MONTREAL PROTOCOL
ON SUBSTANCES THAT DEPLETE
THE OZONE LAYER

UNEP

REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

MAY 2013

VOLUME 2

DECISION XXIV/7 TASK FORCE REPORT
ADDITIONAL INFORMATION TO ALTERNATIVES ON ODS
(DRAFT REPORT)

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DECISION XXIV/7 TASK FORCE DRAFT REPORT
ADDITIONAL INFORMATION ON ALTERNATIVES TO ODS

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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.

The TEAP and its XXIV/7 Task Force thank the Academy for Fire Protection in Moscow, Russian Federation, for hosting the meeting, 9-12 April 2013 where final inputs from Parties were reviewed, the outline for this report was discussed and proposals were made for a next round of drafting in April 2013, after which last reviews took place by email circulation during the first week of May 2013.

Foreword

The May 2013 TEAP Report

The May 2013 TEAP Report consists of three volumes:

Volume 1: May 2013 TEAP Progress Report

Volume 2: May 2013 TEAP XXIV/7 Task Force Draft Report

Volume 3: May 2013 TEAP XXIV/8 Task Force Report

Volume 1
Volume 1 contains the MTOC essential use report, progress reports, the MB CUN report etc.

Volume 2
Volume 2 is the Draft Report of the TEAP XXIV/7 Task Force on additional information on alternatives to ozone-depleting substances.

Volume 3
The separate Volume 3 of the TEAP Progress Report contains the report of the Task Force responding to Decision XXIV/8.

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ADDITIONAL INFORMATION ON ALTERNATIVES TO ODS

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1 Introduction

1.1 Terms of Reference

Decision XXIV/7 of the Twenty-fourth Meeting of the Parties requested the Technology and Economic Assessment Panel (TEAP) to prepare this draft report for consideration by the Open-ended Working Group at its 33rd meeting and a final report for the Twenty-fifth Meeting in 2013.

1.2 Scope and coverage

The text of Decision XXIV/7 is as follows:

1. To request the Technology and Economic Assessment Panel in consultations with experts from outside the Panel with the relevant expertise if necessary, to update information on alternatives and technologies in various sectors and prepare a draft report for consideration by the Open-ended Working Group at its thirty-third meeting and a final report to be submitted to the Twenty-Fifth Meeting of the Parties that would by end use:

(a) Describe all available alternatives to ozone-depleting substances that are commercially available, technically proven, environmentally-sound, taking into account their efficacy, health, safety and environmental characteristics, cost-effectiveness, and their use including in high ambient temperatures and high urban density cities;

(b) Update information provided by previous Panel reports on alternatives under development;

(c) Identify barriers and restrictions to the adoption and commercial use of certain environmentally-sound alternatives to ozone-depleting substances;

(d) Estimate, if possible, the approximate amount of alternatives with negative environmental impacts that could be or could have been avoided or eliminated by both non-Article 5 and Article 5 parties in the process of phasing-out ozone-depleting substances;

(e) Identify the opportunities for the selection of environmentally-sound alternatives to HCFCs in the future;

2. To invite the Panel to take into account any information relevant for the report to be prepared under paragraph 1 of the present decision provided by parties to the Secretariat;

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);
- Roberto Peixoto (Brazil, co-chair RTOC);
- Paul Ashford (UK, co-chair FTOC);
- Samir Arora (India, member FTOC)
- Dave Catchpole (UK, co-chair HTOC)
- Denis Clodic (France, member RTOC)
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- Michael Kauffeld(Germany, member RTOC)
- Tingxun Li (China, RTOC member)
- Keiichi Ohnishi (Japan, co-chair CTOC);
- Rajan Rajendran (USA, RTOC member)

- Enshan Sheng (China, member FTOC);
- Helen Walter Terrioni (USA, member FTOC)
- Samuel Yana-Motta (Peru, outside expert)
- Fred Wang (China, FTOC member)

The XXIV/7 Task Force is co-chaired by Paul Ashford, Lambert Kuijpers and Roberto Peixoto.

A preliminary outline of this draft report was discussed by the TEAP during its meeting in Moscow, Russian Federation, 9-12 April 2013 and key challenges in responding to the Decision were highlighted, especially as they related to Clause 1(d). Co-chairs were also able to review the latest submissions from Parties, including those received immediately prior to the Moscow meeting, before assembling the draft materials already received from the Task Force members and continuing with the drafting activities. Subsequent chapter drafts were then circulated to relevant sub-groups of the Task Force before the final draft was circulated by email to the XXIV/7 Task Force as a whole and the TEAP for endorsement in early May. Although the timescale for wider TEAP review was short, it was recognised that this is a working document (draft report) for the consideration of the Parties at the Open Ended Working Group in June and that further opportunity for comment by TEAP would exist once additional direction had been received from Parties and duly considered by the Task Force.

It should also be noted that the Task Force will also be reporting on a number of additional topics in its final report for the Meeting of the Parties in November 2013, including aerosols, sterilants and metered dose inhalers. The Task Force will also be interested to learn from Parties at the Open Ended Working Group meeting whether there are other sectors which should be considered (e.g. methyl bromide).

1.5 The Structure of the XXIV/7 report

The structure of the TEAP XXIV/7 Task Force Report is as follows:

There is no stand-alone Executive Summary in this draft report since the methodologies adopted within individual chapters are viewed as sufficiently different to make it difficult to consolidate the findings in a helpful way. Executive Summaries have therefore been provided at the Chapter level for each of the sectors reviewed. Once discussion has taken place with Parties at the Open Ended Working Group about the most appropriate approaches of addressing the Decision, consideration can be given to a consolidated Executive Summary.

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

Chapter 2, “Methodological Challenges” describes how the Task Force gave consideration to the request of the Parties, especially with respect to the quantification of negative environmental impact, and explains the decision to allow sectors covered within the report to address the requirements of Clause 1(d) from perspectives seen as most pertinent to their situations.

Chapter 3, “Refrigeration and air-conditioning”, describes the commercially available and technically proven environmentally sound ODS alternatives in R and AC. It also describes the barriers against uptake of alternatives. The sub-sectors considered are domestic, commercial, transport, large size refrigeration, unitary and mobile air conditioning. In response to Clause 1(d), the chapter also seeks to describe consequences of certain HCFC-22 conversions on the “amounts to be avoided”, including the lower impact from the different amounts that will be needed in servicing as a result of conversion.

Chapter 4, “Foams”, describes the technical and economic experience gained with commercially available and emerging ODS alternatives. It also updates the timelines for the commercialisation of the emerging alternatives. In response to Clause 1(d), it seeks to derive some assessment of the impact of ‘missed opportunities’ and potential incremental mitigation from future actions.

Chapter 5, “Fire protection”, describes the use of ODS alternatives in fire protection.

Chapter 6, “Solvents”, describes the ODS alternatives for solvents.

2 Methodological Challenges

2.1 Agreeing on the interpretation of definitions

Chapter 8 of this draft report provides an indication of the approach taken by the Task Force to address the language used in Decision XXIV/7. Some of that language is not new (e.g. low-GWP, cost effectiveness etc.) but some terms (e.g. environmentally sound) had not been used in recent decisions and it was important to consider their relative positioning against similar phrases (e.g. environmentally benign) which had been used in those decisions. The Task Force has sought to make an initial interpretation in these areas but would certainly welcome further input and discussion at the Open Ended Working Group meeting to ensure that the intent of the Parties is addressed fully in the final report. One particular term, *'negative environmental impacts'*, was of particular concern because it is associated with a request for quantification. The following paragraphs give some focus to the aspects considered.

Negative Environmental Impacts

Much of the discussion surrounding the environmental impact of ODS alternatives has focused understandably on climate-related factors. However, there are numerous other environmental parameters that should be legitimately considered. These would at least include ozone depletion, VOC emission and eutrophication. A further factor to be considered would be the extension of the evaluation of impacts to potential breakdown products.

The word 'negative' is inevitably subjective and needs to be measured against some benchmark, since all options will have some environmental footprint. This benchmark would typically be the environmentally sound alternative identified as that with the minimum 'negative environmental impact'. The key question is how ozone depletion, climate change, eutrophication, bio-accumulation etc. should be compared and ranked. The Task Force is not aware of a definitive ranking option at the time of writing.

The Decision asks the Task Force to estimate (quantify) the amount of alternatives with negative environmental impacts. It does not require the quantification of those impacts, although this might have been the intent. In a situation where one alternative might have a more negative impact than the benchmark in climate terms, but a less negative impact in VOC terms, the question would arise about whether the amount of the alternative should be included in the assessment or not. Taking this to its logical conclusion, the quantification of substances with negative environmental impacts would result in different derived values depending on the environmental parameter selected. This is reflected in the various chapter treatments.
For the purposes of this report, the existence of global regulatory drivers has been taken as the basis on which and ranking should be enacted. Therefore the hierarchy of negativity becomes:

- Ozone depletion (excluding those short-lived compounds with de minimis ODPs)
- Climate forcing
- VOC emissions
- Other environmental impacts

Although ozone depletion is rightly deemed as the highest priority for the Montreal Protocol, the fact that the future scenario being considered is the final phase-out of ozone depleting substances means that climate forcing becomes the predominant negative environmental parameter in most cases. Nevertheless, the impact of previous technology selection decisions on ozone layer recovery is taken into account by several of the sectors responding to the Decision.

2.2 Defining the baseline and assessing historic performance

The approach adopted by the Task Force has been to assess the 'negative environmental impacts' from 1990 onwards, since this was viewed as the first date by which the Montreal Protocol could be seen as having its own effects. The baseline in 1990 for most sectors would either be the use of CFCs or Halons. However, in the case of refrigeration and air conditioning, HCFC-22 has had a long history of use and, in many cases, was never a substitute for CFCs. HCFC-22 is therefore a legitimate part of the baseline in a large number of applications as of 1990.

One of the consequences of this reality is that delays in subsequent transition would be less impacting on ozone depletion than similar delays would have been in other sectors. Additionally, where alternatives to HCFC-22 were likely to involve similar or higher climate impact, a delay in transition might even be beneficial to the climate. However, this necessitates a value judgement between residual ozone depletion and climate mitigation, if taken together. A further diluting factor to consider in the case of those sectors involving significant consumption for maintenance purposes is that technology transition for new equipment would not impact the overall environmental footprint for the sector as abruptly as for those sectors without such a maintenance component (e.g. foams).

One approach adopted in this draft report to avoid the need for value judgements between differing environmental impacts is to look at the 'most favourable option' from an ozone perspective and to compare what was actually achieved against the 'potential' related to that 'most favourable option'. Similarly for climate, the potential of the 'most favourable option' for climate would be compared with what actually happened. This ratio can be represented formulaically for each environmental impact as follows:

(*'Baseline'* minus *'Most Favourable Option'*) compared with (*'Baseline'* minus *'Actual Impact'*)
('potential') *('actual achieved')*

If this relationship is provided as a percentage (i.e. 'actual achieved' as a percentage of 'potential') then it is a measure of how well the sector responded to the opportunity. However, it gives no indication about how significant in real terms that shortfall in achievement might have been to the ozone layer or the climate. This only emerges when the size of the sector is considered and the difference between the 'actual achieved' and the 'potential' are quantified for each environmental impact.

In addition, one of the consequences of this approach is that there is no single, <u>absolute</u> 'most favourable option', although in many cases the 'most favourable option' for ozone and climate is the same.

To determine the 'most favourable option' several factors need to be considered:

- Technical feasibility of candidate in the applications being considered
- Economic viability of the candidate in the applications being considered
- Other barriers and restrictions to the adoption of the candidate
- Environmental impact of the systems in which the candidate is being considered

As discussed in the previous section, negative environmental impact is a relative assessment and the candidate with the minimum negative environmental impact becomes the benchmark against which other technological options are compared. However, this assumes that the technical feasibility and economic viability are comparable for all options. In practice, it may be that there are performance trade-offs for the option with the lowest environmental impact or, perhaps, a cost premium. In addition, there may be health and safety or other regulatory/standard factors to be considered in making the final selection of the 'most favourable option'.

The other option would have been to identify an alternative reality of 'what could have been avoided'. However, to do that the Task Force would need to understand the complete scenarios (technical feasibility, economic viability, health & safety and regulatory/standards issues) as they pertained at the time the decision on technology selection was taken. To do this in any other way would otherwise assess previous decisions without consideration of the full facts pertaining at the time. Such an assessment would likely be perceived as inappropriate by stakeholders, since it could lead to unjustified criticism. By adopting the 'most favourable option' approach, without speculating about 'what might have been' or 'what should have been', the analysis stays within bounds that are objective and largely indisputable.

In some instances, the timing of the availability of the 'most favourable option' might not be easily identified retrospectively and almost certainly the option would not have been equally available in all regions of the world at the same time. Where this form of analysis has been undertaken (e.g. in foams), it is assumed that the 'most favourable option' has been available throughout the period from 1990 to the present day and throughout all regions of the world.

2.3 Integrating future estimates

A similar methodology is applied to estimating projected future performance against the 'potential' created by the 'most favourable option'. However, in this instance, the identity of the 'most favourable option' also has to be projected – as does the likely growth rates of markets and forecast uptake of alternative technologies in the business-as-usual scenario. There is clearly a greater level of uncertainty in this analysis - especially with respect to emerging technologies, where costs may not be fully known and market penetration may not yet be assured. The approach of evaluating the maximum contribution of the 'most favourable option' quantifies the 'potential' without making a judgement about availability and future selection. The alternative with the lowest environmental footprint becomes the benchmark against which others, including the projected business-as-usual are assessed.

Since the Task Force understands that the purpose of Clause 1(d) is to limit consideration only to options that are technically feasible and economically viable, it makes sense to eliminate from the assessment those options that, for a given application, are already known not to be technically feasible or economically viable for any significant quantities of replacement. The same might apply to other technology options where the barriers and restrictions are known to be insurmountable within the time-scale available for transition. These are therefore excluded as candidates for the 'most favourable option'.

The Task Force felt uncomfortable to project these parameters beyond 2020 at this point and elected to limit its analysis to 2020 bearing in mind that assessment at 'consumption' (potential emissions) level means that future impacts from products and equipment installed before 2020 are already factored into the analysis. These choices can be revisited during discussion at the Open Ended Working Group meeting if alternative approaches need to be considered within the final report.

As noted in Section 1.5, the Task Force anticipates further discussion at the Open Ended Working Group to define the most appropriate approach in response to Clause 1(d) of the decision. The Task Force is conscious that the lack of a homogeneous approach makes it difficult currently to make comparisons between end-use sectors. However, it is also aware that the circumstances are different for each sector and that a single approach to the objectives might also result in misleading conclusions.

3 Refrigeration and air conditioning

Executive Summary

Initially, the chapter provides generic information relating to selected alternative substances. This includes a description of five classes of alternatives:

- Ammonia (R-717)
- Carbon dioxide (R-744)
- Hydrocarbons (HC-290 and others)
- HFCs (medium and high GWP), and
- HFCs (low GWP)

For each alternative, general efficiency aspects, cost effectiveness and barriers and restrictions are given. Subsequently, additional information, including current trends, is presented in the sub-sector specific sections that follow, wherever applicable.

For this report it was considered under the current circumstances to discuss a small number of currently unassigned refrigerant blends where it is anticipated that they are close to commercialisation and receiving R-number designations.

In **domestic refrigeration**, the main refrigerants used are hydrocarbon HC-600a (isobutane) and HFC-134a. More than 50% of current new production (globally) employs HC-600a, the remainder uses HFC-134a.

HC-600a continues to be the main alternative to HFC-134a. Concerns in connection with the high flammability no longer exist for the low charges applied. No new alternative has matured to become energy-efficient and cost-competitive. Considering the product costs, HC-600a is less expensive than HFC-134a, but additional investment cost for HC-600a products are due to the larger size of compressors. Production cost for refrigerators can be higher due to the requirements for safety systems.

Initial developments to assess HFC-134a replacement with HFC-1234yf have begun, but is not being pursued as a high priority. Still HFC-1234yf has demonstrated the potential for comparable efficiency to HFC-134a. The lower flammability makes its application easier in countries with strong reservations about HC-600a. R-744 (CO2) is also being evaluated, but its application implies additional costs.

In **commercial refrigeration** stand-alone equipment HFC-134a and R-404A are still the dominant refrigerants. HC-600a and HC-290 are used for small commercial equipment with refrigerant charges varying from 15 g to 1.5 kg. R-744 is mainly used in vending machines; the technology is operating well but it is a technical challenge and only one supplier is able to provide an efficient system. The small additional cost associated with safety in HC equipment is integrated in the price, and is not much different compared with HFC equipment. Where it concerns low GWP HFCs, HFC-1234yf can replace HFC-134a in any application. Due to its comparable energy-efficiency with HFC-134a, vending machines with HFC-1234yf have been introduced in countries such as Japan (two manufacturers). One of the lead compressor manufacturers of small reciprocating compressors is already producing them. Currently a main barrier is still (the wide) availability of the chemical.

Regarding condensing units, some new R-744 based units are sold in northern Europe, but the penetration in the market is slow. Several indirect condensing units with HC-290 or HC-1270 are operating in Europe with typical refrigerant charges varying from 1 to 20 kg, with good energy efficiency. Costs for these HC based systems are typically 5 to 15% higher compared with HFC systems.

HFC-134a, R-404A, and, at a small level, R-410A are HFCs of choice for condensing units. As in all other commercial applications, high GWP HFCs are seen as short-term options.

In supermarket refrigeration, the current options for large European commercial companies area HFC-134a system at the medium-temperature level connected to an indirect system or to a R-744 direct system for the low temperature level since this is a global option for all climates. Ammonia is used in indirect centralised systems for large capacities; usually R-744 is used at the low-temperature level. Due to safety issues the number of installations so far is limited. For applying lower GWP options, HFC-134a can be replaced by HFC-1234yf or HFC-1234ze where the lower flammability of these refrigerants can be addressed during the design stage. For non-flammable options, small temperature-glide blends --such as N-13 and XP-10-- can also be used in existing facilities. Two-stage R-744 systems for the medium-temperature level and the low-temperature level have taken a certain market share in Europe and are now installed in more than 1000 stores. R-744 trans-critical cycle developments are on-going to make the technology more energy-competitive under higher ambient conditions. The additional cost is again limited to 10 to 15%. For the non-low GWP refrigerants, R-404A is currently the dominant refrigerant, even if it is now replaced in new installations by HFC-134a at the medium-temperature level. R-407F is proposed as an intermediate option. There are also non-flammable options with lower GWP such as the HFC blends N-40 and DR-33. Two-stage R-744 systems for the medium-temperature level and the low-temperature level have taken a certain market share in Europe and are now installed in more than 1000 stores. R-744 trans-critical cycle developments are on-going to make the technology more energy-competitive under higher ambient conditions. The additional cost is again limited to 10 to 15%.

The refrigerant of choice for **transport refrigeration** systems in non-Article 5 countries is HFCs. R-404A has become a preferred choice for practically all trailers and large trucks. HFC-134a is used in small trucks and vans. Testing of low-GWP HFC and non-HFC alternatives are in progress elsewhere, but not one option seems viable in the short term. The main issue is that the performance of R-404A is difficult to meet. Current and previous tests with trucks using R-744 suggest that introduction of R-744 will be possible when more efficient compressors with more than one compression stage, which are under development, will be commercially available. The use of hydrocarbons (mainly HC-290) in truck refrigeration units has been tested; they would be the preferred choice because they can provide lower energy consumption in the order of 20% or more. HFC-1234yf can be an interesting alternative to HFC-134a due to its lower discharge temperature.

On vessels, hydrocarbons are technically feasible, but the strict safety concerns currently do not favour application of flammable refrigerants aboard. Natural refrigerants have been commercialised to a small extent aboard marine vessels worldwide. For European fishing vessels highly efficient ammonia-CO2-cascade systems are the systems of choice.

Over 90% of the large **industrial refrigeration** installations use R-717 whereas the market share of R-717 is only 5% (India and China) to 25% (Europe and Russia) for smaller industrial refrigeration systems. Energy efficiency is in general 15% higher than HFCs systems. Hydrocarbons are not widely used, other than in situations where safety measures are already required, e.g. in a petrochemical plant.

In Small Self-Contained (SSC) **air conditioners** R-744 is not widely considered for use. The main barriers for SSC air conditioners are related to efficiency and cost implications. Due to efficiency implications, the use of cooling only R-744 systems is not really feasible. However, there are developments on units for specific purposes, where both cooling and heating is needed. HC-290 has been used in portable ACs for many years and several companies are producing them. Window units are also under development. HC-290 seems to be preferred over HC-1270 for smaller capacity systems.

R-410A is used in most SSC ACs, where HCFC-22 is not used. It is feasible to use HFC-32 in SSC ACs, for example, where R-410A is already used. HFC-32 energy efficiency deterioration due to high ambient is a few per cent worse than HCFC-22, but not as severe as R-410A.

HC-290 has been used in split ACs for many years on a limited scale but now some companies are developing and producing them on a larger scale. Although HC-290 seems to be the preferred HC option, HC-1270 is under evaluation by some companies. HC-290 units are available from several companies. Currently, no split air conditioners are available using R-744, although some studies have been carried out.

In hot **water heat pumps and space heating heat pumps**, R-717 is used fairly widely in capacities from 250 kW to very large/industrial-scale (>1 MW). Such systems are located outside or in special machinery rooms in order to handle the higher toxicity characteristics. As with R-717 systems in general, the main barriers are related to the minimal capacity required for cost-effectiveness and certain national regulation controlling installation. A large number of manufacturers globally are producing domestic and small commercial sized hot water heating heat pumps using R-744. Generally, the efficiency that can be achieved by R-744 in hot water heaters is much higher than that of other refrigerants. It is feasible to use HFC-32 in hot water heat pumps, for example, where R-410A is already used. HCs, particularly HC-290, had been used widely in Europe for small (domestic) heat pumps, and there are also large commercial-sized heat pumps being marketed, which use HC-290 or HC-1270. It is feasible to use HFC-32 and the L-20 blend in space heating heat pumps.

Considering the use of low-GWP refrigerants in reciprocating and screw **chillers** the following describes the current situation. R-717 is used fairly widely for process refrigeration, food storage facilities and air conditioning. The efficiency of R-717 is high for chillers in both medium and high temperature applications. The barriers for chillers are consistent with R-717 systems in general. R-744 is now used in reciprocating chillers by many manufacturers. As with other types of systems, the efficiency is compromised with increasing ambient temperatures. The main barrier for R-744 chillers is the poorer efficiency in climates with consistently higher ambient temperatures. Both HC-290 and HC-1270 are produced by a number of manufacturers in Europe and some countries in other regions. There are certain barriers in the case of HC applications, depending upon chiller configurations.

HFC-1234ze(E) is a refrigerant that can be used in existing HFC-134a technologies with minor modifications (compressor sizing), and it has been trialled in systems in Europe. When used in reciprocating, scroll or screw type of compressors, it produces efficiency levels comparable to HFC-134a. In centrifugal compressors, this refrigerant produces efficiency levels slightly better than HFC-134a. HCFC-1233zd(E) can replace HCFC-123 (a low-GWP HCFC) in low pressure centrifugal chillers with slightly better efficiency levels. In chiller applications, both HFC-1234ze(E) and HCFC-1233zd(E) should perform very well in warm climates, due to their high critical temperatures.

Both R-407C and R-410A are widely used in positive displacement chillers as is HFC-134a. HFC-134a is used widely in various capacities of centrifugal chillers..

HCs are used to a limited extent in centrifugal chillers typically within the petro-chemical industries where hazardous area protection is already in common use.

In **mobile air conditioning** systems (dependent on the country), the preferred option is to shift to HFC-1234yf, but the delayed market availability of this refrigerant seems to slow down the shift. Other future options are still being reconsidered by certain car manufacturers; in fact, this would be R-744, while staying with HFC-134a until R-744 would have been commercialised. R-744 has been demonstrated to be as efficient as the best in class HFC-134a system. However, the main barrier for

R-744 systems has been the cost, as well as issues related to safety, compressor durability and leak detection.

A current barrier for HFC-1234yf is related to patent issues between the chemical manufacturers; where mass-production of low GWP HFC systems has been delayed. Even when e.g. the German car industry favours to stay with HFC-134a until R-744 would have been commercialised, the change from HFC-134a to HFC-1234yf seems to be the likely solution because the car industry favours global options for AC systems. This has been supported by LCCP analysis, which showed superiority of HFC-1234yf for most ambient temperatures.

Reduction of negative environmental impacts due to amounts that could have been or could be avoided

In the case of domestic refrigeration, the following can be stated. For the period 2010-2015, the use of HFC-134a (compared to CFC-12) would yield a lower negative environmental impact of 230 Mt CO_2-eq. per year; the use of HC-600a (isobutane) would add another 33 Mt CO_2-eq. annually. In practice, the entire global domestic refrigeration has been converted, with about 50% to HC-600a. So the conversion of all now (2013) remaining HFC-134a to HC-600a would yield a saving of about 17 Mt CO_2-eq. annually.

Whereas relatively simple considerations give insight in the case of domestic refrigeration and similar other uses that do not have to deal with servicing etc., the question in the case of RAC sectors that needs a lot of servicing, is whether in making selections early a consideration of a pure R-410A environment or a pure hydrocarbon environment has any value for common practice. A change of 100% as of a given year to a certain refrigerant with a negligible GWP means that one would avoid 200,000 tonnes of HCFCs in a given year, and servicing amounts of HCFC-22 for the equipment that has not been manufactured in such a year during many future years, i.e., for a 15 years lifetime of the equipment it would be something like 2,400,000 tonnes over a period of 15 years, due to a conversion of 200,000 tonnes in a start-up year.

However, financial constraints will flatten the profile of the introduction of new technologies in new manufacture, and a conversion of 5-10% of the total per year would be a reasonable amount to assume as the maximum achievable.

The table below gives the approximate consumption in HCFC-22 (or HFC blends such as R-404A or R-410A) for non-Article 5 and Article 5 countries in the year 2013. It concerns commercial refrigeration and stationary air conditioning.

It assumes 40% of the consumption being used for new manufacture in developed countries, 20% of the consumption used for new manufacture in the developing countries. It assumes 10% of the new manufacture being converted to alternatives in a given year and gives the numbers for the reduction in negative environmental impact in that year, as well as the influence on the negative environmental impact (i.e., in many cases a reduction) over a period of 15 years after the conversion in manufacture, which is due to the reduction of the impact in the servicing amounts (assumed over a period of 15 years).

A change of 10% in the manufacture for commercial refrigeration in developing countries to HFC blends such as R-404A gives an increase in negative environmental impact of about 4 Mt CO_2-eq., and an increase over 15 years in servicing of 32-64 Mt CO_2-eq. (dependent on whether the servicing per year would be 50-10% of the original charge. Going from HCFC-22 to low GWP options (having an average GWP of 300) yields a decrease in negative environmental impact of 3 Mt CO_2-eq and another 23-46 Mt CO_2-eq reduction over the period of 15 years thereafter.

In particular for refrigeration and air conditioning, it will be clear that a conversion to alternatives with a low negative environmental impact is one of the first priorities. This holds in particular, because a change in manufacturing now will have consequences for many years to come, via servicing amounts. A calculation of the consequence in tonnes in the negative environmental impact should give an adequate first impression.

Countries	Approx. Cons. (t)	Assumed in manufacture	10% of manufacture	Avoidance (Mt CO_2-eq.) per year	Avoidance via servicing in 15 years (Mt CO_2-eq.)
Commercial refrigeration (2013)					
Non-Article 5 countries					
From HCFC-22 to HFCs**	40,000	16,000	1,600	-3.2	-10/ -20
From HFCs** to low GWP	40,000	16,000	1,600	5.4	16-32
Article 5					
From HCFC-22 to HFCs**	100,000	20,000	2,000	-4.2	32-64
From HCFC-22 to low GWP	100,000	20,000	2,000	3	23-46
Stationary Air Conditioning (2013)					
Non-Article 5					
From HCFC-22 to blends/410A	140,000	56,000	5,600	-2.2	17-34
From HFCs to low GWP	140,000	56,000	5,600	10.5	32-64
Article 5					
From HCFC-22 to blends/410A	400,000	80,000	8,000	-3.2	24-48
From HCFC-22 to low GWP	400,000	80,000	8,000	11.8	88-176

** HFCs in commercial refrigeration are given a GWP of 3800 (which would be the GWP of R-404A)
***Low GWP chemicals, which could be different types of blends etc., natural refrigerants, have been given an average GWP of 300

3.1 ODS alternatives

Initially, generic information relating to selected alternatives substances is provided in the first section. This includes a description of each alternative, general efficiency aspects, cost effectiveness and barriers. Subsequently, additional information, including trends is included in the sub-sector specific section, where applicable. Whilst the convention within TEAP reports has been to only discuss refrigerants with ISO/ASHRAE R-number designation only, it was considered under the current circumstances to also discuss a small number of currently unassigned blends where it is anticipated that they are close to commercialisation and receiving R-number designations. This is against a background of an excess of 50 different unassigned blends currently being cited by different refrigerant produces and elsewhere in the literature.

R-717	
Description and discussion of each technology/chemical (including health and safety etc.)	R-717 (ammonia, NH_3) is a single component substance. It has a safety classification of B2 (higher toxicity, lower flammability). It has a zero ODP and zero GWP.
Extent of commercialisation	R-717 has been used for more than 100 years in a variety of different types of refrigerating machines and is widely used today.
Energy efficiency, efficacy (taking into account ambient conditions)	In principle, R-717 has thermo-physical properties which lead to excellent efficiency. The vapour pressure and refrigerating capacity is similar to HCFC-22. However, it has a very high discharge temperature so for lower temperature applications two stage compression is normally needed.
Costs, cost effectiveness (compared to a standard)	The cost of the substance is very low, typically less that $1/kg. Generally systems require the use of steel piping and components and as a result smaller capacity systems can cost much more than HCFC-22 or HFC systems, although as the capacity approaches and exceeds around 400-600 kW, they can become cost-competitive (UNEP 2011, UNEP 2012).
Barriers and restrictions (safety, energy efficiency etc.)	There are several general barriers. From a practical level these include the lack of suitable components for small capacity systems (although some companies are working on these aspects). In addition, the use of R-717 required well-trained and competent technicians (in handling R-717), which can sometimes be difficult. Another is the restriction of use (in direct systems) in occupied spaces due to its higher toxicity. Similarly, certain countries have specific national regulations controlling its use. A comprehensive assessment of the barriers to the use of R-717 and other low-GWP refrigerants is provided in a study for UNEP (Colbourne, 2010).
Hydrocarbons (HCs)	
Description and discussion of each technology/chemical (including health and safety etc.)	Hydrocarbons (HCs) include three main pure refrigerants, HC-290 (propane), HC-1270 (propene) and HC-600a (iso-butane) and a number of mixtures; R-433A, R-433B, R-433C, R-441A and R-443A, some of which also comprise HC-170 (ethane). All pure substances and the mixtures have safety classification A3 (lower toxicity, higher flammability). They have zero ODP and GWP (direct GWP plus indirect GWP) ranges from 1.8 to 5.5 (WMO, 2010).
Extent of commercialisation	The pure substances have been used commercially for decades, whilst mixtures such as R-436A and R-436B have been used since the phase-out of CFC-12. Most of the other mixtures are not known to be used commercially.
Energy efficiency, efficacy (taking into account ambient conditions)	Generally, the efficiency is shown to be good under most conditions. In principle, they have thermo-physical properties which lead to very good efficiency and low discharge temperatures. Performance comparisons for high ambient conditions are sparse, although one study showed performance to be comparable to HCFC-22 (Chen, 2012).
Costs, cost effectiveness (compared to a standard)	The cost of the substances is low, typically less that $1 - $10/kg. Due to the safety classification, there are often additional costs necessary for handling flammability characteristics in the design of the equipment, although thermo-physical properties mean that other costs associated with system construction can be reduced. However, the overall cost implication can vary widely depending upon the type of equipment. Values for cost-effectiveness are included in previous TEAP reports (UNEP, 2011; UNEP, 2012).

Barriers and restrictions (safety, energy efficiency etc.)	The main barriers associated with the use of HCs arise from its flammability. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, concerns by component manufactures means that there are gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling HCs if the flammability is to be dealt with safely. Some building safety codes may ban use flammable refrigerants in certain types of buildings. A comprehensive assessment of the barriers to the use of HCs and other low-GWP refrigerants is provided in a report for UNEP (Colbourne et al, 2010).
R-744	
Description and discussion of each technology/chemical (including health and safety etc.)	R-744 (carbon dioxide, CO2) is a single component substance. It has a safety classification of A1 (lower toxicity, non-flammable). It has a zero ODP and a GWP of 1.
Extent of commercialisation	R-744 has been used from 1900 to 1930 in refrigerating machines and then supplanted by CFCs. Since 1990 CO2 its use was revisited and is used in a variety of different types of systems.
Energy efficiency, efficacy (taking into account ambient conditions)	R-744 has thermo-physical properties which lead to good efficiency for proper levels of temperatures. The vapour pressure is several times greater than usual refrigerants and the volumetric refrigerating capacity is correspondingly higher. However, with a low critical temperature, the cycle efficiency declines as the temperature before the expansion device increases and other features are needed to achieve similar (to R22) efficiency values at high ambient conditions. Compared to the baseline, 10 – 20% energy efficiency improvement can be achieved by applying an ejector instead of an ordinary expansion device (Hafner, 2012). Other features to help improve efficiency in high ambients include economiser (parallel compression), expander, liquid-suction heat exchange and mechanical subcooling.
Costs, cost effectiveness (compared to a standard)	The cost of the working fluid is very low, typically around €1/kg. However, because of the high pressure, certain types of systems require more robust designs for pressure safety which adds cost, while specific tube dimensions are much smaller compared to current technology which gives the advantage of compact tubing and insulation material. However, as the capacity approaches a certain value (depending upon the type of application, between 50 – 500 kW), they can become cost-competitive. Similarly the features that are needed to improve efficiency under higher ambient temperature also result in increased cost. Values for cost-effectiveness are included in previous TEAP reports (UNEP, 2011; UNEP, 2012).
Barriers and restrictions (safety, energy efficiency etc.)	There are two main technical barriers, being components and system design for high operating pressure and performance degradation at high ambient temperatures, leading to a resultant incremental cost increase. (Although such additional costs at the present time are largely influenced by economies of scale.) Also, due to its relatively unusual characteristics, technicians require dedicated training and tooling. A comprehensive assessment of the barriers to the use of R-744 and other low-GWP refrigerants is provided in a study for UNEP (Colbourne, 2010).

HFCs (GWP ≤ 300)	
HFC-1234yf	
Description and discussion of each technology/chemical (including health and safety etc.)	HFC-1234yf is a single component refrigerant with a GWP of about 4. It can replace HFC-134a in same systems since the pressure-temperature characteristics are almost identical. It is classed is under FDIS ISO 817 as an A2L refrigerant (low toxicity, lower flammability).
Extent of commercialisation	This chemical is currently produced at a fairly small scale but commercial scale production is anticipated when there is a sufficient market demand.
Energy efficiency, efficacy (taking into account ambient conditions)	In general this refrigerant produces efficiency levels comparable to HFC-134a although the theoretical COP is several percent below that of HFC-134a.
Costs, cost effectiveness (compared to a standard)	As a new molecule that requires a complex production process, this refrigerant has significantly higher cost than HFC-134a.
Barriers and restrictions (safety, energy efficiency etc.)	The main barriers are related to the safe use lower flammability refrigerants (A2L under FDIS ISO 817). Standards such as ISO-5149 and IEC-60335-2-40 are being updated to accommodate this new class. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, due to uncertainties over future adoption component manufactures means that there are gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling flammable refrigerants if the flammability is to be dealt with safely. Some building safety codes may ban use flammable refrigerants in certain types of buildings.
HFC-1234ze(E)	
Description and discussion of each technology/chemical (including health and safety etc.)	HFC-1234ze(E) is a single component refrigerant with a GWP of 6. It can replace HFC-134a in new equipment where its lower volumetric capacity can be addressed in the design of the equipment. This refrigerant is under FDIS ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	This chemical is already produced at a commercial scale. It is anticipated that this refrigerant will be available as and when there is a market demand.
Energy efficiency, efficacy (taking into account ambient conditions)	When used in with reciprocating or scroll type of compressors, this refrigerant produces efficiency levels comparable to HFC-134a. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used.
Costs, cost effectiveness (compared to a standard)	As a new molecule, this refrigerant has higher cost than HFC-134a. This is mainly due to its different manufacturing process.
Barriers and restrictions (safety, energy efficiency etc.)	The main barriers are related to the safe use lower flammability refrigerants (A2L under FDIS ISO 817). Standards such as ISO-5149 and IEC-60335-2-40 are being updated to accommodate this new class. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, due to uncertainties over future adoption component manufactures means that there are gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling flammable refrigerants if the flammability is to be dealt with safely. Some building safety codes may ban use flammable refrigerants in certain types of buildings.

HCFC-1233zd(E)	
Description and discussion of each technology/chemical (including health and safety etc.)	HCFC-1233zd(E) is a single component refrigerant with a GWP of 6, which reduces substantially the direct environmental impact. This refrigerant is likely to be A1 (low toxicity, non-flammable) under ISO 817.
Extent of commercialisation	This chemical is already produced at a commercial scale for solvents and blowing agent applications. It is anticipated that this refrigerant will be available as and when there is a market demand.
Energy efficiency, efficacy (taking into account ambient conditions)	When used with centrifugal compressors, this refrigerant produces efficiency levels slightly better than HCFC-123, allowing the design of systems with very high energy efficiency.
Costs, cost effectiveness (compared to a standard)	As a new molecule, this refrigerant has higher cost that HCFC-123. Still this cost would be moderate and will have a reasonable payback period due to its high energy efficiency which lowers the expenses for end users.
Barriers and restrictions (safety, energy efficiency etc.)	Being non-flammable and having a moderate cost, this refrigerant is on a fast track for adoption. R-number designation application is expected for 2013.
"L-40" [HFC-32/HFC-152a/HFC-1234yf/HFC-1234ze(E); 40/10/20/30%]	
Description and discussion of each technology/chemical (including health and safety etc.)	L-40 is a mixture of HFCs (HFC-32 and HFC-152a) with the new unsaturated HFCs (HFC-1234yf and HFC-1234ze(E)). With a GWP of 290 it reduces substantially the direct environmental impact. It is intended to replace R-404A in medium and low temperature refrigeration equipment without any major modifications as its pressures are similar. All components of the mixture are under FDIS ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	All components are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years.
Energy efficiency, efficacy (taking into account ambient conditions)	When used in the current R-404A system, L-40 is apparently exceeds the capacity of R-404A with an efficiency improvement of around 10%.
Costs, cost effectiveness (compared to a standard)	The direct cost of this refrigerant is likely to be higher than R-404A. It probably works with existing POE lubricants.
Barriers and restrictions (safety, energy efficiency etc.)	The main barriers are related to the safe use of the mildly flammable refrigerants (class 2L under FDIS ISO 817). Current standards such as ISO-5149 are being updated to accommodate this new class. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, due to uncertainties over future adoption component manufactures means that there are gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling flammable refrigerants if the flammability is to be dealt with safely. Some building safety codes may ban use flammable refrigerants in certain types of buildings.
HFCs (GWP > 300)	
R-407C	
Description and discussion of each technology/chemical (including health and safety etc.)	R-407C is a mixture refrigerant comprising HFC-134a, HFC-125 and HFC-32 with a GWP of 1700. It has been used widely in air conditioning, chiller and heat pump systems, especially to help the transition from HCFC-22. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.

Energy efficiency, efficacy (taking into account ambient conditions)	The efficiency is acceptable, although heat exchangers need to be designed suitably to take account of the temperature glide.
Costs, cost effectiveness (compared to a standard)	The cost of the refrigerant is approximately two to three times greater than HCFC-22. Values for cost-effectiveness are included in previous TEAP reports (UNEP, 2011; UNEP, 2012).
Barriers and restrictions (safety, energy efficiency etc.)	There are no significant barriers to its use.
R-407A	
Description and discussion of each technology/chemical (including health and safety etc.)	R-407A is a mixture of the same components of R-407C but in slightly different proportions. Its GWP is 2100. It is typically used recently for centralised commercial refrigeration systems. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy (taking into account ambient conditions)	The efficiency is acceptable and better than of the R-404A it is normally used to replace. However, heat exchangers need to be designed suitably to take account of the temperature glide.
Costs, cost effectiveness (compared to a standard)	The cost of the refrigerant is approximately two to three times greater than HCFC-22. Values for cost-effectiveness are expected to be similar to those of R-407C and R-404A as detailed in the TEAP reports (UNEP, 2011; UNEP, 2012).
Barriers and restrictions (safety, energy efficiency etc.)	There are no significant barriers to its use.
R-407F	
Description and discussion of each technology/chemical (including health and safety etc.)	R-407F is a mixture of the same components of R-407C but in slightly different proportions. Its GWP is 1820. It is typically used recently for centralised commercial refrigeration systems. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy (taking into account ambient conditions)	The efficiency is acceptable and better than of the R-404A it is normally used to replace. However, heat exchangers need to be designed suitably to take account of the temperature glide.
Costs, cost effectiveness (compared to a standard)	The cost of the refrigerant is approximately two to three times greater than HCFC-22. Values for cost-effectiveness are expected to be similar to those of R-407C and R-404A as detailed in the TEAP reports (UNEP, 2011; UNEP, 2012).
Barriers and restrictions (safety, energy efficiency etc.)	There are no significant barriers to its use.
R-404A	
Description and discussion of each technology/chemical (including health and safety etc.)	R-404A is a mixture refrigerant comprising HFC-134a, HFC-125 and HFC-143a with a GWP of 3700. It has been used widely in commercial refrigeration systems. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy (taking into account ambient conditions)	The efficiency is acceptable.
Costs, cost effectiveness (compared to a standard)	The cost of the refrigerant is approximately two to four times greater than HCFC-22. Values for cost-effectiveness are included in previous TEAP reports (UNEP, 2011; UNEP, 2012).
Barriers and restrictions (safety, energy efficiency etc.)	There are no significant barriers to its use, although it is now becoming considered less desirable within several regions due to its comparatively high GWP.

R-410A	
Description and discussion of each technology/chemical (including health and safety etc.)	R-410A is a mixture refrigerant comprising HFC-HFC-125 and HFC-32 with a GWP of 2100. It is used widely in air conditioning, chiller and heat pump systems. The safety is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy (taking into account ambient conditions)	Generally the efficiency is good, although it deteriorates at higher ambient temperatures.
Costs, cost effectiveness (compared to a standard)	The cost of the refrigerant is approximately two to three times greater than HCFC-22. Values for cost-effectiveness are included in previous TEAP reports (UNEP, 2011; UNEP, 2012).
Barriers and restrictions (safety, energy efficiency etc.)	A slight barrier to its use it the operating pressures being higher than that of HCFC-22, although this is more perceived than practical. For countries which experience high ambient temperatures capacity and efficiency can degrade more rapidly than with HCFC-22.
HFC-134a	
Description and discussion of each technology/chemical (including health and safety etc.)	HFC-134a is a pure substance with a GWP of 1370. It is used in a variety of equipment including heat pumps and chillers. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy (taking into account ambient conditions)	Energy efficiency is good, provided that pipes and heat exchangers are suitably sized.
Costs, cost effectiveness (compared to a standard)	The cost of the substance is greater than HCFC-22 but less than HFC blends. Values for cost-effectiveness are included in previous TEAP reports (UNEP, 2011; UNEP, 2012).
Barriers and restrictions (safety, energy efficiency etc.)	There are no significant barriers to its use.
HFC-32	
Description and discussion of each technology/chemical (including health and safety etc.)	HFC-32 is a single component refrigerant that was originally used as a component of R-410A which is 50% HFC-32 and 50% HFC-125. HFC-125 was used to reduce the flammability of HFC-32 and high discharge temperature. With a GWP of 716, it produces a moderate reduction compared to R-410A or HCFC-22. Pressure and capacity are around 1.5 times higher than HCFC-22 and equivalent to R-410A. It is classed as A2L (low toxicity, lower flammability) under FDIS ISO 817.
Extent of commercialisation	HFC-32 is one of components of R-410A and R-407C, so fairly large production capacity is already available, though commercial availability of cylinders is not yet common.
Energy efficiency, efficacy (taking into account ambient conditions)	The efficiency of HFC-32 systems is similar to R-410A and the theoretical COP is a few per cent better than R-410A at typical air conditioning conditions. The capacity is approximately slightly higher (~ 5%) but it can be easily accommodated with slight adjustment of the compressor displacement in new systems. Its system charge is somewhat lower than for R-410A. It has better heat transfer properties and transport properties than R-410A due to lower molar mass. Discharge temperatures are significantly higher than R-410A, making necessary the use of new lubricant oils (PVE, POE) and some mitigation devices. This is especially required at high ambient temperatures.

Costs, cost effectiveness (compared to a standard)	The direct cost of this refrigerant is similar to R-410A. The new lubricant oils and mitigation devices for high discharge temperature may add some cost. Values for cost-effectiveness are included in previous TEAP reports (UNEP, 2011; UNEP, 2012).
Barriers and restrictions (safety, energy efficiency etc.)	The main barriers are related to the safe use of the lower flammable refrigerants. Current standards such as ISO-5149 and IEC-60335-2-40 are being updated to accommodate this new class. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, due to uncertainties over future adoption component manufactures means that there are gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling flammable refrigerants if the flammability is to be dealt with safely. Some building safety codes may ban use flammable refrigerants in certain types of buildings.
"L-41" [HFC-32/HFC-1234ze(E); 73/27%]	
Description and discussion of each technology/chemical (including health and safety etc.)	L-41 is a mixture of HFCs; HFC-32 and new unsaturated HFC-1234ze. It replaces R-410A in AC equipment. All components of the mixture are classified in FDIS ISO 817 as A2L (lower toxicity, lower flammability). It has a GWP of around 490.
Extent of commercialisation	All components are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe). North America may take longer due to building codes restrictions and lack of regulatory drivers.
Energy efficiency, efficacy (taking into account ambient conditions)	The efficiency of L-41 systems is at the same level of R-410A. The capacity is approximately 6% to 10% lower than R-410A still this capacity is easily recovered in new systems. Discharge temperatures are slightly higher than R-410A, still below the limit of existing compressors technologies. Due to its relative higher critical point compared to other refrigerants, L-41 performs well at high ambient temperatures (warm climates).
Costs, cost effectiveness (compared to a standard)	The direct cost of this refrigerant is similar to R-410A. It works well with existing POE lubricants. Power consumption increases its effectiveness at high ambient temperatures relative to R-410A.
Barriers and restrictions (safety, energy efficiency etc.)	The main barriers are related to the safe use of the class 2L flammable refrigerants . Current standards such as ISO-5149 and IEC-60335-2-40 are being updated to accommodate this new class. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, due to uncertainties over future adoption component manufactures means that there are gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling flammable refrigerants if the flammability is to be dealt with safely. Some building safety codes may ban use flammable refrigerants in certain types of buildings.

"L-20" [HFC-32/HFC-152a/HFC-1234ze(E); 45/20/35%]	
Description and discussion of each technology/chemical (including health and safety etc.)	L-20 is a mixture of HFCs (HFC-32 and HFC-152a) with the new unsaturated HFC-1234ze. With a GWP of 330 it reduces substantially the direct environmental impact. It replaces HCFC-22 in AC equipment without any major modifications as its pressures are similar. All components of the mixture are under FDIS ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	All components are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe).
Energy efficiency, efficacy (taking into account ambient conditions)	When use in the current HCFC-22 technologies, L-20 matches the capacity of HCFC-22 with an efficiency ranging from 95% to 97%. Further improvements can produce better efficiencies, especially for cooling only operation in warm climates. The above mentioned good performance in warm climates is mainly due to its relative high critical point (~93°C) compared with other options such as R410A and HFC-32.
Costs, cost effectiveness (compared to a standard)	The direct cost of this refrigerant is similar to current HFCs such as R-407C. It works well with existing POE lubricants. Due to its good efficiency at high ambient temperatures, power consumption would be lower relative to other options.
Barriers and restrictions (safety, energy efficiency etc.)	The main barriers are related to the safe use of the mildly flammable refrigerants (class 2L under FDIS ISO 817). Current standards such as ISO-5149 and IEC-60335-2-40 are being updated to accommodate this new class. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, due to uncertainties over future adoption component manufactures means that there are gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling flammable refrigerants if the flammability is to be dealt with safely. Some building safety codes may ban use flammable refrigerants in certain types of buildings.
"DR-5" [HFC-32/HFC-1234yf; 72.5/27.5%]	
Description and discussion of each technology/chemical (including health and safety etc.)	DR-5 is a mixture of HFCs (HFC-32) with the new unsaturated HFC-1234yf and has a GWP of 490. It replaces R-410A in AC equipment. All components of the mixture are classified by FDIS ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	All components are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe).
Energy efficiency, efficacy (taking into account ambient conditions)	The efficiency of L-41 systems is at the same level of R-410A. The capacity is approximately 6% to 10% lower than R-410A still this capacity is easily recovered in new systems. Discharge temperatures are slightly higher than R-410A, still below the limit of existing compressors technologies. Due to its relative higher critical point compared to other refrigerants, DR-5 performs well at high ambient temperatures (warm climates).

Costs, cost effectiveness (compared to a standard)	The direct cost of this refrigerant would be slightly high as it contains HFC-1234yf which has an expensive manufacturing cost. It works well with existing POE lubricants. Due to its good efficiency at high ambient temperatures, power consumption would be lower relative to R410A.
Barriers and restrictions (safety, energy efficiency etc.)	The main barriers are related to the safe use of the lower flammable refrigerants. Current standards such as ISO-5149 and IEC-60335-2-40 are being updated to accommodate this new class. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, due to uncertainties over future adoption component manufactures means that there are gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling flammable refrigerants if the flammability is to be dealt with safely. Some building safety codes may ban use flammable refrigerants in certain types of buildings.
"N-13" [HFC-134a/HFC-1234ze(E); 42/58%]	
Description and discussion of each technology/chemical (including health and safety etc.)	N-13 is a binary mixture of HFC-134a and HFC-1234ze(E) which as formulated is non-flammable. It has a GWP of 600 therefore reduces substantially the direct environmental impact. It replaces HFC-134a in new equipment where its lower volumetric capacity can be addressed in the design of the equipment. This refrigerant would be classified by FDIS ISO 817 A1 (low toxicity, non-flammability).
Extent of commercialisation	These chemicals are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe).
Energy efficiency, efficacy (taking into account ambient conditions)	When used in with reciprocating or scroll compressors, this refrigerant produces efficiency levels comparable to HFC-134a. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used.
Costs, cost effectiveness (compared to a standard)	Being a blend of new molecules HFC-1234ze(E) and existing ones (HFC-134a), its cost is moderate and not significant different from existing bends available in the market.
Barriers and restrictions (safety, energy efficiency etc.)	Being non-flammable and having a moderate cost, this refrigerant is on a fast track for adoption. R-number designation is expected for 2013.
"XP-10" [HFC-134a/HFC-1234yf; 44/56%]	
Description and discussion of each technology/chemical (including health and safety etc.)	XP-10 is a binary mixture of HFC-134a and HFC-1234yf which as formulated is non-flammable. It has a GWP of 630 therefore reduces substantially the direct environmental impact. It replaces HFC-134a in new equipment, producing similar capacity end efficiency. As formulated, this refrigerant would be classified by ISO FDIS 817 A1 (low toxicity, non-flammable).
Extent of commercialisation	These chemicals are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe).
Energy efficiency, efficacy (taking into account ambient conditions)	When used in with reciprocating or scroll compressors, this refrigerant produces efficiency levels comparable to HFC-134a. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used. Due to its high critical temperature, it will perform very well in warm climates.

Costs, cost effectiveness (compared to a standard)	Being a blend of a high manufacturing cost molecule (HFC-1234yf) and HFC-134a, its cost is expected to be high.
Barriers and restrictions (safety, energy efficiency etc.)	Its high cost would be the main barrier for widespread adoption by the market.
"N-40" [HFC-32/HFC-125/HFC-134a/HFC-1234yf; 25/25/20/30%]	
Description and discussion of each technology/chemical (including health and safety etc.)	"N-40" is a mixture of saturated HFCs (HFC-32, HFC-125 and HFC-134a) and unsaturated HFC-1234yf which as formulated is non-flammable. It has a GWP of 1330 and is therefore similar to pure HFC-134a. It replaces R-404A in new refrigeration equipment. This refrigerant would be classified by FDIS ISO 817 A1 (low toxicity, non-flammable).
Extent of commercialisation	The component chemicals are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years.
Energy efficiency, efficacy (taking into account ambient conditions)	This refrigerant has a capacity marginally higher than R-404A and a slightly greater efficiency. The same POE lubricant oil can be used as with R-404A.
Costs, cost effectiveness (compared to a standard)	Being a blend which includes HFC-1234yf, its cost is likely to be higher than conventional HFC mixtures.
Barriers and restrictions (safety, energy efficiency etc.)	No significant barriers are anticipated with this refrigerant.
"DR-33" [HFC-32/HFC-125/HFC-134a/HFC-1234yf; 24/25/26/25%]	
Description and discussion of each technology/chemical (including health and safety etc.)	"DR-33" is a mixture of saturated HFCs (HFC-32, HFC-125 and HFC-134a) and unsaturated HFC-1234yf which as formulated is non-flammable. It has a GWP of 1410 and is therefore similar to pure HFC-134a. It replaces R-404A in new refrigeration equipment. This refrigerant would be classified by FDIS ISO 817 A1 (low toxicity, non-flammable).
Extent of commercialisation	The component chemicals are already produced at a commercial scale.
Energy efficiency, efficacy (taking into account ambient conditions)	This refrigerant has a capacity marginally higher than R-404A and a slightly greater efficiency. The same POE lubricant oil can be used as with R-404A.
Costs, cost effectiveness (compared to a standard)	Being a blend which includes HFC-1234yf, its cost is likely to be higher than conventional HFC mixtures.
Barriers and restrictions (safety, energy efficiency etc.)	No significant barriers are anticipated with this refrigerant.

Note: Most of the various HFC mixtures without an assigned R-number have a composition that is not yet finalised. Extensive testing by manufacturers is ongoing so minor changes to the composition are still possible. Final compositions for most of the mixtures are expected to be submitted within 2013.

3.2 Domestic refrigeration

3.2.1 Introduction

Domestic refrigeration sub-sector comprises appliances that are broadly used domestically, such as refrigerators, freezers and combined refrigerator/freezer products. Beverage dispensing machines, commonly included in domestic refrigeration, represent a small fraction of total units.

Approximately 100 million domestic refrigerators and freezers are produced annually, and it is estimated that this quantity is equally divided between non-Article 5 and Article 5 countries. A typical product contains a factory-assembled, hermetically sealed, vapour-compression refrigeration system employing a 50 to 250 watt induction motor, and now also linear motors, containing 50 to 250 grams of refrigerant. Alternative technology to vapour-compression refrigeration is employed in specific products, such as absorption cycles for small fridges in hotels and so. The age distribution of the global installed products is extremely broad with median age estimates ranging from 9 to 19 years at retirement. Long product life and high volume annual production combine for an estimated 1500 to 1800 million unit global installed inventory.

Old refrigerant CFC-12 was replaced by non-ODS refrigerants in almost all new products. Presently, the main refrigerants used are HC-600a and HFC-134a. More than 50% of current new production (globally) employs HC-600a, whilst the remainder uses HFC-134a (approximately 1% employs either HFC-152a or HCFC-22 or blends comprising these). This equates to about 3.8 ktonnes consumption of HFC-134a in non-Article 5 countries and 7.7 ktonnes in Article 5 countries. The reason for such dissimilarity in HFC-134a consumption is related to substantial regional differences; the vast majority of European refrigerators and freezers are produced with HC-600a whereas some other regions use HC-600a to lesser extent. There is fairly widespread production of HC-600a appliances in Asia and to some extent in South and Central America and Southern Africa; it is virtually non-existent in North America although production in Australasia is now increasing.

Improvement in energy efficiency is the main effort in new product development, through the use of advanced components such as variable speed compressors (virtually all new high level products in Europe have frequency variation device) and vacuum insulation panel insulation. Energy benefits are also obtained with the use of electronic controls.

Progress slowly continues on product redesign to facilitate transition from HFC-134a to HC-600a in certain countries.

3.2.2 HFC-134a

HFC-134a has been the predominant refrigerant for domestic refrigeration since the phase-out of CFC-12. It is a class A1 refrigerant (lower toxicity, non-flammable) and as such there are no significant safety implications concerning its use.

Energy efficiency is similar to that of CFC-12, although with continual optimisation the current HFC-134a refrigeration units are considerably more efficient that those that used CFC-12. Generally systems are marginally more costly than HCFC-22 because they are less compact.

Since HFC-134a is well established, it is evident that there are no significant barriers to its use. It is likely that HFC-134a will continue to be a dominant option on domestic refrigeration appliances for a number of years.

3.2.3 HC-600a

HC-600a is the main alternative to HFC-134a. Concerns in connection with the high flammability at the introduction of the refrigerant in 1994 in Europe no longer exist, particularly as the charges required for domestic refrigeration are below 150 g. No new alternative has matured to become energy-efficient and cost-competitive.

When the statutory requirements for safety are met (e.g. IEC 60335-2-89), HC-600a is the ideal refrigerant for such units, giving about higher efficiency than HFC-134a while at the same time reducing noise level of the unit. Considering the product costs, HC-600a is less expensive than HFC-134a, but additional investment cost for HC-600a products are due to larger size of compressors, and also production cost for refrigerators can be higher due to the requirements for safety systems.

In general there are no significant barriers to the use of HC-600a, exemplified by the existence of over 500 m domestic fridges in the market to date. However, in some regions the use of HC-600a is almost non-existent (e.g. USA) and this can be considered to be due to a number of factors. These include general concerns regarding public safety (or the perception of), misconceptions about flammability safety and accidents and are similarly reflected in the restrictive national standards and the reluctance to be one of the early movers in the region. Whilst legal concerns have so far limited the use of HC-600a in USA, in 2011 their Environmental Protection Agency (EPA) approved HC-600a and an HC blend (R-441A) under their Significant New Alternatives Policy Program (SNAP) for household and small commercial refrigerators and freezers. As such some North American manufacturers have started production of high-end products with HC-refrigerants.

HC-600a is the standard refrigerant for European domestic refrigerators and freezers. Worldwide over 50 million appliances each year are produced with HC-600a. Increased energy efficiency and HC-600a refrigerant have drastically reduced the climate impact of household refrigerators, due to mitigation of direct (refrigerant) and indirect (CO2 associated with electricity consumption) GHG emissions.

3.2.4 HFC-1234yf

It is feasible to use HFC-1234yf in domestic refrigerators and freezers and its application can be considered as some way between the use of HFC-134a and HC-600a, since the pressure and capacity are slightly lower than HFC-134a and it has lower flammability characteristics than HC-600a. The lower flammability makes application easier in countries that have still strong reservations related to the application of HC-600a.

Initial developments to assess the HFC-134a replacement by HFC-1234yf have begun. Its use in domestic refrigeration has begun but is not being pursued with high priority, which is more demanding than automotive applications. A preliminary assessment is that HFC-1234yf has the potential for comparable efficiency to HFC-134a, although often slightly worse in practice. As such, investment costs for equipment are estimated to be 1% higher than for HFC-134a technology due to the larger surfaces of heat exchangers applied (to account for poorer energy performance) and given the price, an additional 1% higher investment cost results from the cost of the refrigerant for the first charge. As implied above, two main barriers are the cost implications and the flammability, although in most cases the latter is not of major concern given the acceptability of HC-600a.

3.2.5 R-744

Currently R-744 (considering the transcritical use of R-744, CO2) seems to be the only alternative option with good prospects, in addition to conventional vapour-compression technology for mass produced domestic refrigeration equipment. Experience is available from a large number of vending machines which have been in use since many years, and are similar, low-charged applications.

R-744 application will imply in additional cost, which can be attributed to the greater mass of materials necessary to achieve the minimum level of efficiency, particularly for freezers in all climates and for both refrigerators and freezers in warmer climates. However, since the majority of these appliances are used indoors, the impact of outside temperature will have a lesser impact on the ambient temperature and thus the efficiency degradation. Higher cost is also predicted in the evaporator construction when applying high pressure R-744.

The main barrier associated with the use of R-744 in these systems is that a higher cost requirement associated with the system materials, thus making commodity products uncompetitive. In addition there are some more peripheral hurdles such as a general perceived fear of high pressures, effects of national and international standards which requirements result in greater cost, lack of training materials and higher costs for servicing equipment.

No major domestic refrigerator manufacturers are actively developing R-744 systems for commercialisation, so it is unlikely that its use will become widespread in this sector.
Due to the cost-efficiency implications and the fact that other low-GWP alternatives (such as HC-600a) are widely accepted, it is unlikely that R-744 will become commercialised to any major extent.

3.3 Commercial refrigeration

Commercial refrigeration is characterised by storing and displaying food and beverages at different levels of temperature for chilled and frozen food. The refrigerating capacities of equipment vary from some hundreds of Watts to 1.5 MW. Commercial refrigeration is composed of three main categories of equipment: stand-alone equipment, condensing units, and supermarket systems. Refrigerant choices depend on the refrigerant charge, the level of temperature, energy efficiency, and regulations.

3.3.1 Stand-alone equipment

Stand-alone equipment consists of systems where all refrigeration components are integrated and, for the smallest types, the refrigeration circuit is entirely brazed or welded.

R-717 has not so far been used in these systems due to limitations on its use in occupied spaces related to safety and toxicity concerns.

Carbon dioxide is mainly used in vending machines and bottle coolers; the technology is operating well, but it is a technical challenge. The energy efficiency of the vending machine and bottle cooler cassettes is similar to HFC-134a machines with an energy penalty at high ambient conditions. The cost is slightly higher, but the global company ordering that equipment has made a political and environmental choice. The high technological level of expertise required forms a barrier for the application. R-744 has been chosen instead of hydrocarbons since the safety risk in public areas is lower.

Where it concerns low GWP HFCs, HFC-1234yf can replace HFC-134a in any application but availability of HFC-1234yf is limited and so there is no large amount of available equipment. The energy efficiency of HFC-1234yf will be in the same range, based on published tests. There are reciprocating compressors already approved for use with HFC-1234yf. Vending machines that use this refrigerant have been already introduced in Japan. As mentioned, a barrier for current application is the refrigerant availability question, but also the cost of the substance, to some extent.

HC-600a and HC-290 are the two hydrocarbons used for small commercial equipment. R-600a is chosen for smaller refrigeration capacity. For bottle coolers both refrigerants will be used. Ice machines, small display cases use HC-290. The energy efficiency of a hydrocarbon based system is always as good or even slightly better compared to HCFCs or HFCs commonly used in those applications. The small additional cost associated to safety is integrated in the price, not much different compared to HFC equipment.

The EN 378 standard in Europe allows the use of HCs up to 1.5 kg in public areas if the volume of the room is sufficiently large. Large global companies have committed to not use HFCs in their new systems. The uptake of HCs is significant for small commercial equipment with refrigerant charges varying from 15 g to 1.5 kg.

HFC-134a and R-404A are still the dominant refrigerants for stand-alone equipment; in Europe R-404A is seen as a short-term option. Where it concerns barriers and restrictions, the GWP is the issue for both refrigerants and (future) regulations will require the phase-down of HFC-134a and the phase-out of R-404A at least in Europe. At this stage, there are two possible replacements for R-404A:

1) Non-flammable options such as N-40 and DR-33
2) 2L flammable refrigerants such as L-40, which provides further reduction of the GWP

As for HFC-134a, there are also two types of replacements:

1) Non-flammable options such as N-13 and XP-10
2) 2L flammable refrigerants such as HFC-1234yf and HFC-1234ze(E)

The pure HFCs are still the current standard options but are not seen as viable longer than 10 years.

3.3.2 Condensing units

Condensing units exhibit refrigerating capacities ranging typically from 1 kW to 20 kW. They are composed of one (or two) compressor(s), one condenser, and one receiver assembled into a so-called "condensing unit", which is normally located external to the sales area. Condensing units are typically installed in specialty shops such as bakeries, butcher shops, and convenience stores. In most Article 5 countries there is extensive use of condensing units.

R-717 is never used in these systems for cost and safety issues. Some new carbon dioxide based condensing units are sold in Northern Europe, but the penetration on the market is slow. R-744 systems require double-stage design if high outdoor temperatures occur frequently. Single-stage systems are designed for cold climates. The additional cost for a double-stage system is significant; cost is the main barrier for these R-744 systems. Further development is possible when there are general decisions to not choose HCs; the future market share will be limited.
Several indirect condensing units with HC-290 or HC-1270 are operating in Europe with typical refrigerant charges varying from 1 to 20 kg. The energy efficiency is good. The indirect system energy penalty is limited if the secondary loop is well designed, with larger heat-exchanger areas. Costs for these HC based systems are typically 5 to 15% higher compared to HFC systems.

Choosing hydrocarbons usually requires a "policy" decision of the commercial chain management. The development of hydrocarbons for condensing units depends on the outcome of the competition with future low GWP HFCs. Hydrocarbons are seen as a long-term solution and require a better refrigerant management due to safety precautions for the maintenance.

A number of possible low GWP blends are proposed in presentations at technical conferences but so far there are no viable options in the field.

HFC-134a, R-404A, and, at a small level, R-410A are HFCs of choice for condensing units. HFC-134a is chosen for small capacities and evaporation temperatures > -15°C. R-404A or R-410A are chosen for larger capacities for all temperature levels. HFCs form the energy efficiency references for benchmarking other refrigerants.

As in all other commercial applications, high GWP HFCs are seen as short-term options, even if they are still dominating the market.

3.3.3 Centralised systems

Centralised systems are the preferred option in supermarkets. They operate with racks of compressors installed in a machinery room. Two main design options are used: direct and indirect systems.

Direct systems are the most widespread. The refrigerant circulates from the machinery room to the sales area, where it evaporates in display-case heat exchangers, and then returns in vapour phase to the suction headers of the compressor racks. The supermarket cold rooms are cooled similarly.

Ammonia is used in indirect systems for large capacities; usually carbon dioxide is used at low-temperature level. Due to safety issues the number of installations so far is limited. Ammonia is an efficient refrigerant for refrigeration applications.

The additional cost is in the range of 10 to 15% compared to indirect systems using HFCs and R-744, because of the use of steel instead of copper, although at capacities over several hundred kW the economics become more competitive. Ammonia competes with HFCs, hydrocarbons and even with carbon dioxide in cold climates, however, ammonia will remain dependent to user preferences. Even though being an efficient solution, it is unclear what its future market potential in this sub-sector will be.

Two-stage R-744 systems for the medium-temperature level (-10 to -15°C) and the low-temperature level (-35 to -38°C) have taken a certain market share in Europe and are now installed in more than 1000 stores.

The preferred option for large European commercial companies is HFC-134a at the medium-temperature level connected to an indirect system and a R-744 direct system for the low temperature since it is a global option for all climates. R-744 is efficient when the condensing temperature is below 25°C. For higher outdoor temperatures, the trans-critical cycle implies a significant energy penalty, although developments are on-going to make the technology more energy-competitive under higher ambient temperature conditions. The additional cost is again limited to 10 to 15%.

The lower energy efficiency for hot climates forms one barrier. The high pressure under which R-744 is operated requires higher brazing quality than the usual HFC design. R-744 is seen as a long-term solution for low temperatures in cascade with a medium-temperature refrigerant. Taking into account the ambient climate conditions, R-744 is seen as the main option for northern and central Europe. In summary, R-744 is clearly a significant option for future centralised systems in commercial refrigeration.

Hydrocarbons are used in less than 100 centralised systems in Europe either with HC-290 or HC-1270. HC-290 or HC-1270 is efficient in both medium and low temperatures of commercial refrigeration. The additional costs are related to containment and safety. The refrigerant charge limits associated to regulations and standards form a barrier. The competition with R-744 as a low GWP option has limited the expansion of HCs in centralised systems. In summary, HCs in large centralised systems will have a limited market share due to safety standards.

For low GWP HFCs, the situation is identical as previously mentioned; there is no available single low GWP HFC currently proposed for centralised systems. Non-flammable options such as N-40 and DR-33, which can be used for retrofit of existing systems, may improve energy-efficiency (~7%). Lower flammability refrigerants such as L-40 can be used in indirect systems such as with brine or pumped CO2 where flammability can be addressed. For HFC-134a, there are additional replacements: non-flammable options such as N-13 and XP-10 which can be used for retrofit of existing systems and lower flammability refrigerants such as HFC-1234yf and HFC-1234ze(E), which could be applied in cascade systems
For the non-low GWP refrigerants, R-404A is currently the dominant refrigerant, even if it is now replaced in new installations by HFC-134a at the medium-temperature level. Some trials have been done using R-410A in new installations without a significant success. R-407A and R-407F are proposed as intermediate options. The price levels of R-404A are currently decreasing. The GWP of R-404A will limit its use in Europe in the next few years in particular due to the updated F-Gas regulation that will enter into force. As a conclusion, high GWP HFCs have a limited future in all developed countries, dependent on when regulations enter into force.

3.4 Transport refrigeration

Technical requirements for transport refrigeration systems are extremely complex. The equipment has to operate over a wide range of ambient temperatures and weather conditions (wind, solar radiation, rain, sea water spray, etc.). The equipment has to be able to carry any one of a wide range of cargos with different temperature needs and even different temperatures simultaneously in different compartments.

The refrigerant of choice for transport refrigeration systems within non-Article 5 countries is HFCs, with refrigerant charges from less than 1 kg (refrigerated vans) to more than several kg (trucks, trailers and reefer containers) to 3,000 kg on board large fishing vessels (Schwarz, 2011). Leakage rates are estimated at 20% for trucks/trailers, 30% for vans and up to 40% for fishing vessels (Schwarz 2011). All intermodal containers use hermetic
or semi-hermetic systems, which have an estimated leakage rate below 5%.

Trucks, trailers and intermodal containers.

R-404A has become a preferred choice for practically all trailers and large trucks. One German manufacturer uses R-410A. HFC-134a is used in small trucks and vans, because they can utilise automotive components. Not that HFC-134a is excellent – it is convenient. Some small trucks and vans use R-404A when a higher capacity is needed. ODS have not been used in new equipment for many years.

A phase-out of refrigerants with a non-low-GWP solution would put all road transport equipment on the spot. Testing of low-GWP alternatives is in progress elsewhere, but no option seems viable in the short term. The main issue is that the performance of R-404A is difficult to meet. Although R-410A outperforms R-404A, it has higher pressures (requires technology change for most manufacturers) and it still has a relatively high GWP.

HFC-134a and its low-GWP alternatives may look attractive, but validations for frozen cargo (in addition to chilled cargo where it could be acceptable) have to be done.

Current and previous tests with trucks using R-744 suggest that introduction of R-744 will be possible when more efficient compressors with more than one compression stage, which are under development, will be commercially available. In 2012, two large global manufacturers of transport refrigeration equipment exhibited concepts of trailer refrigeration units with R-744 at a trade show (ThermoKing, 2012, Carrier, 2011), although at least one other manufacturer has developed such products. Among other features reducing the carbon footprint, the units utilise multi-stage compressors.

The use of hydrocarbons (mainly HC-290) in truck refrigeration units has been tested with a small number of vehicles in the UK, Australia and Germany. They would be the preferred choice because they can provide lower energy consumption in the order of 20% or more. Recently, a refrigerated truck with propene (HC-1270) was developed by a German company and is now in field tests for a supermarket chain in Germany. The system was reported to be superior to R-404A and comparable to R-410A (Burke, 2011). For a broader market introduction, manufacturers and customers require specific legal rules and standards for hydrocarbons to ensure safety in mobile applications.

In contrast to trailers, intermodal containers use HFC-134a in most cases and R-404A in some. The reasons for choosing HFC-134a could have been the global availability of HFC-134a, and lower cost per kg, otherwise R-404A (or today R-410A) would be more suitable. Because HFC-134a systems operate at lower pressures, they can have lower leak rates than R-404A but also a higher risk of air intake to circuits with frozen cargo.

Initial field tests with small fleets of containers using R-744 have started. In 2011, a large global manufacturer of transport refrigeration equipment exhibited a container refrigeration system with R-744 at a trade show. By using two-stage compression, cylinder unloading and variable speed drive, the R-744 design was reported to deliver efficiencies equal to their best-in-class HFC container unit (Carrier, 2011).

Hydrocarbons are technically feasible, but the strict safety concerns currently do not favour application of flammable refrigerants aboard vessels (with exceptions, discussed below). Ammonia is deemed unacceptable in all truck, trailer and intermodal container applications because of toxicity and material compatibility.

Cryogenic or open loop systems, which evaporate the liquid CO2 or N2 charged to an insulated container aboard the truck, are alternatives to the vapour compression cycle for recurring distribution routes. The systems have advantages of being quiet and reliable. They offer a constant capacity that is independent of the engine (vehicle) speed. On the other hand, systems that discharge CO2 or N2 to the cargo box (not all do) bear a risk of asphyxiation if not equipped by gas sensors. They require energy for the liquefaction of the cryogenic liquid, which can make the systems more or less expensive to operate, depending on the energy source. The systems need periodic refilling; consequently, the user needs to provide storage and refilling infrastructure for the liquefied gases. Nevertheless, they are fundamentally the most inefficient and least environmentally friendly of all options. This is because their liquid working fluid must be drawn from the environment or recovered from certain processes which invariably demand compression from almost atmospheric pressure thus using many times the energy needed for a closed compression circuit. Consequently when considering lifetime energy use they are unfavourable.

Vessels

The variety of types is great. The majority of them uses HCFC-22, which can be replaced by R-417A or R-422D. Other HFC alternatives, namely R-410A, R-407C and R-427A, require modifications. The GWP of these fluids ranges between 1700 and 2700. Modern cruise ships use R-410A and HFC-134a for air conditioning. Where refrigeration is needed for provision rooms or process cooling, R-404A is used. Low-GWP alternatives are considered, but except R-717 and R-744 in limited numbers, these options have not been commercialised.

An important issue aboard ships is safety – ships are difficult to evacuate. Specific requirements inherent to vessels mean that not all stationary systems can be applied at sea, and if so, they require modifications.

Natural refrigerants have been commercialised to a small extent aboard marine vessels worldwide (ammonia, CO2) (RTOC, 2010). For European fishing vessels highly efficient ammonia-CO2-cascade systems are the systems of choice, using approximately 6% less energy (Schwarz, 2011).

3.5 Large size (industrial refrigeration)

Industrial refrigeration systems are characterized by heat extraction rates in the range 10 kW to 10 MW, typically at evaporating temperatures from –50 °C to +20 °C. About 75% of all industrial refrigeration capacity is installed in the food industry, the rest in industrial processes and leisure applications (Schwarz, 2011). Over 90% of the large industrial refrigeration installations use R-717 whereas the market share of R-717 is only 5% (India and China) to 25% (Europe and Russia) for smaller industrial refrigeration systems (RTOC, 2010). Industrial ammonia systems are in general 15% more energy efficient than their HFC-counterparts and 40% of the European industrial refrigeration systems use R-717 (Schwarz 2011). While industrial refrigeration systems using R717 are very tight due to the pungent smell of R717, HFC systems in the EU show leakage rates of 8-10% at present (Schwarz, 2011).

Alternatives to HCFCs include R-717, which is already widely used, hydrocarbons, R-744 for low temperature (freezing), HFCs and air for very low temperatures.

A replacement of a 3.2 MW HCFC-22 refrigeration system by one using R-717 resulted in 40% reduction of energy consumption (McNeill, 2011). As the new plant utilises heat recovery and water heating by means of an additional heat pump, the total annual cost savings are more than £1.4 million, resulting in a payback time of 2.7 years (McNeill, 2011). Applying improvement levers such as reduced condensing temperature, increased evaporation temperature, variable speed compressors and multistage systems, the energy consumption of the ammonia plants can be drastically reduced (Gerwen, 2011).

Hydrocarbons are not widely used, other than in situations where safety measures are already required, e.g. in a petrochemical plant. They offer excellent efficiency, and compatibility with most materials and lubricants. However the precautions required to prevent ignition are significantly more expensive than those required for ammonia systems (RTOC, 2010).

R-744 is used with excellent efficiency in systems as the low temperature stage to a cascaded upper ammonia system especially in the food industry where the refrigerant has to evaporate in freezing equipment in the factory. According to Van Gerwen (2011) "the use of R-744 as a refrigerant in the low pressure stage of a cascade refrigeration system, with ammonia in the high stage, could be an opportunity for further improvement". In colder climates R-744 is energy efficient as the sole refrigerant.

Air can be used with good energy efficiency in low temperature applications, namely below -60 °C. At least one manufacturer is offering such systems (Machida,2011). According to Unilever: "The refrigerant choice for industrial refrigeration is ammonia, using an optimised standard core design concept and an appropriate safety management system" (Gerwen, 2011).

Nestlé committed to the use of natural refrigerants in 2001, and has since also supported the use of R-717/R-744 systems: "As already publicly stated in 2001, Nestle reiterates its commitment to the use of natural refrigerants that are environmentally friendly. Especially and whenever feasible, carbon dioxide (CO2) in combination with ammonia (NH3) must be used for all low temperature applications. Beyond many technical and economic advantages, carbon dioxide is safer for the environment, people and goods" (Nestle, 2008).

Industrial refrigeration sometimes uses compression chillers; these are discussed in more detail in section 3.7.

3.6 Air conditioning and heat pumps

3.6.1 Small self-contained (window, portable, through-the-wall, packaged terminal)

Small Self-Contained (SSC) air conditioners are small capacity air conditioners in which all of the refrigeration system components are contained within a single package. These products have cooling capacities typically ranging from 1.0 kW to 10 kW. This category of products includes window mounted, through-the wall, portable and packaged terminal air conditioners. Small self-contained air conditioners are designed to heat or cool single spaces, such as bedrooms, small shops, restaurants and offices.

R-717 has so far not been used in these systems due to limitations on its use in occupied spaces related to safety and toxicity concerns. In addition, the construction requirements for smaller capacities would take up too much space as well.

R-744 is not widely considered for use in SSC air conditioners. However, there are developments on units for specific purposes, where both cooling and heating is needed, such as so-called environmental control units (ECUs). Whilst the performance at lower ambient temperatures may be favourable, as the temperature exceeds the critical temperature of R-744 (31°C), efficiency can degrade at a greater rate than refrigerants with much higher critical temperatures. Thus, at standard rating conditions, which typically require a 35°C outside air temperature (e.g., EN 14511) the efficiency of non-enhanced R-744 systems is lower than for other refrigerants. Nevertheless, recent work on this type of system using advances features such as variable speed compressors and ejectors have shown to improve efficiency considerably even at high ambient temperatures (e.g., Liu et al, 2012; Lee et al, 2011). However, when systems are designed also to provide heating, the overall efficiency can even for countries which experience hot climates be favourable (e.g., Hafner et al, 2007). Literature relating to the costs associated with the use of R-744 in SSC air conditioners is sparse, but depending on component selection and material requirements, R-744 units may have greater or lower theoretical cost than those for HCFC-22.

In conclusion it can be said that there are fairly widespread developments ongoing globally for R-744 systems, but no production of systems except for niche applications. The main barriers for SSC air conditioners are those described previously in regards to efficiency and cost implications. In addition, there may also be poor availability of components in certain regions. Due to efficiency implications, the use of cooling only R-744 systems is not really feasible. Where models are developed to also provide heating, this technology is considered to be more interesting. It is possible that some commercially available products will become available in the future but only for regions where both cooling and heating is required.

HC-290 has been used is portable ACs for many years and several companies are producing them. Window units are also under development. HC-290 seems to be preferred over HC-1270 for smaller capacity systems, whilst he other HC blends are not known to be in use.

HC-290 has the same or higher COP than HCFC-22. For example, Teng et al (2012) reports HC-290 has the same or greater cooling capacity and a higher COP than HCFC-22, provided the charge is properly optimised and Devotta et al (2005) found a 2-8% drop in capacity and 8-14% increase in COP for HC-290. At higher ambient temperatures the differences between HCFC-22 and HC-290 show little difference from normal ambient conditions. For SSC systems, there is negligible additional cost, if at all, considering the additional cost for safe electrics and negative costs for heat exchangers. Zheng (2012) reports that the overall cost for HC-290 is less than an R-410A model, whilst gaining 10% reduction in efficiency.

For SSC ACs the safety issues pose less safety-related hurdles than for systems that have to be site-installed because refrigerant handling is not necessary. However, certain safety standards impose obstructive limits on refrigerant charge sizes for certain categories of equipment. Nevertheless, several manufacturers are now newly developing HC-290 SSC ACs.

In conclusion, HC-290 is an attractive refrigerant for SSC ACs, offering good efficiency and cost implications.

R-407C has been used in a large proportion of SSC ACs, more so earlier on in the transition from HCFC-22 in non-Article 5 countries since the vapour pressure is a close match for HCFC-22. Because it is a class A1 refrigerant (lower toxicity, non-flammable) there are no significant safety implications concerning its use. Energy efficiency is typically poorer than HCFC-22, although similar COPs can be achieved if the system is carefully designed. Generally systems are marginally more costly than HCFC-22. Since R-407C is well established, it is evident that there are no significant barriers to its use. Where R-407C has been used widely, it use is declining in favour of R-410A whilst in other countries who transitioned from HCFC-22 later, it is unlikely that it will be used to any significant extent.

R-410A is used in most SSC ACs, where HCFC-22 is not used. The design of the system components is different because of the higher operating pressure. Because it is a class A1 refrigerant (lower toxicity, non-flammable) there are no significant safety implications concerning its use. Energy efficiency is about the same as HCFC-22, although higher COPs can be achieved if the system is carefully designed. As ambient temperatures increase the efficiency (and cooling capacity) degrades at a greater rate than HCFC-22 does. Generally systems are marginally more costly than HCFC-22. Since R-410A is well established, it is evident that there are no significant barriers to its use, except for the issues relating to high ambient temperatures and concerns within the service sector over the higher operating pressures. Currently, R-410A is developing as the standard refrigerant for air conditioning systems.

It is feasible to use HFC-32 in SSC ACs, for example, where R-410A is already used. Although HFC-32 is flammable, the required charge of such units is unlikely to reach concentration that can be ignited (LFL). HFC-32 has the optimum heat transfer at higher flow rate in heat exchanger compared to HCFC-22 and R-410A, so a relatively better COP can be achieved in compact products. Energy efficiency deterioration due to high ambient is a few per cent worse than HCFC-22, but not as severe as R-410A. Under high ambient temperatures the compressor discharge temperature can be very high, compromising reliability of systems or demanding most costly injection technology. The costs of units are equivalent to R-410A and HCFC-22 in small units. Electric components of these units are unlikely to ignite HFC-32, but initial confirmation of it requires certain cost. One major Chinese manufacturer has made an application to commercialise compact SSC units with HFC-32 in Australia.

It is also proposed to use the L-41 blend in SSC ACs, for example, where R-410A is already used. Since L-41 has low flammability, the required charge of such units is unlikely to reach concentration that can be ignited (LFL). In principle the main barrier is the flammability; however, guidelines in the form of international standards do not restrict their use in this type of equipment under most situations. Currently there are no reported developments of L-41 SSC underway.

3.6.2 Mini-split (non-ducted)

Residential and light commercial air-conditioning is often done with non-ducted split air conditioners. Non-ducted split air conditioners are widely applied in commercial buildings, schools, apartments and free-standing residences. They comprise a compressor/heat exchanger unit (condensing unit) installed outside the space to be cooled or heated. The outdoor unit is connected via refrigerant piping to a fan-coil unit located inside the conditioned space, generally on the wall but also can be ceiling or floor mounted designs. Reversible air conditioners (heat pumps) are gaining market acceptance in cool and cold climates where they are used primarily for heating but also provide cooling during summer operation.

R-717 is never used in these systems due to limitations on its use in occupied spaces and the small capacity and installation requirements would also mean that they are not competitive.

Currently no split air conditioners are available using R-744, although some studies have been carried out to investigate the performance and viability of R-744 in these systems. As detailed for SSC air conditioners, the cooling COP at rated conditions makes R-744 seem uncompetitive. However, when considering seasonal efficiency and when including for heating mode, a reversible R-744 air conditioner can achieve the same seasonal efficiency as a state-of-the-art R-410A unit (Hafner, 2009). The cost implications for split air conditioners are the same as with SSC air conditioners using R-744, although a greater cost increment is likely due to site-installed pipework. The barriers for split AC are the same as with SSC air conditioners, although there are additional hindrances associated with installation of the piping and the necessity for technicians to be competent in handling R-744. As with SSC ACs, there are ongoing research and development activities. Due to efficiency implications, the use of cooling only R-744 systems is not really feasible but where models are developed to also provide heating, this technology is considered to be more interesting. It is possible that some commercially available products will become available in the future but only for regions where both cooling and heating is required.

HC-290 has been used is split ACs for many years on a limited scale but now with some companies developing and producing them on a larger scale. Although HC-290 seems to be the preferred HC option, HC-1270 is under evaluation by some companies. The other HC blends are not known to be in use in new systems. In most cases, HC-290 has the same or higher COP than HCFC-22, with numerous studies reporting improvements in COP of up to 15% (without capacity reduction) (Colbourne and van Gerwen, 2012). At higher ambient temperatures even up to 52°C, there is virtually no difference between both capacity and COP of HCFC-22 and HC-290 than from normal ambient conditions (Chen, 2012). There is negligible additional cost; considering the additional cost for safe electrics and negative costs for heat exchangers there can be improvements in cost effectiveness. Additional expenditure is necessary for more in-depth technician training and certain tooling. Two main barriers exist; one is that technicians require additional training in order to handle flammability issues and another is that certain safety standards impose obstructive limits on refrigerant charge sizes for certain categories and characteristics of equipment.

HC-290 units are available from several companies and other manufacturers report that models will become available one production lines are completed. In particular, China has committed to converting some 18 production lines from HCFC-22 to HC-290 by 2015. Commensurate to this, extensive research and development are continuing on safety matters and on charge size reduction. HC-290 is an attractive refrigerant for split air conditions within the smaller capacity range, offering good efficiency and cost implications.

R-407C is used in a proportion of split ACs, more so earlier on in the transition from HCFC-22 in non-Article 5 countries since the vapour pressure is a close match for HCFC-22. Because it is a class A1 refrigerant (lower toxicity, non-flammable) there are no significant safety implications concerning its use. All other aspects are as for SSC ACs.

R-410A is used in most split air conditioners, where HCFC-22 is not used. The design of the system components is slightly different because of the higher operating pressure. Because it is a class A1 refrigerant (lower toxicity, non-flammable) there are no significant safety implications concerning its use. All other aspects are as for SSC ACs.

Again, the L-41 blend is feasible for use in split ACs, for example, where R-410A is already used. Since L-41 has low flammability, the required charge of such units is unlikely to reach concentration that can be ignited (LFL). The efficiency is comparable to that of R-410A, although data has not found for high ambient conditions. The cost implications should be comparable to that of R-410A although marginally greater due to the refrigerant cost. In principle the main barrier is the flammability, however, guidelines in the form of international standards do not restrict their use in this type of equipment under most situations. Currently there is extensive testing and trialling ongoing and manufacturers in Japan, Korea, China and New Zealand are developing prototypes and at least one company has recently showed prototypes in exhibitions.

It is feasible to use HFC-32 in split ACs, for example, where R-410A is already used. Since HFC-32 has low flammability, the required charge of such units is unlikely to reach concentration that can be ignited (LFL) in the event of a leak. HFC-32 has comparable efficiency to that of R-410A and HCFC-22 in many mini-split air conditioners. Drop in tests in high efficiency R-410A units have equivalent performance sometimes, because the flow rate in heat exchanger is optimised for R-410A and is too low for HFC-32. As theoretical COP, heat transfer properties and transport properties are better than R-410A, optimisation to HFC-32 is likely to result in better COP than R-410A and HCFC-22. Under high ambient temperatures the compressor discharge temperature can be very high, compromising reliability of systems or demanding most costly injection technology. Costs of units are equivalent to R-410A and HCFC-22 in small units whilst costs of larger units are equivalent to ones with R-410A, but slightly higher than HCFC-22 due to higher operating pressure. Electric components of these units are unlikely to ignite HFC-32, but initial confirmation of it is required.

One Japanese company commercialised mini-split products with HFC-32 in 2012 in Japan and in 2013 in India. A few companies have recently showed prototypes in exhibitions. In conclusion HFC-32 has a high potential to penetrate this market due to its balanced property in cost, energy efficiency, and safety.

Use of the L-20 blend is feasible in split ACs, for example, where HCFC-22 or R-407C are already used. Since L-20 has low flammability, the required charge of such units is unlikely to reach concentration that can be ignited (LFL) in the event of a leak. The efficiency is comparable to that of HCFC-22, although data has not been found for high ambient conditions. The cost implications should be comparable to that of HCFC-22 and R-407C although probably greater due to the refrigerant cost. In principle the main barrier is the flammability; however, guidelines in the form of international standards do not restrict their use in this type of equipment under most situations. Currently there is extensive testing and trialling ongoing and manufacturers in Japan, Korea and China are developing prototypes.

It is also feasible to use the DR-5 blend in split ACs, for example, where R-410A is already used. Although DR-5 has low flammability, the required charge of such units is unlikely to reach concentration that can be ignited (LFL) in the event of a leak. The efficiency is comparable to that of R-410A, although data has not been found for high ambient conditions. The cost implications should be comparable to that of R-410A although somewhat greater due to the refrigerant cost. Again, the principle barrier is the flammability, however, guidelines in the form of international standards do not restrict their use in this type of equipment under most situations. Currently there is extensive testing and trialling ongoing and manufacturers in Japan and USA are developing prototypes.

3.6.3 Multi-split

A second type of non-ducted products are multi-split; essentially the same as a single split (as described in 3.6.2) but a single condensing unit may feed two or more indoor units (sometimes, up to 50). Whilst dual indoor unit models may be used for residential applications, this category of split systems is more often used in commercial buildings. As with single splits, multi-splits also offer reversible (heating) options. Variable Refrigerant Flow (VRF) systems are a sub-category of the multi-split non-ducted air conditioning systems and are distinguished from regular multi-split systems by their ability to modulate the refrigerant flow in response to the system demand. VRF systems have capacities ranging from 10 kW to over 130 kW.

R-717 is never used in these systems due to limitations on its use in occupied spaces.

There are at least two manufacturers producing multi-split air conditioners using R-744. However, as with other system types described before, it is preferable where at least half of the demand is for heating. The same energy efficiency considerations as for other types of air conditioners also apply for multi-splits. As with single splits, the cost implication for multi-splits is greater than for self-contained systems since site-installed pipework is required, more so than for single splits. The same barriers exist for R-744 multi-splits as with the other types of air conditioners above, however, for larger systems, an additional barrier can be that the use can be restricted due to the possibility of relatively large quantities of refrigerant being leaked into small occupied spaces resulting in acute toxicity effects to occupants. Introducing advanced safety features could help overcome this. It is expected that if not already, other manufacturers will be issuing R-744 multi-split systems for heating and cooling, although these will be aimed at temperature climates and will not be in wide scale use.

At least one manufacturer has developed a dual cooling/heating multi-split system but such systems are unsuitable for situations where the primary demand is for cooling.

Although feasible in a minute proportion of situations, HCs are not used in these systems due to charge size limitations in occupied spaces.

For R-407C and R-410A, all aspects are as with single split ACs.

In principle, it is feasible to use L-41 in multi-split systems, for example, where R-410A is already used. It is likely that the efficiency is comparable to that of R-410A, although again there is no data found for high ambient conditions. The cost implications should be comparable to that of R-410A although slightly greater due to the refrigerant cost and additional features for handling flammability. In principle the main barrier is the flammability where guidelines in the form of international standards can currently introduce some restrictions to their use in this type of equipment. However, work is underway to enable the use more accessible. Currently there are no developments of L-41 multi-splits reported.

It is feasible to use HFC-32 in most types of multi-split ACs. The pressure loss of HFC-32 is lower than HCFC-22 and R-410A due to its smaller molar mass, higher pressure, and lower required circulating mass of refrigerant so it has a greater potential to be used in such systems from an energy efficiency viewpoint. The cost should be equivalent to R-410A and slightly higher than HCFC-22 due to high operating pressure. The concerns over implications over high discharge temperatures in high ambient temperatures are of a lesser concern in multi-split systems and compressor injection technology is less likely to have an observable cost impact. Especially components for large multi-splits are close to the boundary to ignite, detailed tests are necessary. Since multi-split systems has the potential to release the entire charge to one of the many occupied spaces that the system serves it may generate a significant flammable cloud. However, it is proposed that the probability of rapid refrigerant release indoors is not so high so safety measures have to be established to minimise such concentrations. A risk assessment study for multi-split with A2L refrigerants is on-going in Japan. In conclusion the commercialisation of HFC-32 in this category seems to take a few years.

In principle, it is feasible to use L-20 in multi-split systems, for example, where HCFC-22 or R-407C is already used. The efficiency is comparable to that of HCFC-22 and R-407C, although data is not found for high ambient conditions. The cost implications should be comparable to that of R-407C systems although slightly greater due to the refrigerant cost and additional features for handling flammability. In principle the main barrier is the flammability where guidelines in the form of international standards can currently introduce some restrictions to their use in this type of equipment. However, work is underway to enable the use more accessible. Currently there is no development work reported for multi-splits.

In principle, it is feasible to use DR-5 in multi-split systems. Due to the characteristics being very close to those of HFC-32, the same observations can be made. Currently there is no development work reported for this type f equipment.

3.6.4 Split (ducted)

Ducted, split residential air conditioners are typically used where central forced-air heating systems necessitate the installation of a duct system that supplies air to each room of a residence or small zones within commercial or institutional buildings. A condensing unit (compressor/heat exchanger), placed outside the conditioned space, supplies refrigerant to one or more indoor coils (heat exchangers) installed within the duct system or air handler. Air in the conditioned space is cooled or heated by passing over the coil and is distributed to the conditioned spaces by the duct system. Systems can in principle be designed as reversible types, although for this category of ducted air conditioners it is done less frequently. Capacities range from 5 kW to 17.5 kW.

R-717 is never used in these systems due to limitations on its use in occupied spaces and the small capacity and installation requirements would also mean that they are not competitive.

With R-744 the issues in ducted split systems are similar to those of single and multi-split systems.

Although feasible in a small proportion of situations, HCs are not currently used in these systems due to charge size limitations in occupied spaces.

For R-407C and R-410A, all aspects are as with split ACs.

As regards HFC-32, the L-20, the L-41 and the DR-5 blend , their application in ducted splits is feasible and comparable to that of multi-splits.

In particular typical installation of ducted split includes small closet, attic, and such, so the rapid release can generate flammable concentration in a small space. Therefore special design features must be considered and are currently under development. Risk assessment studies have been carried out in the USA. The commercialisation of HFC-32 and the L-41 blend in this category is likely to take a few years.

Currently there is testing and trialling ongoing and manufacturers in Japan, Korea and China are developing prototypes for all of these substances.

3.6.5 Ducted split commercial and non-split air conditioners

Ducted commercial air conditioners and heat pumps are manufactured in two forms: split system units which are matched with an indoor air handler/heat exchanger assembly and single packaged units which contain an integral fan and heat exchanger assembly which is connected by means of ducting to the air distribution system of the commercial structure. The majority of ducted commercial packaged air conditioners and heat pumps are mounted on the roof or outside on the ground of offices, shops, restaurants or institutional facilities. Multiple units containing one or more compressors are often used to condition the enclosed space of low-rise shopping centres, shops, schools or other moderate size commercial structures. Commercial ducted systems are offered in a wide range of capacities from around 10 kW to over 100 kW.

R-717 is never used in these systems due to limitations on its use in occupied spaces and the small capacity and installation requirements would also mean that they are not competitive

There are several companies within Europe that produce R-744 split ducted and rooftop systems, with a wide capacity range. As with other R-744 air conditioners, the efficiency at higher ambient temperatures of non-enhanced R-744 systems tends to be slightly reduced, although when systems are operated at lower ambient temperatures the efficiency is competitive with HCFC-22 and similar refrigerants. The cost effectiveness is similar for other types of R-744 air conditioners.

Although feasible in a small proportion of situations, HCs are not widely used in direct systems due to charge size limitations in occupied spaces, although at least two companies are trialling systems.

For R-407C and R-410A, all aspects are as with split ACs. The application of HFC-32, the L-20, L-41 or DR-5 blend in commercial ducted and rooftop systems is feasible and the issues are essentially the same as for ducted splits.

3.6.6 Hot water heating heat pumps

These are a category of heat pumps designed to heat domestic and other service hot water to temperatures between 55 and 90 °C. These operating temperatures must be considered when selecting the refrigerant. A HPWH consists of a water storage tank and a heat pump water heating unit and in some designs an additional heat exchanger. In the heat pump unit, water supplied from the storage tank or directly from the mains water supply is heated by the condenser (or, for transcritical cycles the gas cooler) and then returned to the storage tank. Stored hot water is supplied to each tapping point, in response to the demand. In order to obtain high water temperatures at low outdoor ambient temperatures, air to water heat pump systems can utilise a cascade refrigerating system with two different refrigerants.

R-717 is used fairly widely in capacities from 250 kW to very large/industrial-scale (>1 MW) heat pumps. Such systems are located outside or in special machinery rooms in order to handle the higher toxicity characteristics but also due to sound reduction. Yearly service and maintenance requirement demands the room to be accessible for qualified technicians and engineers. Systems are often used for district heating and cooling systems but also for process heating and cooling. The efficiency of R-717 heat pumps is known to be very good (Stene, 2008), particularly since the critical point is very high compared to most other refrigerants. The cost effectiveness becomes favourable as the heating capacity approaches 250 kW, relative to HCFC-22.

As with R-717 systems in general, the main barriers are related to the minimal capacity required for cost-effectiveness and certain national regulation controlling installation. Also the perceived danger, true or not, is a barrier. Within Europe and North America, there is an increasing tendency to use R-717 heat pumps, especially in industrial plants that are already familiar with R-717, although this is also commensurate with the increase in the use of heat pump technology anyway. For large commercial and industrial applications, R-717 is generally an attractive option and (neglecting national regulations) can normally be applied in most situations. The use of heat pumps is more restricted by subsidies to the energy sector than by the technology. In many countries the electricity is too expensive compared to cheap subsidised fossil fuels.

Due to the high discharge superheat of R-744 and heat rejection at gliding temperatures, it provides a particular advantage when being used for hot water heating. As such a large number of manufacturers globally are producing domestic and small commercial sized hot water heating heat pumps using R-744. Annual production of domestic sized systems is in the order of several million. The energy efficiency is high. It is also noted that higher ambient temperatures only provide energy advantages in such systems, enhancement technologies like ejectors are commonly used to further improve energy efficiency of these heat pump systems. If the cold side is applied for AC during hot water production a very high total COP’s are achieved. Generally, the efficiency that can be achieved by R-744 in hot water heaters is much higher than that of other refrigerants and therefore it is difficult to make a cost-effectiveness comparison. The main barrier is the cost relative to that of conventional fossil fuel boilers. Hourly electricity rate supports R-744 heat pumps implemented in Smart–grids, so that heat is produced when electricity is cheap. Continued growth for R-744 hot water heaters, particularly in Asia is expected and to some extent in Europe. It is evident that R-744 is one of the most suitable alternatives for these types of heat pumps.

Although HCs are viable alternatives for use in hot water heat pumps, they are not in common use.

For R-407C and R-410A, all aspects are as with split ACs. R-410A is commonly used in such systems in both Article 5 and non-Article 5 countries. HFC-134a is also used in such systems, although due to its lower pressure the systems are less compact and as such incur higher costs.

It is feasible to use HFC-32 in hot water heat pumps, for example, where R-410A is already used. The flammability and cost implications associated with the use of HFC-32 in this application are similar to that of single split systems. The theoretical cycle efficiency is better than R-410A, but slightly less than HCFC-22, whilst the pressure is 1.5 times higher than HCFC-22 and equivalent to R-410A. Discharge temperature is higher at high pressure ratio operation, so application in this category requires more rapid and accurate control of temperatures. It is not known whether any manufacturers are developing HFC-32 based hot water heat pumps commercially.

It is feasible to use the L-20 blend in hot water heat pumps, for example, where HCFC-22 is already used. The flammability implications are the same as with HFC-32.

HFC-1234ze(E) can also be used in HWHPs that can be used in existing HFC-134a technologies with minor modifications (compressor sizing). Due to its lower flammability classification, the safety implications are comparable to those of HFC-32 and L-20 blend applications. Otherwise the application characteristics are close to HFC-134a except that greater incremental costs would be incurred as a result of less compact systems (due to lower pressure) and higher refrigerant price. No information about real performance or whether any manufacturers are developing systems using this option was found.

N-13 is a refrigerant blend that can be used in existing HFC-134a technologies with minor modifications (compressor sizing). The various implications with using this blend would be the same as those with HFC-1234ze(E) except that the flammability issues would not apply. No information about real performance or whether any manufacturers are developing systems using this option was found.

3.6.7 Space heating heat pumps

Comfort heating heats the room by heating water for distribution to an air handling unit, radiator or under floor panel. The required water temperature depend on the types of emitter, low temperature application ranging from 25 to 35 °C for under floor heating, for moderate temperature application such as air handling units around 45 °C, for high temperature application such as radiant heating 55 to 60 °C, and for very high temperature application, as high as 65 to 80 °C, such as for the fossil fuel boiler replacement market. The required warm water temperature affects the selection of refrigerant. Heat pump systems are more efficient at lower sink temperatures, but each product must fulfil the required operating temperature.

R-717 is used fairly widely in systems from 250 kW up to very large/industrial-scale (>1 MW) heat pumps. Such systems are located outside or in special machinery rooms in order to handle the higher toxicity characteristics and giving the necessary space around the system and giving some sound reduction. Systems are normally designed with hot water heating function. The efficiency of R-717 heat pumps is known to be very good (Stene, 2008). The cost effectiveness becomes favourable as the heating capacity approaches 250 kW, relative to HCFC-22. The return on investment of less than 2 years has been reported. As with R-717 systems in general, the main barriers are related to the minimal capacity required for cost-effectiveness and certain national regulation controlling installation. Within Europe and North America, there is an increasing tendency to use R-717 heat pumps, although this is also commensurate with the increase in the use of heat pump technology anyway. For large commercial and industrial applications, R-717 is generally an attractive option and (neglecting national regulations) can normally be applied in most situations.

R-744 is used in space heating heat pumps, but not as widespread as it is for hot water heating. This is mainly due to the efficiency advantages declining as the output water temperature lowers. However, numerous manufacturers (with thermodynamic knowledge) are producing such systems, although mainly in combination with hot water heating systems where dual temperature levels are needed. The relative efficiency of R-744 space heating heat pumps is sensitive to many design considerations, but in general, where the supply air temperature is above 40°C, R-744 provides efficiency benefits (Richter et al, 2001). This is particularly of interest in systems that, for example, utilise radiators (Khoury, 2012). It is also noted that higher ambient temperatures only provide energy advantages in such systems. However, R-744 heat pumps can operate at very low ambient temperatures with acceptable COP's. Water-to-water or air-to-water systems, which are factory sealed arrangements can be comparatively compact and therefore incur reduced material costs. However, the addition of certain components needed to improve efficiency can result in additional cost compared to conventional HCFC-22 systems. Whilst the market penetration is low, the main barrier is cost. However, it is anticipated that as more products enter the market such heat pumps (Smart Grid applicable) will become more competitive. Within Asia and Europe more manufacturers are producing space water and dual temperature level heat pumps using R-744 and it is expected that this trend will continue. The use of R-744 in space heating heat pumps is less straight forwards than for hot water heating, but as the technology develops efficiencies are becoming more competitive and more products are entering the market.

The share of heat demanded for hot water and space heating also plays a decisive role in determining competitive options. According to simulation results of R-744-heat pumps in low energy houses in Norway (in the context of the IEA Heat Pump Centre project on the "economical heating and cooling systems for low energy houses"), R-744 heat pumps for combined space heating and domestic hot water outperforms a conventional (HFC) heat pump if the share of domestic hot water is at least 60%. Using improved R-744 compressor and ejector technology the break-even point is shifted to a domestic hot water share of 50% (Annex32). Moreover, with the trend towards "near Zero Energy" buildings that have minimal needs for space heating, hot water heating is expected to account for most of the heat demand in future new buildings.

Historically, HCs, particularly HC-290, had been used widely in Europe for small (domestic) heat pumps, although the introduction of the EU Pressure Equipment Directive resulted in a decline in its use due to compressor availability. However, in principle their continued use is not otherwise limited and now a number of manufacturers have products on the market. Such systems are located outside or in special ventilated enclosures. In addition, there are also large commercial-sized heat pumps using HC-290 and HC-1270 being sold within Europe. The other HC blends are not known to be currently in use. The efficiency of HC-290 and HC-1270 in heat pumps is known to be very good (Palm, 2005). The cost effectiveness in general is favourable, although sensitive to the design of safety features. As with the use of HCs in general, the main barriers are related to the safety guidelines. For systems with parts which are located in occupied spaces, the charge size can be prohibitively limited, whereas for systems locate outside or in ventilated enclosures there are no major restrictions. Again, it is necessary to ensure that technicians are appropriately trained to handle flammability. Within Europe there is steady use of HCs in heat pumps, with an increase for commercial sized systems. Similarly, research and development is also continuing. In conclusion for small and commercial sized applications, HCs are viable alternatives for space heating heat pumps.

Both R-407C and R-410A are widely used in these heat pumps. All aspects apply as with split ACs.

It is feasible to use HFC-32 and the L-20 blend in space heating heat pumps, as with hot water heat pumps. Their efficiency implications are comparable and the cost implications similar to those of hot water heat pumps. If refrigerant water heat exchanger is located in outside occupancy, the safety issue is easier to solve. It is not known whether any manufacturers are developing HFC-32 or L-20 hot water heat pumps commercially.

3.7 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. They 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 such as data processing and communication centres, electronics fabrication, precision machining, and moulding. District cooling is another application that provides air conditioning to multiple buildings through a large chilled water distribution system, as opposed to air conditioning each building with separate systems. Chiller operation is driven by cooling requirements but provision for heat recovery may be included. The principal components of a vapour-compression chiller are one or more compressors driven by electric motors (or less commonly, engines or turbines using open drive compressors), a liquid cooler (evaporator), a condenser, a refrigerant, a lubrication system, a refrigerant expansion and flow control device, a power handling device (commonly a starter or variable speed electronic drive), and a control and protection unit. The complete chiller usually is factory assembled and tested; no connection between refrigerant-containing parts is required on site by the installer except for very large chillers which may be shipped as multiple assemblies. Installation is accomplished by connection to water, power, and control systems. Vapour-compression chillers are identified by the type of compressor they employ; centrifugal or positive displacement compressors. Chillers can be further divided according to their condenser heat exchanger type, the most common being water-cooled or air-cooled and less common are evaporatively-cooled condensers and dry coolers.

3.7.1 Positive displacement chillers

Positive displacement chillers include those with reciprocating piston, screw, and scroll compressors. Smaller capacity models tends to be air cooled, which accounts for the majority of chillers, but as the capacity increases above around 350 kW water-cooled models become more frequent. Capacities can exceed several MWs.

R-717 is used fairly widely in reciprocating and screw chillers for process refrigeration, food storage facilities and air conditioning. Chillers must be located outside or in special machinery rooms in order to handle the higher toxicity and flammability characteristics. The sound levels from this kind of high capacity systems also require a sound limiting room. This type of chillers has been widely used in airports and similar high capacity areas. The efficiency of R-717 is high for chillers in both medium and high temperature applications (RTOC, 2010). The cost effectiveness becomes favourable as the cooling capacity approaches 200 kW and up to about 6 MW, relative to HCFC-22. The barriers for chillers are consistent with R-717 systems in general. However R-717 is more accepted in industrial and large capacity systems. The regulations have been successfully in place for many years. However, there are concerns of possible changes to certain standards. Within Europe and North America, there is an increasing tendency to use R-717 chillers, although the total number is still small compared to HCFC-22 and HFC machines.

For large commercial and industrial applications, R-717 is generally an attractive option and (neglecting national regulations) can normally be applied in most situations.

R-744 is now used in reciprocating chillers by many different manufacturers. The capacities range to up to several hundred kW and cover both air conditioning and refrigeration applications. As with other types of systems, the efficiency is compromised with increasing ambient temperatures. As such water-cooled chillers are of more interest in countries with hotter climates. However, where chillers are also used for heating purposes, seasonal efficiency benefits can be achieved. With knowledge in thermodynamics and system understanding, new concepts are under development, which are more energy efficient (SPF) compared to current HCFC and HFC systems. The cost of small capacity R-744 chillers is higher than that of HCFC-22 systems due to the piping and component design necessary to handle higher pressures, however, at capacities of around one hundred kW the relative cost approaches parity. Consistent with other applications, the main barrier for R-744 chillers is the poorer efficiency in climates with consistently higher ambient temperatures. At least within Europe, there is an increase in the output of R-744 positive displacement chillers. R-744 chillers are widely available and are increasingly being used for both air conditioning and refrigeration applications. However, due to efficiency constraints their use if preferred for cooler climates.

Both HC-290 and HC-1270 are produced by a number of manufacturers in Europe and some countries in other regions. Historically they have been used widely in petro-chemical industry but are now being applied for air conditioning, food storage and process refrigeration. The majority of chillers are reciprocating and screw type. The use of the various HC blends appears not to be currently used in chillers. The efficiency of HC-290 and HC-1270 is the same or greater than HCFC-22 in both medium and high temperature applications. Most manufacturers report that their HC models have higher COP than their equivalent HCFC/HFC models. Generally the cost implications of applying HCs in chillers are negligible, although the incremental cost depends on how safety measures are handled.

There are certain barriers with HCs, depending upon the chiller configuration. For air-cooled or water-cooled chillers that are positioned in the open air (within certain separation distances), there are no significant hindrances. For systems installed in machinery rooms, electrical equipment must be suitable for hazardous areas and gas detection with emergency ventilation is required (although in fact this should be applied to any refrigerant). The main barrier is that unless properly designed with additional safety measures, HC chillers cannot be used below ground level (such as in cellars). In addition, technicians must be suitably trained. At least within Europe and some other regions, there is an increasing tendency to use HCs in chillers, although the total number is still small compared to HCFC-22 and HFC machines. For commercial and industrial applications, HCs are generally a viable, efficient cost effective alternative except for situations that require installation below ground level.

HFC-1234ze(E) is suitable for chillers and has been trialled in systems in Europe. When used in with reciprocating, scroll or screw type of compressors, this refrigerant produces efficiency levels comparable to HFC-134a. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used. For screw compressors, the same type of oil (POE) can be used but the viscosity grade should be verified with the equipment manufacturer. Although HFC-1234ze(E) is a low flammability refrigerant, there are guidelines and standards available which provide guidance on safe installation, at least for outdoor locations. HFC-1234ze(E) is a refrigerant that can be used in existing HFC-134a technologies with minor modifications (compressor sizing). Due to its high critical temperature, it will perform very well in warm climates.

Both R-407C and R-410A are widely used in positive displacement chillers and all aspects are as with split and other types of ACs and heat pumps.

HFC-134a is used widely in various capacity reciprocating, scroll and screw chillers. The design of the system components is slightly different from HCFC-22 (and R-407C and R-410A) because of the lower operating pressure. Because it is a class A1 refrigerant (lower toxicity, non-flammable) there are no significant safety implications concerning its use. The energy efficiency is similar to that of HCFC-22, although higher COPs can be achieved if the system is carefully designed. Generally systems are marginally more costly than HCFC-22 because they are less compact. Since HFC-134a is well established, it is evident that there are no significant barriers to its use. Currently, HFC-134a use in chillers is neither declining nor increasing significantly.

The L-20 blend is a replacement for HCFC-22 or R-407C in positive displacement chillers that employ reciprocating or scroll compressor technologies. No major modifications are needed as its pressures are similar to HCFC-22 and R-407C. Although L-20 is a low flammability refrigerant, there are guidelines and standards available which provide guidance on safe installation. These are the same as those for the flammability aspects of R-717 for both chiller design and machinery room requirements. It is not known what the real performance implications are relative to HCFC-22 and similarly it is not known whether any manufacturers are developing equipment with this refrigerant.

The N-13 blend is feasible for use in positive displacement chillers and can be used in existing HFC-134a technologies with minor modifications (compressor sizing). When used with reciprocating, scroll or screw type of compressors, this refrigerant produces efficiency levels comparable to HFC-134a. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used. For screw compressors, the same type of oil (POE) can be used but the viscosity grade should be verified with the equipment manufacturer. Due to its high critical temperature, it will perform very well in warm climates. Testing and trials are being carried out in reciprocating and screw chillers and prototypes are under development by manufacturers in Europe and the USA.

The XP-10 blend is feasible for use in positive displacement chillers as is the N-13 blend in systems based on HFC-134a architecture with only minor modifications (primarily compressor sizing). When used in with reciprocating or scroll compressors, this refrigerant produces efficiency levels comparable to HFC-134a. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used. It is not known what the real performance implications are relative to HFC-134a chiller and similarly it is not known whether any manufacturers are developing equipment with this refrigerant.

It is feasible to use HFC-32 in positive displacement chillers, for example, where R-410A is already used, provided that the flammability characteristics are handled appropriately. The energy efficiency is equivalent or slightly better than HCFC-22 and R-410A due to its better heat transfer properties. Larger capacity per compressor swept volume is beneficial for chiller with large scroll compressors. On the contrary, it is disadvantage for ones with small screw compressors. Better heat transfer properties are beneficial for chillers as they are limiting factor in water heat exchangers. Lower pressure drop in air cooled heat exchanger is a merit of HFC-32 for large air cooled chillers. Flammability requirements for machinery rooms are comparable to those for R-717. Electric switching components for large chillers have potential to ignite HFC-32, but ventilation in machinery room is mandatory to prevent flammable concentration. So, requirements for such switching components are not established for A2L specifically. A risk assessment study for chillers with A2L refrigerants is on-going in Japan. HFC-32 may be employed for small chillers, but large ones will probably employ the HFC-1234 series substance mainly.

3.7.2 Centrifugal chillers

These are chillers which employ centrifugal compressors with one, two, and three compression stages. Centrifugal compressors most commonly are used in water cooled systems, especially those with capacities exceeding 1 MW. Air cooled centrifugal chillers are less common. They are generally used for air conditioning applications in very large buildings and for district cooling.

R-717 is seldom used in centrifugal chillers, although products are available and installed for certain applications. R-744 is not currently used in centrifugal chillers.

HCs are used to a limited extent in centrifugal chillers typically within the petro-chemical industries where hazardous area protection is already in common use. However, they are not generally considered as alternatives for replacement of HCFC centrifugal chillers.

Where it concerns HFC-1234ze(E) use in centrifugal compressors, this refrigerant produces efficiency levels slightly better than HFC-134a. Since most of these chillers are located outside, the safety concerns are minor, but nevertheless, the same as for positive displacement chillers. Due to its high critical temperature, it will perform very well in warm climates. There are already several chillers using this refrigerant currently in use.

HFC-1233zd(E) can replace HCFC-123 (a low-GWP HCFC) in low pressure centrifugal chillers. When used in centrifugal compressors, this refrigerant produces efficiency levels slightly better than HCFC-123, allowing the design of systems with high energy efficiency. As a new molecule, this refrigerant has a higher cost than HCFC-123. Still this cost would be moderate and will have a reasonable payback period due to the high energy efficiency of the refrigerant which lowers the expenses for end users. This refrigerant is currently under evaluation by manufacturers. Most of the information available has been presented in public forums for refrigerants, solvents and blowing agents applications.

HFC-134a is used widely in various capacities of centrifugal chillers. The design of the system components is slightly different from HCFC-123 because of the higher operating pressure. Because it is a class A1 refrigerant (lower toxicity, non-flammable) there are no significant safety implications concerning its use. The energy efficiency is marginally lower than that of HCFC-123. Generally, systems are comparable to HCFC-123. Since HFC-134a is well established, it is evident that there are no significant barriers to its use. Currently, the HFC-134a use in chillers is neither declining nor increasing significantly.

It is feasible to use HFC-32 in centrifugal chillers, provided that the flammability aspects are handled appropriately. The thermal conductivity is basically better than R-410A, but due to high internal leak flow and high pressure difference with smaller molar mass, the compressor efficiency is not as high as one with HFC-134a or other low pressure refrigerants such as HFC-1234ze. In addition, boiling volume is not as high as HFC-134a and HFC-1234ze, so use of HFC-32 will result in a larger evaporator. Consequently, the use of HFC-32 is very limited and negligible in general centrifugal chillers.

3.8 Mobile air conditioning

Cars and truck cabins used the same refrigerants CFC-12 from the 50’s to 1992; then it was replaced by HFC-134a, which is still in use everywhere, even if the European ban should have begun in 2012. Depending on the country, the preferred option is to keep going with HFC-134a or to shift to HFC-1234yf, but the delayed wide market availability of this refrigerant seems to slow down the shift and other options are to be reconsidered for the future, mainly CO2.

For city or long haul buses and also trains cabins, choices have always been more open: CFC-12 and HCFC-22, and then followed by HFC-134a and R-407C. In Germany some buses are operated on R-744 and the alternative air cycle (Brayton-Joule) technology has been installed on more than 100 ICE trains.

3.8.1 Cars

The car industry has organized its global production (more than 60 million vehicles in 2012) with a high level of specialization. Air-conditioning systems are supplied by tier 1 suppliers that manufacture the complete AC system: heating, cooling and ventilation, and the control system. The car companies organize a strong competition among their suppliers and the consequence is that the best refrigerant is a single, unique, and global one. The refrigerant has to be a commodity. The history shows that HFC-134a has been the only refrigerant chosen by all car companies to replace CFC-12, and now the expectation is still to have a single refrigerant worldwide.

As previously said, R-744 has seen a number of developments from 2000 to 2010 and several manufacturers reportedly reached “implementation readiness”. Tier 1 suppliers as well as car makers have developed several technical options with R-744: internal heat exchangers, external control compressors, micro-channel gas coolers, and evaporators dedicated to R-744. New hoses with ultra-low permeation have been developed. In 2013 there has been a renewed interest in R-744 MAC, with several German OEMs announcing their intention to develop such systems (see e.g. www.R744.com, 2013) and prefer to stay with HFC-134a until R-744 will have been commercialised.

A number of tests have been performed in hot and cold climates. R-744 has been demonstrated to be as efficient as best in class HFC-134a system, except when the vehicle is idling and under very hot conditions.

The main barrier for R-744 systems has been their cost . Even for series of at least 150,000 R-744 AC systems per year, costs were at least doubled compared to the baseline. Another barrier has been that the solution was not a global one, requiring two AC systems (R-744 and HFC-134a) to be mounted on the same assembly line. Two other barrier issues were related to reliability and servicing:

- the shaft of the open-type compressor was a highly potential leak-prone component with no lessons learned at large scale
- R-744 servicing requires special training and also specific equipment requiring to develop a new world-wide servicing for global car companies

For electric cars or hybrid cars with high voltage available, hermetic compressors can be used. Consequently, the shaft seal issue disappears, which makes the R-744 MAC system reliable. Nevertheless the cost issue remains. In summary, R-744 is technically difficult and creates a barrier in terms of technical offer; only the best in class Tier 1 companies have been able to develop efficient R-744 compressors.

Hydrocarbons are efficient refrigerants and as other refrigerants have to be chosen according to their condensing and evaporating pressures. When safety is not taken into account, additional costs are limited. Safety is a clear and strong barrier against the use of HCs in cars. During the competition between R-744 and HFC-152a, HFC-152a received a very strong opposition from the German car makers that are vehemently against any use of flammable refrigerants in cars.

The sales of HC blends for car AC systems will continue in some countries but do not constitute a global trend and will not receive the support of any car company. In conclusion, HCs are not a global option for car AC systems and will remain marginal.

Because of the flammability issue, new low-GWP non-flammable blends such as Blend H and DP-1 have been proposed by chemical manufacturers as of 2003; Blend-H failed for decomposition issues and DP-1 for toxicity of one of its component.

A major step forward was the proposal and introduction of HFC-1234yf. Even though slightly flammable, its thermodynamic properties are very close to those of HFC-134a and so the adaptation is easy without significant constraints due to its very moderate flammability.
Many tests have been performed and some adaptations on the suction line diameter and on the heat-exchanger tuning have been done in order to match HFC-134a energy performances. Developments have been made and no significant differences are measured compared to the best in class HFC-134a systems.

The cost is announced to be 5 to 7 times more than that of HFC-134a systems, but it is known that, in the chemical industries, prices could vary from 1 to 10 depending on the sales volume.
A current barrier is related to patent issues between the chemical manufacturers; the patent has been invalidated in both US and EU patent courts and is under appeal by the manufacturer Honeywell. As a result, the mass-production of low GWP HFC systems is being delayed. HFC-1234yf with its low GWP of 4 is seen as the solution for the car industry, even if the current low availability creates uncertainties, especially in Europe where the regulation requires refrigerants with a GWP < 150 for new cars since 2011. The change from HFC-134a to HFC-1234yf seems to be one of the likely options because the car industry favours global options for AC systems. The preference of companies outside Germany would be to change to HFC-1234yf, because there are too many barriers perceived to the introduction of R-744, in particular related to safety, compressor durability and leak testing. It is also supported by LCCP analysis, which shows that HFC-1234yf would be superior to R-744 for most ambient temperatures. It can be mentioned that HFC-1234yf is currently available to some extent and the first cars using this refrigerant are therefore in production now.

HFC-134a is currently the only refrigerant in use except the refilling of existing AC systems with HC blends. Due to the absence of mass-produced HFC-1234yf, even in Europe HFC-134a is currently charged in new AC systems. HFC-134a AC systems are the bench mark technology for all alternatives. The cost is also the reference for mass produced AC systems with a strong competition among Tier 1 suppliers. Obviously the only barrier is its GWP. It is likely that HFC-134a will be replaced under different schedules in the various world regions.

3.8.2 Public transport

AC systems of trains and buses are similar and are produced in small series of some hundreds per year. The cooling capacities vary from 10 to 35 kW depending on the size of the bus or the train car. Due to the small market of this application, technologies in use are coming from stationary air-conditioning industry for heat exchangers. For buses, compressors are open-type compressors driven by the engine as for the car AC system. For trains, compressors are electrically-driven hermetic compressors. So the refrigerant choice could be different for those applications.

Carbon dioxide has been developed in Germany since 1996 by one company and the total fleet is about 50 city buses. In moderate climates, R-744 performs well and lessons learned from several years of experiences do not show significant troubleshooting. Another German manufacturer proposes and sells R-744 based AC systems for trains. The energy efficiency seems to be in the range for the German climate conditions. For hot climates, the energy efficiency is lower at equal design efforts. The main barrier is related to cost, design habits and also sophisticated designs for hot climates. R-744 systems, developed for refrigerated transport by companies manufacturing also AC systems for buses and trains, may trigger the development of R-744 systems for buses and trains.

In conclusion, AC systems for buses and trains are a niche application. New developments with R-744 will be a consequence of developments in larger market application and regulatory constraints.

HCs are not applicable in trains and buses based on safety issues for common transportation.

The HFC-1234yf development for car AC systems will have direct consequences for buses and trains cars AC systems operating currently with HFC-134a. The shift can be done based on first lessons learned in the car industry. For train AC systems operating with R-407C, new blends including HFC-1234yf or HFC-1234ze could be proposed in the near future.

As mentioned for car AC systems, the energy efficiency can be as good as the reference line with HFC-134a, based on simple adaptations taking into account thermodynamic properties of HFC-1234yf. The refrigerant cost, although greater than the usual price, is not a strong barrier, because its cost represents less than 1% of the total cost of those AC systems. The current barrier is related to the fact that no current regulation constraints exist. The change from HFC-134a to HFC-1234yf is a relatively easy option, as well as the possible shift from R-407C to new low GWP blends.

Air systems based on the reverse Brayton-Joule cycle with air compressors and turbines are the standard system for airplane AC systems. The difference between airplanes and trains is the outdoor temperatures (-50°C for airplanes). The efficiency of air systems is relatively poor and intrinsically lower compared to vapour compression systems. For hot outdoor temperatures, the cooling capacity is decreasing rapidly. During the summer of 2010, several ICE trains equipped with AC air systems were not able to provide sufficient cooling in Germany, showing the limit of a design based on fair weather. For moderate climates, air systems are possible. The advantage is the absence of refrigerant; the drawback is the limited cooling capacity for high outdoor temperatures.

The two dominant refrigerants are currently HFC-134a and R-407C in developed countries and HFC-134a and HCFC-22 in developing countries. R-407C is often chosen for train cars due to the necessary compactness of the AC system to be integrated in the roof of the train car. Barriers are based on the GWP of those refrigerants even if those applications could be exempted of using low-GWP refrigerants for some years in Europe. In the next 10 years R-407C is expected to be replaced by all the different alternatives previously mentioned.

The current HFCs could be used longer in those niche applications, the shift from high-GWP refrigerants to alternatives will be related to the overall evolutions in AC systems.

3.9 Reduction of negative environmental impact due to amounts that could have been or could be avoided

As mentioned in section 2.4, the most transparent approach for investigating “amounts avoided” would be to investigate the environmental impact of certain refrigerants or chemical choices, compared to a certain baseline. As can be seen in chapter 4 under foams and its subsectors this is feasible. Consumption is then seen as potential emissions. Domestic refrigeration can be compared to PUR appliance foam. In the case of domestic refrigeration a consumption could be assumed as baseline or as consumption profile over the period 1990-2020 using the original chemical (CFC-12), since consumption is rather straightforward and the domestic refrigeration sector is not significantly impacted by servicing, maintenance and safety concerns, as with some the other sectors of refrigeration and air conditioning. Particularly considering a baseline for CFC-12 up to the year 2020 in domestic refrigerator applications makes the negative environmental impact decrease (or the smallest negative environmental impact) by the selection of the two available options very clear. It is obvious in this case that a large step is made by the conversion from CFC-12 to HFC-134a, both in ODP and in GWP (climate) terms. Use of the hydrocarbon option HC-600a reduces the negative environmental impact even further, but compared to the first step from CFCs to HFCs (when 85% of the reduction in tonnes CO2 equivalent can be made), a further reduction (to hydrocarbons) can at maximum be another 15% of the baseline, as implied by the respective GWPs of the refrigerants.

Assuming a global consumption of 25,000 tonnes annually for the period 2010-2015, the use of HFC-134a (compared to CFC-12) would yield a lower negative environmental impact of 230 Mt CO_2-eq. per year; the use of HC-600a would add another 33 Mt CO_2-eq. annually. In practice, the entire global domestic refrigeration has been converted, with about 50% to HFC-134a, the rest to HC-600a. So the conversion of all now (2013) remaining HFC-134a to HC-600a would yield a saving of about 17 Mt CO_2-eq. annually.

It would be desirable if one could make a similar exercise for other sectors in refrigeration and air conditioning. This could be possible, in principle, by assuming a baseline of HCFCs starting in the 20th century (1990) and going to 2020-2030 following a BAU trend. Other cases would be the consideration of only R-404A or R-410A starting in the 20th century (i.e., hypothetically in 1990) and simply proceeding into the future following the BAU scenario, or mixtures of HFC-32 with low GWP HFCs, other blends or simply hydrocarbons (HC-290 or HC-1270).

Whereas this kind of consideration gives insight in the case of domestic refrigeration and similar other uses that do not have to deal with servicing etc., the question in the case of many other RAC sectors where refrigerant handling and large charge sizes of refrigerant are involved , is whether a consideration of a sole replacement with, e.g., R-410A or a sole replacement with, e.g., hydrocarbon in making selections early has any value for common practice. This in particular since the considerations of low GWP cases as of 1990 (or even before) would yield a picture of a very low environmental impact in manufacture and in service throughout the decades, which is far from the current reality.

Two issues are important here:

- the fact that one would assume low GWP options (or others) to start at a very early phase, would also imply that regulatory decisions and costs considerations how to deal with flammability issues, would have been resolved in all sub-sectors of RAC, which could have led to a completely different reality in a given year, far from the usual discussion on conversions and retrofits to reduce the need for common refrigerants (such as HCFCs, and also HFCs at present).

- the fact that a change from a refrigerant such as HCFC-22 to a certain other refrigerant or blends of refrigerants would occur in a given year, does not mean that the negative environmental impact would have much to do with the impact of the new refrigerant to which one has converted (to a certain degree) in new manufacture. For 10-15 years, the servicing needs for the "old" refrigerant (which are in the order of 60-80% in the total in an equilibrium scenario) will play a substantive role in the total negative environmental impact, before that the change to new refrigerants will be clearly visible. This of course will depend on the economic growth (the growth in the numbers of equipment), the percentage of (the new) refrigerant that will take over in manufacture, and the lifetime of the average equipment.

As an example, assuming that a certain group of countries is completely dependent on a certain chemical (i.e., HCFC-22), with 80% of the total consumption of say, 1,000,000 tonnes per year, used for servicing, it means that 200,000 tonnes per year would be used in new manufacture. A change of 100% in a given year to a certain refrigerant or blend with a negligible GWP means that one would avoid 200,000 tonnes of HCFCs in that year, and servicing amounts of HCFC-22 for the equipment that has not been manufactured in that year during future years, i.e., for a 15 years lifetime of the equipment it would be something like 2,400,000 tonnes over a period of 15 years, due to a conversion of 200,000 tonnes in one first year.

However, financial constraints will flatten the profile of the introduction of new technologies in new manufacture, and a conversion of 5-10% of the total per year would be a reasonable amount to assume as the maximum achievable (depending upon the size of the sector and distribution of main manufacturers). This implies that, after a given year when a decision would have been made to convert 10% of the original HCFC based equipment to an alternative with a low environmental impact (with the original HCFC consumption at 1,000,000 tonnes), the HCFC consumption with a new (low GWP) alternative would be 180,000 tonnes for new manufacture. The amount that can be avoided in servicing would be 16,000 tonnes (being 80% of the amount of 20,000 tonnes that had been converted). The total amount avoided in the year after conversion would then be 36,000 tonnes (of which 20,000 tonnes due to the conversion in manufacture).

Two years of each 10% conversion would lead to a reduction of slightly more than 10% in total (HCFC) consumption, or in the case of a low GWP alternative, to the same reduction of the negative environmental impact in climate terms. In this case one would have avoided 100,000 tonnes in a given year, and dependent on the penetration rate of the alternative, once could calculate all kinds of consequences over the period 2015-2030. It is believed that forecasting for the future 15 years is rather uncertain. The above therefore just serves as a first example.

In order to demonstrate how difficult the reality is and how consequences of decisions in 2013-2015 can be deducted, an example from commercial refrigeration is given here. One could assume a certain HCFC baseline in a given year in the past. At a certain stage HFCs as well as the blend R-404A (with a GWP more than twice that of HCFC-22) gradually take over. This implies that in the period 2000-2012 one has different types of profiles for the consumption of the different refrigerants (with each having certain servicing percentages in their total consumption). The negative environmental impact has considerably increased due to the introduction of, in particular, R-404A. As of a given stage after the year 2010, new alternatives enter the market in large quantities or expand their share considerably, from having "HCFC-22 level" GWPs, to lower GWPs (several blends), to negligible ones (in the case of ammonia, carbon dioxide etc.).

If the HCFC-22 BAU curve for consumption is declining, whilst the R-404A curve is increasing over the years, with each of them having considerable impacts on the total via the servicing amounts, the following question comes up. The question is what the introduction of 5-10% in a given year of blends or low GWP refrigerants in new manufacture would mean. It would definitely imply a substantial amount if one would look at the consumption of HCFC-22 it would replace, but it would not mean anything, rather, it would not be visible if the R-404A consumption would increase due to an increasing equipment base and further increasing servicing amounts. The question then is in how far a consideration or study of separate HCFC-22, R-404A and low GWP blend consumption curves make sense. If one would look at the consequences for the negative environmental impact, the decision to convert 5-10% of the equipment may not be visible in the environmental impact, even when it would be there, due to much larger effects of the existing capacities and servicing (particularly in the case of high GWP refrigerants). In summary, the answer to the question ”what could be avoided”, the calculation of the “avoidance potential” (the forward looking question), would actually be a quite complicated one and would ask for an extensive analysis.

Nevertheless, in order to give an impression of the order of magnitude of the reduction in negative environmental impact, and then essentially in reduction of potential GWP emissions in Mt CO_2-eq.) Table 3.1 below gives some numbers.

The table gives the approximate consumption in HCFC-22 (or HFC blends such as R-404A or R-410A0 for non-Article 5 and Article 5 countries in the year 2013. It concerns commercial refrigeration and stationary air conditioning.

It assumes 40% of the consumption being used for new manufacture in non-Article 5 countries, and 20% of the consumption used for new manufacture in Article 5 countries. It the assumes 10% of the new manufacture being converted to alternatives in a given year and gives the numbers for the reduction in negative environmental impact in that year, as well as the influence on the negative environmental impact (i.e., in many cases a reduction) over a period of 15 years after the conversion in manufacture, which is due to the reduction of the impact in the servicing amounts (assumed over a period of 15 years).

A change of 10% in the manufacture for commercial refrigeration in developing countries to HFC blends such as R-404A gives an increase in negative impact of about 4 Mt CO_2-eq., and an increase over 15 years in servicing of 32-64 Mt CO_2-eq. (dependent on whether the servicing per year would be 50-10% of the original charge. Going from HCFC-22 to low GWP options (assuming an average GWP of 300; this is an assumption for the average of a number of alternatives that could be applied) yields a decrease in negative environmental impact of 3 Mt CO_2-eq and another 23-46 Mt CO_2-eq reduction over the period of 15 years thereafter, compared to the use of HCFC-22.

In particular for refrigeration and air conditioning, it will be clear that a conversion to alternatives with a low negative environmental impact is one of the first priorities. In particular because a change in manufacturing now will have consequences for many years to come via the amounts consumed in servicing. A calculation of the consequence in tonnes in the negative environmental impact should give an adequate first impression.

Table 3.1: Amounts (tonnes, Mt CO_2-eq.) reduced in negative environmental impact when converting from HCFC-22 (or HFCs) in commercial refrigeration and stationary air conditioning

Countries	Approx. Cons. (t)	Assumed in manufacture	10% of manufacture	Avoidance (Mt CO_2-eq.) per year	Avoidance via servicing in 15 years (Mt CO_2-eq.)
Commercial refrigeration (2013)					
Non-Article 5 countries					
From HCFC-22 to HFCs**	40,000	16,000	1,600	-3.2	-10/ -20
From HFCs** to low GWP	40,000	16,000	1,600	5.4	16-32
Article 5					
From HCFC-22 to HFCs**	100,000	20,000	2,000	-4.2	32-64
From HCFC-22 to low GWP	100,000	20,000	2,000	3	23-46
Stationary Air Conditioning (2013)					
Non-Article 5					
From HCFC-22 to blends/410A	140,000	56,000	5,600	-2.2	17-34
From HFCs to low GWP	140,000	56,000	5,600	10.5	32-64
Article 5					
From HCFC-22 to blends/410A	400,000	80,000	8,000	-3.2	24-48
From HCFC-22 to low GWP	400,000	80,000	8,000	11.8	88-176

** HFCs in commercial refrigeration have a GWP of 3800 (which would be the GWP of R-404A or similar)
***Low GWP chemicals, which could be different types of blends etc., natural refrigerants, have been given an average GWP of 300

Similar calculations can be done for stationary air conditioning, with a current large consumption of HCFC-22. Conversion of 10% of the manufacture in developing countries to low GWP blends (with an average GWP of 300) would result in a lower negative environmental impact of about 12 Mt CO_2-eq. in a given year, and a further reduction (due to servicing) of 88-176 Mt CO_2-eq. over the 15 years thereafter, quite a considerable amount.

The whole of this can be analysed in more detail, but this should be the subject of a separate study.

Thinking this over, in particular for refrigeration and air conditioning, it will be clear that a conversion to alternatives with a low negative environmental impact is one of the first priorities. In particular because a change in manufacturing now will have consequences for many years to come. A calculation of the consequence in tonnes in the negative environmental impact should give first impressions.

However, it should be stated that an investigation

- whether and how regulations can be adjusted for a quicker introduction of certain flammable refrigerants in certain products, or
- how approaches can be put in place to have more expensive equipment with more expensive low GWP refrigerants or blends entering the market faster would be very important and would have considerable impact on the calculation of the reduction in negative environmental impact.

4 Foams

Executive Summary

The foams sector has made transitions from its CFC baseline, through HCFCs in some cases, to either high-GWP or low-GWP non-ozone depleting solutions. As of 2013, the residual reliance on HCFC use in Article 5 regions rests to some extent in polyurethane appliance foams (often within commercial appliances), but mostly in PU Spray and XPS Board.

It is important to note that, of the 5.6 million ODP baseline footprint of the foam sector between 1990 and 2012, over 80% of the footprint was avoided. Similarly, for a cumulative baseline climate footprint of 26.3 billion tonnes CO_2-eq over 66% has been avoided. This assessment has taken the rather stringent approach of not correcting for the 10 year grace period given to Article 5 Parties, so the avoided baseline percentages against regulatory requirements are considerably higher. A similarly stringent approach has been taken with respect to the availability of non-ozone depleting alternatives and low-GWP solutions. It has effectively been assumed that these were available throughout the period of analysis and thereby over-estimates the ‘missed opportunities’ in order to place a worst case perspective to the data generated and avoid subjective scenarios. The following graphs illustrate the missed opportunities analysed in this way for both ozone and climate:

The reasons for these ‘missed opportunities’, especially for the XPS board sector, are fully explained in the foams chapter and it remains difficult to identify significant areas where the transition process could have been accelerated substantially given the constraints faced. It should also be noted that the effect of changes in thermal performance have not been factored into the climate assessment in view of the complex and non-determinable usage patterns to which most building insulation foams are subject.

Moving forward to assess the potential for further savings, the period of assessment has been limited to 2013-2020 in view of the uncertainties surrounding market growth in the foam sector beyond that date. However, it should be noted that the potential savings will be under-estimated by taking this relatively cautious approach. The following four charts show the potential savings available assuming an immediate transition in 2013. While recognizing that this is not possible in most cases, it does compensate to some extent for the relatively short assessment period:

Again, it should be noted that, although these savings are assumed to remove all of the remaining ozone and climate impacts for the period 2013-2020, the ozone-related savings represent only 2.3% of the footprint that would have existed without the Montreal Protocol. Similarly, the removal of the remaining climate impacts only represents 13.3% of the climate footprint that would have existed without the Montreal Protocol.

With HCFC Phase-out Management Plans now well into their first phase, it is clear that most of the significant sectors identified in Article 5 Parties are already being addressed. However, this is not necessarily the case in non-Article 5 Parties where the drivers for further transition need to come from the climate agenda, bearing in mind that the phase-out of ozone-depleting substances is already complete. Apart from regulatory intervention, one of the key drivers may ultimately be the improvement in thermal efficiency offered by low-GWP substitutes such as unsaturated HFCs, unsaturated HCFCs or blends containing them.

It is clear that the timing of further transitions is less critical to the environment than was the case for CFC phase-out, where delay had substantial consequences. There are still some difficult transitions to address (e.g. in the XPS sector) and it may be that waiting for the maturing of emerging technologies will offer better long-term solutions than forcing the transition too soon. Where this is unavoidable because of ODS phase-out commitments, it may still be better to consider a low-cost interim solution in order allow for a subsequent transition.

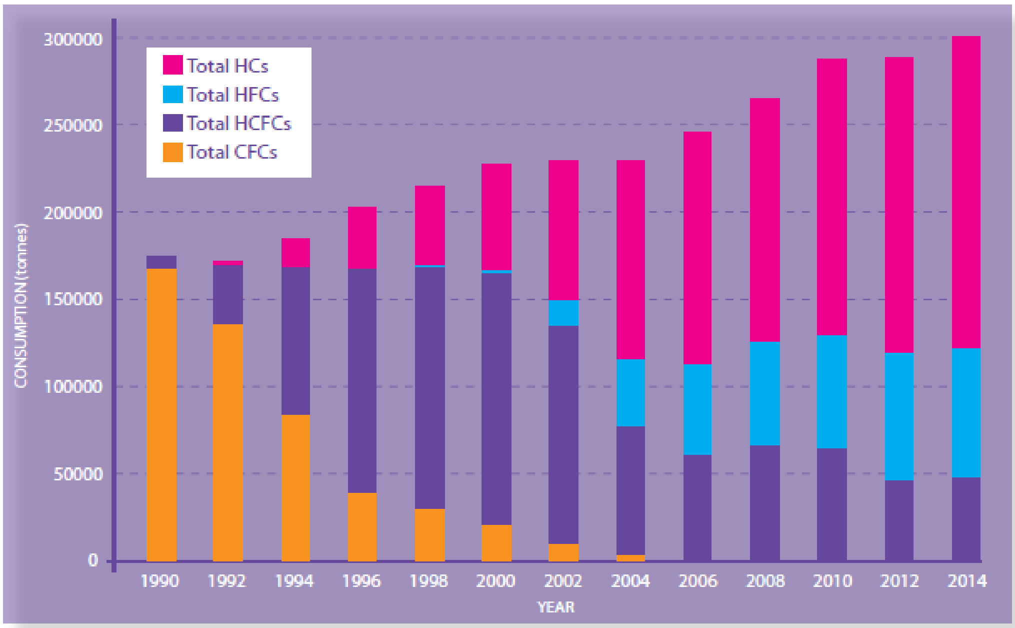
4.1 ODS alternatives

The foam sector has made significant strides in addressing the phase-out of ozone depleting substances since the signing of the Montreal Protocol in 1987. The availability of hydrocarbons at an early stage of the transition period has made it that a genuine low-GWP and cost-effective alternative has been available for large parts of the foam sector throughout that period, even at the time of the phase-out of CFCs in non-Article 5 Parties. Therefore, the account of the transition history since 1987 in the polyurethane and phenolic product sectors is dominated by whether a specific foam sub-sector could adopt hydrocarbon technologies or not. There have been a number of reasons cited over the period to explain why hydrocarbon solutions were not appropriate. These have included:

- The flammability risks associated with the production/deposition process
- The flammability risks associated with product installation and use
- The higher gaseous thermal conductivity leading to poorer thermal efficiency of the foam
- The cost of flame-proofing measures for production processes in relation to the size of the manufacturing plant (lack of economies of scale)
- Local health & safety regulations
- Local regulations on volatile organic compounds (VOCs)
- Waste management issues

Some of these have largely been discounted in more recent times, but others continue to be of importance and some are even growing in significance (e.g. waste management issues) as hydrocarbon blown foams reach end-of-life. Nevertheless, the market penetration of hydrocarbon technologies has had a substantial impact as shown by the graph below:

Global Trends in Blowing Agent Consumption by Type (1990-2014)



The dominance of the hydrocarbon technologies is even greater than it appears from the graph, since the blowing efficiency of hydrocarbon blowing agents is considerably better than the CFCs and HCFCs that were replaced. This means that the amount of foam blown by the 170,000 tonnes of hydrocarbons predicted to be used in the foam industry in 2014 will be 30-40% greater than would be achieved by the same quantity of CFCs. The optimisation of hydrocarbon technologies over the years has also resulted in improvements in thermal performance through improved cell structure, thereby negating some of the earlier concerns about poorer thermal efficiency.

It can be seen that the other major groups of blowing agents being used for the polyurethane and phenolic foam sectors at this point are HCFCs (in Article 5 Parties) and HFCs (in non-Article 5 Parties. The reasons for this will be explained in the sections that follow within this chapter.

In the Extruded Polystyrene sector, the main low-GWP and cost-effective alternative has been CO_2 itself. Again, the main challenge throughout has been to understand why this solution could not be universal in its application. Reasons have included:

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

For these reasons considerable proportions of the extruded polystyrene (XPS) industry have remained using HCFCs and HFCs rather than CO_2. This will be explained further in section 4.8 of this chapter.

In the intervening years, the search for low-GWP, high performance blowing agents without the limitations of hydrocarbons and CO_2 has been continuing. For the first time, the emergence of unsaturated HCFCs and HFCs seems to be offering a level of performance which not only allows the replacement of blowing agents with high-GWPs such as HCFCs and saturated HFCs, but also threatens to replace some elements of the hydrocarbon and CO_2-blown sectors, based primarily on improved thermal properties. However, the continuing unknowns with these technologies are the overall system cost and the global availability. Until, these issues are fully addressed, it will be difficult to elevate their status beyond 'emerging'. Most manufacturers are indicating levels of commercialisation between late 2013 and 2015. However, in the first instance, this availability is likely to be targeted in markets within non-Article 5 Parties where the requirement for improved thermal efficiency is best identified. Even in these markets, it is expected that blowing agent blends will become predominant, especially where unsaturated HCFCs and HFCs can be blended with hydrocarbons to obtain better thermal performance with minimum system cost increase.

Other blowing agents are also emerging as potential replacements for HCFCs and HFCs. These include a group of oxygenated hydrocarbons (HCOs) which include methyl formate and methylal. These are generally seen as less flammable than the hydrocarbons themselves, although the significance of those differences can often depend on local product codes and the regulatory frameworks governing foam manufacture. Again, there is a growing tendency to see these used as components of tailored blends where they can contribute to overall performance criteria.

For the XPS sector, the emergence of gaseous unsaturated HFCs such as HFO-1234ze also presents a significant opportunity to replace any remaining HCFCs, saturated HFCs and even CO_2 in some instances. However, cost remains a key issue and blending with oxygenated hydrocarbons (e.g. dimethyl ether) may well be required to deliver a commercially viable alternative technology.

In summary, the following table provides an overview of the blowing agent classes which have either previously offered, or are currently offering, alternatives to ozone depleting substances in the sectors being specifically considered in this chapter.

Sector	CFCs	HCFCs	HFCs	HCs	HCOs	HFOs	CO_2-based
	ODS being replaced						
PU Appliances	CFC-11	HCFC-141b HCFC-22	HFC-245fa HFC-365mfc/227ea	cyclo-pentane cyclo/iso-pentane	Methyl[Δ] Formate	HFO-1233zd(E) HFO-1336mzzm(Z) AFA-1 (undisclosed)	CO_2 (water)*[Δ]
PU Board	CFC-11	HCFC-141b	HFC-365mfc/227ea	n-pentane cyclo/iso pentane		HFO-1233zd(E) HFO-1336mzzm(Z) AFA-1 (undisclosed)	
PU Panel	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc/227ea	n-pentane cyclo/iso pentane		HFO-1233zd(E) HFO-1336mzzm(Z) AFA-1 (undisclosed)	CO_2 (water)*
PU Spray	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc/227ea			HFO-1233zd(E) HFO-1336mzzm(Z) AFA-1 (undisclosed)	CO_2 (water)* Super-critical CO_2
PU In-situ/Block	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc/227ea	n-pentane cyclo/iso pentane		HFO-1233zd(E) HFO-1336mzzm(Z) AFA-1 (undisclosed)	CO_2 (water)*
PU Integral Skin	CFC-11	HCFC-141b HCFC-22	HFC-245fa HFC-134a		Methyl Formate/ Methylal		CO_2 (water)*
XPS Board	CFC-12	HCFC-142b HCFC-22	HFC-134a HFC-152a	Iso-butane	DME	HFO-1234ze(E)	CO_2 CO_2/ethanol
Phenolic	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc/227ea	n-pentane cyclo/iso pentane		HFO-1233zd(E) HFO-1336mzzm(Z) AFA-1 (undisclosed)	

*CO_2(water) blown foams rely on the generation of CO_2 from reaction of isocyanate with water in the PU system itself
[Δ] Primarily in the commercial refrigeration sector (e.g. vending machines)

4.2 Polyurethane - appliances

In the strictest sense, this sector covers both domestic and commercial appliances, although the major trends characterised in this section of the chapter will be related to the larger, and more homogeneous, domestic sector. However, the statistical information presented graphically will cover both groups of appliances.

4.2.1 Historical perspective (including non-Article 5 / Article 5 Party differences)

The adoption of polyurethane foams within the appliance sector took place substantially in the late 1960s and 1970s as concerns began to rise about energy use in the wake of oil crises of the period. An additional advantage was identified, in that polyurethane foams also contributed to the physical strength of refrigeration cabinets and allowed for a reduction in the steel structures used and, as a consequence, the weight of the cabinets themselves. This has ultimately been beneficial for both the economics and the environmental footprint of the industry.
Although there have been regional differences in the design of refrigerators and freezers over the last 40 years, the ability to transport units over long distances has resulted in a gradual levelling of the global refrigerator market over time. Nevertheless, there continues to be a substantial range of units on offer, from the large ‘American style’ cabinets to the smaller compact European, Japanese and Chinese models.

Polyurethane foam is now the insulation of choice for over 99% of the global market. There is increasing interest in the use of vacuum panels in some quarters, but the market penetration is expected to be limited to highly energy-sensitive areas of a cabinet, since cost remains an issue.
At the time of the transition out of CFCs in the early-to-mid 1990s, the design differences were truly on a regional basis. Indeed, the ‘American style’ refrigerator used throughout North America created transitional challenges that were not seen in either Europe or Japan. These challenges were largely down to the manufacturing processes and product designs in operation at that time. Effectively, the adoption of hydrocarbons as a direct alternative for CFCs was not seen as an option for two major reasons:

- The inappropriateness of the existing manufacturing facilities to accommodate the use of hydrocarbons for such large cabinets
- The poorer thermal performance of hydrocarbon blown foam when compared with CFC-containing foam and HCFC-containing foam, which was seen as the other obvious replacement at that time
- Risk of violating existing local regulation on volatile organic compound (VOC) limits

Despite some initial issues with the interaction between HCFC-141b and the refrigerator liners, HCFCs became the accepted alternative for CFC-11 in North America in contrast to the rest of the developed world, where the adoption of hydrocarbon was widespread. It is estimated that this approach led to additional ozone-related consumption of approximately 13,500 ODP tonnes in the period from 1995-2002 (~72% of the developed country total for appliances in that period). However, it should be noted that this total was equivalent to around 9 months of non-Article 5 Party consumption in 1990. This observation brings into sharp relief the situation at the time, which was that delays in implementation would be more costly to the ozone layer than the precise choice of ODS alternative. This was a time when HCFCs were seen by most as *'part of the solution rather than* part of the *problem'*. The combined impact of the delay in converting out of CFCs in the post-1990 period and the choice of HCFCs in North America is seen in the graph below – amounting to approximately 125,000 ODP tonnes in all:

Since 2003, the use of HCFCs in domestic appliances has largely been eliminated in non-Article 5 countries, meaning that the subsequent periods have broadly maximised their potential for avoiding further ozone depletion.

For Article 5 Parties, the CFC phase-out date was set 10 years later than for non-Article 5 Parties. However, in those Article 5 Parties, the use of domestic refrigerators and freezers was less widespread in the period between 1990 and 2000. Accordingly, the impact of deferred phase-out date was less severe than it would have been had it been applied in non-Article 5 Parties. Nevertheless, the overall implication in the 1990-2000 period was 188,000 ODP tonnes but reducing in the subsequent decade to 27,500 ODP tonnes indicating the efforts applied in Article 5 Parties, with the support of the Multilateral Fund to ensure that CFC transitions in the appliance sector were achieved well ahead of the final 2010 phase-out deadline. The following graph illustrates the extent to which the appliance sector in Article 5 Parties has limited its impact on the ozone layer, not only through its preference for early transition, but also through the avoidance of HCFCs in a number of key markets.

It should be noted that Article 5 Party strategies for CFC phase-out have not been uniform from region to region. China, and other parts of Asia, have focused primarily on transitioning from CFCs directly to hydrocarbons, whereas much of the domestic appliance sector in Latin America took a different route, with a focus on HCFC-141b as an alternative for its CFC phase-out. This was driven in part by the growing importance of the North American market for its exports.

With respect to climate impacts, the initial choice taken in North America has continued to impact subsequent choices when phasing out HCFC-141b use, with saturated HFCs being preferred to hydrocarbons. Again, the main reason cited was the superior thermal efficiency of the fluorinated substitutes. The following graph illustrates the significance of these subsequent choices on the overall climate impacts for the period from 2000-2010 and those projected for the following decade.

The overall impact of not choosing low-GWP alternatives in the period from 2000-2020 is currently estimated to be around 400,000 ktCO_2-eq. However, if low-GWP alternatives could be adopted immediately, this would be reduced by approximately 175,000 ktCO_2-eq. in the period to 2020. Of course, this simple analysis fails to account specifically for the potential energy benefits from using fluorinated substitutes such as saturated HFCs and this matter will be picked up again in Section 4.2.3.

For Article 5 Parties, the retained use of CFCs in the period to around 2005 dominates the assessment of climate impact because of the high global warming potential associated with CFC-11. However, the large-scale switch directly to hydrocarbons showed considerable benefits for the on-going climate impact of the appliance sector. Nonetheless, the residual impact of the use of higher GWP solutions (e.g. HCFCs) through until 2020 is estimated to be in the order of 190,000 ktCO_2-eq, as is shown in the graph below:

4.2.2 Commercially available alternatives to Ozone Depleting Substances

The Task Force Report in response to Decision XXIII/9 provided a full list of HCFC replacement options and offered a summary of the pros and cons of each option, as well as some additional commentary on critical aspects for decision-making in the appliance sector. Decision XXIV/7 has requested that the commercially available options and the alternatives under development (emerging options) be treated separately. Therefore, the Decision XIII/9 Report tables have been reconstituted and updated accordingly.

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
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	
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

The assessment of these alternatives against the criteria of commercial availability, technical proof of performance, environmental soundness (encompassing efficacy, health, safety and environmental characteristics), cost effectiveness (capital and operating) and processing versatility in challenging ambient conditions is, in itself a challenging objective. Typically, performance against such criteria can only be judged fully on a case-by-case basis and assessments made at a higher level will only be indicative. With this in mind, the following table seeks to give such an indicative assessment based on a nominal ranking of seven categories from ‘+++’ (the best) to ‘---‘ (the worst):

	c-pentane	*i-pentane*	*HFC-245fa*	*HFC365mfc/227ea*	*CO_2(water)*	*Methyl Formate*
Proof of performance	+++	+++	+++	++	+	+
Flammability	---	---	++	+(+)	+++	--
Other Health & Safety	0	0	+	+	-	0
Global Warming	+++	+++	--	---	++	++
Other Environmental	-	-	0	0	++	-
Cost Effectiveness (C)	---	---	++	++	++	0
Cost Effectiveness (O)	+++	+++	--	--	+	+
Process Versatility	++	++	++	+	0	0

As has been noted in previous reports, the mix of performance properties (technical, economic and environmental) does not lead unambiguously to one single selection. Indeed, the proliferation of blends across the whole of the foam sector and nowhere more so than the appliance sector is an indication of the reality that there is no single best solution. Often a key factor is the size of the manufacturing plant, since the economies of scale have a considerable bearing on the relative importance of capital and operational costs. Cost also is a major factor in the consideration of the major emerging technologies.

4.2.3 Emerging alternatives

As noted in the 2012 Task Force Report in response to Decision XXIII/9, the major emerging technologies in the appliance sector are based mostly around liquid unsaturated HCFCs/HFCs. These are all fairly similar in their properties and all seem to suggest a stepwise improvement in thermal performance over other low-GWP alternatives. The following table provides an overview of the 'pros' and 'cons' of these technologies.

HCFC REPLACEMENT OPTIONS FOR APPLIANCES (DOMESTIC & COMMERCIAL), TRUCKS & REEFERS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Domestic refrigerators/freezers			
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			
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			
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

The range of unsaturated HCFCs/HFCs remains unchanged from the Decision XXIII/9 Report, with the disclosure of the molecule behind Arkema's code name AFA-L1 still awaited. However, the following table provides an analysis of these new molecules against the criteria considered for the commercially available alternatives based on limited experience in appliance sector trials.

	HFO-1234ze(E)	*HFO-1336mzzm(Z)*	*HFO-1233zd(E)*	*AFA-L1*
	gaseous	*liquid*	*liquid*	*Liquid*
Proof of performance	+	++	++	+
Flammability	++	+++	+++	+++
Other Health & Safety	+	+	+	+
Global Warming	+++	+++	+++	+++
Other Environmental	+	+	+	+
Cost Effectiveness (C)	++	++	++	++
Cost Effectiveness (O)	--	--	--	--
Process Versatility	+	+	+	+

The appliance sector is clearly one of the most sensitive to the thermal performance of the insulation contained within the cabinet, since this dictates both external dimensions and internal storage space. Evidence from trials in the sector continue to reinforce the fact that unsaturated HCFCs/HFCs will deliver 8-12% better thermal performance than cyclo-pentane and 2% better performance than HFC-245fa. The key question is whether these differences will be sufficient to drive the adoption of these alternatives, in place of existing hydrocarbon technologies, in both non-Article 5 and Article 5 Parties. For HFC-245fa replacement in non-Article 5 parties, the driver will be more about environmental pressure to transition from high-GWP solutions. Finally, where HCFCs are still in use within Article 5 Parties, the question is whether these new blowing agents will be commercially available in time to pose a genuine alternative to hydrocarbon options.

4.2.4 Barriers and restrictions

As noted above, the commercialisation time-line and global availability of the various unsaturated HCFCs/HFCs will have a considerable bearing on their widespread adoption under the HCFC Phase-out Management Plans currently being enacted. Two of the three potential manufacturers are committing to timelines of 2015 or better, but the supply/demand curves for these alternatives are still not fully understood.

One factor in the adoption of these new technologies is the potential use of blends of unsaturated HFCs/HCFCs with hydrocarbons to achieve intermediate thermal performance benefits at affordable cost. If the compromises made are too great, then the benefits will be too marginal to justify transition from existing hydrocarbon solutions where they are already in place, and to prefer unsaturated HCFC/HFC solutions over hydrocarbon where they are not. However, with the cost of these new compounds not completely established at this point, it is not clear whether solutions maximising the thermal performance benefits will be affordable.

For those still using HCFC-141b, one strategy being considered in the case of some manufacturers is to make an intermediate transition to a high-GWP (lower investment) technology option such as saturated HFCs on the written understanding that a further transition to a low-GWP option will follow within a specified period. The choice would be left open until such time as optimum technology approaches have been established.

For transitions directly from HCFC-141b to hydrocarbons, there are potential strategies to reduce the investment costs for smaller enterprises. These include the potential for using pre-blended mixes containing cyclo-pentane. However, this approach is not expected to impact the domestic appliance sector too greatly, since economies of scale would generally support a more comprehensive conversion strategy. However, in the case of some manufacturers of commercial appliances (e.g. vending machines), there may be more relevance. Further information is covered under Section 4.4.4.

4.3 Polyurethane - boardstock

This is one of the largest markets for rigid polyurethane foams in non-Article 5 Parties, but has only recently started to grow significantly in Article 5 Parties as requirements for building energy efficiency have increased. The historical analysis therefore focuses primarily on the non-Article 5 experiences.

4.3.1 Historical perspective (including non-Article 5 / Article 5 Party differences)

The adoption of polyurethane boardstock (also known as flexibly-faced continuous laminate) has varied substantially across the range of non-Article 5 Parties because of substantial differences in building practices. In North America, the widespread use of timber-frame construction techniques has led to the use of boardstock as a siding material. Similar trends have occurred in Japan where metal-framed construction systems are also quite prevalent. In Europe, however, where brick and block cavity construction has been more typical for residential buildings, the bulk of the early uptake of polyurethane boardstock was in the non-domestic sector, particularly in offices, warehouses and industrial buildings. These non-domestic applications have also been evident in Japan and North America as well, but have been less conspicuous in view of the residential demand. In more recent times, the European residential buildings have also embraced polyurethane boardstock, since increasing insulation requirements have meant that wall cavities have not been able to accommodate the thicknesses required of less efficient insulation types.

CFC-11 was the predominant blowing agent throughout the early development of the polyurethane boardstock market. In the early stages of the search for a replacement blowing agent, HCFC-123 had emerged as an option, but was subsequently ruled out on the basis of unfavourable toxicity. This led to a broad consideration of HCFC-141b, especially in North America. However, after substantial consideration of the flammability implications and reformulation to include flame retardants in some products, it was decided that, to a large extent, it would be possible to leapfrog HCFCs and move directly to hydrocarbons – typically pentanes. In order to limit the loss of thermal performance resulting from this transition, cyclo-pentane was often favoured in the blends chosen – so much so that there was concern for a while about the availability of sufficient supplies. As foam formulations have been optimised, some of the blends have been able to switch towards n-pentane. However, choices continue to vary.

The graph above illustrates the consequence of the delay while boardstock manufacturers made their decisions in exiting CFC consumption. However, in the decade from 2001-2010 the lack of significant HCFC use resulted in the achievement of a virtually complete phase-out of ozone depleting substances.

From a climate perspective, the continuing use of CFC-11 in the period from 1990-2000 had a detrimental effect in excess of 900 million tonnes CO_2-eq in view of its high global warming potential compared with the alternatives. However, it could be argued that this impact was somewhat offset in the next decade by the avoidance of widespread HCFC-141b use. Once again, the balance between the speed of transition and the relative efficacy of the alternatives is an obvious discussion point.

The first comment to make with respect to the manufacture and use of PU boardstock in Article 5 Parties is this that it is relatively minor when compared to non-Article 5 activity. Back in the 1990s the total consumption of blowing agent was less than 1% of that in developed regions. Those few manufacturers in Article 5 Parties understandably waited for a technology lead from the larger producers and this resulted in a relatively measured transition between 2001 and 2010. Again, with the major alternative being hydrocarbons, the impact on consumption of ODS after 2010 has been minimal, as shown in the following graph.

The impact on climate from the slow transition out of CFCs was no more than 6.3 million tonnes CO_2-eq. The growth of the sector since 2005, especially in places like China, has been achieved through the adoption of hydrocarbon technologies from the outset and therefore there has been little overall ‘missed opportunity’ since then. This trend is expected to continue in the period to 2020 as is shown in the graph below.

4.3.2 Commercially available Alternatives to Ozone Depleting Substances

Again, drawing from the evaluations conducted for Decision XXIII/9 with relevant updates where necessary, the following table illustrates the commercially available options for the polyurethane boardstock sector.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Boardstock – 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)

In general, saturated HFCs have shown little uptake in most PU boardstock markets because the hydrocarbon-based products have been shown to be fit-for-purpose at a more competitive cost. Since new capacity in the industry can accommodate hydrocarbon process safety issues at the design stage, the high incremental capital costs associated with later transitions can be mitigated to some extent.

As building energy standards increase, there could be increasing pressure for better thermal efficiency, especially where space is limited and product thickness is constrained. There has therefore been some interest in possible blends of hydrocarbons with saturated HFCs. Indeed, it is suspected that some manufacturers may have adopted this strategy commercially, although it is difficult to track because no further plant modifications would normally be necessary. Such trends may also be short-lived, since there is increasing market pressure (e.g. through LEED and other environmental building schemes) to avoid the use of saturated HFCs.

According to the chosen criteria, the relative performance of alternative technology solutions in this sector can be summarised as follows:

	c-pentane	*n-pentane*	*i-pentane*	*HFC-245fa*	*HFC365mfc/227ea*
Proof of performance	+++	+++	+++	++	++
Flammability	---	---	---	++	+(+)
Other Health & Safety	0	0	0	+	+
Global Warming	+++	+++	+++	--	---
Other Environmental	-	-	-	0	0
Cost Effectiveness (C)	--	--	--	++	++
Cost Effectiveness (O)	++	+++	+++	--	--
Process Versatility	++	++	++	++	+

The slight environmental concerns reflected for hydrocarbon options relate to some emerging concerns about local VOC regulations. In some regions there are exemptions for thermal insulation manufacturing plants, but this approach is not universal.

4.3.3 Emerging alternatives

The market pressure on saturated HFCs outlined in the previous section opens up the possibility for hydrocarbon blends with unsaturated fluorocarbons (both HCFCs and HFCs). The uncertainty of cost makes this option even less clear cut for PU boardstock than it is for domestic appliances. Nonetheless, there continues to be sufficient interest in the option to justify its inclusion in this section as an emerging technology – albeit as a blend with hydrocarbons.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Boardstock – continuously produced			
Liquid Unsaturated HFC/HCFCs (HFOs)	Low GWP	High operating costs	First expected commercialization in late 2013
	Non-flammable		Trials in progress, particularly with blends
			Low incremental capital cost

The overall assessment of the criteria for unsaturated HCFCs/HFCs is very similar to that shown for PU appliances.

	HFO-1234ze(E)	*HFO-1336mzzm(Z)*	*HFO-1233zd(E)*	*AFA-L1*
	gaseous	*Liquid*	*liquid*	*liquid*
Proof of performance	+	++	++	+
Flammability	++	+++	+++	+++
Other Health & Safety	+	+	+	+
Global Warming	+++	+++	+++	+++
Other Environmental	+	+	+	+
Cost Effectiveness (C)	++	++	++	++
Cost Effectiveness (O)	--	--	--	--
Process Versatility	+	+	+	+

The only potential difference is that the use of a gaseous option being used in the PU Boardstock sector is less likely than for PU Appliances. Nevertheless, it has been retained for completeness.

4.3.4 Barriers and restrictions

In practice, the quantity of PU boardstock foam still using HCFCs is very limited and this fact alone testifies to the lack of barriers to appropriate transition. As noted earlier, much of the new capacity in the sector has been installed since the ozone issue emerged and the necessary requirements for hydrocarbon have typically been designed in.

The only likely transition pressure now emerging relates to the on-going goal of improved thermal efficiency. The major barrier to the adoption of blends of saturated HFCs with hydrocarbons is market pressure, while the potential barrier to the wider use of unsaturated HFCFs/HFCs is one of cost and, in the short term, availability.

4.4 Polyurethane - panels

In the context of this analysis, the primary panels being referred to are steel-faced and either continuously or discontinuously produced. The market for such panels has developed very differently in various regions of the world, with the early adoption being mostly in Europe. However, the prefabricated approach to building that these panels allow is becoming increasingly widespread globally and manufacturing capacity has continued to grow to meet the need.

4.4.1 Historical perspective (including non-Article 5 / Article 5 Party differences)

Back in the 1990s, the panel market was split between emerging building cladding applications such as those described above and the commercial refrigeration market (both mobile and stationary) where polyurethane-cored panels have been used for both walk-in cold rooms and refrigerated transport applications. A substantial portion of the market was served by discontinuous manufacturing equipment at that time. However, continuous manufacture has grown to dominate the sector as the greater demand in the building sector created consistency of demand and economies of scale.

As was the case with other insulation foams, CFC-11 was the blowing agent of choice in the period through to 1990. Since much of the manufacturing equipment at that stage was discontinuous there was a considerable reluctance to experiment with hydrocarbons and the natural replacement was HCFC-141b. Initial transitions took place alongside those in other foam sectors in the period between 1994 and 1996. However, as capacity began to increase for continuously produced panel, it became possible to design plants to accommodate hydrocarbon while minimising the impact on investment cost. The thermal performance disadvantages of hydrocarbon at the time were of less importance in the panel sector than in the PU boardstock sector. This reflects the fact that the thickness of panels is generally driven by the requirements on them for structural integrity over long spans rather than by the thermal performance itself.

The impact of these trends is shown in the graph below, where the initial transition decision-making process caused some lost time and arguably missed opportunities. However, despite the selection of a number of HCFC transitions, they became less significant in the 2001-2010 decade as the continuous panel industry grew based, as it is on hydrocarbon (typically pentanes).

The climate consequences of these transitions are a little more clear-cut and the on-going use of HCFCs, and later HFCs, in the discontinuous panel sector looks likely to deliver the same pattern going forward, as shown below.

The Task Force's analysis suggests that the impact of the HCFC and HFC technology selections in the discontinuous panel sector may have resulted in an additional climate burden of over 700 million tonnes CO_2-eq. and could provide a future avoidance of up to 170 million tonnes CO_2-eq by 2020 if appropriate low GWP solutions can be introduced. The barriers to this are covered in Section 4.4.4.

In Article 5 Parties, except those supplying markets in adjacent non-Article 5 Parties, the economies of scale have historically been too low to support continuous panel production. This is changing as the larger economies amongst the Article 5 Parties grow strongly, but the account still holds true for the bulk of developing countries. With a substantial base of discontinuous plants, the tendency was to retain the use of CFCs for the bulk of the ten year available grace period in order to take advantage of the technology developments occurring in parallel small and medium enterprises in non-Article 5 Parties. This impact of this decision to wait is clearly seen in the 1990-2000 period of the graph below.

The on-going impact of the discontinuous panel sector and its limited choice of options is also evident from the bars in the chart covering later periods. These indicate that HCFC phase-out will not be complete in the panel sector before 2020. The impact of the use of high GWP substitutes for CFCs is also seen in the following chart:

However, the missed opportunity is slightly less severe at 322 million CO_2-eq because of the smaller size of the market currently in developing regions. It seems likely that future growth in panels for buildings in the larger economies will be served by new investment and the transplant of hydrocarbon technologies from non-Article 5 Parties. This will serve to ‘dilute’ the overall impact of the panel sector, particularly if the improved energy savings are factored in.

4.4.2 Commercially available alternatives to Ozone Depleting Substances

The following table illustrates the main commercially available alternatives in the panel sector.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Steel-faced 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)
Steel-faced panels – discontinuously produced			
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		

As noted earlier, the pressure for improved thermal performance in the architectural (cladding) panel is less pronounced than it is for other building insulation types because of the structural requirements which are associated with that application. However, the same cannot be said for refrigerated transport where additional benefits in thermal performance can improve the load-carrying capacity of a vehicle. Therefore, there is on-going interest in saturated HFCs as legitimate alternatives, or at least components of blends for that application.

In the discontinuous sector, there are other potential technologies based around CO_2 (water) and HCOs such as methyl formate. These reduce the perceived risks associated with the use of hydrocarbons on discontinuous plants but do result in some compromises in foam properties including higher density and potentially poorer thermal performance. Nonetheless, they do offer low-GWP solutions in markets which may not be too sensitive to thermal performance issues. These are all important considerations in the Article 5 context where the need to phase-out HCFCs requires the widest range of alternatives, especially for small and mixed use discontinuous panel facilities. The strengths and weaknesses of these alternatives are once again shown in the following table – this time relating to the panel sector.

	c-pentane	*i-pentane n-pentane*	*HFC-245fa*	*HFC365mfc/227ea*	*CO_2(water)*	*Methyl Formate*
Proof of performance	+	++	++	++	++	+
Flammability	---	---	++	+(+)	+++	--
Other Health & Safety	0	0	+	+	-	0
Global Warming	+++	+++	--	---	++	++
Other Environmental	-	-	0	0	++	-
Cost Effectiveness (C)	--	---	++	++	++	0
Cost Effectiveness (O)	++	+++	--	--	+	+
Process Versatility	++	++	+	++	+	+

4.4.3 Emerging alternatives

Again, the major emerging alternatives are unsaturated HCFCs/HFCs. In view of the relative abundance of commercially available alternatives, these blowing agents are likely to be focused on niche markets in the panel sector.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Steel-faced panels – continuously produced			
Liquid Unsaturated HFC/HCFCs (HFOs	Low GWP	High operating costs	First expected commercialization in 2013
	Non-flammable		Trials in progress
			Low incremental capital cost
Steel-faced panels – discontinuously produced			
Liquid Unsaturated HFC/HCFCs (HFOs	Low GWP	High operating costs	First expected commercialization in 2013
	Non-flammable		Trials in progress
			Low incremental capital cost

In principle, unsaturated HCFCs/HFCs offer opportunities for improving thermal performance while retaining a low-GWP blowing agent. For reasons stated in respect of other foam sectors, the cost of these blowing agents is still uncertain and could prevent reliance on them in isolation. That said, the added value of a panel is certainly greater than that of boardstock, so the ability to adsorb cost could be greater in this sector. Nevertheless, the most likely approach will be the adoption of blends with hydrocarbons provided that an incremental improvement in thermal performance can be achieved. This will be particularly important for the thermally sensitive applications such as refrigerated transport. The proof of performance is at a lower level in this sector than elsewhere and this is reflected in the following table:

	HFO-1234ze(E)	*HFO-1336mzzm(Z)*	*HFO-1233zd(E)*	*AFA-L1*
	gaseous	*liquid*	*liquid*	*liquid*
Proof of performance	0	+	+	0
Flammability	++	+++	+++	+++
Other Health & Safety	+	+	+	+
Global Warming	+++	+++	+++	+++
Other Environmental	+	+	+	+
Cost Effectiveness (C)	++	++	++	++
Cost Effectiveness (O)	--	--	--	--
Process Versatility	+	+	+	+

4.4.4 Barriers and restrictions

The major barriers to the substitution of alternatives in the panel sector are not primarily related to the technologies available but to the wide range of enterprises involved (both in size and location) and the broad spectrum of applications served. Versatility is a key necessity for any technology in the discontinuous sector, but no single solution has emerged as being as versatile as the ozone depleting substances replaced. This may act as a deterrent to early phase-out of the remaining HCFC use in Article 5 enterprises where local requirements need to be matched.

4.5 Polyurethane - spray

Polyurethane spray foam has been used for many years as an efficient means of insulating structures which would be difficult to insulate in other ways, because of shape or location An example would be that of an insulated road tanker. Another would be the insulation of large flat roofs which may not be as flat as might be presumed! More recently, however, polyurethane spray foams have emerged as a vital component of renovation strategies for existing buildings. Again, the efficiency and versatility of application, as well as the relative durability and thermal efficiency are all characteristics which have contributed to the rapid growth of PU spray foam in both developed and developing regions.

4.5.1 Historical perspective (including non-Article 5 / Article 5 Party differences)

Polyurethane spray foam differs from a number of other products in that it is manufactured (applied) on site. In this respect, the system needs to be more robust and resilient than most factory controlled foam processes. For example, the process needs to cope with a wide variety of ambient temperatures.

Once again, CFC-11 was the original blowing agent of choice in the pre-1990 period. At the time of the first transition, the three major spray foam markets were North America, Spain and Japan. In the early stages of the transition there was considerable optimism in North America that hydrocarbons (particularly cyclo-pentane) could be used successfully as a replacement for CFCs. However, a series of incidents when spraying in confined areas confirmed that the management of the process was too sensitive to be deployed on a commercial basis, despite the best efforts of Exxon and others to provide appropriate guidance. The net outcome was that the industry defaulted to HCFC-141b and the impact is shown in the graph below. However, because spray is a fairly emissive process, the transition was prioritised by the industry and much of the benefit from early transition was gained.

The absence of a good low-GWP alternative has meant that the industry around the world has struggled with the global warming impact of substitutes. Once of the major HCFC substitutes was saturated HFCs (HFC-245fa in North America and HFC 365mfc/227ea in parts of Europe). In Japan, there was some hope that super-critical CO_2 would signal the way forward but this has remained rather a niche technology. CO_2 (water) blown foams have also been adopted in some areas but the quality of foams has been variable, especially from a thermal perspective. Such foams have, however, found widespread use as low density, gap filling foams to counter air infiltration in residential buildings. These foams tend to be completely open celled and do not offer particular value in other applications. The lack of a good low-GWP solution is reflected in the graph below which shows that the actual/projected avoided impacts are considerably lower than would be associated with a true low-GWP solution.

Although the size of the PU spray foam market in Article 5 Parties was relatively small in 1990, the graph below illustrates the substantial growth than has occurred in the sector since then. The graph also illustrates that the phase-out of HCFCs is still some way off since projections out to 2020 continue to indicate that the fact that the complete avoidance of ODS consumption is not yet predicted.

This is also reflected in the assessment of climate impacts, which are also sub-optimal, as they are in other non-Article 5 regions.

4.5.2 Commercially available alternatives to Ozone Depleting Substances

The commercially available technologies have been largely referenced already in the narrative, but can be summarised as follows:

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Spray foam			
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

It is important to note that the impacts of the saturated HFCs have been reduced by co-blowing with CO_2 (water) in order to deliver a lower overall global warming impact. However, one of the other major drivers has been to reduce cost. As will be seen in Section 4.5.3, this may be an important approach for the future. It should also be noted that although hydrocarbons with appropriate boiling points are available, they are not currently seen as ‘options’ for this sector because of process flammability risks.

By contrast, HCOs (most notably methyl formate) have been used for some PU spray work. The potential of supplying the system to site as blended polyol is believed to contribute to the management of risk, but it is still unclear whether the hazards seen with hydrocarbons in confined spaces have been avoided using the slightly less flammable methyl formate. Work continues in this area, although some systems are already being used commercially. The performance of these ODS alternatives against the criteria for this report can be summarised as follows:

	HFC-245fa	*HFC365mfc/227ea*	*Super-critical CO_2*	*CO_2(water)*	*Methyl Formate*
Proof of performance	+++	+++	++	++	+
Flammability	++	+(+)	++	+++	--
Other Health & Safety	+	+	+	-	0
Global Warming	--	---	++	++	++
Other Environmental	0	0	+	++	-
Cost Effectiveness (C)	++	++	0	++	0
Cost Effectiveness (O)	--	--	+	++	++
Process Versatility	++	++	+	+	+

4.5.3 Emerging alternatives

Alongside the appliance sector, the PU spray foam sector is attracting the most interest for potential adoption of the unsaturated HCFCs/HFCs. The rapid growth rate for the sector overall, the absence of serious low-GWP contenders and the fact that relatively high emission rates make the climate impact more immediate all align to encourage the manufacturers to focus on this application.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Spray foam			
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

The cost of the alternatives remains the key question but this consideration is slightly diffused by the fact that the CO_2 (water) technology developed around HFC-245fa and HC-365mfc/227ea looks transferable to the unsaturated blowing agents as well. Manufacturers are in the process of field trials and the development of fairly sophisticated life cycle assessments to ensure that they have assessed the environmental impacts correctly. The co-blowing solution does not detract significantly from the overall thermal performance of the foam and the introduction of a low-GWP solution of this type would clear the way for widespread use of PU spray foam in a wide variety of refurbishment applications over the next 30-50 years as global attention focuses increasingly on building energy efficiency in existing stock. A summary of these blowing agents against the report criteria is as follows:

	HFO-1234ze(E)	*HFO-1336mzzm(Z)*	*HFO-1233zd(E)*	*AFA-L1*
	gaseous	*liquid*	*liquid*	*liquid*
Proof of performance	0	++	++	0
Flammability	++	+++	+++	+++
Other Health & Safety	+	+	+	+
Global Warming	+++	+++	+++	+++
Other Environmental	+	+	+	+
Cost Effectiveness (C)	++	++	++	++
Cost Effectiveness (O)	--	--	--	--
Process Versatility	+	++	++	+

4.5.4 Barriers and restrictions

Since the future of the sector rests largely on the emerging technologies, the main barriers relate to the economics and availability of the unsaturated blowing agents. Much of the PU spray foam activity in China remains reliant on HCFC-141b and there is reluctance to make a transition to a sub-optimal solution when an emerging technology could out-perform it within 5 years. Various strategies are being considered including a two-step option via saturated HFCs. However, there is a need to gain commitment to the second conversion at the outset.

4.6 Polyurethane – in-situ/block

One of the enduring advantages of polyurethane chemistry in general, and polyurethane foams in particular, is their ability to meet a broad range of applications. Since these applications can be diverse, ranging from cavity filling (e.g. buoyancy on leisure boats) to the fabrication of complex shapes required for pipe and flange insulation, the in-situ and block processes provide a resource to meet these needs. Self-evidently, these applications are also difficult to track in any organised way since they vary so much. Nevertheless, it is possible to track the manufacturing facilities that provide these products and services.

4.6.1 Historical perspective (including non-Article 5 / Article 5 Party differences)

Once again, the traditional blowing agent for these applications was CFC-11. It offered the versatility and the tolerance to be able to deal with the wide range of applications described. Accordingly, the natural replacement for CFC-11 was HCFC-141b which was the closest to a drop-in solution available at that time. However, even in the 1990-2000 period, there were a few block applications which were able to switch directly to hydrocarbons. Another application which moved to hydrocarbons directly was pipe-in-pipe which is broadly an in-situ process used for district heating pipe manufacture. These pipes had been particularly widely used in the centralised economies of the former Soviet Union, but have been more recently growing as a result of the growth in micro-generation (small-scale CHP).

For non-Article 5 Parties the switch from ozone depleting substances was generally smooth and by 2005 most technologies were based on ODS substitutes, as shown in the graph above. However, when the climate impact is considered in the second of the two graphs (below), it is clear that one of the significant transitions was to relatively high-GWP substitutes, resulting in some missed climate opportunities which persist to the present day. The estimate of these is approximately 200 million tonnes CO_2-eq across the non-A5 regions. Moving forward, it is estimated that a further 25 million tonnes CO_2-eq of climate impact could be avoided by prompt action to introduce low GWP options in this sector.

For block and in-situ foams in Article 5 regions the application area are once again varied, but include applications not widely seen in non-Article 5 regions. These include such items as thermoware, which are designed for keep food insulated from the ambient conditions. The graph below illustrates that the phase-out of CFC-11 in these enterprises was relatively slow and that the use of HCFC-141b remains fairly widespread and is likely to do so until at least 2020. This reflects the reality that this sector is heavily populated with small and micro enterprises, making the economies of scale unattractive for conversion. These enterprises have often been captured as umbrella projects centre around the systems houses that serve them. Indeed, a similar approach is likely to be adopted in a number of HCFC Phase-out Management Plans (HPMPs) over the next 5-10 years.

Unsurprisingly, the ability to avoid high-GWP solutions has also been lacking in a number of these operations. It is estimated that around 315 million tonnes CO_2-eq has been missed as a result of the absence of a cost-effective low-GWP solution and a further 50 million tonnes CO_2-eq will be missed in the period to 2020 without further action.

As will be seen in the following sub-sections, the technical alternatives do exist, but the deployment of those technologies remains a challenge.

4.6.2 Commercially available alternatives to Ozone Depleting Substances

The commercially available alternatives to HCFCs in the in-situ and block sectors are summarised in the following table:

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Insulated pipes (pipe-in-pipe for district central heating systems)and other in-situ 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		

As with other thermal insulation sectors, saturated HFCs are used in block foams with a CO_2 (water) co-blowing agent to limit climate impact and also to optimise the cost/performance relationship. It has generally been found that levels of saturated HFC can be lowered in these formulations to around 50-60% of the blowing agent mix without having a detrimental effect on thermal performance. The blowing agent criteria for block and in-situ foams are shown below. In some instances, more than one rating is providing reflecting the fact that there is a disparate set of processes represented in this category.

	c-pentane	*n-pentane*	*HFC-245fa*	*HFC365mfc/227ea*	*CO_2(water)*
Proof of performance	+/++	+/++	++	++	++
Flammability	---	---	++	+(+)	+++
Other Health & Safety	0	0	+	+	-
Global Warming	+++	+++	--	---	++
Other Environmental	-	-	0	0	++
Cost Effectiveness (C)	--	---	++	++	++
Cost Effectiveness (O)	++	+++	--	--	+
Process Versatility	++	++	++	++/+++	+/++

4.6.3 Emerging alternatives

In this instance, the Task Force has chosen to categorise methyl formate in the emerging alternative category. This reflects the fact that some of the applications across the sector have yet to be trialled using this HCO blowing agent. There are expected to be some limitations based on densities achievable and risks of corrosion with some equipment, but the availability of a relatively low cost, low-GWP solution with lower flammability than the pentanes may still prove of relevance for the sector going forward.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Block foams for various applications including panels, pipe insulation section, etc			
HCO (Methyl Formate)	Low GWP	Higher density required	Density increase necessary through role of MF as a solvent
Liquid Unsaturated HFC/HCFCs (HFOs	Low GWP	High operating costs	Trials in progress
	Non-flammable		

The option of liquid unsaturated HCFCs/HFCs in this sector is legitimate, but there is some concern that price and geographic availability may be significant limiting factors. Again, co-blowing with CO_2 (water) may prove helpful for cost reasons, but uptake is expected to be more limited than in other sectors of the foam industry. The following table shows an assessment against the report criteria:

	Methyl Formate	*HFO-1336mzzm(Z)*	*HFO-1233zd(E)*	*AFA-L1*
		liquid	*liquid*	*liquid*
Proof of performance	0/+	++	++	0
Flammability	--	+++	+++	+++
Other Health & Safety	+	+	+	+
Global Warming	+++	+++	+++	+++
Other Environmental	+	+	+	+
Cost Effectiveness (C)	++	++	++	++
Cost Effectiveness (O)	--	--	--	--
Process Versatility	+	++	++	++

4.6.4 Barriers and restrictions

One of the major barriers to transition in this sector is the size and location of the enterprises involved. The provision of sophisticated low-GWP alternatives does not extend easily to these more diffuse networks and the effectiveness of transitions relies massively on the competence and commitment of the systems houses supplying the small and micro-enterprises. Efforts are needed to raise the profile of these operations with blowing agent technology providers and their supply networks.

4.7 Polyurethane – integral skin

Integral skin foams are the one group of foams using HCFCs and saturated HFCs which are not primarily used for thermal insulation purposes. They sub-divide into two types – 'rigid integral skin' (typically items such as steering wheels in automobiles) and 'flexible integral skin' (typically covering items such as shoe soles and some packaging foams). As the name suggests, the primary feature of integral skin products is their ability to encapsulate a relatively low density core (for weight saving purposes) with an integrated skin which is made from the same material and in the same process. As a polymer, polyurethane is particularly versatile in forming a resilient skin when moulded and this provides a level of utility which is rarely seen in other product types.

4.7.1 Historical perspective (including non-Article 5 / Article 5 Party differences)

As with many of the other foam sectors, PU Integral Skin foams relied on CFC-11 as their blowing agent in the pre-1990 period. With thermal performance not being a primary requirement, the blowing agent was chosen more for its ability to process well and to be used safely. Hence boiling points and flammability limits were key. When the CFC-phase-out was mooted in the sector, the natural transition was to HCFC-141b, even though there was some concern initially about its potential for limited flammability. One other characteristic to consider is the fact that most of the blowing agent is lost from these products within the first two years. Hence any environmental impacts are magnified by their rapid pathways to the surroundings. Other options used in the sector have been HCFC-22 and or HCFC-22/142b blends.

The Foams Technical Options Committee has not routinely monitored consumption in this sector of use, since one of the initial purposes of tracking consumption was to estimate long-term banks in products. However, as the focus moved to quantifying emissions, there have been some one-off assessments for the purposes of reports like this. Nevertheless, there is no set of base data available at this time which allows the assessment of missed opportunities and future potential avoidance. The Task Force is considering an attempt to fill this data gap in time for the Final Report in November 2013, although source data such as the AFEAS data collection reports have collected information at relatively high level – e.g. closed cell and open cell. It seems likely that rigid and flexible integral skin may have been categorised differently within this data set making it difficult to isolate the tonnages of blowing agent allocated to each type. This serves to illustrate that product definition remains a challenge in this sector.

Of the estimates that do exist, the energy-absorbing automotive market has been believed to consume around 50,000 tonnes of PU per year. However, formulations in the sector use typically less than 5% by weight of blowing agent making the annual consumption of blowing agent relatively modest at 1,500-2,500 tonnes per annum. Although there are a large number of other Integral Skin Foam applications to consider, it is estimated that no more than 10,000 tonnes goes to this sector annually, making its significance relatively modest.

Concern over flammability has limited the use of hydrocarbons in this application, but it is known that some manufacturers have adopted the technology. Other options adopted following the phase-out of HCFCs have included HFC-134a and HFC-245fa. These might be considered as detrimental choices from a climate perspective but produce high quality products, especially in the shoe sole application. The other technology option that has been the focus of much attention has been CO_2 (water). However, early experiences with this technology were dominated by poor skin quality. The use of in-mould coatings was trialled but the economics of this approach were understandably less favourable. Several major systems houses have worked further on this technology since and acceptable commercial systems are no available. The following section looks at the commercially available options currently.

4.7.2 Commercially available alternatives to Ozone Depleting Substances

The following table lists the commercially available options as of today:

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
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 or HFC-245fa	Used to give required skin in town shoes	High GWP/Cost	

The specific ranking of these blowing agent options is shown in the table below.

	n-pentane	*HFC-134a*	*HFC-245fa*	*CO_2(water)*
Proof of performance	++	++	+	++
Flammability	---	+++	++	+++
Other Health & Safety	0	+	+	-
Global Warming	+++	---	---	++
Other Environmental	-	0	0	++
Cost Effectiveness (C)	---	++	++	++
Cost Effectiveness (O)	+++	--	--	+
Process Versatility	++	++	++	0

4.7.3 Emerging alternatives

The area of most interest with respect to emerging technologies is the potential use of oxygenated hydrocarbons (HCOs). Both methyl formate and methylal are being considered for these applications and the early indications are that they could be significant future alternatives in the sector. Although both a flammable, the level of flammability is less than that associated with pure hydrocarbons. There is also the potential that systems houses may be able to formulate blended systems in such a way as to avoid flammability issues in the workplace. One area of concern for methyl formate is the potential corrosion of moulds, but at the levels of addition, this may not be a problem in practice. The other issue relating to both HCOs the high solvency power of the blowing agents which could lead to some softening of the skins. The following table summarises the issues:

HCFC REPLACEMENT OPTIONS FOR INTEGRAL SKIN PU FOAMS FOR TRANSPORT & FURNITURE APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Integral skin foams			
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			
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

Again, the specific performance ranking of the blowing agents is shown in the table below:

	Methylal	*Methyl Formate*
Proof of performance	+	++
Flammability	--	--
Other Health & Safety	0	0
Global Warming	++	++
Other Environmental	-	-
Cost Effectiveness (C)	+	0
Cost Effectiveness (O)	++	++
Process Versatility	+(+)	+(+)

It is noteworthy to mention that unsaturated HFCs/HCFCs are not seen as a realistic emerging technology in this sector because of the cost implications and the lack of any significant performance enhancement.

4.7.4 Barriers and restrictions

There are no fundamental barriers to the introduction of the emerging technologies, although pilot projects on the pre-blending of HCOs in polyols will be necessary. There have been some concerns in the past about the implications of the limited supplier base and access to intellectual property, although these have been largely addressed. However, the biggest challenge to the replacement of any remaining use of ozone depleting substances will be the roll-out of these technologies on a sufficiently widespread basis.

If the widespread introduction of HCOs can be successful, there is likely to be the gradual replacement of both saturated HFCs (HFC-134a and HFC-245fa) and CO_2 (water) blown technologies. The replacement of saturated HFCs, will certain deliver some additional climate benefits.

4.8 Extruded polystyrene - board

Extruded polystyrene board is unique amongst the foam sectors considered in this report in that it is blown exclusively with gaseous blowing agents. This is a consequence of the extrusion process. Extruded polystyrene (XPS) should not be confused with expanded polystyrene (EPS – also sometimes called 'bead foam') which uses pre-expanded beads of polystyrene containing pentane. EPS has never used ozone depleting substances and is seldom addressed in UNEP Reports for the Montreal Protocol. XPS is used primarily as a building insulation and often competes with PU Boardstock. Its particular competitive advantage is in relation to its moisture resistance which makes it especially useful for under-floor insulation applications. There is another form of XPS known as 'Sheet' which is typically used for non-insulating applications such as leisure products (e.g. surf boards) and packaging materials. XPS sheet exited from CFC use early in the history of the Montreal Protocol and has used hydrocarbons almost exclusively ever since.

4.8.1 Historical perspective (including non-Article 5 / Article 5 Party differences)

The blowing agent of choice for XPS manufacturers in the pre-1990 period was CFC-12. Although this was allocated the same ozone depletion potential as CFC-11, the global warming potential was significantly higher, being well in excess of 10,000 when assessed over a 100 yr time horizon. Combined with the relatively significant losses of blowing agent during the processing of XPS, this made the product the focus of close attention from the introduction of the Montreal Protocol in 1987. It also put a priority on the early identification of alternatives.

Initial work in the global XPS industry focused on the switch to HCFCs and, in particular, combinations of HCFC-22 and HCFC-142b. HCFC-22 was already established as a readily-available, well-studied alternative based on its widespread use as a refrigerant. However, the drawback was that HCFC-22 was more soluble in polystyrene than CFC-12 and would defuse from foam cells more easily. The purpose of using HCFC-142b was therefore to ensure that sufficient blowing agent remained in the product over the lifecycle of the product to deliver reliable thermal performance.

Since HCFC-142b was typically more expensive than HCFC-22, the ratio of the blends used tended to reflect the priority that was being placed on long-term thermal performance.

The limited missed opportunity from an ozone perspective, as shown in the graph above, is testimony to the rapid transition from CFC-12 that was managed by the industry in the decade from 1990 to 2000. However, the transition from HCFCs proved to be considerably more challenging.

The major point to emerge in the period of HCFC phase-out was just how varied the markets for XPS were in different regions of the world. The North American market was primarily in sheathing products for the timber-framed residential market. This is a highly cost-sensitive market with large surface areas of relatively thin board being applied. This contrasted significantly with the European market where products were primarily for the commercial building market, requiring thicker profiles with higher added value. In Japan, the market was something of a hybrid of these two extremes, but was also governed by fire codes that would permit the use of hydrocarbon blowing agents in products for some applications. This opened up an alternative which was not likely to be available for either Europe or North America.

The graph above illustrates the dominance of the global warming potential of CFC-12 in the 1990-2000 period, even though it was in use for a relatively short time. However, with HCFC-22 and HCFC-142b themselves having global warming potentials above 1500, the climate impact was significant. The impact was also more long-lasting than it might have been because of the differences in regional approach being proposed and the difficulties that this created for the multi-national producers. For example, in Germany (by far the largest market for polystyrene insulation in Europe), there was substantial pressure on an early phase-out of HCFCs. This led to the development of CO_2 blown technology (in several variants) for the more tolerant European product range. Even then, the technology could not make all grades of product, involved substantial capital cost and also was governed by a substantial base of patents. This was not unreasonable based on the research and development investments that had been made.

The emergence of such technologies did not help solve the transition challenge in North America because the product portfolio was totally different and the costs the industry could absorb were also more limited. This left the North American industry looking primarily at variants of gaseous HFC solutions including HFC-134a and HFC-134a/152a blends. Within the blend approach, HFC-134a was seen to fulfil the former role of HCFC-142b, while HFC-152a would be more emissive, in similar fashion to HCFC-22. Although there would be more emission in the short term from HFC-152a, this was compensated for by the relatively low GWP of HFC-152a (~ 150). The emission rates did, however, raise other issues, such as the impact of local VOC regulations. The net result of these uncertainties was that transition out of HCFC-142b and HCFC-22 did not occur in North America until 2009/10, with the alternatives not having a substantially better climate profile than the HCFCs they replaced.

The overall lost opportunity arising from these transitional challenges is in the order of 2.4 billion tonnes making it far and away the most significant individual sector in its contribution to the ‘missed opportunity' discussion. However, the converse argument is that its prompt action over CFC-12 was one of the greatest contributors to early gains for the Montreal Protocol.

The development of XPS markets in Article 5 countries has been more difficult to track, but the graph below illustrates that close to exponential growth has occurred in the period from 1990 to date and this is expected to continue through until 2020. One of the main engines of this growth has been China, where the focus on building energy efficiency, coupled with the relatively low investment levels for small extruders has created a network of regional and sub-regional producers.

As much of this growth has taken place since 2005, the plants installed have tended to bypass CFCs and are largely based on HCFC-142b and HCFC-22. However, as a result of cost and availability, HCFC-22 has understandably been the dominant component of most blends. The challenge now facing the industry in Article 5 countries is which of the technology options being practiced in non-Article 5 Parties should be followed. The use of HFC blends represents the least-cost transition from an investment perspective, but the adoption cost perspective. However, they do raise important issues in terms of product flammability. The graph below illustrates the on-going impact of these selection decisions on past and future climate impacts.

The implication of previous decisions may have led to a missed opportunity in this sector of approximately 1.18 billion tonnes of CO_2-eq in Article 5 Parties, although it may be harsh to convey the situation in these terms bearing in mind the uncertainties about substitutes that continue to exist. The opportunity going forward offers the prospect of climate impact avoidance in the order of nearly 900 million tonnes of CO_2-eq. in the period to 2020, although achieving this will depend on the availability of meaningful alternatives in due time.

4.8.2 Commercially available alternatives to Ozone Depleting Substances

The following table illustrates the commercially available alternatives in the extruded polystyrene sector:

HCFC REPLACEMENT OPTIONS FOR XPS FOAM			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Extruded Polystyrene Foams			
Butane	Low GWP	Highly flammable	
	Low operating costs		
HFC-134a/HFC-152a	Non-flammable	High GWP	
	Good foam properties, especially thermal performance	Medium/high operating costs	
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

As described earlier in this section, these three alternatives describe the primary options available in each of the three main non-Article 5 regions of the world. It should be noted that blends of saturated HFCs (HFC-134a/HFC-152a) are substantially used in Europe and, to a lesser extent in Japan, primarily by smaller producers who do not have the access to CO_2 technology or serve markets that cannot accept the flammability of hydrocarbon solutions. The assessment of these blowing agents via the criteria of this report is shown in the following table:

	butane	*HFC-134a/ HFC-152a*	*CO_2 with ethanol or DME*
Proof of performance	++	+++	++
Flammability	---	+++	++
Other Health & Safety	0	+	+
Global Warming	+++	---	+++
Other Environmental	-	0	0
Cost Effectiveness (C)	--	++	---
Cost Effectiveness (O)	+++	--	++
Process Versatility	++	++	+

4.8.3 Emerging alternatives

HCFC REPLACEMENT OPTIONS FOR XPS FOAM			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Extruded Polystyrene Foams			
Gaseous unsaturated HFCs (HFOs)	Low GWP	High unit cost	Semi-commercial availability – under evaluation

For all the reasons expressed in this section, there is considerable interest in the potential of unsaturated gaseous HCFCs/HFCs as either blowing agents or co-blowing agents with HCOs such as ethanol or dimethyl ether (DME). The technological solution has the potential of becoming a relative standard in the industry, but the key deciding factor in that respect will be the cost. This aspect is reflected in the criteria assessment below:

	HFO-1234ze(E)
	Gaseous
Proof of performance	+
Flammability	++
Other Health & Safety	+
Global Warming	+++
Other Environmental	+
Cost Effectiveness (C)	++
Cost Effectiveness (O)	--
Process Versatility	++

4.8.4 Barriers and restrictions

For the HCFC consuming market in China and elsewhere, the challenge is to decide whether there is a transitional option that moves to a low-GWP alternative before the availability of unsaturated HFCs such as HFO-1234ze(E) is secured. It is clear that hydrocarbons would have been an obvious option and that would have been a high priority for a number of producers in China operating under the HCFC Phase-out Management Plan there. However, in recent years, there have been a series of fires (mostly in the construction phase of major building projects) which have caused a reaction against organic insulation materials in general and XPS in particular. One of the underlying problems has been the inconsistency in use of flame retardants within XPS formulations, with recycled feedstock not being properly characterised in some instance. The XPS industry is making a strong case that properly formulated XPS board can be used safely throughout its lifecycle, but these developments have created a further barrier to the introduction of hydrocarbons as blowing agents at this sensitive time.

The introduction of unsaturated HFCs will certainly avoid such a controversy, but the availability of such technology in Article 5 Parties is uncertain – particularly when the technology is yet to be commercially adopted elsewhere. There is also the unanswered question concerning the impact on cost. A temporary switch to saturated HFC blends could ensure that the Montreal Protocol objectives are met, but this will do little to benefit the climate when over 1 billion tonnes of CO_2-eq could be avoided by a more benign solution.

4.9 Phenolic foams

Phenolic foams are manufactured by a number of different processes, many of which shadow those already discussed for polyurethane foams. The largest markets for the product are as phenolic boardstock (manufactured by continuous lamination) and block foams, used primarily for fabricating pipe work insulation. Although the product made an entry into the North American market in the early 1980s, the particular technology was dogged with problems. As a result, there is little use of phenolic foam in that region today. However, successful phenolic boardstock technologies emerged in both Europe and Japan, with sales of the product continuing to grow, not only because of overall increases in the demand for thermal insulation, but also because of gains in market share. Phenolic foam’s main competitive advantage rests in its intrinsic fire and smoke properties. However, since it is made by an emulsion process, it also offers smaller cells which result in improved thermal performance. More recently, the product has begun to emerge on the Chinese market - in part as a response to concerns over recent fires.

The use of phenolic foam as pipework insulation also stems from the intrinsic fire and smoke properties of the product and the growth of the product's use has been particularly strong in regions where internal fire regulations are strict or where the high rise nature of construction requires additional fire precautions.

4.9.1 Historical perspective (including non-Article 5 / Article 5 Party differences)

Apart from the occasional phenolic block foam plant, the vast majority of installed phenolic foam capacity was in non-Article 5 regions in the pre-1990 period. As with other technologies, CFC-11 was the predominant blowing agent as phenolic foam technologies became established during the mid/late 1980s. In line with other technologies, the phenolic foam industry was able to manage a CFC transition to HCFC-141b in the mid-1990s. However, there was more concern at that stage about moving directly to hydrocarbons (as the bulk of the PU boardstock industry had done) for fear of compromising the intrinsic fire properties. Nevertheless, when the subject was re-visited in the late 1990s ahead of the pending HCFC phase-out, it was found that the fears were unsubstantiated and the fire properties held up, even with hydrocarbon blowing agents inside. However, hydrocarbon was not possible for discontinuous block foam plants because of process risks and saturated HFCs (typically HFC-365mfc/227ea) were adopted instead.

In one specific phenolic boardstock technology, 2-chloropropane had been used as an alternative to CFC-11from the outset. Although the blowing agent is chlorinated, it has such a short atmospheric lifetime that it has never been a candidate for inclusion under the Montreal Protocol – along with a number of other short-lived compounds. Interestingly, 2-chloropropane could therefore have been used as an alternative to HCFC-141b in the earlier transitions, but this never widely trialled – possibly because of patent constraints at the time.

The graph below illustrates the impact of relatively trouble-free and timely transitions across the industry. The delay in the implementation of non-ODS substitutes will have resulted in some contribution to the 7,500 ODP tonne 'missed opportunity', but the proportion will have been small.

The equivalent graph (overleaf) for climate impacts in non-Article 5 countries shows a similar, and relatively non-controversial, transitional impact. However, the persisting shortfall against the 'best available option' is indicative of the continuing use of saturated HFCs in the phenolic block foam sector. Since most of this product is destined for pipe insulation, efforts have been made to find alternative manufacturing strategies to bypass the need for HCFCs. More recently, in markets where there is sufficient demand for pipe insulation of a specific dimension, it has been possible to transfer substantial portions of the previous production to continuous pipe section laminators. This, in turn, has enabled a shift from saturated HFCs to hydrocarbon (typically pentane) blowing agents.

The overall missed opportunity in climate terms for phenolic foam is estimated to be less than 50 million tonnes CO_2-eq in non-Article 5 countries. Moving forward the maximum additional saving achievable in the period through to 2020 is likely to be no more than 5 million tonnes CO_2-eq.

For Article 5 regions, the first thing to note is the relatively low level of consumption involved. Indeed, the very few block foam manufacturers in the pre-2000 period elected to run their plants through to CFC phase-out and then close them down. This explains the lack of any actual consumption avoided in the decade from 1990-2000.

From 2000 onwards, new capacity began to emerge, but this was either already based on HCFCs (for discontinuous processes) or on hydrocarbons for continuous lamination processes. With phenolic boardstock demand being the continuing driver of growth, particularly in China, the significance of any remaining HCFC use has continued to diminish. This is also reflected in the climate assessment shown in the following graph. The dominance of hydrocarbon in more recent years means that there is now little to gain from a climate perspective for further action in the phenolic foam sector, with maximum potential savings being less than 300,000 tonnes of CO_2-eq.

Perhaps one point to retain in mind throughout these discussions is that the analysis has not tried to adjust for variations in energy efficiency between technology options. This would have been too complex in sectors where the use of insulation foams is not pre-determined. However, it is worth recalling that there could still be substantial interest in phenolic boardstock manufacturers considering solutions around unsaturated HFC/HCFC technologies if they were to deliver improved thermal performance, particularly in applications where space is constrained.

4.9.2 Commercially available alternatives to Ozone Depleting Substances

The following table sets out the commercially available alternatives for the phenolic foam sector:

HCFC REPLACEMENT OPTIONS FOR PF FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Continuous processes (including flexibly-faced lamination and pipe section manufacture)			
n- pentane/iso-pentane	Low GWP	Highly flammable	High incremental capital cost
	Low operating costs		Industry standard
	Good foam properties		
HFC-365mfc/277ea	Non-flammable	High GWP	
	Good foam properties	High operating costs	
2-chloropropane	Low GWP	Negligible ODP	
	Non flammable		
Block foams for various applications including panels, pipe insulation section, etc			
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)	

The lack of low-GWP alternatives for discontinuous block foams signals the need for further work in this area. However, the ranking of these options against the report criteria can be summarised as follows:

	n-pentane i-pentane	*2-chloropropane*	*HFC-365/227ea*
Proof of performance	+++	+++	+
Flammability	---	0	++
Other Health & Safety	0	0	+
Global Warming	+++	+++	---
Other Environmental	-	0	0
Cost Effectiveness (C)	---	-	++
Cost Effectiveness (O)	+++	+	--
Process Versatility	++	+	++

4.9.3 Emerging alternatives

As with other sectors, there is considerable focus on the potential of unsaturated HFCs/HCFCs.

HCFC REPLACEMENT OPTIONS FOR PF FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	**PROS**	**CONS**	**COMMENTS**
Continuous processes (including flexibly-faced lamination and pipe section manufacture)			
Unsaturated HFC/HCFC liquids	Non-flammable	Low conversion costs	Limited trials at this stage
	Good foam properties	High operating costs	
Block foams for various applications including panels, pipe insulation section, etc			
Unsaturated HFC/HCFC liquids	Non-flammable	Low conversion costs	Limited trials at this stage
	Good foam properties	High operating costs	

One drawback for the adoption of this technology in phenolic foam is that there is no CO_2(water) co-blowing to offset some of the cost. Another option might be to use unsaturated HFCs/HCFCs as components of blends with hydrocarbons or other blowing agents. However, care will need to be taken with discontinuous block foams to avoid process flammability issues. The following table summarises the current status of these emerging options with respect to phenolic foam.

	HFO-1336mzzm(Z)	*HFO-1233zd(E)*	*AFA-L1*
	liquid	*liquid*	*liquid*
Proof of performance	0	-	--
Flammability	+++	+++	+++
Other Health & Safety	+	+	+
Global Warming	+++	+++	+++
Other Environmental	+	+	+
Cost Effectiveness (C)	++	++	++
Cost Effectiveness (O)	--	--	--
Process Versatility	+(+)	+(+)	+(+)

4.9.4 Barriers and restrictions

The main technical barriers to the transition to unsaturated HFCs/HCFCs have already been set out in the previous section and these need to be addressed in a first stage assessment. However, even if the technical hurdles are overcome, the investment case may not be compelling for the transition out of saturated HFCs in the discontinuous block foam sector in view of the small quantities consumed. It may require market pressure on the continued use of saturated HFCs or evidence of significant thermal performance improvements to provide additional support for the next transition step.

5 Fire protection alternatives to Ozone Depleting Substances

Executive Summary

Ozone depleting substances (ODS) used as fire extinguishants possess unique efficacy and safety properties that serve as a basis of fire protection systems where the application of water (by hose stream or sprinkler heads), dry chemical agents, or aqueous salt solutions is problematic. This is especially true in high-value, commercial electronics environments and in military systems, to name only two of many applications where such systems had many serious technical disadvantages.

Commercially available, technically proven alternatives to ODS for Fire Protection have been developed and include: halocarbon agents, e.g., HFCs and a fluoroketone (FK); inert gases, e.g., nitrogen and argon and their blends; carbon dioxide; water mist technologies; inert gas generators; fine solid particles (powders); dry chemicals; and aqueous film-forming foam. Several environmentally sound alternatives to ODS fire extinguishing agents for both total flooding and local applications uses have been introduced to the market. If an environmentally sound alternative agent works in any specific application, there is no barrier to its adoption other than economic considerations. Additional environmentally sound alternatives are presently under development that may increase the number of applications where environmentally sound alternatives are technically viable.

The production of PFCs and HFCs for use in fire extinguishing systems and portable fire extinguishers as well as the production of alternatives (without negative environmental impacts) to these agents for uses in the same applications is performed by very few manufacturers, all of whom treat the information on their historical, present and projected production as proprietary. Without a clear understanding of these production levels for the alternatives without negative environmental impacts, and also for the PFCs and HFCs, there is no basis for making a sound judgment about the overall utility of any alternatives in replacing PFCs and HFCs in the fire protection sector.

Nevertheless, we can say that the fire protection community has acted responsibly in dealing with what have turned out to be unsuitable alternatives from an environmental impact perspective. The availability of several HFCs that collectively could perform as well as the PFCs in certain applications, and at the same time present a more favorable environmental impact, led to the collapse of the use of PFCs in those applications.

However, the need for chemical agents remains as inert gases, water mist and other agents are not suitable for many fire protection applications that had previously used halon. HFCs have filled that role and, since about 2005, a fluoroketone (FK) has increasingly become more accepted. There is no evidence to suggest that this FK is or is not living up to the expectations of the fire protection industry, which is still evaluating alternatives that have low environmental impacts.

The use of HCFCs in fire protection is declining, with the only total flood agent being provided for the maintenance of legacy systems that are themselves phasing out. Only HCFC-123 is used in any quantity in portable extinguishers and if the development of 2-Bromo-3,3,3-trifluoropropene proves to be commercially successful, it would be the natural replacement for it and halon 1211 – particularly in the aviation industry.

5.1 Introduction

This section addresses the requirements of “Decision XXIV/7: Additional information on alternatives to ozone-depleting substances” (given in chapter 1) as it pertains to fire protection. The Halons Technical Options Committee (HTOC) has provided these responses at the request of the Task Force addressing the Decision.

The production and consumption of halons used in fire protection ceased in non-Article 5 Parties on January 1, 1994 and ceased elsewhere on January 1, 2010. The production and consumption of HCFCs for use in fire protection continues. Ozone depleting substances (ODS) used as fire extinguishants possess unique efficacy and safety properties that serve as a basis of fire protection systems where the application of water (by hose stream or sprinkler heads), dry chemical agents, or aqueous salt solutions is problematic, especially in high-value commercial electronics environments and in military systems, to name only two of many applications where such systems had many serious technical disadvantages.

Development of alternatives to ODS fire extinguishing agents, beginning in the early 1990's, has progressed steadily and is now relatively mature. Interest remains, however, in development of new alternatives that offer further advancements in efficacy, safety, and environmental characteristics. This section summarizes the alternatives to ODS fire extinguishing agents that have achieved a significant presence in the marketplace, their key physical, safety, and environmental characteristics, and the status of prospective new alternatives that have yet to be commercialized.

The following terms, used in the tables below, have the meanings indicted.

Efficacy refers to suitability for fire extinguishing. Values of minimum design concentrations (MDC) are given for Class A and Class B hazards. [1]

Agent toxicity is benchmarked against the maximum agent concentration in air for which use in normally occupied spaces is allowed in many jurisdictions. The exposure limit for halogenated agents is related to inhalation toxicity and the risk of causing an adverse cardiac effect. The exposure limit is usually one of the following: [2]

(a) the NOAEL (No Observed Adverse Effect Level) value; or
(b) the LOAEL (Lowest Observed Adverse Effect Level) value; or
(c) a value based on PBPK (physiologically-based pharmaco-kinetic) modeling.

For the use of inert gas agents, other than carbon dioxide, in normally occupied spaces, the limiting agent concentration is related to the minimum allowed residual oxygen concentration achieved after discharge. On this basis the limiting inert gas agent concentration has been set at 52 vol% (See ISO 14520-1).

Carbon dioxide is not suitable for use as a total flooding fire extinguishing agent in normally occupied spaces owing to its toxicity.

Safety characteristics are taken to mean with respect to aspects of an agent that relate to safe operational and handling activities.

Environmental characteristic refers to ozone depletion potential (ODP) and GWP (100-year Global Warming Potential) or other characteristics, if applicable.

The use of ODS in fire protection applications in high ambient temperatures and high urban density cities does not require special attention, i.e. they have no impact on the use.

The use of ODS in fire protection applications at low ambient temperatures (below -20 °C) is addressed.

[1] See ISO 14520 parts 5, 8, 9, 10, 12, 13, 14, and 15

[2] See ISO 14520-1:2006, Annex G (informative), Safe personnel exposure guidelines.

5.2 Response to Question 1 (a)

5.2.1 Commercially Available, Technically Proven Alternatives to ODS for Total Flooding Fire Protection Using Fixed Systems

In the tables below, cost effectiveness is represented by an index that is benchmarked against carbon dioxide total flooding systems, averaged over a wide range of application sizes, exclusive of the cost of pipe, fittings and installation and is based on 2003 data. Owing to commercial confidentiality, it has not been possible to use more current data, but nevertheless the indices are believed to be relatively accurate.

5.2.1.1 Halocarbon Agents

Agent	FK-5-1-12	HFC-23	HFC-125	HFC-227ea
Efficacy	For use in occupied spaces MDC(A)[3] = 5.3 vol% MDC(B) = 5.9 vol%	For use in occupied spaces MDC(A) = 16.3 vol% MDC(B) = 16.4 vol% • Suitable for inerting some flammable atmospheres at concentrations below the LOAEL value. • Suitable for use at low temperatures (below -20 C).	For use in occupied spaces MDC(A) = 11.2 vol% MDC(B) = 12.1 vol%	For use in occupied spaces MDC(A) = 7.9 vol% MDC(B) = 9.0 vol%
Toxicity	NOAEL = 10 vol% LOAEL > 10 vol%	NOAEL = 30 vol% LOAEL > 30 vol%	NOAEL = 7.5 vol% LOAEL = 10 vol% • Approved for use in occupied spaces at up to 11.5 vol% based on PBPK modelling.	NOAEL = 9 vol% LOAEL = 10.5 vol% • Approved for use in occupied spaces at up to 10.5 vol% based on PBPK modelling.
	Some acidic decomposition products are formed when a halogenated fire extinguishing agent extinguishes a fire.			
Safety Characteristics	Liquid at 20 °C B.P. = 49.2 °C	Liquefied compressed gas. B.P. = -82 °C	Liquefied compressed gas. B.P. = -48.1 °C	Liquefied compressed gas. B.P. = -16.4°C
Environmental Characteristics [4]	ODP = 0 GWP = 1[5]	ODP = 0 GWP = 12 000	ODP = 0 GWP = 3400	ODP = 0 GWP = 3500
Cost-Effectiveness, avg. for 500 to 5000 m3 volume (2003 data)	~1.7 to 2.0	~2.0 to 2.3	Not available	~1.5

[3] MDC(A) and MDC(B) refer to the minimum design concentration for a Class A or Class B fire hazard.

[4] 100-year GWP, IPCC Third Assessment Report: Climate Change 2001

[5] Reported by manufacturer

5.2.1.2 Inert Gas Agents

Agent	IG-01	IG-100	IG-55	IG-541
Efficacy	For use in occupied spaces MDC(A) = 41.9 vol% MDC(B) = 51 vol%	For use in occupied spaces MDC(A) = 40.3 vol% MDC(B) = 43.7 vol%	For use in occupied spaces MDC(A) = 40.3 vol% MDC(B) = 47.5 vol%	For use in occupied spaces MDC(A) = 39.9 vol% MDC(B) = 41.2 vol%
Toxicity	52 vol% limit for 5 min. egress			
Safety Characteristics	High-pressure compressed gas up to 300 bar			
Environmental Characteristics	No adverse characteristics			
Cost-Effectiveness, avg. for 500 to 5000 m3 volume (2003 data)	~1.8	~1.8	~1.8	~1.8

5.2.1.3 Carbon Dioxide

Agent	Carbon dioxide, CO2
Efficacy	For use in unoccupied spaces Basic design concentration = 34 vol% for a "material factor" of 1. Design concentrations for specific combustible materials are determined by multiplying the basic design concentration by an applicable material factor. [6]
Toxicity	Progressively more severe physiological effects as exposure concentration increases, especially above 10 vol%. Carbon dioxide concentrations that exceed 17 vol% present an immediate risk to life. [7] Pre-discharge alarm and discharge time delay required.
Safety Characteristics	Liquefied compressed gas Storage pressure: High-pressure cylinder: 55.8 bar at 20 °C Low-pressure tanks (refrigerated): 21 bar at -18 °C Sublimes at -78.5 °C at atmospheric pressure; cold exposure hazard. Vapours are denser than air and can accumulate in low-lying spaces.
Environmental Characteristics	GWP = 1
Cost-Effectiveness, avg. for 500 to 5000 m3 volume (2003 data)	1

[6] See ISO 6183:2009

[7] See U.S. Environmental Protection Agency, "Carbon Dioxide as a Fire Suppressant: Examining the Risks," February 2000.

5.2.1.4 Water Mist Technology

Agent	Water mist
Efficacy	For use in occupied spaces. Uses ~1/10th water as a traditional sprinkler system to suppress fires, where tested.
Toxicity	None
Safety Characteristics	No adverse safety characteristics
Environmental Characteristics	No adverse characteristics
Cost-Effectiveness, avg. for a 3000 m^3 application space	~2

5.2.1.5 Inert Gas Generators

Agent	Inert gas by pyrotechnic generator
Efficacy	For use in occupied spaces.
Toxicity	None for generators that produce nitrogen or nitrogen-water vapour
Safety Characteristics	Potentially hot-gas discharge; potential hot surfaces of generator body. Insulating consideration required by generator manufacturer.
Environmental Characteristics	No adverse characteristics
Cost-Effectiveness	Not available

5.2.1.6 Fine Solid Particles (Powders)

Agent	Fine solid particles
Efficacy	For use in normally unoccupied spaces.
Toxicity	Precautions require evacuation of spaces before discharge.
Safety Characteristics	For establishments manufacturing the agent or filling, installing, or servicing containers or systems to be used in total flooding applications, United States EPA recommends the following: - adequate ventilation should be in place to reduce airborne exposure to constituents of agent; - an eye wash fountain and quick drench facility should be close to the production area; - training for safe handling procedures should be provided to all employees that would be likely to handle containers of the agent or extinguishing units filled with the agent; - workers responsible for clean-up should allow for maximum settling of all particulates before re-entering area and wear appropriate protective equipment
Environmental Characteristics	No adverse characteristics
Cost-Effectiveness	Not available

5.2.2 Commercially Available, Technically Proven Alternatives to ODS for Local Application Fire Protection Using Portable Systems

In the tables below, cost effectiveness is represented by an index benchmarked against the approximate cost of a portable carbon dioxide extinguisher unit that has a UL 10B rating.

5.2.2.1 Carbon Dioxide

Agent	Carbon dioxide, CO_2
Efficacy	For use on Class B fires Can be used on most electrically energized equipment fires.
Toxicity	High exposure risk where carbon dioxide gas accumulates in confined spaces that may be entered by personnel.
Safety Characteristics	Liquefied compressed gas Storage pressure: 55.8 bar at 20 °C Solid CO_2 (“dry ice”) sublimes at -78.5 °C at atmospheric pressure. Presents a cold-exposure hazard. Vapours usually flow to floor level so personnel exposure risk is normally low.
Environmental Characteristics	GWP = 1
Cost-Effectiveness	1

5.2.2.2 Halogenated Agents

Agent	Halogenated agents
Efficacy	For use on Class A fires For use on Class B fires For use on fires involving electrified equipment
Toxicity	Vapour exposure risk usually low. Vapour toxicity low to moderate.
Safety Characteristics	Pressurised hand-held container.
Environmental Characteristics	HFC agents: ODP = 0; GWP = 1430 to 9810 [8]
Cost-Effectiveness	Varies from about 1 to about 2

5.2.2.3 Dry Chemical

Agent	Dry chemical
Efficacy	For use on Class A fires For use on Class B fires For use on fires involving electrified equipment Dry chemical applied to some electrical or sensitive equipment may cause damage otherwise not caused by a fire.
Toxicity	Low
Safety Characteristics	Pressurised containers
Environmental Characteristics	Low environmental risk
Cost-Effectiveness	~ 0.2

[8] IPCC 4th Assessment Report: Climate Change, 2007. 1.

5.2.2.4 Water

Agent	Water, straight stream , ~9 litre
Efficacy	Where approved for use on Class A fires, water-stream extinguishers should not be used on fires involving electrified equipment or that involve materials that are reactive with water (e.g. metals). Not suitable for Class B fires. Water applied to some electrical or sensitive equipment may cause damage otherwise not caused by a fire.
Toxicity	Non-toxic
Safety Characteristics	The possibility of electrocution if used on electrically energized equipment.
Environmental Characteristics	No significant risk
Cost-Effectiveness	~0.5

5.2.2.5 Fine Water Spray

Agent	Water, fine spray
Efficacy	For use on Class A fires including use on electrified equipment up to 10 kV. Not suitable for use on materials that are reactive with water (e.g. metals). Not suitable for Class B fires. Water applied to some electrical or sensitive equipment may cause damage otherwise not caused by a localized fire.
Toxicity	Non-toxic
Safety Characteristics	No adverse characteristics
Environmental Characteristics	No significant risk
Cost-Effectiveness	~0.6 (~9 litre extinguisher unit; cost index compared to a 10B-rated CO_2 unit)

5.2.2.6 Aqueous Salt Solutions

Agent	Aqueous salt solutions, fine spray
Efficacy	For use on Class A fires not involving electrified equipment or materials that are reactive with water (e.g. metals). Suitability for use on Class B fires depends on formulation and means of delivery. Used on cooking oil fires where nozzle design limits splatter of hot oil. Salt solutions may cause damage to some electrical equipment not otherwise damaged by fire.
Toxicity	Varies from low to moderate.
Safety Characteristics	pH usually basic varying from 8 to 13. Possible short-exposure skin irritation depending on duration of exposure if wetted with agent.
Environmental Characteristics	No significant risk
Cost-Effectiveness	~0.7 to 1 (~9 litre extinguisher unit; cost index compared to a 10B-rated CO_2 unit)

5.2.2.7 Aqueous Film-forming Foam

Agent	Aqueous film-forming foam (AFFF)
Efficacy	For use on Class A fires not involving electrified equipment or materials that are reactive with water (e.g. metals). For use on Class B fires.
Toxicity	Moderate.
Safety Characteristics	pH is approximately neutral, varying between about 6.5 and 8.
Environmental Characteristics	Uncontained run-off of agent poses risks of contamination of soil, streams, and rivers.
Cost-Effectiveness	~0.6 (~9 litre extinguisher unit; cost index compared to a 10B-rated CO2 unit)

5.3 Response to Question 1 (b)

5.3.1 Alternative Total Flooding Agents Under Development For Use In Fixed Systems

One chemical producer reports that significant progress has been made on a new, but as yet undisclosed, chemical agent. Physical, toxicological, and fire extinguishing properties have not yet been published. The chemical producer has an undetermined amount of additional work to complete in order to establish efficacy and approval under national and international standards.

5.3.2 Alternative Local Application Agents Under Development For Use In Portable Systems

5.3.2.1 FK–6–1–14, C7 fluoro-ketone blend

This substitute is a blend of two C7 isomers:

3-Pentanone, 1,1,1,2,4,5,5,5-octafluoro-2,4-bis(trifluoromethyl)- 813-44-5 (55 – 65%)
3-Hexanone, 1,1,1,2,4,4,5,5,6,6,6-undecafluoro-2-(trifluoromethyl)- 813-45-6 (35 – 45%)

Currently under review for use as a streaming agent in non-residential applications. Product approval program to be completed.

5.3.2.2 2-BTP, 2-Bromo-3,3,3-Trifluoropropene, CAS#: 1514-82-5

This substitute has been under study for more than ten years.

Its environmental properties are: ODP ~ 0.0098, GWP ~ 0.007 to 0.03

It is reported by one manufacturer that research on the efficacy of 2-BTP in some applications has looked sufficiently promising to continue development to achieve final approval.

Final performance research and toxicity testing remain to be completed.

For information on 2-BTP research see references.

5.4 Response to Question 1 (c)

Every fire hazard is unique and needs to be assessed by a fire protection engineer or other competent person skilled in modern fire protection technologies. Previously when using ODS for fire protection applications, the agent choice was usually very simple; halons were the agent-of-choice for fixed flooding applications, as well as for local application and portable applications. Today, the user is faced with a wide range of potential fire protection options, and they need to make a choice in a logical, hierarchical manner.

Working through a logical decision process will lead the user to selection of a suitable ODS-alternative fire extinguishing agent and system. In some cases there will be a different "weighting" among the several requirements. In some regions of the world there are economic barriers to the adoption of environmentally-sound alternatives. There are, however, no other barriers to adoption of an environmentally sound alternative to an ODS fire extinguishing system.

Several environmentally sound alternatives to ODS fire extinguishing agents for both total flooding and local applications uses have been introduced to the market. If an environmentally sound alternative agent works in any specific application there is no barrier to its adoption other than economic considerations. New environmentally sound alternatives are presently under development that may increase the number of applications where environmentally sound alternatives are technically viable.

5.5 Response to Question 1 (d)

The HTOC is of the opinion that it is not possible to report or even estimate values in response to the question posed.

The production of PFCs and HFCs for use in fire extinguishing systems and portable fire extinguishers as well as the production of alternatives (without negative environmental impacts) to these agents for uses in the same applications is performed by very few manufacturers, all of whom treat the information on their historical, present and projected production as proprietary. The required factual data is thus not available. So, without a clear understanding of these production levels for the alternatives without negative environmental impacts and also for the PFCs and HFCs, there is no basis for making a judgment about the overall utility of any alternatives in replacing PFCs and HFCs in the fire protection sector, and doing so may result in data that is misleading.

Regarding the PFCs, we can also say that the fire protection community has acted responsibly in dealing with what have turned out to be unsuitable alternatives from an environmental impact perspective. The subject of the use of PFCs was debated at the International Maritime Organization (IMO) over a three years period and in the end PFCs were prohibited in fire extinguishing systems on all merchant ship new builds. The IMO decision was based entirely on the availability of several HFCs that collectively could perform as well if not better than the PFCs in shipboard applications and at the same time present a more favorable environmental impact. The prohibition of PFCs by IMO led to the collapse of any demand for the agent as other major industries, e.g., oil and gas production, followed suit, and led to the manufacturer abandoning the products.

However, the need for chemical agents remains as inert gases, water mist and other agents are not suitable for many fire protection applications that had previously used halon. HFCs have filled that role and, since about 2005 a fluoroketone (FK) has increasingly become more accepted – cost was initially a barrier but its physical properties also make it unsuitable in some applications, e.g., aviation and use in very cold climates.

With respect to HFCs, as stated above, although specific production data has not been provided, according to one HFC producer, estimates for volumes sold 2008-2012 (see the following table), are reasonably accurate and the percent over that time frame, worldwide, is fairly constant ±3-5%. Note this is not GWP weighted or emissions, just raw tonnage sold globally.

Sector	Percentage
Refrigeration	68%
Foam Expansion	23%
Propellants	5%
Pharmaceutical	1.1%
Fire Protection	1.0%
Electronic Gases	0.3%
Cleaning	0.17%
Miscellaneous	1.43%

Unlike the other sectors, fire protection is highly regulated and there are design standards that have to be followed in consideration of life safety and property protection. As the agents are very valuable and are easily contained, recycling of HFCs in this sector is already mature.

With respect to the FK, there is no evidence to suggest that it is or is not living up to the expectations of the fire protection industry, which is still evaluating alternatives that have low environmental impacts.

5.6 Response to Question 1 (e)

The use of HCFCs in fire protection is declining, with the only total flood agent being provided for the maintenance of legacy systems that are themselves phasing out. Only HCFC-123 is used in any quantity in portable extinguishers and if the development of 2-Bromo-3,3,3-trifluoropropene proves to be commercially successful, it would be the natural replacement for it and halon 1211 – particularly in the aviation industry.

6 Solvents

Executive Summary

The 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. The elimination of HCFCs from solvent applications still leaves many options available. Many alternative solvents and technologies developed so far since 1980s are the candidates for HCFC alternatives, which include, not- in kind technologies such as aqueous cleaning, semi-aqueous cleanings, hydrocarbon and alcoholic solvents, and in-kind solvents such as chlorinated solvents, a brominated solvent, and fluorinated solvents with 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 are said 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. Among them, HCFOs are unique in their balanced solvency due to the presence of chlorine and fluorine atom in the molecule. If HCFOs with appropriate boiling points, low toxicity and enough stability to the practical use be on market, they may replace HCFCs totally in the future.

6.1 Introduction

This section provides the updated information on alternatives that are used for solvent applications to addresses the requirements of “Decision XXIV/7”, which is given in chapter 1.

Solvents are widely used as process agents in a variety of industrial manufacturing processes although they are not contained in the final products to consumers. The main applications of solvents are metal cleaning, electronics cleaning, precision cleaning. Then career solvents and heat transfer media have minor shares.

Among ODSs controlled by Montreal Protocol, CFC-113 and 1,1,1-trichloroethane (TCA) use as solvents were banned in both of Article-5 and non-Article 5 countries except one essential use exemption.

Several reports that describe the use of HCFCs in solvent applications have been published in the past. These include the IPCC TEAP Special Report, the TEAP Decision XXI/9 Task Force Report, XXIII/9 Task Force Report, and the Assessment Reports of CTOC and STOC.
Among ODSs controlled by Montreal Protocol, CFC-113 and 1,1,1-trichloroethane (TCA) use as solvents were banned in both of Article-5 and non-Article 5 countries except one essential use exemption.

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. 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. 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.

The elimination of HCFCs from solvent applications still leaves many options available. Many alternative solvents and technologies developed so far since 1980s are the candidates for HCFC alternatives, which include, not- in kind technologies such as aqueous cleaning, semi-aqueous cleanings, hydrocarbon and alcoholic solvents, and in-kind solvents such as chlorinated solvents, a brominated solvent, and fluorinated solvents with various levels of acceptance. However, no single option seems well suited to replace HCFCs completely.

The following terms, used in the tables below, have meanings as given.

Efficacy refers to suitability for solvent applications. It indicates merits of the agents in cleaning performances
Toxicity refers to Threshold Limit Value (TLV) or Occupational Exposure Limit (OEL). As solvents are usually used as process agent in the cleaning process, their toxicity concerns are mainly focused on the allowable exposure limit to those who works in the process.
Safety characteristics refer to flammability of agents. The flash point and the combustible range are also noted in in-kind solvents.
Environmental characteristic refers to ozone depletion potential (ODP) and GWP (100-year Global Warming Potential) or other characteristics, if applicable
Cost effectiveness refers to investment cost and solvent cost. Due to the wide variety of alternatives available to replace HCFCs, a full discussion of the costs of these alternatives is not practical. So the capital investment is roughly compares as one time cost and solvent cost is roughly compared as operating cost. Solvent cost is classified as shown below.
Solvent Cost ($/kg): A=~5, B=5~10, C=11~20, D=21~50, E=51~80

6.2 Response to Question 1(a)

6.2.1 Commercially Available, Technically Proven Alternatives for Solvent Cleanings

6.2.1.1 Not in-kind alternatives

Aqueous Cleaning

Agent	Water, surfactant, alkali/acidic agent , other additives
Efficacy	Applicable to wide range of materials and parts to be cleaned by choosing additives
Toxicity	Depend on additives
Safety Characteristics	Non flammable Corrosive when alkali or acidic agents are used
Environmental Characteristics	ODP: 0 GWP: 0 Waste water treatment is necessary
Cost Effectiveness* Investment cost Solvent cost	 Very large A-B

*May 2012 TEAP Task Force Report

Semi-aqueous Cleaning

Agent	Glycol ethers/water, terpenes, Glycol ethers
Efficacy	Applicable to wide range of materials and parts to be cleaned
Toxicity	low to moderate (depend on organic solvents used)
Safety Characteristics	Some organic solvents are flammable. Explosion proof equipments are necessary in the case.
Environmental Characteristics	ODP: 0 GWP: low Waste water treatment is necessary VOC
Cost Effectiveness* Investment cost Solvent cost	 Very large A~D

*May 2012 TEAP Task Force Report

These aeqeous and semi-aequeous processes can be good substitutes for metal degreasing or even electronics and 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

Agent	n-Paraffin, iso-Paraffin, aromatic solvents
Efficacy	High solvency to oil and grease
Toxicity	Low to moderate (depend on solvents)
Safety Characteristics	Flammable: to avoid explosion, the solvents with high flash points (>55°C) are used. Explosion proof equipments are necessary
Environmental Characteristics	ODP: 0 GWP: low VOC
Cost Effectiveness* Investment cost Solvent cost Retrofitting	 Large A – C Difficult

*May 2012 TEAP Task Force Report

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

Agent	iso-propyl alcohol (IPA)
Efficacy	High solvency to flux resin
Toxicity (TLV or OEL)	200 ppm
Safety Characteristics	Flammable Explosion proof equipments are necessary
Environmental Characteristics	ODP: 0 GWP: low VOC
Cost Effectiveness* Investment cost Solvent cost Retrofitting	 Large A Difficult

*May 2012 TEAP Task Force Report

These substances have been used for many years in cleaning applications. IPA is the most popular solvent. 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.

6.2.1.2 In-kind alternatives

Chlorinated solvents

Agent	Trichloroethylene	Tetrachloroethylene	Dichloromethane
Boiling point	87˚C	121˚C	40˚C
Efficacy	High solvency due to the presence of chlorine atom. Good to remove oil and grease. Incompatible with some materials		
Toxicity* TLV or OEL(USA)	10ppm	25ppm	50ppm
Safety Characteristics* Flash point Combustible range	 Non 8-10.5[vol%]	 non non	 non 13-23[vol%]
Environmental Characteristics*	ODP:0.005 GWP:5 Lifetime: 13days	ODP:0.005 GWP:12 Lifetime: 0.3yrs	ODP:0.005 GWP:9 Lifetime: 0.38yrs
Cost Effectiveness* Investment cost Solvent cost Retrofitting	 Medium A Possible		

*May 2012 TEAP Task Force Report

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. Therefore, material compatibility of cleaned parts must be checked if HCFCs are replaced by these chlorinated solvents.

Brominated solvent

Agent	n-Propyl bromide
Boiling point	72˚C
Efficacy*	High solvency due to the presence of bromine atom. Good to remove oil and grease. Incompatible with some materials
Toxicity TLV or OEL(USA)*	(0.1ppm)
Safety Characteristics* Flash point Combustible range	 Non Non
Environmental Characteristics*	ODP: 0.0049-0.01 GWP: very low Lifetime: 20~25days
Cost Effectiveness* Investment cost Solvent cost Retrofitting	 Medium C Possible

*May 2012 TEAP Task Force Report

A brominated solvent, n-propyl bromide has been another alternative for TCA and CFC-113 because of its similar cleaning properties. However, there has been significant concern about the toxicity of n-propyl bromide. ACGIH proposed the reduction of the TLV for n-propyl bromide from 10 ppm to 0.1 ppm in February 2012. No additional information has been announced yet.

HFC solvents

Agent	HFC-43-10mee	HFC-365mfc	HFC-c447ef
Boiling point	55˚C	40˚C	82˚C
Efficacy*	Easy drying, good material compatibility due to their mild solvency		
Toxicity* TLV or OEL(USA)	200 ppm	1000 ppm**	120 ppm
Safety Characteristics* Flash point Combustible range	 non non	 ≤27˚C** 3.6~13.3 [vol%]**	 non non
Environmental Characteristics*	ODP: 0 GWP: 1640 Lifetime: 15.9yrs	ODP: 0 GWP: 794 Lifetime: 7.0yrs	ODP: 0 GWP: 250 Lifetime: 3.4yrs
Cost Effectiveness* Investment cost Solvent cost Retrofitting	 Medium C – E Possible		

*May 2012 TEAP Task Force Report
**Data were supplied by the manufacturers

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

Agent	HFE-449s1	HFE-569sf1	HFE-64-13s1	HFE-347pc-f2
	61˚C	72˚C	98˚C	56˚C
Efficacy*	Easy drying, good material compatibility due to their mild solvency			
Toxicity* TLV or OEL(USA)	750ppm	200ppm	100ppm	50ppm
Safety Characteristics* Flash point Combustible range	 non non	 Non 2.1~10.7[vol%]	 non non	 non non
Environmental Characteristics	ODP: 0 GWP: 297 Lifetime: 3.8yrs	ODP: 0 GWP: 59 Lifetime: 0.77yrs	ODP: 0 GWP: 210 Lifetime: 3.8yrs	ODP: 0 GWP: 580 Lifetime: 7.1yrs
Cost Effectiveness* Investment cost Solvent cost Retrofitting	 Medium D – E Possible			

*May 2012 TEAP Task Force Report

HFE (hydrofluoroether) is a new homologue of fluorinated solvents. 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.

6.3 Response to Question 1(b)

6.3.1 Alternatives Under Development

6.3.1.1 Unsaturated solvents (HFOs and HCFOs)

Agent	HCFO-1233zd
Boiling point	19^{0}C
Efficacy	Easy drying, good material compatibility, good solvency to common soils
Toxicity TLV or OEL(USA)	300ppm**
Safety Characteristics** Flash point Combustible range	 Non Non
Environmental Characteristics***	ODP: 0.00024~0.00034 GWP: 4.7~7
Cost Effectiveness Investment cost Solvent cost Retrofitting	 Medium (C- D) Possible: chiller unit must be strengthened to minimize the emission.

*** Federal Register Volume 78, Number 32

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) is now announced for its commercial production. It 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. Due to the balanced solvency, HCFO solvents are potential replacements for HCFCs and potential high GWP HFC solvents.

6.4 Response to Question 1(c)

6.4.1 Barrier and restrictions; the feasibility of options to HCFCs in solvents

The next three tables summarize the feasibility of the alternative solvents in metals cleaning (Table 6.4.1), electronics cleaning (Table 6.4.2) and precision cleaning (Table 6.4.3).

Table 6.4.1 Metals cleaning *[1]

					Environmental Effect*[2]			Market Price*[3]
					GWP	ODP	Others	
ODS	Hydrochlorofluorocarbon	HCFC-225ca/HCFC-225cb	Good	Difficult	C	C	ODS	D
		HCFC-141b	Good	Good	C	D	ODS	C
Alternatives	Chlorinated solvents	Trichloroethylene Perchloroethylene Dichloromethane	Good	Good	A	B	VOC Water&Soil Pollutant	A
		trans-1,2-Dichloroethylene Blending with other solvents	Good	Good	A	B	VOC Water&Soil Pollutant	A-B
	Brominated solvents	n-Propyl bromide	Good	Good		B		C
	Fluorinated solvents	HFEs HFE-449s1 HFE-569sf1 HFE-347pcf2 (Blending with other solvents	Difficult	Difficult	B-C	A		D-E
		HFCs HFC-43-10mee HFC-365mfc (Blending with other solvents	Difficult	Difficult	C-	A		C-E
		Unsaturated Fluorocarbons(HFOs, HCFOs) HCFO-1233zd	Difficult to Good	Difficult	A	A		C-E
	Hydorocarbons	n-Paraffine, iso-Paraffin, Aromatic solvents	Good	Good	-	-	VOC Water&Soil Pollutant	A-C
	Siloxane	Methyl siloxanes	Good	Difficult	-	-		
	Semi-aqueous	Glycol Ethers/Water Terpenes, Glycol Ethers/ Water	Good	Difficult to Good	-	-		
	Alchoholic	iso-Propyl alcohol	Difficult	Good	-	-		
	Aqueous	Basic, Neutral, and Acidic systems	Good	Difficult to Good	-	-		
	Others	Supercritical fluids, Plasma cleaning, UV / Ozone irradiation	Difficult	Difficult	-	-		

*1 Cleaning applications are classified according to the definition of SNAP (EPA Significant New Alternatives Policy)
*2 Environmental Effect
GWP: A=~100 B=100~300, C=300~1000, D=1000~
ODP: A=~0.001, B=~0.01, C=~0.1, D=0.1~
*3 Market Price May 2012 TEAP XXIII/9 Task Force Report)
Cost($/kg): A=~5, B=5~10, C=11~20, D=21~50, E=51~

Metal cleaning is removing contaminants such as cutting oils, grease, or metal fillings from metal parts. High solvency is required to solvents to remove such contaminants. The cleaning is generally cost sensitive because most of the metals to be cleaned are not so expensive. So the chlorinated solvents, brominated solvent and hydrocarbon solvents are widely used in this application.

Table 6.4.2 Electronics Cleaning *[1]

					Environmental Effect*[2]			Market Price*[3]
					GWP	ODP	Others	
ODS	Hydrochlorofluorocarbon	HCFC-225ca/HCFC-225cb HCFC-141b (Blending with other solvents	Good	Good	C	C-D	ODS	C-D
Alternatives	Chlorinated solvents	Trichloroethylene Perchloroethylene Dichloromethane	Difficult to Good	Good	A	B	VOC Water&Soil Pollutant	A
		trans-1,2-Dichloroethylene (Blending with other solvents	Difficult to Good	Good	A	B	VOC Water&Soil Pollutant	A-B
	Brominated solvents	n-Propyl bromide	Difficult to Good	Good		B		C
	Fluorinated solvents	HFEs HFE-449s1 HFE-569sf1 HFE-347pcf2	Difficult	Good	B-C	A		D-E
		(Blending with other solvents	Difficult to Good	Good				
		HFCs HFC-43-10mee HFC-365mfc	Difficult	Good	C-	A		C-E
		(Blending with other solvents	Difficult to Good	Good				
		Unsaturated Fluorocarbons(HFOs, HCFOs) HCFO-1233zd	Difficult to Good	Good	A	A		C - E
	Hydorocarbons	n-Paraffine iso-Paraffin Aromatic solvents	Good	Good	-	-	VOC Water&Soil Pollutant	A-C
	Semi-aqueous	Glycol Ethers/Water Terpenes, Glycol Ethers/ Water	Good	Difficult to Good	-	-		A-D
	Alchoholic	iso-Propyl alcohol	Good	Good	-	-		A-B
	Aqueous	Basic, Neutral, and Acidic systems	Good	Difficult to Good	-	-		A-B
	Others	Supercritical fluids Plasma cleaning UV / Ozone irradiation	Good	Difficult to Good	-	-	-	-

*1 Cleaning applications are classified according to the definition of SNAP (EPA /Significant New Alternatives Policy
*2 Environmental Effect
GWP : A=~ 100 B=100~300, C=300~1000, D=1000~
ODP: A=~0.001, B=~0.01, C=~0.1, D=0.1~
*3 Market Price May 2012 TEAP XXIII/9 Task Force Report)
Cost($/kg): A=~5, B=5~10, C=11~20, D=21~50, E=51~

Electronics cleaning is removing contaminants, primarily solder flux residues, from electronics or circuit boards. Milder solvency is required in this cleaning so that the parts to be cleaned may not be damaged during the process. In the case of HFCs and HFEs, blending with other solvents is commonly applied to enhance the solvency.

Table 6.4.3 Precision cleaning *[1]

					Environmental Effect*2			Market Price*3
					GWP	ODP	Others	
ODS	Hydrochlorofluorocarbon	HCFC-225ca/HCFC-225cb HCFC-141b	Good	Good	C	C-D	ODS	C-D
Alternatives	Chlorinated solvents	Trichloroethylene Perchloroethylene Dichloromethane	Difficult to Good	Good	A	B	VOC Water&Soil Pollutant	A
		trans-1,2-Dichloroethylene (Blending with other solvents	Difficult to Good	Good	A	B	VOC Water&Soil Pollutant	A-B
	Brominated solvents	n-Propyl bromide	Difficult to Good	Good		B		C
	Fluorinated solvents	HFEs HFE-449s1 HFE-569sf1 HFE-347pcf2 (Blending with other solvents	Good	Good	B-C	A		D-E
		HFCs HFC-43-10mee HFC-365mfc (Blending with other solvents	Good	Good	C-	A		C-E
		Unsaturated Fluorocarbons(HFOs, HCFOs) HCFO-1233zd	Good	Good	A	A		C-E
	Hydorocarbons	n-Paraffine iso-Paraffin Aromatic solvents	Difficult	Good	-	-	VOC Water&Soil Pollutant	A-C
	Semi-aqueous	Glycol Ethers/Water Terpenes, Glycol Ethers/ Water	Good	Good	-	-		A-D
	Alchoholic	Iso-Propyl alcohol	Good	Good	-	-		A-B
	Aqueous	Basic, Neutral, and Acidic systems	Good	Good	-	-		A-B
	Others	Supercritical fluids Plasma cleaning UV / Ozone irradiation	Good	Difficult to Good	-	-	-	-

*1 Cleaning applications are classified according to the definition of SNAP (EPA /Significant New Alternatives Policy
*2 Environmental Effect
GWP : A=~ 100 B=100~300, C=300~1000, D=1000~
ODP: A=~0.001, B=~0.01, C=~0.1, D=0.1~
*3 Market Price May 2012 TEAP XXIII/9 Task Force Report)
Cost($/kg): A=~5, B=5~10, C=11~20, D=21~50, E=51~

Precision cleaning is cleaning to a specific grade of cleanliness in order for products to maintain their value. Generally the solvent cost is not an issue because the cleaning performance is quite important rather than the cost performance in this cleaning. Depending on the required cleanliness level, materials used in the cleaned parts, the shape of cleaned parts, wide variety of solvents can be the alternative candidates to HCFCs.

Although the conversion of HCFCs to alternative solvents has been taken place steadily in each application, the following should be considered when replacing HCFCs.

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, 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. The relatively high cost of these materials limits their use.

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 has a high solvency with common soils and may be used as a direct replacement for HCFCs. The relatively high cost of these materials would limit their use.

6.5 Response to Question 1(d)

The CTOC is of the opinion that it is not possible to report or even estimate values in response to the question posed. However, it should be noted that more than 90% of the ODS solvent use has been reduced already through conservation and substitution with not-in-kind technologies.

6.6 Response to Question 1(e)

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. Among them, HCFOs are unique in their balanced solvency due to the presence of chlorine and fluorine atom in the molecule. If HCFOs with appropriate boiling points, low toxicity and enough stability to the practical use be on market, they may replace HCFCs totally.

7 Material submitted by Parties

The U.S. government submitted the following list with reference material (4 February 2013):

SUMMARY of SUBMISSION

1. <u>Recent (2011-2012) Relevant U.S. EPA Final SNAP Regulations and Listings</u>

- 1.1. U.S. EPA, Significant New Alternatives Policy, 2011 Ruling on Hydrocarbon Refrigerants
- 1.2. U.S. EPA, Significant New Alternatives Policy, 2011 Ruling on HFO-1234yf in Motor Vehicle AC
- 1.3. U.S. EPA, Significant New Alternatives Policy, 2012 Ruling on CO_2 in Motor Vehicle AC
- 1.4. U.S. EPA, Significant New Alternatives Policy, 2012 Acceptability Determination 27

2. <u>Fact Sheets on Alternatives</u>

- 2.1. Commercial Refrigeration HFC Fact Sheet
- 2.2. Domestic Refrigeration HFC Fact Sheet
- 2.3. Transport Refrigeration HFC Fact Sheet
- 2.4. MVAC HFC Fact Sheet
- 2.5. Unitary AC HFC Fact Sheet
- 2.6. Construction Foams HFC Fact Sheet
- 2.7. Alternatives to HFCs Fact Sheet

3. <u>HFCs Under the Montreal Protocol</u>

- 3.1. Benefits of Addressing HFCs under the Montreal Protocol
- 3.2. Frequently Asked Questions on the North American Amendment Proposal to Phase Down HFCs under the Montreal Protocol

4. <u>Available and Emerging Alternative Technologies</u>

- 4.1. Advancing Ozone and Climate Protection Technologies: Next Steps
- 4.2. Montreal Technology Forum on Climate-friendly Alternatives in Commercial Refrigeration
- 4.3. GreenChill Webinar Series on Alternative Technologies in the Commercial Refrigeration Sector HFC-Free Technologies Are Available in the Supermarket Retail Refrigeration Sector
- 4.4. HFC-Free Technologies Are Available in the Supermarket Retail Refrigeration Sector
- 4.5. Greenpeace - Cool Technologies: Working without HFCs Report
- 4.6. Purdue University 2012 Conference Presentations
- 4.7. AHRI Low-GWP Alternative Refrigerants Evaluation Program Reports
- 4.8. ASHRAE/NIST Refrigerants Conference 2012 Presentations and Conference Papers

1. Recent (2011-2012) Relevant U.S. EPA Final Regulations and Listings

1.1. U.S. EPA, Significant New Alternatives Policy, 2011 Ruling on Hydrocarbon Refrigerants

Title: Protection of Stratospheric Ozone: Listing of Substitutes for Ozone Depleting Substances - Hydrocarbon Refrigerants

Description: Adds isobutane (R–600a) and R–441A to the SNAP list of acceptable refrigerants, subject to use conditions, in household refrigerators, freezers, and combination refrigerators and freezers. Additionally adds propane (R –290), subject to use conditions, in retail food refrigerators and freezers (standalone units only).

Available at: http://www.gpo.gov/fdsys/pkg/FR-2011-12-20/pdf/2011-32175.pdf

Filename: SNAP Rule on Hydrocarbon Refrigerants for Household and Stand-alone Commercial Refrigerators and Freezers.pdf

1.2. U.S. EPA, Significant New Alternatives Policy, 2011 Ruling on HFO-1234yf in Motor Vehicle AC

Title: Protection of Stratospheric Ozone: New Substitute in the Motor Vehicle Air Conditioning Sector Under the Significant New Alternatives Policy (SNAP) Program

Description: Finds hydrofluoroolefin (HFO)–1234yf as acceptable, subject to use conditions, as a substitute in motor vehicle air conditioning for new passenger cars and light-duty trucks.

Available at: http://www.gpo.gov/fdsys/pkg/FR-2011-03-29/pdf/2011-6268.pdf

Filename: SNAP Rule on HFO-1234yf in MVAC.pdf

1.3. U.S. EPA, Significant New Alternatives Policy, 2012 Ruling on CO_2 in Motor Vehicle AC

Title: Protection of Stratospheric Ozone: New Substitute in the Motor Vehicle Air Conditioning Sector Under the Significant New Alternatives Policy (SNAP) Program

Description: Adds carbon dioxide (CO_2) or R–744 to the SNAP list of acceptable refrigerants, subject to use conditions, in the motor vehicle air conditioning systems designed specifically for the use of CO_2 refrigerant in passenger cars, light-duty and heavy-duty vehicles.

Available at: http://www.gpo.gov/fdsys/pkg/FR-2012-06-06/pdf/2012-13189.pdf

Filename: SNAP Rule on CO2 in MVAC.pdf

1.4. U.S. EPA, Significant New Alternatives Policy, 2012 Acceptability Determination 27

Title: Protection of Stratospheric Ozone: Determination 27 for Significant New Alternatives Policy Program

Description: Adds low-GWP alternatives to the SNAP list of acceptable refrigerants, for commercial comfort air conditioning, heat transfer, vending machines, foam blowing, aerosols, and fire suppression.

Available at: http://www.gpo.gov/fdsys/pkg/FR-2012-08-10/pdf/2012-19688.pdf

Filename: HFC-Free Technologies Are Available in the Supermarket Retail Refrigeration Sector.pdf

2. Fact Sheets on Alternatives

2.1. <u>Commercial Refrigeration HFC Fact Sheet</u>

Title: Transitioning to Low-GWP Alternatives in Commercial Refrigeration
Description: This fact sheet provides information on low-GWP alternatives in newly manufactured commercial refrigeration equipment.
Available at: http://www.epa.gov/ozone/downloads/EPA_HFC_ComRef.pdf
Filename: Commercial Refrigeration HFC Fact Sheet.pdf

2.2. <u>Domestic Refrigeration HFC Fact Sheet</u>

Title: Transitioning to Low-GWP Alternatives in Domestic Refrigeration
Description: This fact sheet provides information on low-GWP alternatives in newly manufactured domestic refrigeration equipment.
Available at: http://www.epa.gov/ozone/downloads/EPA_HFC_DomRef.pdf
Filename: Domestic Refrigeration HFC Fact Sheet.pdf

2.3. <u>Transport Refrigeration HFC Fact Sheet</u>

Title: Transitioning to Low-GWP Alternatives in Transport Refrigeration
Description: This fact sheet provides information on low-GWP refrigerant and foam blowing agent alternatives used in transport refrigeration equipment.
Available at: http://www.epa.gov/ozone/downloads/EPA_HFC_Transport.pdf
Filename: Transport Refrigeration HFC Fact Sheet.pdf

2.4. <u>MVAC HFC Fact Sheet</u>

Title: Transitioning to Low-GWP Alternatives in MVACs
Description: This fact sheet provides information on low-GWP alternatives in newly manufactured MVACs.
Available at: http://www.epa.gov/ozone/downloads/EPA_HFC_MVAC.pdf
Filename: MVAC HFC Fact Sheet.pdf

2.5. <u>Unitary AC HFC Fact Sheet</u>

Title: Transitioning to Low-GWP Alternatives in Unitary Air Conditioning
Description: This fact sheet provides information on low-GWP alternatives in new equipment in unitary air conditioning.
Available at: http://www.epa.gov/ozone/downloads/EPA_HFC_UAC.pdf
Filename: Unitary AC HFC Fact Sheet.pdf

2.6. <u>Construction Foams HFC Fact Sheet</u>

Title: Transitioning to Low-GWP Alternatives in Building/Construction Foams
Description: This fact sheet provides information on low-GWP foam blowing agent alternatives used in building and construction applications.
Available at: http://www.epa.gov/ozone/downloads/EPA_HFC_ConstFoam.pdf
Filename: Construction Foams HFC Fact Sheet.pdf

2.7. Alternatives to HFCs Fact Sheet

Title: CCAC Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants: Fact Sheet - Alternatives to HFCs

Description: This fact sheet provides information on HFCs and the advancement of HFC reduction efforts; including projects to promote the international exchange of information on HFC use, emissions reductions strategies, alternative technologies, and standards.

Available at: http://www.unep.org/ccac/Portals/24183/PartnersArea/pdf/CCAC FACT SHEET-HFCs-EN-LR.pdf

Filename: CCAC Alternatives to HFCs Fact Sheet.pdf

3. HFCs Under the Montreal Protocol

3.1. Benefits of Addressing HFCs under the Montreal Protocol

Title: Benefits of Addressing HFCs under the Montreal Protocol, June 2012

Description: This paper presents an analysis of the potential benefits from globally reducing consumption of HFCs and reducing byproduct emissions of HFC-23 under the Montreal Protocol. This paper discusses the environmental downsides of continued HFC consumption and emissions; the proposal from Canada, Mexico and the United States to amend the Montreal Protocol to address HFCs, the availability of alternatives for meeting the reduction schedule; transitioning to low-GWP alternatives; case studies in the transition to low-GWP alternatives; and byproduct emissions of HFC-23. This paper was also presented at the ASHRAE/NIST conference in October, 2012, at the National Institute of Standards & Technology.

Available at: http://www.epa.gov/ozone/downloads/Benefits of Addressing HFCs Under the Montreal Protocol, June 2012.pdf

Filename: Benefits of Addressing HFCs under the Montreal Protocol.pdf

3.2. Frequently Asked Questions on the North American Amendment Proposal to Phase Down HFCs under the Montreal Protocol

Title: Frequently Asked Questions on the North American Amendment Proposal to Phase Down the Use of Hydrofluorocarbons under the Montreal Protocol On Substances That Deplete The Ozone Layer

Description: Frequently asked questions and responses relating to the North American amendment proposal to phase down the use of hydrofluorocarbons under the Montreal Protocol on Substances that Deplete the Ozone Layer (Submitted by Canada, Mexico and the United States of America in November 2012)

Available at: http://conf.montreal-protocol.org/meeting/mop/mop-24/presession/Information Documents/MOP-24-INF-7.pdf

Filename: Frequently Asked Questions on the North American Amendment Proposal.pdf

4. Available and Emerging Alternative Technologies

4.1. Advancing Ozone and Climate Protection Technologies: Next Steps

Title: Advancing Ozone & Climate Protection Technologies: Next Steps – Meeting Summary

Description: This report summarizes the outcomes of the Bangkok Technology Conference and technology exhibition; including discussion of various alternatives and approaches to ensure that the phase out of CFCs and HCFCs is done in such as way as to limit the climate contribution of high-GWP HFCs. Forum discussion included both policy and technical aspects of this transition in the refrigeration, air conditioning and foams sectors.

Available at:
http://www.unep.org/ccac/Portals/24183/docs/Bangkok%20Technology%20Conference%20-%20Report%20and%20Cover%20-%20FINAL.pdf

Filename: Bangkok Technology Conference - Report and Cover - FINAL.pdf

Title: Hydrocarbons in Air-conditioners – The Godrej Experience

Description: This presentation from the Advancing Ozone & Climate Protection Technologies: Next Steps technology conference shares one company's experience with hydrocarbon refrigerants in air conditioning systems.

File Name: Session-V Air Conditioning (Dilip Rajadhyaksha - Godrej).pdf

4.2. Montreal Technology Forum on Climate-friendly Alternatives in Commercial Refrigeration

Title: Montreal Technology Forum on Climate-friendly Alternatives in Commercial Refrigeration – Meeting Summary

Description: This summary report from the Montreal Commercial Refrigeration Technology Forum held in December, 2012, provides information on various topics discussed during the conference, including; the technical, financial and environmental aspects of some of the key low-GWP, energy-efficient alternative technologies that are available or emerging in the commercial refrigeration sector; potential applicability of these technologies in developing countries; and dialogue among government representatives, international organizations, industry, technology users and technology providers, on the opportunities and challenges involved in successfully adopting such technologies in developing countries.

Available at: http://www.unep.org/ccac/Techforum/tabid/105036/Default.aspx

Filename: The document is in the process of being finalized in early February. We will transmit the document when it becomes available.

4.3. GreenChill Webinar Series on Alternative Technologies in the Commercial Refrigeration Sector

Description: Information regarding new technologies being deployed in the commercial refrigeration sector can be accessed through archived webinars, presentations, and additional items; including the following webinars:

- Transcritical CO2 Refrigeration Systems
- Cascade CO2 Refrigeration Systems
- Ammonia Cascade Systems

Available at: http://www.epa.gov/greenchill/events.html

HFC-Free Technologies Are Available in the Supermarket Retail Refrigeration

SectorTitle: HFC-Free Technologies Are Available in the US Market for the Supermarket - Retail Refrigeration Sector

Description: This report discusses the availability of climate-friendly technologies for the refrigeration sector in U.S. supermarkets that will allow for the rapid phase-out of HFCs.
Available at: http://eia-global.org/PDF/USSUPERMARKETREPORT.pdf
Filename: HFC-Free Technologies Are Available in the Supermarket Retail Refrigeration Sector.pdf

4.4. Greenpeace - Cool Technologies: Working without HFCs Report

Title: Greenpeace – Cool Technologies: Working without HFCs, Examples of HFC-Free Cooling Technologies in Various Industrial Sectors, 2012 Edition

Description: This report documents the current availability of HFC-free cooling technologies in most sectors and more are rapidly coming on line. The report surveys an extensive list of companies and enterprises using HFC-free technologies, documenting the already wide array of safe and commercially proven HFC-free technologies for meeting nearly all needs formerly met by fluorocarbons.

Available at: http://www.greenpeace.org/international/Global/international/publications/climate/2012/Fgases/Cool-Technologies-2012.pdf

Filename: Cool-Technologies-2012.pdf

4.5. Purdue University 2012 Conferences Presentations

Title: 21st International Compressor Engineering Conference at Purdue, 14th International Refrigeration and Air Conditioning Conference at Purdue, 2nd International High Performance Buildings Conference at Purdue – July 16-19, 2012 at Purdue University

Description: Links to various sessions with presentations on alternative technologies including:

Session: **Low GWP Refrigerants I**

Title: Low Global Warming Potential (GWP) Alternative Refrigerants Evaluation Program (Low-GWP AREP)
Title: R32 And HFOs As Low-GWP Refrigerants For Air Conditioning
Title: Performance and Capacity Comparison of Two New LGWP Refrigerants Alternative to R410A in Residential Air Conditioning Applications
Title: Drop-in Performance of Low GWP Refrigerants in a Heat Pump System for Residential Applications
Title: Study of R161 Refrigerant for Residential Air-conditioning Applications

Available at: http://www.conftool.com/2012Purdue/index.php?page=browseSessions &form_session=3

Session: **R-31: Low GWP Refrigerants II**

Title: A Reduced GWP Replacement for HFC-134a in Centrifugal Chillers: XP10 Measured Performance and Projected Climate Impact
Title: Latest Developments of Low Global Warming Refrigerants for Chillers

Title: Low Global Warming Refrigerants For Commercial Refrigeration Systems
Title: The Circulation Composition Characteristic of the Zeotropic Mixture R1234ze(E)/R32 in a Heat Pump Cycle
Title: Development of Refrigeration Oil for Use With R32
Title: Investigation Of Low GWP Refrigerant Interaction With Various Lubricant Candidates

Available at: http://www.conftool.com/2012Purdue/index.php?page=browseSessions&form_session=31

Session: **Industrial/Commercial Refrigeration**

Title: Drop-in Testing of Next-Generation R134a Alternates in a Commercial Bottle Cooler/Freezer

Title: Development of Low Global Warming Potential Refrigerant Solutions for Commercial Refrigeration

Title: Modeling and Simulation of a Desiccant Assisted Brayton Refrigeration Cycle

Title: Taking a Sensible Choice of Sustainable Super Market Refrigeration Equipment

Title: Evaluation Of Defrost Options For Secondary Coolants In Multi-temperature Indirect Transport Refrigeration: Mathematical Modeling & Sensitivity Analysis

Available at: http://www.conftool.com/2012Purdue/index.php?page=browseSessions&form_session=14

4.6. AHRI Low-GWP Alternative Refrigerants Evaluation Program Reports

Title: Air-Conditioning, Heating, and Refrigeration Institute Low-GWP Alternative Refrigerants Evaluation Program final test reports.

Description: Final test reports evaluating low-GWP alternative refrigerants, including:

Title: System Drop-in Test of R-410A Alternative Fluids (ARM-32a, ARM-70a, DR-5, HPR1D, L-41a, L-41b, and R-32) in a 5-RT Air-Cooled Water Chiller (Cooling Mode)

File Name: AHRI Low-GWP AREP-Rpt-001.pdf

Title: System Drop-In Test of L-40, L-41a and N-40b in Ice Machines

File Name: AHRI Low-GWP AREP-Rpt-002.pdf

Title: System Drop-In Test of R-32/R-152a (95/5) in 5-ton Air Source Heat Pump

File Name: AHRI Low-GWP AREP-Rpt-003.pdf

Available at: http://www.ahrinet.org/ahri+low_gwp+alternative+refrigerants+evaluation+program.aspx

4.7. ASHRAE/NIST Refrigerants Conference 2012 Presentations and Conference Papers

Title: 2012 ASHRAE/NIST Refrigerants Conference: Moving Towards Sustainability, October 29-30, 2012, Gaithersburg, Maryland

Description: Link to various presentations on alternative technologies

Available at: https://www.ashrae.org/membership--conferences/conferences/ashrae-conferences/ASHRAE-NIST-Refrigerants-Conference

On 15 March 2013, TEAP received the following correspondence from the European Commission:

Dear Ozone Secretariat:

Decision XXIV/7 invites parties to submit information relevant to the work of the TEAP as outlined in paragraph 1 of XXIV/7, so that this information may be taken into account for the production of the TEAP draft report for consideration by the 33rd OEWG.

The European Union wishes to invite TEAP to take into account the following studies:

Schwarz et al. (2011): Preparatory study for a review of Regulation (EC) No 842/2006 on certain fluorinated greenhouse gases – Final Report.
http://ec.europa.eu/clima/policies/f-gas/docs/2011_study_en.pdf
Annexes:
http://ec.europa.eu/clima/policies/f-gas/docs/2011_study_annex_en.pdf

SKM Enviros (2012): Phase Down of HFC Consumption in the EU – Assessment of Implications for the RAC Sector.
SKM Enviros (2012): Further Assessment for Policy Options for the Management and Destruction of Banks of ODS and F-gases in the EU.
http://ec.europa.eu/clima/policies/ozone/research/docs/ods_f-gas_destruction_report_2012_en.pdf

Umweltbundesamt (2011): Avoiding Fluorinated Greenhouse Gases – Prospects for Phasing out.
European Commission (2012): IMPACT ASSESSMENT - Review of Regulation (EC) No 842/2006 on certain fluorinated greenhouse gases
http://ec.europa.eu/clima/policies/f-gas/legislation/docs/swd_2012_364_en.pdf

Yours sincerely,

Dr. ARNO KASCHL
Policy Officer

European Commission
Directorate-General for Climate Action
Transport & Ozone

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On 8 April 2013, the Commission submitted four reports, on renewable cooling and sustainable cooling for datacenters and on fishery to the TEAP Task Force.

8 Technical, economic and environmental definitions

Technical and economic deasibility

Technical feasibility addresses whether a particular alternative depicted by equipment/systems using an ODS substitute can be made to work, and where/how they can be applied.

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.

Cost Effectiveness

There are two basic components of cost which are well understood by the Montreal Protocol – capital cost and operating cost. In simple terms, cost effectiveness would need to be defined in the context of whole life costing based on a certain required internal rate of return. The main problem is that this requirement will vary by geographic region, company size and the competing investment environment.

Equally, there is also a need to decide whether this is going to be assessed at alternative level (only applicable to drop-ins) or system level. In addition we have to consider where the cost will be borne.

At the level at which cost effectiveness is being determined, there is no real option but to make comparisons with the economics of previous conversions and decide whether there is a benchmark that can be drawn from the existing literature, outside of the rather narrow determinations made by the Multilateral Fund.

Environmentally sound

The 'Business Dictionary' defines an 'environmentally sound' product or process as:

Product or manufacturing process that, from beginning to end, is in essential harmony with its environment and the associated ecological factors.

Taken at face value, this is a high bar since it requires something that is in 'essential harmony' with its surroundings. In this context it is at least comparable with 'environmentally benign' and possibly higher according to this definition. The term 'environmentally benign' had been used previously in Decision XXIII/9, although authors of that Report had been unable to find a clear definition for the term. In normal English usage, 'environmentally benign' would be seen as a higher bar than 'environmentally sound' since the word 'sound' would convey 'fitness for purpose' or 'reliability', whereas 'benign' would be seen as 'creating no negative impacts'.

It can be argued that no solution is 'environmentally sound' against the Business Dictionary definition. However, the definition set out under the Agenda 21 Framework (and also adopted by the Global Development Research Centre) offers a more comparative approach. It states that:

Environmentally Sound Technologies (ESTs) encompass technologies that have the potential for significantly improved environmental performance relative to other technologies. Broadly speaking, these technologies:-

- Protect the environment
- Are less polluting

- Use resources in a sustainable manner
- Recycle more of their wastes and products
- Handle all residual wastes in a more environmentally acceptable way than the technologies for which they are substitutes

It can be seen that this approach is one which provides a measure ‘relative to other technologies’, which, in turn, is more meaningful to the language of Decision XXIV/7, bearing in mind that all alternatives have some form of environmental footprint.

Where all other technical and economic factors are comparable, the Task Force has adopted the approach of taking ‘environmentally sound’ as meaning the alternative which delivers the least ‘negative environmental impact’. This, in turn, has been expressed in this draft report as the ‘most favourable option’, although, as noted in Chapter 2, this identity of the ‘most favourable option’ may vary depending on the environmental impact being considered. This then links it to the next definition.

Low GWP

There have been numerous discussions about the nomenclature that should characterise the level of global warming potential displayed by ODS alternatives. In some sectors, the available alternatives have all been seen to be below a GWP of 25, and these have been classed as ‘low-GWP’. In other sectors, the benchmark is a GWP of 1,500 or above and alternatives with GWPs at 1,000 or 300 can also be considered as ‘low’. The challenge is that the terms are used in a ‘relative’ rather than an ‘absolute’ way.

The Task Force has considered whether there should be a formal nomenclature applied across all sectors involving terms such as ‘moderate’ (<1,000), ‘low’ (<300) and ultra-low (<25), but this type of approach was seen as controversial when proposed in the response to Decision XXIII/9.

The definition of environmentally sound technologies adopted under Agenda 21 makes an important further point in its expanded version. It notes that *‘…environmentally sound technologies are not just “individual technologies” but total systems which include know*-how, procedures, goods and *services, equipment as well as organisational and managerial procedures’* The implication is that a systems approach is essential to truly identify what is environmentally sound.

The evaluation of ODS alternatives has embraced this concept through a number of methodologies such as TEWI, LCCP and wider Life Cycle Assessment (LCA). However, such analyses are inevitably specific to the applications against which they are applied and are difficult to extrapolate for wider policy purposes.

With these factors in mind, the Task Force has concluded that it is better to refer to holistic approaches such as TEWI, LCCP and LCA only in the context of individual applications and scenarios. It also believes that adopting a formal nomenclature for classes of global warming potential is misleading, since it implies a hierarchy which is not always borne out when other factors are taking into consideration (e.g. energy efficiency). Therefore, references to climate impacts are mostly related to the overall impact of technologies where such information is available. In addition, where reference is made to ‘low-GWP’ solutions, the terminology should be treated as a generic label of improved climate performance rather than a prescribed band of GWP values.

9 List of acronyms and abbreviations

ABC	Dry Chemical Powder
AIHA	American Industrial Hygiene Association
ASTM	American Society for Testing and Materials
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
LCA	Life Cycle Analysis
LCCP	Life Cycle Climate Performance
VCLCG	Liquefied Compressed Gas
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
PFC	Perfluorocarbon
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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