODS saw the introduction of the US Environmental Protection Agency's (EPA) Significant New Alternatives Policy (SNAP) Program. This is EPA's program to evaluate and regulate substitutes for ozone-depleting chemicals that are being phased out under the stratospheric ozone protection provisions of the US Clean Air Act (CAA). Under this policy, EPA is authorized to identify and publish lists of acceptable and unacceptable substitutes for ozone-depleting substances. EPA has determined that a large number of alternatives exist that reduce overall risk to human health and the environment. The purpose of the program is to allow a safe, smooth transition away from ozone-depleting compounds by identifying substitutes that offer lower overall risks to human health and the environment. With respect to the halons, the SNAP program has approved alternatives for total flooding applications, i.e., applications where a specific concentration of extinguishing agent is achieved in an enclosed area by discharge of an automatic system; and alternatives for streaming applications, i.e., applications where an extinguishing agent is directed to a fire using portable fire extinguishers. The SNAP program is important because its recommendations have been adopted by many countries that don't have a similar program to evaluate alternatives to ODS. Obviously in countries where SNAP recommendations are not observed, the alternative does not have to be SNAP listed, but many manufacturers want their products to be SNAP listed because of the larger market that it offers for their products. All HCFCs used in fire protection and their alternatives discussed in this section are SNAP listed.

As with the halons, the use of HCFCs in fire protection is driven by the fire protection application as described below.

5.1.1 Total flooding applications

Three HCFCs or blends of them are listed by the SNAP program for total flood applications. These are: HCFC-22, HCFC-124 and HCFC Blend A.

HCFC-22 on its own was never commercialised for this application, and HCFC-124 on its own was only developed and commercialised for a specific marine application. However, new systems are no longer marketed and haven't been for two years.

Per the 2010 Report of the Halons Technical Options Committee, HCFC Blend A is comprised of the following:
HCFC-22: 82%
HCFC-124: 9.2%
HCFC-123: 4.75%
D-Limonene: 3.75%

Owing to its toxicity profile, HCFC Blend A can only be used in occupied areas for Class A fires, and in unoccupied areas for Class A and B fires. It was first marketed in 1992 and has been sold primarily in Europe, the Middle East and Asia. Its use restrictions compared with equivalent alternatives have limited its market acceptance, as has the ban on HCFCs in fire protection in the European Union (EU). Most recent sales are in Israel and South Korea, where it still has limited acceptance. However, changes in South Korean technical standards and regulations in 2011 mean that its future use in that country will be limited to recharge needs rather than new systems. Known use in 2011 was approximately 230 MT, but this is expected to drop by 60 to 70% in 2012 and this downward trend is expected to continue.

5.1.2 Streaming applications

Six HCFCs or blends of them are approved for fire protection streaming applications by the SNAP program. These are: HCFC-123, HCFC-124, HCFC Blend B, HCFC Blend C, HCFC Blend D and HCFC Blend E. With the exception of HCFC-124, these were all commercialised and sold in either portable extinguishers or wheeled units. However, most did not gain a significant market share and were abandoned some time ago. Today only HCFC Blend B is marketed in both non-Article 5 and Article 5 countries, with a market ratio of 4 to 1 respectively. Limited quantities of HCFC-123 and HCFC Blend E are still marketed in portable extinguishers in some Article 5 countries such as India and Indonesia.

HCFC Blend B is comprised of the following:
HCFC-123: >96%
CF_4: <4%
Argon: <4%

Production of HCFC Blend B in 2006 was 250 MT (Wuebbles, 2009) with an estimated growth rate of 3% per annum. However, the manufacturer currently estimates the growth rate to be a more modest 1% per annum. This would give a production in 2011 of 262 MT.

HCFC Blend E is comprised of the following:
HCFC-123: 90%
HFC-125: 8%
D-Limonene: 2%

According to the manufacturer, production of HCFC Blend E in 2011 was 27 MT and, although production will likely continue, production growth is not expected.

The production of HCFC-123 for use in portable extinguishers on its own is unknown. It is suspected that produced HCFC-123 is being diverted from other uses to the production of low cost portable extinguishers in some Article 5 countries such as India. The quality and performance of these extinguishers is unknown as they do not conform to internationally recognized standards.

5.2 Technically proven and economically viable alternatives to HCFCs in Fire Protection

HCFCs and their blends only replaced approximately 1% of the former halon market and only where a clean agent was required. Thus the alternatives to HCFCs in fire protection are essentially the other clean agent alternatives to halon for a given application.

It is also important to remember that the fire extinguishing performance of different agents varies depending on the type (Class) of fire to be extinguished. The common types of fires are Class A – fires in ordinary combustible materials, such as wood, cloth, paper, rubber, and many plastics; Class B – fires in flammable liquids, combustible liquids, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, alcohols, and flammable gases; and Class C – fires that involve energized electrical equipment where the electrical non-conductivity of the extinguishing media is important.

5.2.1 Total flooding applications

The only HCFC clean agent still marketed for total flood systems is HCFC Blend A, and recent market information (see 5.1.1 above) indicates that future sales will be for recharge of existing systems only. Clean agent alternatives to this agent include inert gases (nitrogen, argon or blends of these two, sometimes incorporating carbon dioxide as a third component), HFCs, and a fluoroketone (FK). Although PFC systems were initially used to help in the transition away from halons, owing to their impact to the climate system and lack of performance advantage over other alternatives, they are not considered an acceptable alternative for HCFC Blend A systems. While carbon dioxide systems have been used for many years and the technology is well developed, its use as a total flooding agent in occupied spaces involves significant life safety considerations. This is because the concentration needed to extinguish a fire is lethal. Numerous incidents of fatalities have been reported (Wickham, 2003). Carbon dioxide systems are therefore not included here.

After elimination of the agents either found unsuitable for occupied spaces, withdrawn from standards, or not commercialized in fire extinguishing systems, the list of potential gaseous total flooding agents is reduced considerably to: HFC-23, HFC-125, HFC-227ea, FK-5-1-12, and the inert gases.

Table 5-1: Comparisons of average values in the 500 to 5,000 m3 range (per cubic metre of protected volume at the concentration indicated). Class B Fuel Applications.

		HCFC Blend A	**HFC-23**	**HFC-227ea**	**HFC-125**	**FK 5-1-12**	**Inert Gas**
Concentration	Vol. %	13	19.5	8.7	12.1	5.5	40.0
Weight*	kg/m^3	1.1	2.3	1.1	1.1	1.2	4.3
Footprint **	$10^4\ m^2/m^3$	7.1	12.0	6.8	7.4	7.3	28.2
System Cost***	$US\$/m^3$	8	39.77	28.05	26.37	35.98	34.07
Agent Cost****	$US\$/m^3$	2.31	18.33	19.08	16.81	26.59	9.62

Note 1: HCFC Blend A was not included in the IMO study as the required concentration of agent meant that the space could not be occupied. Data has been provided by the manufacturer.
* Weight includes the storage containers and contents but not the weight of piping, hangers, etc.
** Footprint is that area occupied by the agent containers defined by a square or rectangle circumscribing the agent cylinder bank
*** System cost is the average selling price of the system components charged by a manufacturer to a distributor or installer, and includes agent, agent storage containers, actuators, brackets, discharge and actuation hoses, check valves, stop valves and controls, time delay, manually operated stations, pre-discharge alarms, pilot cylinders and controls. Cost does not include agent distribution piping and fittings, pipe supports and hangers, actuation tubing and fittings, electrical cables and junction boxes or labor to install, packing or freight.
**** Agent cost is the average selling price charged by a manufacturer to a distributor or installer.

In both the IPCC/TEAP SROC and the TEAP response to Decision XX/8, a comparison was made of the agent storage container weights and costs of several types of systems to protect volumes of 500, 1,000, 3,000 and 5,000 m^3 under the rules of the International Maritime Organisation (IMO) for the protection of shipboard machinery spaces (Wickham, 2003). The results are shown in Table 5-1.

The primary environmental factors to be considered for the alternative agents to HCFCs are ozone-depletion potential (ODP), global-warming potential (GWP), and atmospheric lifetime. These factors are summarized in Table 5-2. It is important to select the fire protection choice with the lowest environmental impact that will provide the necessary fire protection performance for the specific application.

Table 5-2: Clean Agent Alternatives – Environmental Factors

Generic Name	Ozone Depletion Potential	Global Warming Potential, 100 yr. (1)	Atmospheric Life Time, yr.(1)
HCFC Blend A: HCFC-22	0.055	1,790	11.9
HCFC Blend A: HCFC-124	0.022	619	5.9
HCFC Blend A: HCFC-123	0.02	77	1.3
HFC-23	0	14,200	222
HFC-227ea	0	3,580	38.9
HFC-125	0	3,420	28.2
FK-5-1-12	0	1**	7–14 Days*
Inert Gases	0	0	n/a

Note 1: Source: 2010 Scientific Assessment of Ozone Depletion
* These are approximate lifetimes for short-lived gases, though actual lifetimes for an emission will depend on the location and season of that emission
** Data were supplied by the manufacturer.

From Table 5-2, it is clear that on a purely environmental impact basis, HFC-23 may not be a good choice as a replacement for HCFC Blend A, and in fact this agent has normally only been used in specialist applications. The inert gas systems have no environmental impact as a replacement for HCFC Blend A and FK 5-1-12 has almost negligible environmental impact. However, the system costs of these alternatives are significantly higher than the two closest HFC alternatives, and the footprint of the cylinders necessary for the inert gases is three times that of its competitors because of the amount of agent required for extinguishment.

Thus it can be concluded that there exist alternatives to HCFCs in total flood fire protection applications that have minimal environmental impact. Although the system costs for these alternatives are significantly higher than for HCFC Blend A, the latter is limited to unoccupied spaces only for Class B fires.

5.2.2 Streaming applications

HCFC-123 is the primary component of the HCFC clean agents commercialized for use in streaming applications, i.e., HCFC-123 (100%), HCFC Blend B (96% HCFC-123), and HCFC Blend E (90% HCFC-123). HCFC Blend B has by far gained the most market share. Therefore for this exercise it has been chosen for comparison with non-HCFC alternatives.

In order to deal with the different types of extinguishers and match them up with the needs of the end users, one must have an understanding of the rating system for the extinguishers. Disregarding very specialized extinguishers, as mentioned above, the common types of fires are Classes A, B and C. Underwriters Laboratories, Inc. (UL) has, together with industry, developed fire testing procedures and a rating system for portable extinguishers. These requirements cover rating and performance during fire tests of fire extinguishers intended for use in attacking Class A, B, and C fires. The ultimate rating of an extinguisher or the prescribed use of an extinguisher or agent is based on its fire-extinguishing potential as determined by fire tests. Obviously some extinguishing agents can achieve listing for all three classifications while others may be limited to two or perhaps even just one. As an example, a commonly specified extinguisher is 2-A:10-B:C rating, where “A” indicates it is suitable for use on Class A fires and the preceding number indicates its degree of effectiveness on those types of fires as determined in testing by approval laboratories; "B" indicates it is suitable for Class B fires and the preceding number indicates its degree of effectiveness on those types of fires; and "C" indicates it is safe for use around energized electrical equipment.

From a fire code standpoint, the most commonly specified extinguisher is one with a 2-A:10-B:C rating. (Wickham, 2002) compared the agent charge, fire rating and average selling price of several types of extinguishers. This is shown in Table 5-3 below.

Table 5-3: Portable Extinguishers – cost comparisons

Type	**Agent Charge**		**Fire Rating**	**Average Selling Price US$**
HCFC Blend B	15.5 pounds	7.03 kg	2-A:10-B:C	415
HFC-236fa	13.3 pounds	6.03 kg	2-A:10-B:C	493
Multipurpose Dry Chemical	5.0 pounds	2.27 kg	3-A:40-B:C	30
Carbon Dioxide	10.0 pounds	4.54 kg	10-B-C	175
Water	2.5 gallons	9.5 litre	2-A	63

Referring to the units in Table 5-3, end users have a choice of using the 5 pounds ABC dry chemical unit for an average end user cost of US $30 each, the 13.3 pounds HFC-236fa unit for US $483, the 15.5 pounds HCFC Blend B unit for US $415 extinguisher, or both a ten-pound carbon dioxide unit and a 2.5 US gallon water extinguisher with a combined average end user cost of US $235. Given the cost multiplier of 13 to16 for the HCFC Blend B and HFC agents respectively, it is clear that these agents are limited to those applications where users consider cleanliness a necessity. Thus, the only commercially available alternative to HCFC Blend B for this application is HFC-236fa.

As indicated in Table 5-4, HFC-236 is not environmentally benign or even environmentally negligible. Thus, when considering this option as an alternative to HCFC Blend B for streaming applications, one must compare the environmental impacts of both agents. Of concern are ODP, GWP, and Atmospheric Lifetime. The ODP of HFC-236fa is 0 and that of HCFC-123 0.02. According to (Wuebbles, 2009), the 2006 worldwide installed bank for HCFC Blend B and HCFC-123 for fire extinguishing is estimated as 1800 MT. Given the short atmospheric lifetime of HCFC-123, in a realistic situation, the emissions are expected to remain small enough that the equivalent chlorine would never get anywhere close to a level of concern relative to other forcings on ozone.

HCFC-123 has a 100-year integrated Global Warming Potential (GWP) of 77. This value is much less than the value of 9,810 for HFC-236fa. However, the HCFC Blend B formulation contains a small percentage of CF_4, a high GWP gas. According to (Wuebbles, 2009), accounting for the CF_4 content, however, one could emit over 40 times the amount of HCFC Blend B before one would have the same impact on climate as using HFC-236fa. However, CF_4 lasts in the atmosphere for many thousands of years, so its effects on climate would continue for a very long time. The amount of CF_4 emissions worldwide from HCFC Blend B are currently estimated to be less than 1 MT annually, but its long atmospheric lifetime and strength as a greenhouse gas make it a concern.

Table 5-4: Clean agent portable extinguishers – environmental factors

Type	Chemical Composition		Environmental Factors		
	Weight %	Species	ODP	GWP 100 yr.	Atmospheric Lifetime
HCFC Blend B	>96%	HFCF-123	0.02	77	1.3
	<4%	CF_4	0	7,390	>50,000
	<4%	Argon	0	n/a	n/a
HFC-236fa	$CF_3CH_2CF_3$		0	9,820	242

From the above, it would appear that from an economic and environmental impact point of view, replacing HCFC Blend B with HFC-236fa as a clean agent for streaming purposes may not be a good choice. Currently there are no other alternatives commercialised for this purpose, although others are being studied. As noted in subsection 5.3 below, an unsaturated hydrobromofluorocarbon (HBFC). 3,3,3-trifluoro-2-bromo-prop-1-ene (2-BTP), has completed fire testing and many of the toxicity tests required for SNAP approval. Should it receive final approvals, it would be an effective substitute for HCFC Blend B, although it may be more expensive.

5.3 The feasibility of options to ODS in fire protection

5.3.1 Introduction

With the exception of aircraft cargo bays, fire extinguishing agent alternatives to ODSs, in the form of non-ozone depleting gases, gas-powder blends, powders and other not-in-kind technologies (i.e., non-gaseous agents) are now available for virtually every fire and explosion protection application once served by ODSs. However, retrofit of existing systems that use ODS may not always be technically and/or economically feasible.

Gaseous extinguishing agents that are electrically non-conductive and which leave no residue are referred to as “clean” agents. Several clean agents and new “not-in-kind” alternative technologies have been introduced to the market.

5.3.2 Alternatives to ODSs for total flooding Fire Protection using fixed systems

A number of fire extinguishing agent technologies have been commercialised as alternatives to ODSs for use in total flooding applications. These are summarised in Table 5-5.

Table 5-5: Fire extinguishing agent alternatives to ODSs for use in total flooding applications

Agent	Constituents
Inert gases, pressurised	
IG-01	Argon, Ar
IG-100	Nitrogen, N_2
IG-541	Nitrogen, 52 vol. %; Argon, 40 vol. %; Carbon dioxide, 8 vol.%
IG-55	Nitrogen, 50 vol. %; Argon, 50 vol. %
Carbon dioxide	Carbon dioxide, CO_2
Inert gases, pyrotechnically generated	
Nitrogen	Nitrogen
Nitrogen-water vapour mixture	Nitrogen and water

Agent	Constituents
Water mist	Water
Hydrofluorocarbons	
HFC-125	C_2HF_5 – Pentafluoroethane
HFC-23	CHF_3 - Trifluoromethane
HFC-227ea	CF_3CHFCF_3 - 1,1,1,2,3,3,3-heptafluoropropane
HFC-236fa	$CF_3CH_2CF_3$ - 1,1,1,3,3,3-hexafluoropropane
HFC Blend B	HFC-134a, CH_2FCF_3, 1,1,1,2-tetrafluoroethane, 86 wt.%; HFC-125, C_2HF_5, Pentafluoroethane, 9 wt.%; Carbon dioxide, CO_2, 5 wt.%
Fluoroketone	
FK-5-1-12	$CF_3CF_2(O)CF(CF_3)_2$ – Dodecafluoro-2-methylpentan-3-one
Iodofluorocarbons	
FIC-13I1	CF_3I – Iodotrifluoromethane
FIC-217I1	C_3F_7I – Iodoheptafluoropropane
Gaseous Agents Containing Particulate Solids	
HFC227BC	HFC-227ea with 5 to 10 wt.% added sodium bicarbonate
Gelled mixture of HFC plus dry chemical additive.	HFC-125 plus ammonium polyphosphate or sodium bicarbonate HFC-227ea plus ammonium polyphosphate or sodium bicarbonate HFC-236fa plus ammonium polyphosphate or sodium bicarb.
Aerosol Powders	
Powdered Aerosol A	Proprietary formulation
Powdered Aerosol C	Proprietary formulation
Powdered Aerosol D	Proprietary formulation
Powdered Aerosol E	Proprietary formulation

Several agents listed in Table 5-5 have been approved for use in normally occupied spaces. These agents include the named inert gas agents, HFC agents, FK-5-1-12 agent, and gaseous agents containing particulate solids. These agents may be used for total flooding fire protection in normally occupied spaces provided that the design concentration is below safe exposure threshold limits.

Agents listed in Table 5-5 that are not suitable for use in occupied spaces include carbon dioxide, FIC-13I1, FIC-217I1, and the aerosol powders.

In addition to gaseous agents, powders, and mixtures of these, a number of other technologies have been evaluated for fire extinguishing applications where ODSs might have formerly been used. These include water-foam technologies and several types of water mist systems.

Water mist system technologies strive to generate and distribute within a protected space very small mist droplets which serve to extinguish flames by the combined effects of cooling and oxygen dilution by steam generated upon water evaporation.
Chapter 2.0, Section 2.2 of the 2010 Report of the Halons Technical Options Committee (HTOC) describes in detail the attributes of the alternatives to ODS for total flooding applications including, agent toxicity, environmental factors, physical properties,

physiological effects, minimum extinguishing concentrations, agent exposure limits and agent quantity requirements for Class A and Class B combustible hazard applications.

Selection of the best fire protection method is often a complex process. Either alternative gaseous fire extinguishing agents, so called in-kind alternatives, or not-in-kind alternatives may replace ODSs but the decision is driven by the details of the hazard being protected, the characteristics of the gaseous agent or alternative method, and the risk management philosophy of the user. Chapter 2.0, Section 2.3 of the report lists system design considerations for fixed systems.

5.3.2.1 New or emerging technologies in total flooding applications

1. Water mist technologies continue to evolve. Recently commercialised innovations include:
    a. New atomisation technology using two-fluid system (air and water) to create ultrafine mist with spray features that are adjustable by changing the flow ratio of water to air;
    b. Water mist combined with nitrogen to gain extinguishing benefits of both inert gas and water mist.
2. Pyrotechnic products. Development continues on the use of pyrotechnic products to generate nitrogen or mixtures of nitrogen and water vapour, with little particulate content, for use in total flooding fire extinguishing applications.
3. Low GWP HFCs. One chemical manufacturer is developing unsaturated HFC compounds for various uses including as total flooding fire extinguishing agents. The molecules of these chemicals contain a double carbon-carbon bond which causes them to have short atmospheric lifetimes and, therefore, low values of GWP.

5.3.3 Alternatives for local application and portable extinguishers

A number of fire extinguishing agent technologies have been commercialised as alternatives to ODSs for use in local application / portable extinguishers in addition to the traditional streaming agents that were sold alongside ODS. These are summarised in Table 5-6.

Table 5-6: Fire extinguishing agent alternatives to ODSs for use in local application Fire Protection

Substitute	Constituents	Approved for Residential Use?
Gelled Halocarbon/Dry Chemical Suspension	Halocarbon plus dry chemical plus gelling agent	Yes
Surfactant Blend A	Mixture of organic surfactants and water	Yes
Carbon dioxide	CO_2	Yes
Water	H_2O	Yes
Water Mist Systems	H_2O	Yes
Foam	-	Yes
Dry Chemical	-	Yes
HFC-227ea	CF_3CHFCF_3	No
HFC-236fa	$CF_3CH_2CF_3$	No
FIC-13I1 *	CF_3I	No
FK-5-1-12	$CF_3CF_2C(O)CF(CF_3)_2$	No
Hydrofluoro-polyethers	Hydrofluoro-polyethers	No

Chapter 2.0, Section 2.4 of the 2010 Report of the Halons Technical Options Committee (HTOC), describes in detail the attributes of the alternatives to ODS for local applications / portable extinguishers including agent toxicity and environmental factors. Chapter 2.0, Section 2.5 of the report gives an assessment of the alternative streaming agents, and Section 2.6 provides guidance on selection of portable extinguishers.

5.3.3.1 New or emerging technologies in local application systems

1. Phosphorus tribromide, PBr_3. PBr_3 is a clear liquid with a boiling point of 173°C. It reacts vigorously with water liberating HBr and phosphorous acid and is, therefore, a toxic substance at ambient conditions. Though the agent contains bromine, it poses little risk to stratospheric ozone. The agent decomposes rapidly in the atmosphere and the HBr formed is quickly eliminated by precipitation. PBr_3 is an effective fire extinguishant in part due to its bromine content. Given its high boiling point, and low volatility, this agent must be delivered as a spray or mist into the fire zone in order to be effective. It has been commercialised for use as a fire extinguishant in one small aircraft engine application.
2. Water with additives. One manufacturer has introduced a novel non-corrosive and low toxicity water-based agent by employing multiple salts to achieve a very low freezing point (-70°C) without the use of glycols (spills are non-reportable) and excellent fire extinguishing effectiveness that includes film-forming capability. Initial commercial applications are as fixed local application systems in industrial vehicles such as mining and forestry.
3. The unsaturated hydrobromofluorocarbon (HBFC). 3,3,3-trifluoro-2-bromo-prop-1-ene (2-BTP), CAS 1514-82-5. This agent is currently undergoing the final toxicity tests needed for SNAP approval and could be commercialised as early at the beginning of 2013. It has been shown to be an effective extinguishing agent that offers promise for replacing ODSs in aviation applications.

4. Trifluoromethyliodide. CF_3I is offered by one manufacturer and is available for research in fire extinguishing applications.

5. Fluoroketone. A recently identified fluoroketone is under development for streaming applications.

6 Solvents

6.1 Key issues

Among ODSs controlled by Montreal Protocol, CFC-113 and 1,1,1-trichloroethane (TCA) were used primarily in precision and metal cleaning.

While some key properties of solvents such as low surface tension, easy drying, and material compatibilities are required in precision cleaning, degreasing performance of solvents plays a key role in metal cleaning.

Many alternative solvents and technologies have been developed since the 1980s, thus, over 90% of the ODS solvent use had been reduced through conservation and substitution with not-in-kind technologies by 1999. The remaining less than 10% of the solvent uses are shared by several organic solvent alternatives, which include, chlorinated solvents, a brominated solvent, and fluorinated solvents. Fluorinated solvents are essentially used for alternatives to CFC-113, and HCFCs are included in this category as well as HFCs and HFEs (hydrofluoroethers).

The elimination of HCFCs from solvent applications still leaves many options available and they have found various levels of acceptance. However, no single option seems well suited to replace HCFCs completely.

Recently unsaturated HFCs (HFOs) with zero ODP and unsaturated HCFCs (HCFOs) with negligibly small ODP are stated to be under development. They have ultra low GWP (<10) and are expected to replace high GWP-HFCs and low or moderate GWP HFE solvents. They also could be candidates to replace HCFCs in certain solvent applications.

6.2 Use (market) data of HCFCs in solvents

Several reports that describe the use of HCFCs in solvent applications have been published in the past. These include the IPCC TEAP Special Report (IPCC, 2005), the TEAP Decision XXI/9 Task Force Report (TEAP, 2010), Assessment Reports of the CTOC (CTOC, 2006; CTOC, 2010) and the (former) STOC (STOC, 1998; STOC, 2002) as well as (IPC, 2011) and (Kanegsberg, 2011).

As mentioned above, most of the former solvent market of ODSs is shared by not-in kind alternatives. In-kind alternatives such as HCFCs have a lower than 10% market share.

The characteristics of those not-in-kind and in-kind solvents are summarized in Table 6-1.

The only HCFC solvents currently used are HCFC-141b and HCFC-225ca/cb with ODP of 0.11 and 0.025/0.033 and GWP-100yr of 713 and 120/586, respectively. Although HCFC-141b use as solvents in non-Article 5 countries was banned by 2010, its use in Article 5 countries may still be increasing. The accurate volume for solvent use is unclear, however as HCFC-141b is also used in foam application and the volume reported as HCFC-141b is a combined figure.

HCFC-225ca/cb has been used as drop-in replacement for CFC-113 in many cases, as it resembles CFC-113 in its chemical and physical properties. HCFC-225ca/cb is still advantageously used in the applications where the other alternative solvents can hardly be applied, such as oxygen system cleaning for military and space rocket applications, and is also directed to niche applications in precision cleaning and as a carrier solvent. It is higher in cost compared to CFC-113 and the market for it seems to remain only in Japan and USA with consumption of the order of thousand metric tons level.

Table 6-1: Characteristics of not-in-kind and in-kind solvents

Solvents	Equipment	Features of Cleaning Process	Environmental Effect
Aqueous[(1)]	Ultrasonic Heating device Pure water supply Wastewater treatment	Many rinsing sumps Large floor space needed Long cycle time Incompatible with plastics	ODP: 0 GWP: 0 Waste Treatments
Semi-Aqueous[(2)]	Explosion proof Same as "Aqueous"	Same as "Aqueous" Flammable, if any Cleaner recyclable	ODP: 0 GWP: Low VOC
Hydrocarbon[(3)]	Explosion proof Ultrasonic Heating device Distillation system Ventilation equipment	Not many sumps Long cycle time Flammable Cleaner recyclable Incompatible with plastics	ODP: 0 GWP: Low VOC
Alcoholic[(4)]	Explosion proof Ventilation equipment Indirect heating device	Flammable Medium cycle time	ODP: 0 GWP: Low VOC
Chlorinated[(5)]	Same as "Hydrocarbon" except Explosion proof	Not many sumps Short cycle time Cleaner recyclable	ODP : Low GWP: Low
Brominated[(6)]	Same as "Chlorinated"	Same as "Chlorinated"	ODP: Low GWP : Low
Fluorinated[(7)]	Ultrasonic Heating device Distillation system Ventilation equipment	Same as "Chlorinated" Incompatibility with plastics: HCFCs: yes HFCs and HFEs: no	HCFCs: ODP and GWP: Middle HFCs and HFEs: ODP: 0 GWP: Middle to High

(1) Basic, Neutral and Acidic Systems
(2) Aqueous mixture with glycol ether, N-methyl pyrrolidone, terpene or hydrocarbons
(3) n-paraffin, iso-paraffin, naphtene etc.
(4) iso-propyl alcohol
(5) methylene chloride, trichloroethylene, tetrachloroethylene
(6) n-propyl bromide
(7) HCFCs, HFCs and HFEs

6.3 Technically proven and economically viable alternatives to HCFCs

The elimination of HCFCs in solvent applications still leaves many options available and they have found various levels of acceptance. All of the alternative solvents listed in Table 6-1 could be candidates, but no single option seems well suited to replace HCFCs completely.

6.3.1 Not in-kind alternatives

Aqueous and semi-aqueous cleaning

These processes can be good substitutes for metal degreasing or even precision cleaning when corrosion of the materials is not an issue. The availability of good quality water and water disposal issues need to be taken care of, right from the start of the process conception. Some aqueous cleaning processes have a low environmental impact (no VOC, low GWP, no ODP) and a low toxicity. However, others involving additives may emit VOCs and use toxic and corrosive chemicals. Investment costs can be high but operating costs are generally lower than those with solvents alternatives.

Hydrocarbon solvent cleaning

This process has proven to be a good solution with paraffin hydrocarbon formulations; cleaning is efficient but the non-volatile or less-volatile residues can be incompatible with some downstream manufacturing or finishes. Their environmental impact is low (low GWP, no ODP) but they are generally classified as VOC and emissions are subject to regulation. Their toxicity is also low. Owing to their combustibility (flashpoint > 55°C), they have to be used in open tank equipment at a temperature at least 15°C below their flashpoint.

Alcoholic solvents

These substances have been used for many years in cleaning applications. Their cost and environmental impact are low (low GWP and zero ODP), but they are classified as VOCs and may contribute to ground level ozone pollution. Also they require explosion proof equipment.

6.3.2 In-kind alternatives

Chlorinated solvents

The primary in-kind substitute for TCA has been the chlorinated alternatives such as trichloroethylene, tetrachloroethylene and methylene chloride. These substitutes have very small (0.005-0.007) ozone depletion potentials and are generally classed as zero-ODP. They have similar cleaning properties to TCA.

Brominated solvent

A brominated solvent, n-propyl bromide is another alternative for TCA and CFC-113 because of its similar cleaning properties. Its ODP is calculated to be in the range of 0.0049 – 0.011, similar to those of HCFCs. However, there has been significant concern about the toxicity of n-propyl bromide. Recent publication from ACGIH in February 2012 showed the reduction of the TLV for n-propyl bromide from 10 ppm to 0.1 ppm.

HFC solvents

There are two HFC solvents commercially available. They are HFC-43-10mee (2,3-dihydro-decafluoropentane, $C_5H_2F_{10}$) and HFC-c447ef (heptafluoro-cyclopentane; c-$C_5H_3F_7$).

HFC-43-10mee is a non-flammable solvent with low toxicity. It has an atmospheric life-time is 15.9 years and a GWP-100yr of 1,640. HFC-43-10mee readily forms azeotropes with alcohols, chlorocarbons and hydrocarbons to give blends enhanced cleaning properties. The blends are used in applications such as precision cleaning, defluxing flip chips and printed wiring boards (PWB). Also HFC-43-10mee is advantageously used as a solvent for the coating of fluorinated lubricants on hard disc devices.

HFC-c447ef is non-flammable with a boiling point of 82 ^{0}C. It has an atmospheric lifetime of 3.4 years and a GWP-100yr of 250, which is lower than that of most HFCs and HFEs.

Although HFCs are available in all regions, their uses have been primarily in non-Article 5 countries, due to relatively high cost and important demands in high tech industries. On account of increasing concern about their high GWP, uses are focused in critical applications for which there are no other substitutes. Therefore, growth is expected to be minimal.

HFE solvents

HFE (hydrofluoroether) is a new homologue of fluorinated solvents. Four HFEs have been introduced into the non-Article 5 market. These are HFE-449st (perfluorobutylmethylether, $C_4F_9OCH_3$) with GWP-100yr of 297, HFE-569sf1 (Perfluorobutylethylether, $C_4F_9OCH_2CH_3$) with GWP-100yr of 59, HFE-347pd-f (2,2,2-trifluoroethyl 1,1,2,2-terafluoroethylether, $CF_3CH_2OCF_2CHF_2$) with GWP-100yr of 580, and HFE-64-13s1 (Perfluorohexylmethylether, $C_6F_{13}OCH_3$) with GWP-100yr of 210.

All of these compounds are used as replacements for CFCs, HCFCs and are potential replacement for high GWP HFC solvents. The pure HFEs are limited in use in cleaning applications owing to their mild solvency. Therefore HFEs are usually used as azeotropic blends with other solvents such as alcohols and trans-1,2-dichloroethylene and in co-solvent cleaning processes giving them broader cleaning efficacy. The relatively high cost of these materials limits their use compared to lower cost solvents such as chlorinated solvents and hydrocarbons.

Unsaturated solvents (HFOs and HCFOs)

Recently unsaturated fluorochemicals such as HFOs and HCFOs have been proposed. They are a new class of solvents specifically designed with a low atmospheric lifetime. The unsaturated molecules are known to be unstable in the atmosphere and therefore they show these low atmospheric lifetimes.

HFOs with zero ODP and ultra low GWP (<10) are being developed for the replacement of high GWP HFC and low or moderate GWP HFE solvents. They also could be candidates to replace HCFCs in certain solvent applications.

HCFO-1233zd (trans-1-chloro-3,3,3-trifluoropropene) has an atmospheric lifetime of less than one month and a (100 yr) GWP smaller than 5. The ODP is negligibly small due to its very short atmospheric lifetime. HCFO solvents are potential replacements for CFCs, HCFCs and potential high GWP HFC solvents.

6.4 Feasibility of options to HCFCs in solvents

In the case of not in-kind solvent cleanings, some conversion to aqueous cleaning is likely but there are limits to its use because some products/processes simply can’t tolerate water. There is also the additional requirement that an aqueous cleaning step be followed by a drying step which can be energy-intensive and need more floor space.

Hydrocarbons and alcohols are effective solvents but are extremely flammable. Engineering controls, some of which are costly, can reduce the risk but flammability concerns may constrain growth. Additionally, most of the commonly used hydrocarbons are VOCs, which may further constrain growth in some countries.

As for in-kind solvents, the boiling points and safety properties, and environmental properties are summarized together with those of HCFCs in Table 6-2 and Table 6-3, respectively.

Chlorinated solvents will be available as replacements for HCFCs in a variety of cleaning applications owing to their high solvency. However, large-scale conversions to chlorinated solvents would seem unlikely because of toxicity concerns. Those solvency powers are more aggressive than those of HCFCs. Therefore material compatibility should be evaluated carefully when HCFCs are replaced by chlorinated solvents.

n-PB is an effective and useful solvent but widespread growth in its use would seem unlikely because of toxicity concerns. ACGIH announced the reduction of the TLV for n-propyl bromide from 10ppm to 0.1ppm in February 2012.

HFC and HFEs are also good candidates for the replacement for HCFCs.

Due to their mild solvency, however, some modification may be necessary when HCFCs are replaced by HFCs and HFEs. All of HFCs and HFEs have zero ODP. Their GWP values vary depending on their structures. One HFC and some HFE
have relatively low GWPs as shown in Table 6-2.

The relatively high cost of these materials limits their use.

Table 6-2: Physical and safety properties of in-kind solvents

Solvents	**b.p.(^oC)**	**Flash Point (^oC)**	**Combustible Range[(1)]**	**TLV or OEL (USA)**
Chlorinated				
Trichloroethylene	87	Non	8 – 10.5 [vol%]	10 ppm
Tetrachloroethylene	121	Non	non	25 ppm
Methylene chloride	40	Non	13 – 23 [vol%]	50 ppm
Brominated				
n-PB	72	Non	non	0.1ppm
HFCs				
HFC-43-10mee	55	Non	non	200 ppm*
HFC-c447ef	82	Non	non	120 ppm*
HFEs				
HFE-449s1	61	Non	non	750 ppm*
HFE-569sf1	72	Non	2.1 – 10.7 [vol%]	200 ppm*
HFE-347pc-f2	56	Non	non	50 ppm*
HFE-64-13s1	98	Non	non	100 ppm*
HCFOs				
HCFO-1233zd(E)	19	Non	non	300 ppm*
HCFCs				
HCFC-225**	54	Non	Non	100 ppm*
HCFC-141b	32	Non	6.5 – 15.5 [vol%]	500 ppm

(1) Tag closed-cup tester (in air)
* Data supplied by manufacturers, ** Blend of HCFC-225ca and 225cb

Table6-3: Environmental properties of in-kind solvents

Solvents	**ODP**[(1)]	**GWP (100yr)**[(2)]	**Atmospheric Lifetime**[(2)]
Chlorinated			
Trichloroethylene	0.005	5*	13 days[(3)]
Tetrachloroethylene	0.005	12*	0.30 yrs[(3)]
Methylenedichloride	0.007	9*	0.38 yrs
Brominated			
n-PB	0.0049-0.01[(3)]	(Very Low)	20 – 25 days[(3)]
HFCs			
HFC-43-10mee	0	1640	15.9 yrs
HFC-c447ef	0	250**	3.4 yrs**
HFEs			
HFE-449s1	0	297	3.8 yrs
HFE-569sf1	0	59	0.77 yrs
HFE-347pc-f2	0	580	7.1 yrs
HFE-64-13s1	0	210**	3.8 yrs**
HCFOs			
HCFO-1233zd(E)	~0**	< 5**	< 1 month**
HCFCs			
HCFC-225ca	0.025	122	1.9 yrs
HCFC-225cb	0.033	595	5.8 yrs
HCFC-141b	0.11	725	9.3 yrs

(1) (IPCC, 2005), (2) (IPCC, 2007) , (3) (Wuebbles, 2010)
*JAHCS, http://www.jahcs.org/leaflet/leaflet02-09.htm
** Data were supplied by the manufacturers

Furthermore, unsaturated HFCs and HCFCs (HFOs and HCFOs) are also stated to be under development for the replacement of high GWP HFC and low or moderate GWP HFE solvents. Both HFOs and HCFOs have ultra low GWPs. HFOs also could be candidates to replace HCFCs in certain solvent applications. HCFO-trans-1233zd can have a high solvency due to the presence of chlorine atom and may be used as a direct replacement for HCFCs. The relatively high cost of these materials would limit their use.

6.5 Cost information

Due to the wide variety of alternatives available to replace HCFCs, a full discussion of the costs of these alternatives is not practical. However, there are several universal cost components that should be considered when evaluating alternative solvents and technologies. These cost components can be split into two groups, one-time costs and recurring costs.

One-time costs are those costs that are incurred only at the beginning of a project and are not repeated throughout the project life. The most significant of these costs is often the capital investment of new equipment or in the retrofit of existing equipment. Other one-time costs may include items such as laboratory and production testing, environmental, health, and safety impact studies, equipment installation, process control means and methods, personnel training, documentation revisions, and environmental permitting or licensing.

Recurring costs are primarily operating costs. These are incurred throughout the life time of the equipment or cleaning process. Recurring costs may include costs for raw materials (cleaning detergents, solvents, water, water purification, energy usage, recycling, waste treatments/disposal, and equipment maintenance.

The key cost factors are roughly summarized in Table 6-4.

Generally speaking, aqueous and semi-aqueous cleanings require high capital investments, but their operating costs are lower than those with solvent system.
Explosion proof equipment is necessary for hydrocarbon and alcoholic systems, but the solvents are cheaply available.

For in-kind alternatives, the cleaning equipment is similar to those for HCFCs. Therefore, retrofitting the equipment may be possible to lower the investments. The price range of the in-kind solvents go from the rather inexpensive chlorinated solvents, n-PB, HCFC-141b, then the higher priced other fluorinated solvents such as HCFC-225ca/cb, HFCs, unsaturated HFCs and HCFCs (HFOs and HCFOs) as well as HFEs.

Table 6-4: Key cost factors of alternative solvents

Solvents	**Solvent Cost(1)**	**Capital Investment**	**Retrofitting**
Aqueous: Basic, Neutral and Acidic Systems	A-B	Very Large	X
Semi-Aqueous Aqueous mixture with glycol ether, N-methyl pyrrolidone, terpene or Hydrocarbons	A-D	Very Large	X
Hydrocarbon n-paraffin, iso-paraffin, naphthene	A-C	Large	X
Alcoholic Iso-propyl alcohol	A	Lagre	X
Chlorinated Methylene chloride, trichloroethylene, tetrachloroethylene	A	Medium	possible
Brominated n-PB	C	Medium	possible
Fluorinated HCFCs, HFCs HFEs, HCFOs, HFOs	D-E	Medium	possible

(1) Cost ($/kg): A=~5, B=5~10, C=11~20, D=21~50, E=51~80

7 List of Acronyms and Abbreviations

ABC	Dry Chemical Powder
AFFF	Aqueous Film Forming Foam
AIHA	American Industrial Hygiene Association
ASTM	American Society for Testing and Materials
BSI	British Standards Institute
BTP	Bromotrifluoropropene
CEFIC	European Chemical Industry Council
CEN	European Committee for Standardisation
CFC	Chlorofluorocarbon
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CTOC	Chemicals Technical Options Committee
EC	European Commission
EPA	US Environmental Protection Agency
EU	European Union
FIC	Fluoroiodocarbon
FK	Fluoroketone
FTOC	Foams Technical Options Committee
GWP	Global Warming Potential
HARC	Halon Alternatives Research Corporation
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HCO	Oxygenated hydrocarbon
HFC	Hydrofluorocarbon
HFE	Hydrofluoroether
HFO	Hydrofluoroolefin
HTOC	Halons Technical Options Committee
IIR	International Institute for Refrigeration
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
ITH	Integrated Time Horizon
LCA	Life Cycle Analysis
LCCP	Life Cycle Climate Performance
VCLCG	Liquefied Compressed Gas
LOAEL	Lowest Observed Adverse Effect Level
MAP	Monoammonium Phosphate
MEC	Minimum Extinguishing Concentration
MT	Metric Tonnes
NFPA	National Fire Protection Association
NOAEL	No Observed Adverse Effect Level
n-PB	n-Propyl Bromide
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substance
OEL	Occupational Exposure Limit
PBPK	Physiologically-based Pharmacokinetic
PFC	Perfluorocarbon
PGA	Pyrotechnically Generated Aerosols
RTOC	Refrigeration AC and Heat Pumps Technical Options Committee
SNAP	Significant New Alternatives Policy
STOC	Solvents, Coatings and Adhesives Technical Options Committee

TEAP	Technology and Economic Assessment Panel
TEWI	Total Equivalent Warming Impact
TLV	Threshold Limit Value
UL	Underwriters Laboratories Inc.
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
VOC	Volatile Organic Compound

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