MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

2014 REPORT OF THE REFRIGERATION, AIR CONDITIONING AND HEAT PUMPS TECHNICAL OPTIONS COMMITTEE

2014 Assessment

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The names of chapter lead authors, co-authors and contributors are given at the start of each chapter. Addresses and contact numbers of the chapter lead authors and all other authors of the UNEP TOC Refrigeration, A/C and Heat Pumps can be found in the Annex.

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Key Messages

Refrigerants

- Whatever refrigerant is chosen will always have to be a balance between several factors, the availability and cost of the refrigerant (and the associated equipment), the system energy efficiency, the safety and convenience of applicability, environmental issues and many more.
- The perfect refrigerant does not exist, and is unlikely to come into existence. Choices will therefore include the existing low GWP refrigerants (e.g. R-717, R-744 or HCs) and the newly applied or developed chemicals. Many new alternatives are proposed which create a challenge in finding the right refrigerant for each application. One aspect of particular importance is that refrigerants with low direct impact on climate change are often flammable to some extent. With new refrigerant characteristics comes the need for new technology development and increased need for training.
- 21 refrigerants obtained standardized designations and safety classifications since the 2010 RTOC assessment report, including one new molecule: HCFC-1233zd(E). Approximately a quarter of the new refrigerants are blends which are replacements for HCFC-22. Of the new refrigerants twelve are blends of saturated HFCs and unsaturated HFCs (HFOs) of which seven blends are with class 2L flammability.

Domestic appliances

- Globally, new refrigerator production conversion from use of ODS was essentially completed by 2008. HC-600a or HFC-134a continue to be the refrigerant option for new production.
- It is projected that by 2020 about 75% of new refrigerator production will use HC-600a (possibly with a small share applying unsaturated HFC refrigerants) and the rest will use HFC-134a.
- Initial efforts to assess the use of HFC-1234yf in domestic refrigeration have begun, but they are not being pursued with high priority, due to cost implications and flammability.
- The heat pump clothe (laundry) dryer (HPCD) sales using HFC-134a are fastly growing in the EU. HPCDs using R-407C and HC-290 have also been introduced. Alternative refrigerant solutions that are being explored include R-744, HC-600a and low GWP HFCs.

Commercial refrigeration

- In commercial refrigeration stand-alone equipment, hydrocarbons (HCs) and R-744 are replacing HFC-134a and R-404A and represent a significant market share in Europe and in Japan.
- Because of their high GWP, R-404A and R-507 are seen as refrigerants in many non-Article 5 countries as refrigerants to be replaced and, depending on the refrigeration capacities, hydrocarbons, R-744 or HFC refrigerant blends with lower GWP are the current chosen options.
- In supermarkets in Europe, two-stage CO_2 systems are recognized as viable option especially in moderate temperature countries. The technology is now spreading to other areas and development of concepts for hot climates is ongoing.
- Plug-in units with air and/or water cooled condensers are gaining market share. Particularly in the USA, distributed systems (condensing units with water cooled condensers installed in the sales area) are also installed in large numbers.

Industrial systems

- R-717 is widely used in industrial systems, but its adoption as a low GWP alternative to HCFC-22 in Article 5 countries is not universal due to safety concerns. The key requirements to facilitate this transition are education and training of designers and operators.
- Although HFCs are technically feasible for large industrial systems, the market sector is extremely cost sensitive and more expensive refrigerants are not favoured due to the large charge quantity required.

Transport refrigeration

- Low-GWP candidates for transport refrigeration include R-744, hydrocarbons, and HFC blends; however, various challenges are currently preventing them from widespread use. Intermodal container applications are at the forefront of developments; here the R-744 based system is available.
- In the case of a regulation banning the use of refrigerants above a certain GWP level (as in the EU), HFC blends will likely play a role in the 2020 timeframe as a retrofit to R-404A and (possibly) HFC-134a: their GWP is significantly lower and performances are close.
- Cryogenic and eutectic systems consist of potentially HFC-free stationary units and periodically recharged vehicle systems; they can be used on some transport routes.

Air-to-air air conditioners and heat pumps

- HCFC-22 is still widely used in new and existing systems in Article 5 countries and to some extent in existing systems in non-Article 5 countries.
- The majority of new systems using an alternative to HCFC-22 use R-410A; some others are using R-407C, HFC-134a, HC-290 and HFC-32.
- There are a growing number of alternatives which have a medium to low GWP and are flammable that are being considered and evaluated by research entities and enterprises, meaning there is some degree of uncertainty over future selection of alternatives.

Water heating heat pumps

- For water heating heat pumps most systems commercialised today make use of R-410A, HFC-134a, R-407C, HC-290, HC-600a, R-717 or R-744. The majority of new equipment uses R-410A.
- In some Article 5 countries HCFC-22 is used. There are no technical barriers for replacing HCFC-22 by a non-ODS refrigerant in new systems. The main parameters in the selection of alternatives when switching over from HCFC-22 are efficiency, cost effectiveness, economic impact, safe use and easiness of use.
- HFC-32 and other medium and low-GWP HFC blends are under way to become commercially available. R-744 based water heating heat pumps have been mainly developed and commercialised in Japan. However, the expansion of this technology to other countries is limited by its high cost. R-717 has also been used in a small number of reversible heat pumps and absorption heat pumps.

Chillers

- The phase-out of ozone depleting refrigerants in chillers is going well. The use of HCFC-22 in chillers has been phased out in developed countries but use still continues in some Article 5 countries. The primary refrigerants currently used in chillers are HFC-134a, R-410A, and HCFC-123. HC-290, R-717 and R-744 are used as refrigerants, however, to a lesser extent.
- A number of new refrigerants with lower global warming potentials have been proposed for use in chillers. Evaluations by manufacturers and other laboratories are underway, but it is not clear which ones will be selected for commercialization. Tradeoffs are apparent among GWP, energy efficiency, safety, and applied costs.
- Climate effects from chillers are dominated by their energy use. Thus, the ultimate goal in choosing new chiller refrigerant alternatives is to achieve the highest energy efficiency while remaining viable to chiller manufacturers, regulators, and users.

Vehicle air conditioning

- Now, at the end of 2014, it looks like as if more than one refrigerant will be used in the coming years for new car and light truck air conditioning. HFC-134a will remain largely adopted worldwide, HFC-1234yf will continue its growth in new models at least in the near future, and R-744 is expected to be implemented by German OEMs starting in 2017.
- New refrigerant options have GWPs enabling the GHG credits in US and are below the EU threshold of 150; both can achieve fuel efficiency comparable to the existing HFC-134a systems with appropriate hardware and control development.
- The worldwide spread of the two new refrigerants (HFC-1234yf and R-744) will be governed significantly by additional aspects like safety, costs, regulatory approval, system reliability, heat pump capability (especially for electric driven vehicles) and servicing.
- At the moment, it cannot be foreseen whether or not the old and new refrigerants will remain parallel in the market for a long period of time. It is also unclear if the bus and train sector will follow these trends. The use of hydrocarbons or blends of hydrocarbons has not received support from vehicle manufacturers due to safety concerns.

Sustainable refrigeration

- Refrigeration addresses fundamental human needs. In order to become more sustainable, the industry may consider the enhancement of current practices to: minimize the extraction of natural resources; avoid the emission of man-made substances such as refrigerants and solvents; protect fertile ecosystems from mining, water usage, and landfill of waste; promote education for sustainable production and consumption.
- From the persepective of refrigeration, air conditioning, and heat pumps, sustainability mainly refers to energy efficiency, use of renewable energy, and other options to reduce GHG emissions and the use of natural resources. In aparticular, the responsible choice and management of refrigerants are important sustainability aspects.

Abstract Executive Summary

Refrigerants

Current status

Whatever refrigerant is chosen will always have to be a balance between several factors, the availability and cost of the refrigerant (and the associated equipment), the system energy efficiency, the safety and convenience of applicability, environmental issues and many more. The refrigerant options emerging today address the phase-out of ODS, especially HCFC-22, as well as concerns about climate change. The perfect refrigerant does not exist and is unlikely to come into existence. Choices will therefore include existing low GWP refrigerants (e.g. R-717, R-744 or HCs) and the newly applied or developed chemicals. Many new alternatives are proposed, which create a challenge in finding the right refrigerant for each application. One of the important aspects is that refrigerants with a low direct impact on climate change are often flammable to some extent.

What is left to be achieved

The industry will keep searching for the right candidate for each application. In some cases this may be as simple as changing the refrigerant, while in other cases this will require redesign of the system or even a change of system topology. The search is a trade-off between cost, safety, energy efficiency, while limiting the need for redesign. One particular concern is the acceptance of flammability in some form or the other.

The way forward

There is a complex selection process ahead, where the market will need to find out which of the many proposed new and old refrigerants will be used in each application. Part of the complexity is that the market is unlikely to be able to support many different refrigerants for the same application.

This will result in a period in time, likely to last a couple of decades, where the industry will have to work with both the currently established refrigerants as well as new refrigerants addressing ozone depletion and/or climate change concerns. In the long run, the number of candidates is likely to fall, but it is too early to tell which or even how many of the current refrigerant candidates will survive.

Domestic appliances

Current status

Globally, new refrigerator production conversion from the use of ODS was essentially completed by 2008. HC-600a or HFC-134a continue to be the refrigerant options for new production. Initial efforts to assess the use of HFC-1234yf in domestic refrigeration have begun, but it is not being pursued with high priority, as in automotive applications, due to cost implications and flammability.

The heat pump clothe (laundry) dryer (HPCD) using HFC-134a is fastly growing in the EU, with manufacturers from both the EU and Japan. HPCDs using R-407C and HC-290 have also been introduced.

What is left to be achieved

It is projected that, by 2020, about 75% of new refrigerator production will use HC-600a (possibly with a small share applying unsaturated HFC refrigerants) and the rest will use HFC-134a. Alternative low GWP refrigerant solutions are being explored for HPCDs. This includes R-744, HC-600a and low GWP HFCs.

The way forward

A number of improved energy efficiency design options are fully mature, and future improvements of these options are expected to be evolutionary. Extension of these to an all-global domestic market would yield significant benefit, but is generally constrained by the availability of capital funds and related product cost implications.

Commercial refrigeration

Current status

Commercial refrigeration is one of the application sectors where the refrigerant demand is the highest for servicing, due to the large emission level of refrigerants from supermarket systems. The phase-out of HCFC-22, being the dominant refrigerant in Article 5 countries, is important for supermarkets, where it can be replaced by high-GWP refrigerants such as R-404A or R-507A or lower GWP options from the R-407 family (R-407A, C or F) or the low GWP options such as R-744 or HCs. For stand-alone equipment, large global companies have taken commitments to phase-out, where low GWP HFCs, CO_2, and hydrocarbons are the leading choices.

What is left to be achieved

In Article 5 countries, the phase-out of HCFC-22 in the case of condensing units and centralized systems asks for rapid refrigerant choices. The current low-GWP options require a significant technical background to implement, particularly for e.g., two-stage CO_2 systems, this in high ambient temperature conditions. So the HFC refrigerant blends, with GWPs ranging from 1500 to 2100 are possible immediate options, rather than choosing R-404A or R-507A.

The way forward

Low environmental impact, energy efficiency, simple maintenance, low refrigerant emissions and costs are the drivers for the next generation of refrigerants in commercial refrigeration. For the low refrigeration capacities of stand-alone systems, many of those criteria are currently met by R-744 or HCs. For large refrigeration capacities and for all climate conditions there are still a number of options open. The phase-out of high GWP refrigerants is a certainty, the replacement options R-744 and hydrocarbons are known, but the replacement low-GWP HFCs options are still not well known.

Industrial systems

Current status

Non-fluorinated refrigerants are widely used in industrial systems, particularly in Europe, Scandinavia and North America. The most common refrigerant in these systems is R-717, used in a few cases in cascade systems with R-744. Safety standards and regulations are well developed in these markets and the incidence of serious injury and fatal accidents is extremely low. The HFC use in these markets is confined to specialist niches.

What is left to be achieved

R-717 use is less common in some sub-sectors in Europe and North America, for example in France and New Jersey, where regulations make it more difficult to construct new ammonia systems; as a result, HCFC-22 was favoured in these jurisdictions. This matches the situation in many Article 5 countries where R-717 is not widely used, due to a lack of expertise in designing and operating systems. There is no inexpensive and widely available low GWP alternative to HCFC-22 for industrial systems in the currently available group of HFCs and unsaturated HFCs. The options for addressing the HCFC phase-out in Article 5 countries are therefore to find ways to use R-717, to accept the higher refrigerant cost for existing HFCs or to develop a suitable low GWP fluorinated refrigerant.

The way forward

The main conclusion drawn from this survey is that greater training of designers, installers, operators and maintenance crews is required to facilitate the move away from ozone depleting substances in all subsectors of industrial systems. New fluids are unlikely to be developed for the majority of industrial systems. The low GWP refrigerants R-717, R-744 and HCs are the dominant choices in several of the applications covered, and this is expected to remain in the future. However, there are some niche applications that use high GWP HFCs, which applications need to be addressed in the future.

Transport refrigeration

Current status

The vast majority of trucks, trailers, vans and intermodal containers uses the non ozone depleting refrigerants R-404A and HFC-134a. While most new vessels use HFC refrigerants, new fishing vessels increasingly use R-717 or R-744. However, the installed base at sea is still largely dominated by HCFC-22. The industry has been focusing on numerous environmental issues, making progress in reductions of engine pollution emissions, fuel consumption, noise levels and refrigerant charge. In addition, some manufacturers have made commitments to replace the current refrigerants with R-744 or R-452A in some first applications.

What is left to be achieved

Refrigerated vessels using HCFC-22 will continue being retrofitted with R-417A, R-422D and R-427A. In parallel, the industry will be looking for lower GWP alternatives in all sub-segments including R-717 and R-744 in shipping vessels. Cooperation between governments and manufacturers must continue in order to reflect the very specific transport refrigeration requirements. While introducing lower GWP solutions, the industry must ensure the best trade-offs among GWP, performance, indirect emissions, life cycle costs, etc., while safety and compliance are in no way compromised.

The way forward

In the short term, the industry will progressively introduce lower GWP alternatives to R-404A such as R-452A (GWP around 2000, it will be introduced in Europe for new production in 2015), R-448A and R-449A (GWP around 1400), R-744. In a longer time frame, other HFC blends and -within certain charge limits- possibly hydrocarbons or other flammable alternatives will be addressed. Lower GWP refrigerants will also be gradually applied in vessels when their applications mature in other segments and gain more confidence. Cryogenic and eutectic systems are proven solutions, and will continue playing a role on road transport.

Air-to-air air conditioners and heat pumps

Current status

Air-to-air air conditioners and heat pumps: HCFC-22 remains the dominant refrigerant in use, where the refrigerant bank for unitary air conditioners is estimated to be in excess of 1 million tonnes. In new systems, HCFC-22 is only being used in Article 5 countries. The HFC blend R-410A is the most common alternative, further, to a limited extent R-407C along with HFC-134a are used in regions with high ambient temperatures. HC-290 is being used in split systems, window and portable air conditioners. HFC-32 is being used in split systems and is being proposed for larger ducted and multi-split systems. These various alternatives have also been found to achieve performance approaching, as good as or better than HCFC-22.

What is left to be achieved

In general there is still a significant proportion of the sector throughout almost all Article 5 countries that remains to be shifted from HCFC-22 to a zero ODP alternative. Because of the high GWP of R-410A, investigations into medium and low GWP alternatives are continuing. In cooler climates, R-744 is available for commercially sized systems and the technology is further being explored. There are a large number of new mixtures being considered for air conditioning systems primarily consisting of HFCs and unsaturated HFCs, such as R-444B, R-446A and R-447A. Although there is concern over the use of R-410A in high ambient temperatures, appropriate design measures can be used to help remedy the relatively greater degradation in performance; nevertheless, work is underway to investigate this and other refrigerants further.

The way forward

The forthcoming direction remains unclear in terms of which alternatives this sector, sub-sectors and regions will settle upon. It is likely that different manufacturers and countries will opt for a variety of alternatives before any single option is chosen (if at all). In the meantime, investigations will continue into medium GWP flammable HFCs, HFC/unsaturated HFC blends and HCs for normal operating conditions as well as high ambient temperature conditions.

Water heating heat pumps

Current status

Air-to-water and water-to-water heat pumps have experienced significant growth in Japan, Australia, China, and Europe during the last ten years. HCFC-22 is still used in some Article 5 countries. The HFC blends R-410A and R-407C are currently used in Europe and other countries. R-744 heat pump water heaters were introduced to the market in Japan in 2001 and have seen a steady growth since then due to strong government support. In the past, the number of HC-290 applications in Europe has decreased, due to the Pressure Equipment Directive, however, recently a range of HC-290 compressors have become available. R-717 is mainly used for large capacity heat pump systems.

What is left to be achieved

Based on regulations in Europe, the water heating heat pump industry is looking to alternatives with a lower GWP than the one for R-410A.

The main challenge is to come with an efficient, cost effective, safe and easy to use solution. It is expected that other regions will follow the tendency to reduce the GWP value of refrigerants.

The way forward

For water heating heat pumps, HFC-32 or blends with unsaturated HFCs will be studied for future use by taking into account the performance, costs and the necessary safety regulations in relation to their lower flammability. R-744 systems will be optimised and used wherever possible, taking into account costs that will apply. HC-290 and R-600a will be used where possible, taking into account the costs involved and safety in regards to flammability.

Chillers

Current status

The phase-out of ozone-depleting refrigerants in chillers is moving along well. The CFCs have been essentially phased out for new equipment and the CFC banks are decreasing in existing chillers. The current generation of chillers using zero-ODP refrigerants had been introduced without a sacrifice in reliability or energy efficiency. HC-290, R-717 and R-744 are also being used in chillers. Water as a refrigerant is currently being used in absorption chillers and had been recently announced in vapour compression based chillers. The use of HCFC-22 in new equipment has been phased out in developed countries; many Article 5 countries also have stopped its use in new equipment. Limits set for HCFC-22 production and its rising costs have contributed to the conversion of new and existing chillers to zero ODP refrigerants.

What is left to be achieved?

The energy consumption of chillers dominates their environmental impact because the latest generation of chillers has low leak rates and, therefore, low direct global warming impact. The issue, then, is to determine which of the new refrigerants has high energy efficiency in chillers while being safe to use and having acceptable application costs. Major efforts have been launched to propose and test new lower-GWP refrigerants to replace the higher-GWP refrigerants currently in use.

The way forward

Testing of new, lower GWP refrigerants started several years ago and is continuing. At this juncture it is not clear which refrigerants may be selected for commercialisation. Tradeoffs are apparent among GWP, energy efficiency, safety, and applied cost. Refrigerants that are non-flammable with the A1 refrigerant safety classification generally have GWPs of 600 or more. Refrigerants with low GWP (<150) generally are flammable. All flammable refrigerants require special safety considerations. A2L refrigerants will not be widely used without changes to safety standards and building codes.

Vehicle air conditioning

Current status

Today the overwhelming majority of new AC equipped passenger cars world-wide use HFC-134a. The transition from CFC-12 is complete for new systems, but there are still cars in use especially in Article 5 countries. In order to meet the EU MAC Directive and to harvest potential US EPA CO2 credits, OEMs evaluated several refrigerant options for new car (and truck) air conditioning systems. As a result, some car manufacturers have started to equip certain models with HFC-1234yf. Owing to safety concerns regarding the A2L-refrigerant HFC-1234yf, other car manufacturers work on R-744 systems in order to introduce them into the market by the year 2017. Both options have GWPs enabling the GHG credits in US, they are below the EU threshold of 150 and both can achieve fuel efficiency comparable to the existing HFC-134a systems with appropriate hardware and control development. Also owing to safety concerns the use of hydrocarbons or blends of hydrocarbons has not received support from vehicle manufacturers. Most new bus or train air conditioning systems are currently equipped with the refrigerants HFC-134a or R-407C; fleet tests of R-744 systems in buses are on-going.

What is left to be achieved

At the end of 2014 it looks likely that more than one refrigerant will be used in the coming years for car and light truck air conditioning. HFC-134a will remain largely adopted worldwide, HFC-1234yf will continue its growth in new models at least in the near future, other new low GWP synthetic refrigerants or refrigerant blends (e.g. R-445A) may be implemented, and R-744 is expected to be implemented by German OEMs starting in 2017.

The way forward

Along with the Global Warming Potential issue the future spreading of the two refrigerants HFC-1234yf and R-744 in the worldwide vehicle air conditioning market will be significantly governed by additional considerations like safety, costs, regulatory approval, system reliability, heat pump capability (especially for electric driven vehicles) and servicing. At the moment, it cannot be foreseen whether or not the old and the new refrigerants will see parallel use in the market for a long period of time. Without existing regulations it is also unclear whether the bus and train sector will follow these trends.

Sustainable refrigeration

Current status

Refrigeration, air conditioning, and heat pump equipment are vital means to address the human fundamental needs in areas such as food conservation, food security, health care, water heating, and thermal comfort worldwide. There are however a number of negative environmental impacts from the use of such equipment that need to be minimized through careful consideration of design, operation, and end of life aspects of these equipment and the refrigerants they use.

What is left to be achieved?

Negative environmental impacts from refrigeration, air conditioning, and heat pump equipment must be managed through careful and systematic assessment when choosing new refrigerants, by reducing CO_2 emissions along the equipment life cycle, and through environmentally sound and socially fair end of life procedures.

The way forward

Enhancement towards sustainability demands proper national and regional regulation, expansion of voluntary programs aiming higher levels of energy efficiency, adoption of state-of-the-art energy management technologies, use of life cycle assessment tools, expansion of awareness and training initiatives across the industry value chain.

Executive Summaries of all Chapters

Refrigerants

The chapter discusses and provides tabular summaries for identifiers as well as physical, safety, and environmental data for refrigerants and includes brief descriptions of refrigerants treated in this report.

Whatever refrigerant is chosen will always have to be a balance between several factors, the availability and cost of the refrigerant (and the associated equipment), the system energy efficiency, the safety and convenience of applicability, environmental issues and many more.

The perfect refrigerant does not exist, and is unlikely to come into existence. Choices will therefore include existing very low GWP refrigerants (e.g. R-717, R-744 or HCs) and the newly applied or developed chemicals. Many new alternatives are proposed which create a challenge of finding the right refrigerant for each application. In some cases this may be as simple as changing the refrigerant, while in most cases this will require redesign of the system or even change of system topology. The search is a trade-off between cost, safety, energy efficiency, and limiting the need for redesign. One of the important aspects is that refrigerants with low direct impact on climate change are often flammable to some extent.

So far 21 refrigerants obtained standardized designations and safety classifications since the 2010 RTOC assessment report. One new molecule HCFC-1233zd(E) is in this group of new refrigerants and is an unsaturated HCFC (also referred to as HCFO) with potential to replace HCFC-123. Approximately one quarter of the new refrigerants are blends which are replacements for HCFC-22. Of the new refrigerants twelve are blends of saturated HFCs and unsaturated HFCs (HFOs) of which seven blends are with class 2L flammability.

The new refrigerants address climate concerns, and ozone depletion concerns with replacement refrigerants for ozone-depleting substances.

Domestic appliances

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

Globally, new refrigerator production conversion from the use of ODS was essentially completed by 2008. HC-600a or HFC-134a continue to be the refrigerant options for new production. No other new refrigerant has matured to become an energy-efficient and cost-competitive alternative. Refrigerant migration from HFC-134a to HC-600a is expected to continue, driven either by local regulations on HFCs or by the desire for reduced global warming impact from potential emissions. Excluding any influence from regulatory interventions, it is still projected that by 2020 about 75% of new refrigerator production will use HC-600a (possibly with a small share by unsaturated HFC refrigerants) and the rest will use HFC-134a.

According to some industrial sources, initial developments to assess the use of HFC-1234yf in domestic refrigeration have begun, but it is not being pursued with high priority, as in automotive applications. Given the cost disadvantage, flammability and investment requirements for product development, HFC-1234yf suffers significant disadvantages. With the lack of activity by manufacturers, HFC-1234yf is not likely to displace HC-600a or HFC-134a in the foreseeable future.

Alternative refrigeration technologies for domestic refrigeration continue to be pursued for applications with unique drivers such as very low noise, portability or no access to the electrical energy distribution network. In the absence of unique drivers, no identified technology is cost or efficiency competitive with conventional vapour-compression technology for mass-produced domestic refrigerators.

The other domestic appliance covered in this chapter is the heat pump clothe (laundry) dryer (HPCD). It is included in this chapter for the first time and the title has been accordingly modified as “Domestic Appliances” instead of “Domestic Refrigerators” used earlier. The market for HPCD is fast growing in the EU with manufacturers from both the EU and Japan. The current market share of HPCDs in Article 5 countries is insignificant. These dryers mostly use HFC-134a as a refrigerant and refrigerant charge amounts vary from 200 to 400 g. HPCDs using R-407C and HC-290 have also been just introduced. Alternative low GWP refrigerant solutions are being explored, including R-744, HC-600a and low GWP HFCs.

Non-Article 5 countries completed conversions of new equipment production to non-ozone depleting substances (ODSs) more than 15 years ago. Later, a few Article 5 countries also completed their conversion, e.g., India by 2003. Therefore, most products containing ozone depleting refrigerants are now approaching the end of their life cycle. Field conversion to non-ODS refrigerants has significantly lagged original equipment conversion. The distributed and individual proprietor character of the service industry is a barrier to co-ordinated efforts to convert from ODS refrigerants. Field service procedures typically use originally specified refrigerants. Refrigerant blends developed specifically for use as drop-in service alternatives have had limited success.

Both mandatory and voluntary energy efficiency regulation programs catalysed industry product efficiency development efforts. A number of improved energy efficiency design options are fully mature, and future improvements of these options are expected to be evolutionary. Extension of these to an all-global domestic market would yield significant benefit, but is generally constrained by availability of capital funds and related product cost implications.

Commercial refrigeration

Commercial refrigeration can be broadly classified as three different groups of systems: centralised systems (refrigerant is field charged) installed in supermarkets, condensing units (refrigerant is field charged) installed mainly in small shops and restaurants, and self-contained or stand-alone units (refrigerant is factory charged). On a global basis, HCFC-22 continues to represent a large refrigerant bank in commercial refrigeration and is used at all temperature levels. The most widely used HFC is R-404A and this for all temperature levels. Over the last decade, HCs --for low refrigerant charge systems-- and CO_2 --for supermarkets-- have taken significant market share, especially in Europe. In parallel, progress has been made to improve energy efficiency and leak tightness especially for centralized systems. The progressive phase-out of HCFC-22 in developing countries requires making informed choices on the best replacement options.

Stand-alone Equipment: Even if they have very different GWPs, HFC-134a and R-404A can be expected to be phased-out progressively in developed countries. Lower GWP HFC and HFC blends, hydrocarbons and CO_2 are replacing R-404A and HFC-134a in new stand-alone equipment. Minimum energy standards have been issued or updated in many countries making a new competition between manufacturers in order to reach higher energy efficiency in stand-alone systems.

Condensing Units: Condensing units are designed for several capacities and are standardized equipment; their cooling capacities vary from 5 to 20 kW with a refrigerant charge varying from 1 to 5 kg. HCFC-22 is still the most used refrigerant in all Article 5 countries. For new systems, R-404A is still the leading choice, and intermediate blends such as R-407A or R-407F are proposed as immediate options to replace R-404A. Global companies are now offering hydrocarbon condensing units for smaller capacities.

Supermarket systems: The size of centralised systems can vary from refrigerating capacities of about 20 kW to more than 1 MW relative to the size of the supermarket. Refrigerant charges range from 40 up to 3000 kg per installation. In Article 5 countries, HCFC-22 is still the dominant refrigerant used in centralised systems. In Europe, new systems have been mainly charged with R-404A; R-744 is now taking a significant market share with improved energy efficiency by using two-stage systems, options well known from industrial refrigeration. For small and medium size supermarkets, the so-called "booster system" has been designed to use CO_2 at the low and the medium temperature levels. For large supermarkets, the cascade system is preferred with CO_2 at the low temperature level and CO_2 or HFC-134a at the medium temperature level. Distributed systems are also quite common, gaining market share with improved energy efficiency, lower charge levels and lower emission rates. Indirect systems are also popular in order to limit the refrigerant content by more than 50% and to drastically lower refrigerant emission levels. For developing countries, the important issue remains the replacement of HCFC-22, either for retrofit or for new installations. Blends such as R-407A or R-407F constitute options offering significantly lower GWP than R-404A and R-507A.

Industrial systems

The majority of large industrial systems use R-717 as the refrigerant. When R-717 is not acceptable in direct systems in these countries, options include R-744 or glycol in secondary systems or HCFCs or HFCs in direct systems. In countries where R-717 has not been the preferred solution, or in market segments with smaller systems, the transition from HCFC-22 is not straightforward. It requires acceptance of higher cost fluorocarbons in systems similar to the types used with R-22 or the adoption of more expensive systems with the cheaper refrigerants R-717 and R-744. This transition is slow and is constrained by a lack of trained personnel and lack of experience of the local end-users. It has been facilitated by corporate policy from multinational food and beverage manufacturers. The process of moving from HCFCs to zero ODP, low GWP alternatives would be accelerated by a concerted education and training programme including operational experience and lessons learned from existing systems. This conclusion has been reinforced by several recent fatal accidents in Article 5 countries. These accidents appear to be caused by the acceptance of low standards of safety that would not be acceptable in more mature markets. Suitable safety standards already exist, for example those published by the International Organisation for Standardization (ISO).

In markets where R-717 is accepted as the preferred refrigerant there is no indication of any likelihood of new refrigerants gaining any significant market share. It is self-evident that if the current range of HFC fluids that could be used in these applications are being avoided due to concerns about refrigerant price and long term availability in bulk quantities then new fluids, which are expected to be even more expensive than current HFCs will not be any more successful. There are a few exceptions to this general rule. For example, HFC-1234ze(E) has been demonstrated in large district heating systems as a possible replacement for HFC-134a, however its performance is not any better than HFC-134a which is already limited in application and efficiency compared for example with R-717. HFC-1234ze(E) has also been demonstrated in centrifugal chillers which could be used in process cooling or in district cooling installations. This may be a key player in addressing the challenge of rapid market growth in the Gulf Co-operation Countries over the next twenty years.

The industrial sectors covered by this chapter are too diverse to facilitate the level of development expenditure required to bring a new fluid to market. It therefore follows that if any new development gains market share in industrial systems, it will be a fluid developed for some other purpose, either as a refrigerant in smaller mass-market systems or as a foam-blowing agent, solvent or other specialty chemical. Apart from absorption systems there is no significant growth of other not-in-kind cooling or heating solutions.

Transport refrigeration

Transport refrigeration is a small segment comprising delivery of chilled or frozen products by means of trucks, trailers, vans, intermodal containers and boxes. It also includes the use of refrigeration and air conditioning on merchant, naval and fishing vessels above 100 gross tonnes (GT) (over about 24 m in length).

Since 2010, most development has taken place in the intermodal container industry. Although many of the lessons are applicable to road transport, differences between containers and road vehicles should not be neglected, and may lead to different system solutions and (possibly) to different refrigerant choices.

For new systems, hydrocarbons offer high energy efficiency, but the safety risks in transport refrigeration applications appear significant and must be mitigated. On the other hand, R-744 has been tested in the field since 2011. Its non-flammable characteristics make R-744 attractive, but the gap in efficiency in high ambient temperatures and the limited component supply base are limiting its penetration into the market.

Recently there has been an initiative to consider the design and service best practices for flammable and high pressure refrigerants which it is hoped will lead to a fast track ISO standard on how these refrigerants can be applied to intermodal container refrigeration. The framework of this initiative has not yet been set.

In the case of a regulation banning the use of refrigerants above a certain GWP level (as in the EU), HFC blends are likely to play a role as a retrofit to R-404A and (possibly) HFC-134a systems: their GWP is significantly lower than R-404A and performances are relatively close. Candidates include but are not limited to R-407A, R-407F, R-448A, R-449A and R-452A.

One also sees “non-conventional” solutions such as open loop systems or eutectic systems. These solutions offer specific advantages in some transport routes, furthermore, the fact that vehicles are HFC free and that the supporting installation can be HFC free will continue making them attractive.

New information about vessel type and existing refrigerant charge is provided based on the 2012 IMO study. It appears that the differences in type are large and that segmentation will be needed in future. The designers must factor in specific safety requirements, space and reliability, but in general, they closely follow developments in industrial and air-conditioning systems.

Based on research, the road vehicle fleet size previously estimated at 4 million --in the 2006 and 2010 RTOC Assessment Reports-- has been downsized to 2 million. This changes the overall picture in that the refrigerant banks in vessels almost double the banks in other transport sub-segments.

The bottom line is that while CFCs and HCFCs can still be found in older equipment, virtually all new transport refrigeration systems continue to utilize HFCs, with a prevalence of HFC-134a and R-404A. Some systems aboard vessels utilize HCFC-22 in both non-Article 5 and Article 5 countries.

Air-to-air air conditioners and heat pumps

On a global basis, air conditioners for cooling and heating (including air-to-air heat pumps) ranging in size primarily from 2.0 kW to 35 kW (although in some cases up to over 750 kW) comprise a significant segment of the air conditioning market. Nearly all air conditioners and heat pumps manufactured prior to 2000 used HCFC-22. Most Article 5 countries continue to utilise HCFC-22 as the predominant refrigerant in air conditioning applications, although several major producing countries within Asia, Middle East and South America are now initiating HCFC Phase-out Management Plans (HPMPs) to introduce non-ODS alternatives.

R-410A is the dominant alternative to HCFC-22 in air-conditioners and is being used in manufacturing in most non-Article 5 and several Article 5 countries. This particularly is the case in China, where there is a large export market satisfying demand in non-Article 5 countries. However, R-410A units are not widely sold in the domestic market because of their higher cost. Whilst the use of R-407C in new product designs was common early on because it required minimal design changes, it is currently decreasing although it is still preferred in for regions with high ambient temperatures. The other main alternatives under consideration are HC-290, HFC-32, R-744, HFC-161 and a number of blends of HFCs and unsaturated HFCs such as R-444B, R-446A and R-447A (but also many currently without R-number designations).

Except for R-744, all of the medium and low GWP alternatives are flammable and should be applied in accordance with appropriate regulations and/or safety standards (that are continuously under development), considering refrigerant charge amount, risk measures and other special construction requirements. Some safety standards limit the system charge quantity of any refrigerant within occupied spaces; in some countries the application of such guidelines are voluntary although in some they are mandatory, whilst flammable gas regulations take precedence. Where national regulations place controls on the use of flammable substances, they normally require a risk-based approach and do not impose arbitrary charge size limits (e.g., EU Atex directive). Most manufacturers apply the safety standards. Some countries are introducing bans on imports of HFC-containing air conditioners.

HC-290 and HC-1270 are mainly considered for systems with smaller charge sizes, whilst the operating pressures and capacities are similar to HCFC-22 and the efficiency is higher than HCFC-22. Split air conditioning systems using HC-290 have been available in Europe and Australia, are in production in India and HCFC-22 equipment production capacity is being converted to HC-290 in China (however, with limited output at present). R-744 is considered to have limited applicability for air conditioning appliances in Article 5 countries, due to the reduced efficiency when the ambient temperature approaches or exceeds about 31°C. There is continuing research on cycle enhancements and circuit components, which can help improve the efficiency under such conditions, although they can be detrimental to system cost. HFC-161 is currently under evaluation for systems with smaller charge sizes due to flammability. The operating pressure and capacity is similar to HCFC-22 and the efficiency is at least as high as HCFC-22, although there is concern over its stability. HFC-32 is currently on the market for various types of air conditioners and has recently been applied in split units in several countries and some OEMs are also considering it for other types of systems. The operating pressure and capacity are similar to R-410A and its efficiency is similar or better than that of R-410A. There are various proprietary mixtures targeted for air conditioning applications, which comprise, amongst others, HFC-32, HFC-125, HFC-134a, HFC-152a, HFC-161, HFC-1234yf, HFC-1234ze, HC-600a, HC-600, H-1270 and HC-290. Some mixtures have been assigned R-numbers, such as R-444B, R-446A and R-447A, whilst most are still under development. These mixtures tend to have operating pressures and capacities similar to HCFC-22 or R-410A, with GWPs ranging from 150 to around 1000 and flammability class 1 (for higher GWPs) and class 2L (medium GWPs). Currently, most of these mixtures are not commercially available on a broad scale and adequate technical data is not yet in the public domain. Other low GWP single component HFCs, such as HFC-1234yf and HFC-152a, are unlikely to be used extensively as a replacement for HCFC-22 in air conditioners principally because of their low volumetric refrigerating capacity.

A major concern in some regions is the efficacy of the various alternatives to HCFC-22 in high ambient conditions (particularly R-410A). Whilst this problem for R-410A can be addressed through design and selection, work has fairly recently been carried out on a number of other alternatives, such as HC-290 and some of the new blends of HFCs and unsaturated HFCs, that show that performance degradation with higher ambient temperatures is similar to or not notably worse than with HCFC-22. Another issue is the possible impact on required refrigerant charge, where hotter regions can imply greater heat loads, larger system capacity and thus larger refrigerant charge; limits on refrigerant charge may be approached at smaller capacities, where additional (safety) measures would then have to be applied to the equipment. Systems using low-GWP refrigerants are not currently available for large capacity systems in high ambient temperature regions.

Water heating heat pumps

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

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

HFC-134a, R-744 and HFC blends R-407C, R-417A and R-410A are commercially available solutions that have the highest grade of safety and easiness to use. R-410A is most cost effective for small and medium size systems, while for large systems HFC-134a is most efficient. R-407C and R-417A are the easiest alternatives for HCFC-22 from a design point of view, but cannot compete with the other HFC-solutions.

Chillers

Chillers have low emission rates and low direct global warming impact. The issue, then, is to determine which of the new refrigerants has high energy efficiency in chillers while being safe to use and having acceptable application costs. Though most HFCs in use today are considered to have relatively high GWPs, this is not a governing factor for chillers because emissions are minimal.

The required global phase-out of HCFCs and the need to manage the lifetime operation of HCFC-based equipment, coupled with concerns to reduce global warming, continue to drive the transition from ozone depleting substance (ODS) refrigerants. The refrigerants that were used in the transition generally were HFCs with global warming potentials (GWPs) that are sufficiently high to cause environmental concerns, so a second transition has begun. Major efforts have been launched to propose and test new, lower GWP refrigerants to replace higher GWP refrigerants. A number of candidates have been proposed and are in the early stages of testing as possible replacements for higher-GWP HFCs.

The new candidates generally are unsaturated HFCs or blends which may contain HFCs, HCs, and/or unsaturated HFCs. A number of the new candidates have an A2L safety rating which is associated with flammability. They have a low flame velocity, distinguishing them from more flammable chemicals such as propane (HC-290). It is too early to tell which lower-GWP refrigerants will be successful as replacements for the higher GWP HFCs now in use. The parameters to be sorted out require balancing energy efficiency, flammability (including application standards and regulations), GWP values, cost, worldwide availability, retrofit considerations, and level of system design complexity that is required to use the new candidates successfully.

Vehicle air conditioning

In spite of existing regulations in the US (supporting the use of low-GWP refrigerants) and legislation in Europe (banning the use of refrigerants with GWP > 150), the overwhelming majority at present (year 2014) of the newly sold passenger cars and light trucks worldwide are still equipped with air conditioning systems, which use HFC-134a as refrigerant.

At the end of 2014 it looks likely that more than one refrigerant will be used in the coming years for car and light truck air conditioning: HFC-134a will remain largely adopted worldwide, HFC-1234yf will continue its growth in new models at least in the near future, other new low GWP synthetic refrigerants or refrigerant blends (e.g. R-445A) may be implemented and R-744 is expected to be implemented by 2017. All options have GWPs below the EU threshold and can achieve fuel efficiencies comparable to modern HFC-134a systems. Currently it cannot be forecast whether or not all these refrigerants will see parallel use in the market for a long period of time. It is also unclear whether the bus and train sector will follow these trends.

The global warming impact is almost identical for the above mentioned refrigerant options when considered on a global basis and in comparison to the CO_2 tailpipe emissions. Adoption of any of the refrigerant choices would therefore be of similar environmental benefit. The decision of which refrigerant to choose will have to be made based on other considerations. Here, especially safety, cost, and system reliability are important concerns, but also other aspects have to be taken into account, like regulatory approval, heat pump capability, suitability for hybrid electric vehicles, servicing, and risk of illegal use of high-GWP refrigerants in systems designed for low-GWP refrigerants. In the year 2012, HFC-1234yf seemed to be the worldwide accepted alternative to HFC-134a. However, based on new findings regarding the on-the-road flammability of HFC-1234yf (classified as A2L) most German OEMs abandoned this option and decided to further develop and eventually use R-744 in their future air conditioning systems. Further, one Japanese OEM decided to not use HFC-1234yf on the European market. Similar to the 2012 acceptance of HFC-1234yf, these decisions are subject to change as the OEMs continue their pursuit of alternative refrigerants to meet regulatory requirements and other concerns mentioned above.

Owing to safety concerns hydrocarbons and their blends are not considered as viable refrigerant options by OEMs. Although HFC-1234yf is also flammable, it has a lower heat of combustion, burning velocity and minimum ignition energy compared to hydrocarbons, and has been the subject of several safety assessments by OEMs and other research bodies. Today, some OEMs use HFC-1234yf as refrigerant in some of their car models.

OEMs and suppliers do also work on future not-in-kind refrigeration concepts. However, the development status of such refrigeration technologies, like sorption, thermoelectric or magneto caloric systems, are still far away from serial production and presently show very poor price competitiveness and poor system performance and efficiency. These concepts are briefly discussed in Annex C of this report.

The increasingly rapid evolution of hybrid electric vehicles and electric vehicles with reversible air conditioning and heat pump cycles, which use semi hermetic electrically driven compressors introduces new challenges for any new alternative refrigerant.

At present, no regulations exists that control the use of fluorinated greenhouse gases as refrigerants for MAC systems in buses and trains. It is likely that the choice of refrigerant of passenger car air conditioning systems, as well as developments in the stationary heat pump market, will influence the choice of refrigerant for air conditioning systems in buses and trains.

Sustainable refrigeration

Refrigeration, air conditioning, and heat pump equipment are vital means for sustainability to address the fundamental needs of humans in areas such as food conservation, food security, healthcare, water heating, and thermal comfort worldwide. There are, however, a number of negative environmental impacts from the use of this equipment that need to be minimized through careful consideration of design, operation, and end of life aspects of these equipment and the refrigerants they use.

The most relevant environmental impacts can be minimized by:

a. The use of assessment tools enabling manufacturers to plan for continual improvement of the design and operation of their equipment. A number of available assessment tools are referenced in this chapter.

b. The careful choice of refrigerants with lower environmental impact, both direct (due to chemical composition) and indirect (such as use of energy and materials). The wide range of gases already available in the market, as well as those in the development process, stresses the need of conveying updated, unbiased information to both product designers, service technicians, and users through initiatives fostered by local governments and industry associations.

c. The proper management of the selected refrigerants in response to growing environmental, regulatory, and economic concerns associated with refrigerant emissions, through:
   - Charge minimization through simple measures such as checking the amount of refrigerant being charged, or by innovative technologies such as cascade systems and secondary loops;
   - Improved design for leak tightness;
   - Care taken during manufacturing, installation, service, and maintenance;
   - Refrigerant conservation, using commercially available equipment for recovery, recycling and recovery, as well as destruction of refrigerants at the end of life.

d. The reduction of CO_2 emissions from energy use, achievable through:
   - Minimum energy efficiency performance standards applied through national regulation;
   - The use of renewable energy sources; and
   - Better energy management related to smart grid technologies, waste energy analysis, heat recovery, and anti-cyclical storage.

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

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

Chapter 1

Introduction

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1 Introduction

1.1 Montreal Protocol developments

In 1981, the United Nations Environment Programme (UNEP) began negotiations to develop multilateral protection of the ozone layer. These negotiations resulted in the Vienna Convention for the Protection of the Ozone Layer, adopted in March 1985. In September 1987, 24 nations, amongst which the United States, Japan, the Soviet Union, certain country members of the European Community, the developing countries Egypt, Ghana, Kenya, Mexico, Panama, Senegal, Togo and Venezuela, as well as the European Community, signed the Montreal Protocol on Substances that Deplete the Ozone Layer. The Montreal Protocol entered into force on January 1, 1989. This international environmental agreement originally limited production of specified CFCs to 50 percent of the 1986 levels by the year 1998 and called for a freeze in production of specified halons at 1986 levels starting in 1992. By April 1991, 68 nations had already ratified the Protocol: these countries represented over 90 percent of the 1991 world production of CFCs and halons.

Shortly after the 1987 Protocol was negotiated, new scientific evidence conclusively linked CFCs to the depletion of the ozone layer and indicated that depletion had already occurred. Consequently, many countries called for further actions to protect the ozone layer by expanding and strengthening the original control provisions of the Montreal Protocol, and they decided that a first assessment should be carried out in the year 1989. Numerous assessments followed.

The 23rd Meeting of the Parties, held in Montreal in Bali, Indonesia, November 2011, considered the 2010 Assessment Reports, next to a large number of other issues. Parties decided to request the Assessment Panels to update their 2010 reports in 2014 and submit them to the Secretariat by 31 December 2014 for consideration by the Open-ended Working Group and by the Twenty-Seventh Meeting of the Parties in 2015 (MOP-27). In the relevant Decision (XXIII/11), the Parties also requested the TEAP (and its TOCs) in paragraph 6 to consider potential areas of focus:

(a) The impact of the phase-out of ozone-depleting substances on sustainable development, particularly in Parties operating under paragraph 1 of Article 5 and countries with economies in transition;

(b) Technical progress in all sectors;

(c) Technically and economically feasible choices for the reduction and elimination of ozone-depleting substances through the use of alternatives, taking into account their impact on climate change and overall environmental performance;

(d) Technical progress on the recovery, reuse and destruction of ozone-depleting substances;

(e) Accounting for: the production and use in various applications of ozone-depleting substances; ozone-depleting substances in inventories; ozone depleting substances in products; and the production and use in various applications of very short-lived substances;

(f) Accounting of emissions of all relevant ozone-depleting substances with a view to updating continuously use patterns and co-ordinating such data with the Scientific Assessment Panel in order periodically to reconcile estimated emissions and atmospheric concentrations.

Together with the Science and Environmental Effects Assessment reports, the 2014 TEAP Assessment Report --together with the 2014 TOC Assessment Reports-- forms the direct response to the above-mentioned decision.

1.2 The UNEP Technology and Economic Assessment Panel

Four Assessment Panels were defined in the original Montreal Protocol as signed 1987, i.e. Assessment Panels on (1) Science, and on (2) Environmental Effects, (3) a Technical Assessment and (4) an Economics Assessment Panel. The Panels were established in 1988-89; their Terms of Reference can be found in the Meeting Report of the 1st Meeting of the Parties, held in Helsinki in 1989. Under the Technical Assessment Panel five Subsidiary Bodies, the so called Technical Options Committees were defined (see Meeting Report of the First Meeting of the Parties in Helsinki). The Technical and Economics Assessment Panels were merged after the Meeting in London in 1990 to the Technology and Economic Assessment Panel. At the Meeting in Copenhagen, it was decided that each Assessment Panel should have up to three co-chairs, with at least one from an Article 5 country. After the discussions on methyl bromide held at the meeting in Copenhagen, the Methyl Bromide Technical Options Committee was founded at The Hague in early 1993. From 1993 until 2001, the UNEP Technology and Economic Assessment Panel (TEAP) had 7 standing Technical Options Committees (TOCs). In 2001, the Economics Options Committee was disbanded, which resulted in a number of 6 Committees. In 2005, the Aerosols TOC and the Solvents TOC were disbanded, and a new Medical TOC and a Chemicals TOC were formed by merging certain parts of the Aerosols and the Solvents TOC, and replenishing the membership with additional, new experts. Currently there are the following TOCs:

1. **Chemicals** Technical Options Committee
2. **Flexible and Rigid Foams** Technical Options Committee
3. **Halons** Technical Options Committee
4. **Medical** Technical Options Committee
5. **Methyl Bromide** Technical Options Committee
6. **Refrigeration, A/C and Heat Pumps** Technical Options Committee

Where, originally, the Panels were considered as the bodies that should carry out assessments pursuant to Article 6 under the Montreal Protocol (at least every four years), it is particularly the TEAP that has become a “standing advisory group” to the Parties on a large number of Protocol issues. The evolving role of the TEAP -and its Technical Options Committees and other temporary Subsidiary Bodies- can be explained by the fact that the focus of the Montreal Protocol has shifted from introducing and strengthening control schedules (based upon assessment reports) to the control of the use of controlled chemicals and to compliance with the Protocol. This implies the study of equipment, of use patterns, of trade, imports and exports etc. In the case of the Medical and the Methyl Bromide Technical Options Committees, the emphasis of the work has largely shifted to the evaluation and recommendation of certain essential (MTOC) and critical (MBTOC) use applications.

At the MOP-19 in Montreal an important Decision was taken on the accelerated phase-out of HCFCs in Article 5 countries. In the decision, a reduction schedule for production and consumption was defined for the period 2013-2030, with a freeze in 2013 and a servicing tail until 2040. Apart from the specific percentages, the decision mentioned:

“….To encourage Parties to promote the selection of alternatives to HCFCs that minimize environmental impacts, in particular impacts on climate, as well as meeting other health, safety and economic considerations” and
“….To agree that the Executive Committee, when developing and applying funding criteria for projects and programmes, and taking into account paragraph 6, give priority to cost-effective projects and programmes which focus on, *inter alia*:

"Phasing-out first those HCFCs with higher ozone-depleting potential, taking into account national circumstances", and
"Substitutes and alternatives that minimize other impacts on the environment, including on the climate, taking into account global-warming potential, energy use and other relevant factors."

In this decision it became clear that climate considerations, i.e., a focus on substitutes with an overall low climate impact, became very important in the conversion away from HCFCs.

As a first consequence of Decision XIX/6, the Parties requested the TEAP and its RTOC in Decision XIX/8, to report on the status of substitutes and alternatives to HCFCs under high ambient conditions. The report was done by a Subcommittee of the RTOC, and submitted to Parties in a preliminary form in 2009 and in its final form in 2010.

In 2008, Parties requested the TEAP and its committees, in Decision XX/8, to look at the status of alternatives in the different sectors and subsectors, as covered by the six Technical Options Committees. In a report by a Task Force, a large amount of material was summarised; this report also contained updated information on banks and emissions from all sectors, including refrigeration, AC and heat pumps as well as foams. In 2009, in Decision XXI/9, on HCFCs and environmentally sound alternatives, Parties requested the TEAP to update the information from the XX/8 report, and to report on the status of low GWP alternatives for the replacement of HCFCs, and to report on the comparison of performances of high and low GWP alternatives. TEAP established again a Task Force, which reported on the definition of the term "low-GWP" and "high-GWP", and particularly on the 2009/2010 status of (low GWP) substitutes and alternatives to HCFCs in all sectors and subsectors. In 2011, 2012, 2013, the Parties requested a number of Task Force reports under Decisions XXIII/9, XXIV/7 and XXV/5. It should be noted that the request in Decision XXIII/9 was made in parallel with the request for new assessment reports to be submitted by the end of 2014, requesting information on the costs of alternatives to HCFCs, on alternatives that were technically proven, economically viable, environmentally benign, and which could be used in high ambient temperature conditions.

The information requested for these Task Force reports was very much related to the information requested on how to deal with a conversion from ODS (particularly HCFCs) to environmentally sound alternatives (which definition includes low global warming characteristics). For the report under Decision XXIV7, Parties requested to update information on alternatives, but also to identify barriers and restrictions to the adoption of environmentally sound alternatives, as well as an estimation of the approximate amount of alternatives with negative environmental impacts that could be avoided. The Task Force XXIV/7 report elaborated on the methodological approach, gave a long description of the alternatives that would be environmentally sound, in particular for the RAC, foams, as well as the fire protection and solvents sectors. It also determined amounts on alternatives with negative environmental impacts that could be avoided (e.g. it was estimated that, integrated over the period 2013-2020, 15% could be avoided in the RAC sector).As a result of this XXIV/7 reporting, in 2013, the Parties requested a new report under Decision XXV/5. The Terms of Reference mentioned that it should report on (1) alternatives that should be commercially available, technically proven and environmentally sound, easy and safe to use (also in high urban densities), alternatives that would be economically viable and cost effective. It also mentioned to again report on the suitability of alternatives under high ambient temperature conditions. The decision also requested to assess the economic costs, implications and environmental benefits of various scenarios of avoiding high GWP alternatives. The decision further asked to expand on the demand issue and to report on scenarios for the current and future demand of alternatives.

The XVV/5 reported in two steps, with a draft report for the OEWG in 2014 and a final report for the MOP of the Parties in that same year. The report presented a long list of alternatives available and alternatives that would become available, it listed GWPs and costs for alternatives as far as information was available and mentioned information related to the operation under high ambient conditions -- where available. It reported on alternatives and future developments for the refrigeration, AC, foams, fire protection, medical uses and solvents sectors.

The XXV/5 report also presented demand scenarios for the period up to 2030 for environmentally sound alternatives to ODS for the sectors refrigeration and AC and foams. BAU scenarios were defined for non-Article 5 and Article 5 Parties, and it was decided to present two mitigation scenarios for the demand, based upon bans for certain refrigerant (blowing agent) chemicals in certain years. In these scenarios it was shown that the demand in the RAC sector was very much dominant over the demand in other sectors. The assumption of two types of mitigation scenarios showed that the growth of high global warming alternatives could be curbed. This would be possible with certain plausible (partly already ongoing) measures in non-Article 5 countries. Furthermore, stringent (but still plausible) measures as of 2020-2030 could lead to a real reduction of the demand for non-environmentally benign alternatives during the period 2020-2030 in Article 5 countries.

As an example, the XXV/5 Task Force reported that the first (MIT-1) scenario could cumulatively deliver a saving of 3,000 Mtonnes CO_2-eq. by 2030 and that the second (MIT-2) could deliver 11,000 Mtonnes CO_2-eq over that same time period.

As a result of the discussions concerning the information provided in the XXV/5 report, Parties requested an update of the report via Decision XXVI/9. This report is expected to be delivered by a TEAP Task Force in the course of 2015, that is, after that this 2014 Assessment Report has been published. Amongst other information, the XXVI/9 report will use information from the XXV/5 Task Force report and from the RTOC 2014 Assessment Report.

The information collected for the various Task Force reports mentioned above (XXIII/9, XXIV/7 and XXV/5) has, of course, been used in the preparation of the 2014 TOC Assessment Reports, in particular for the 2014 RTOC Assessment Report. The final versions of the Task Force reports are available on the Internet (http://www.unep.org/ozone).

Where Terms of Reference for the TEAP and its TOCs had been drafted in 1996, Parties, in Decision XXII/22, requested the TEAP to report on guidelines for nominations, on the appropriate expertise when appointing members etc. The report by TEAP resulted in Decision XXIII/10 (2011), which requested the Panel to update information on nominations and operational procedures of the TEAP and its technical committees, also related to the duration of appointments and various other procedures. Delivery of the TEAP XXIII/10 report resulted in a new Decision XXIV/8 (2012), which gave –in an 8 page long description- (updated) Terms of Reference, a code of conduct and disclosure and conflict of interest guidelines for the TEAP and its technical options committees and temporary subsidiary bodies. Decision XXV/6 requested information on issues such as the implementation as well as the proposed configuration of the TOCs as of 1/1/2015; it also requested to streamline annual progress reporting. In its future operations, after delivery of this 2014 Assessment report, the RTOC will consider all elements that have been mentioned in these decisions, when deciding on the organisation of the Refrigeration, AC and Heat Pumps Technical Options Committee, its size, expertise and further operational procedures.

The 2014 Technical and Economic Assessment has been carried out by the Technology and Economic Assessment Panel and its six Technical Options Committees. The six Committees consisted of more than 120 experts from a large number of countries (for a list, see the annex to the Technology and Economic Assessment Panel Report 2014). The 2014 Refrigeration, AC and Heat Pumps Assessment forms an important part of all the 2014 Assessment efforts.

Most Technical Options Committee reports (including the 2014 Refrigeration, AC and Heat Pumps Assessment Report) have been subject to a peer review before final release. The final version of the reports will be distributed internationally by UNEP and will also be available on the Internet (http://www.unep.org/ozone).

1.3 The Technical Options Committee Refrigeration, A/C and Heat Pumps

This Technical Options Committee Assessment Report on Refrigeration, A/C and Heat Pumps (hereafter called "RTOC Assessment Report") forms part of the UNEP review pursuant to Article 6 of the Montreal Protocol.

It is part of the 2014 assessment work of the Technology and Economic Assessment Panel (requested by the Parties in Montreal (Decision XXIII/11)). The information collected (particularly in the form of the Executive Summaries) will also be part of the Technology and Economic Assessment Report 2014, as well as the overall 2014 Synthesis Report composed by the three Assessment Panel co-chairs, the beginning of 2015.

The 2014 RTOC Assessment Report has been drafted in the form of a number of chapters. There are chapters on refrigerants and their properties, on the different R/AC application areas and one chapter on sustainable refrigeration. The structure of the report was chosen more or less similar to the structure of the 2010 RTOC Assessment Report.

Table 1-1: "Member countries" of UNEP's Refrigeration, A/C and Heat Pumps Technical Options Committee

Belgium	Egypt	Lebanon
Brazil	France	Netherlands
China	Germany	Norway
Croatia	India	South Africa
Czech Republic	Jamaica	United Kingdom
Denmark	Japan	United States

Each of the chapters was developed by 2-6 experts in the specific sector, and the chapter was chaired by a Chapter Lead Author - who did the larger part of the drafting and the co-ordination.

The 2014 RTOC included 40 representatives from Asian, European, Middle-East, Latin and North American companies, universities and governments, as well as independent experts (see Table 1-1). These representatives have been full (reporting) members; as resource persons the RTOC also had a small number of reviewing members.

Affiliations of the members are listed in Table 1-2 (40 organisations (including consultancies) were involved in the drafting of the report). The names and contact details of all members are given as an appendix to this RTOC Assessment Report.

Several drafts of the report were made, reviewed by the separate chapters and discussed in five RTOC meetings (outline August 2011, preliminary draft May 2013, a draft December 2013, a draft May 2014, a draft September 2014, the peer review draft October 2014 and a final report December 2014).

A preliminary committee meeting was held in Prague (during the IIR congress), August 2011. Drafting and reviewing meetings were held in France (Paris), May 2013, Canada (Montreal), December 2013, Italy (Torino), May 2014, and Germany (Karlsruhe), December 2014.

Table 1-2: Affiliations of the members of UNEP's Technical Options Committee on Refrigeration, A/C and Heat Pumps

1	A/genT Consultancy (Tech. Univ., Eindhoven)	Netherlands
2	Alaa Olama Consultancy	Egypt
3	Bassam Elassaad, Consultant	Lebanon
4	Bitzer Industries	Brazil, U.S.A.
5	Braunschweig University	Germany
6	Carrier Corporation	U.S.A.
7	CRT Cambridge	UK
8	Daikin Europe N.V.	Belgium
9	Danfoss	Denmark
10	Danish Technological Institute	Denmark
11	Devotta Consultancy, Chennai	India
12	EREIE Consultancy, Palaiseau	France
13	Emerson	U.S.A.
14	Fiat Ricerche Torino	Italy
15	GEA Industries, Consultant	South Africa
16	General Electric, Consumer and Industrial	U.S.A.
17	Indian Institute of Technology Delhi	India
18	Ingersoll Rand	Czech Republic
19	James M. Calm, Engineering Consultant	U.S.A.
20	Johnson Controls	Denmark
21	Johnson Controls	U.S.A.
22	JRAIA	Japan
23	Karlsruhe University of Applied Sciences	Germany
24	Maua Institute of Technology	Brazil
25	Nelson Consultancy	Jamaica
26	Panasonic	Japan
27	Petra Industries	Jordan
28	Ref-tech Engineering	Germany
29	Re/genT b.v.	Netherlands
30	Re-phridge Consultancy	United Kingdom
31	Shanghai JiaoTong University	P.R. China
32	SINTEF Energy Research, Trondheim	Norway
33	Star Refrigeration	United Kingdom
34	Sun Yat-sen University, Guangzhou	P.R. China
35	The Trane Company	U.S.A.
36	University of Zagreb	Croatia
37	U.S. Environmental Protection Agency	U.S.A
38	Vodianitskaia Hapy Consultancy	Brazil
39	Zhejiang University, Hangzhou	P.R. China

The report has been peer reviewed by a number of institutions and associations, plus some experts in their personal capacities, each of them reviewing the different chapters sections in a co-ordinated effort in a tight timeframe, i.e., between the last week of October and the end of November 2014 (see Table 1-3 for the organisations and experts involved, total 20). Peer review comments were collected and sorted out, and subsequently sent to all RTOC members.

All peer review comments were studied and sorted for a study by the Chapter Lead Authors before the RTOC Meeting in December 2014. The RTOC members in plenary decided on whether or not to amend the text on the basis of the peer review comments during the RTOC meeting in Karlsruhe, Germany, December 2014.

The RTOC greatly acknowledges the voluntary support given by the peer review institutions and the experts in their personal capacities.

Table 1-3: Organisations that participated in the peer review of the UNEP RTOC Assessment Report

AIRAH	*Australian Institute of Refrigeration, Air Conditioning and Heating*
AHRI	*Air Conditioning, Heating and Refrigeration Institute*
AREMA	*AC and Refr Equipment Manufacturers Association of Australia*
CAR	*Chinese Association of Refrigeration*
CHEAA	*China Household Electric Appliances Association*
CRAA	*Chinese Refrigeration and Air Conditioning Association*
DKV	*German Refrigeration Association*
EIA	*Environmental Investigation Agency*
EPEE	*European Partnership for Environment and Energy*
Eurammon	*European Industry Association for Ammonia etc.*
JRAIA	*Japanese Refrigeration and Air-conditioning Industry Association*
IIR	*International Institute of Refrigeration*
IOR	*Institute of Refrigeration UK*
Refrigerants Naturally	*A global not-for-profit initiative of companies to combat climate change and ozone depletion (by substituting fluorocarbons)*
SAE	*Society of Automobile Engineers (via members Atkinson, Hill)*
Shecco	*A Market Development Expert helping companies to bring their climate friendly solutions faster to market*
WSC	*World Shipping Council*
Lundqvist	*Personal Review (KTH Stockholm, Sweden)*
Polonara	*Personal Review (Universita delle Marche, Italy)*
Roke	*Personal Review (Fisher and Paykel, New Zealand)*

1.4 Refrigeration, air conditioning and heat pumps

1.4.1 General remarks

Refrigeration, air conditioning and heat pump applications represent more than 70% of the ODS and replacement substances used; it is also one of the most important energy using sectors in the present day society. Estimates are difficult to give but as an average for the developed countries, its share in electricity use is thought to vary between 10 and 30%.

The economic impact of refrigeration technology is much more significant than generally believed; 300 million tonnes of goods are continuously refrigerated. While the yearly consumption of electricity may be huge, and where the investment in machinery and equipment may approach US$100,000 million, the value of the products treated by refrigeration either alone will be four times this amount. This is one of the reasons that economic impacts of the phase-out of refrigerant chemicals (such as CFCs in the past, and HCFCs in Article 5 countries in the foreseeable future) have been and still are difficult to estimate.

Refrigeration and air conditioning applications vary enormously in size and temperature level. A domestic refrigerator has an electrical input between 50-250 W and contains less than 30-150 g of refrigerant (dependent on the type of refrigerant), whereas industrial refrigeration and cold storage is characterised by temperatures between -10 C and -40 C, with electrical inputs up to several MW and refrigerant contents of many hundred kilograms. Air conditioning and heat pumps may show evaporation temperatures between 0 C and +10 C, significantly different from refrigeration applications, and vary enormously in size and input.

In principle one can therefore discriminate between four main areas which each have subsectors: (i) the food chain in all its aspects, from cold storage via transport to domestic refrigeration, (ii) process air conditioning and refrigeration, (iii) comfort air conditioning, from air cooled equipment to water chillers, including heat pumps, and (iv) mobile air conditioning, with very specific, different aspects. This is one of the reasons that all the equipment is considered in this report in a large number of separate chapters or sections.

Options and aspects for the refrigeration vapour compression cycle deserve most attention, since it is unlikely that during the next 10-20 years other principles will take over a substantial part of the market. In all application sectors described in the separate chapters in this report, most of the attention is focused on the vapour compression cycle. As stated, this cycle has so far provided the simplest (?), economic, efficient and reliable way for refrigeration (this includes cycles using ammonia, fluorochemicals and hydrocarbons as refrigerants).

The process of selecting a refrigerant for the vapour compression cycle is rather complex, since a large number of parameters need to be investigated concerning their suitability for certain designs, including:

- thermodynamic and transport properties;
- temperature ranges
- pressure ratios
- compressor requirements;
- material and oil compatibility;
- health, safety and flammability aspects;
- environmental parameters such as ODP, GWP and atmospheric lifetime.

These selection criteria were elaborated upon in various chapters of various UNEP RTOC Assessment Reports, and these selection criteria have not changed during the last years. Since then, it is the emphasis on the emissions of greenhouse gases that has increased; this can be directly translated to thermodynamic efficiency and quality of the equipment (leakage of refrigerant).

The future of mankind, and his food supply in particular, depends on the availability of sufficient energy and on the availability of efficient refrigeration methods. Of course, this aspect must be more than balanced by a concern for the conservation of the biosphere, including in particular the global warming effect. Energy efficiency, therefore, is one of the most important aspects.

1.4.2 Long term options and energy efficiency

CFC production has been phased out since a decade in the developed countries, and the CFC phase-out in the developing countries, which was scheduled for 2010, has been completed. Where HCFCs have been largely phased out in the developed countries, the phase-out in the Article 5 countries is now asking full attention. In both developed and developing countries, HFCs have so far been important substitutes for CFCs and HCFCs. In many applications, alternatives to HCFCs have become commercially available, as pure HFCs, as blends of HFCs or as non-HFC alternatives. Therefore, HFCs have gained a large share of the replacement market. In particular the necessary incentives remain to be provided to Article 5 countries to transition from HCFCs to non-HCFC refrigerants, which will include both HFCs and non-fluorocarbon alternatives.

It should be noted, however, that the changing refrigerant options are only part of the driving force for innovations in refrigeration and A/C equipment. Innovation is an ongoing independent process, which has to take into account all the environmental issues involved.

In the long term, the role of non-vapour compression methods such as absorption, adsorption, Stirling and air cycles etc. may become more important; however, vapour compression cycles are thought to remain the most important candidates.

For the long term, there remain, in fact, only five important different refrigerant options for the vapour compression cycle in all refrigeration and A/C sectors, listed alphabetically:

- ammonia (R-717);
- carbon dioxide (R-744);
- hydrocarbons and blends (HCs, e.g. HC-290, HC-600a, HC-1270 etc.);
- hydrofluorocarbons (unsaturated HFCs (HFOs) with a four digit number, HFC-blends with 400 and 500 number)
- water (R-718).

The five refrigerant options above are in different stages of development or commercialisation. Although high GWP HFCs are (still) widely used in many sectors, low GWP HFCs and low GWP HFC blends are now increasingly being applied. Ammonia and hydrocarbons enjoy growth in sectors where they can be easily accommodated, and for certain applications, CO_2 equipment is being further developed and a large number of CO_2 demonstration installations have been extensively tested on the market. It may well be that CO_2 will take a substantial part of the commercial refrigeration equipment market. Water is used and may see some increase in use in limited applications. Work is being done by several committees in developing standards to permit the application of new refrigerants, and it is the intent of companies to reach world-wide accepted limits in those different standards.

Similarly, energy efficiency research is partly spurred by the role of energy production in carbon dioxide emissions. Options for energy efficient operation of equipment form an important issue in each of the chapters of this 2014 RTOC Assessment report.

1.4.3 Set up of the 2014 RTOC Refrigeration, A/C and Heat Pumps Assessment Report

Chapter 2 presents refrigerants and all their aspects. It elaborates on Ozone Depleting Potentials, and on ODP and GWP data for reporting purposes. It also investigates the status and research needs for data, i.e., thermophysical, heat transfer, compatibility and safety data.

Chapters 3, 4, 5 and 6 deal with the food chain and investigate the technical feasibility of options. They all consider non-ODP options and deal with aspects such as the use of non-fluorochemicals, the reduction of charges, energy efficiency improvements etc. Particularly the energy efficiency aspect plays an important role in chapter 3 on domestic refrigeration. Chapter 4 discusses the options for the 3 types of commercial refrigeration equipment. Chapter 5 deals with industrial refrigeration and cold storage, chapter 6 with transport refrigeration. Chapters 7 and 8 deal with air conditioning and heat pumps. Chapter 9 deals with the various aspects of chillers, which includes important considerations on energy efficiency. Chapter 10 describes the options for mobile air conditioning; in a first instance, it deals extensively with HFC-134a, but it also evaluates the potential the options carbon dioxide, hydrocarbons, the unsaturated HFCs (i.e., HFC (HFO)-1234yf) and other options will have. Chapter 11 deals with sustainability issues in refrigeration.

All chapters have drafted an executive summary; these summaries were put together and are presented in the first part of the report. The executive summaries are preceded by a shortened ("abstract") executive summary (e.g. for policy makers) which has been abstracted from the separate executive summaries. This is again preceded by key messages derived from the abstract executive summaries.

Chapter 2

Refrigerants

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2 Refrigerants

2.1 Introduction

Since the 2010 assessment report 21 refrigerants obtained standardized designations and safety classifications. One new molecule, HCFC-1233zd(E), can be found in this group of new refrigerants; it is an unsaturated HCFC (HCFO) with potential to replace HCFC-123. Approximately a quarter of the new refrigerants are blends which are replacements for HCFC-22. Twelve of the new refrigerants are blends of high global warming potential (GWP) saturated HFCs and low GWP unsaturated HFCs (HFOs), and seven of these blends are with class 2L flammability.

The search for new refrigerants addresses both climate and ozone concerns, in particular by reducing the GWP of the refrigerant and replacing ozone-depleting substances.

The search for new refrigerants addresses both climate concerns and ozone depletion concerns, in particular by reducing the GWP of the refrigerants and replacing ozone-depleting substances, such as HCFC-22.

2.1.1 Refrigerant progression

The historic progression of refrigerants encompasses four phases based on defining selection criteria (Calm, 1997; Calm, 2012):

- 1830s-1930s – whatever worked: primarily familiar solvents and other volatile fluids including ethers, ammonia (NH_3, R-717), carbon dioxide (CO_2, R-744), sulphur dioxide (SO_2, R-764), methyl formate ($HCOOCH_3$, R-611), HCs, water (H_2O, R-718), carbon tetrachloride (CCl_4, R-10), hydrochlorocarbons (HCCs), and others; many of them are now regarded as “natural refrigerants” (more exactly non-fluorinated since nearly all actually are synthesized, refined, or at least industrially purified).

- 1931-1990s – safety and durability: primarily chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), ammonia, and water (mostly used in absorption cycles).

- 1990-2010s – stratospheric ozone protection: primarily HCFCs (for transition use), hydrofluorocarbons (HFCs), ammonia, water, hydrocarbons, and carbon dioxide.

- Beyond 2012 – global warming mitigation: to be determined, but likely to include refrigerants with very low ($< 10^{-3}$) or no ozone depletion potential (ODP), low global warming potential (GWP), and high efficiency; likely to include, at least initially, unsaturated hydrofluorocarbons (hydrofluoroolefins, HFOs discussed below), ammonia, carbon dioxide, hydrocarbons and water.

2.1.2 Unsaturated hydrofluorochemicals

Facing regulatory pressures to eliminate refrigerants with high GWPs, the major refrigerant manufacturers have pursued unsaturated fluorochemicals. They are chemicals consisting of two or more carbon atoms with at least one double bond between two or more of them as well as fluorine, hydrogen, and possibly also chlorine or other halogens. Unsaturated fluorocarbons also are identified as fluoro-alkenes or fluoro-olefins. Double carbon-carbon bond(s) make(s) the compounds more reactive. The result is short atmospheric lifetimes and, thereby, very low ODPs and GWPs.

The unsaturated HFC (also identified as hydrofluoro-alkene or hydrofluoro-olefin, HFO) family is a focal example with varying extents of halogenation, in part, as a trade-off between flammability associated with a lower degree of stability and high GWP associated with a higher degree of stability. Chemical producers are pursuing alternatives for the most widely used low-, medium-, and high-pressure refrigerants.

In the naming of unsaturated halocarbons the prefix for unsaturated HCFC, and unsaturated HFC can alternatively be chosen to be HCFO and HFO respectively, where the O replaces the carbon C (ISO 817:2014). In this report the prefix used is the default HCFC and HFC respectively.

The extent of long- term acceptability of unsaturated HFCs or more broadly unsaturated hydro-halochemicals is uncertain, though a number of initial studies looking at the trifluoroacetic acid (TFA) build up resulting from the use of unsaturated HFCs in mobile air-conditioning indicate manageable environmental impacts (Kajihara, 2010; Luecken, 2010; Papasavva, 2009).

2.1.3 Recent assessment on current and future refrigerants and GWP

There are a number of studies providing assessments of a broad number of alternative refrigerants.

For example, the AHRI Low-GWP Alternative Refrigerants Evaluation Program (AHRI/AREP) phase 1 evaluated more than 30 new refrigerants (AHRI, 2013), most of them blends and most of them based on unsaturated HFCs mixed with traditional HFCs. The refrigerant categories and corresponding 100 year GWP values are given in Table 2-1 (calculated based on the GWP values of Table 2-7).

Table 2-1: 100 year GWPs for AHRI/AREP alternative refrigerants

Safety Class	**Range of GWP for Alternatives to**		
	HFC-134a	**HCFC-22, R-404A, R-407C, and R-507A**	**R-410A**
A1	540 – 900	950 – 1600	
A2L	≤ 110	200 – 970	280 – 740
A3	14 – 20	1,8 – 5	

This table illustrates the relationship between the pressure and the flammability of a fluid, although it can be argued that not all the proposed R-410A replacements have high enough capacity to be considered replacements for R-410A. There is a clear trend that the higher the pressure the higher the minimum GWP that is needed for pure compounds or blends to be non-flammable. The above also gives a good estimate of which levels of GWP are to be expected for various capacity/pressure levels for a given flammability class.

Another recent study (McLinden, 2014) started with a database of 100 000 000 chemicals, screening the more than 56 000 small molecules and finding non ideal. The conclusion is that the perfect cheap, energy efficient, non-toxic, non-flammable, and broadly applicable refrigerant with negligible GWP does not exist, and is highly unlikely to come into existence.

2.1.4 Flammable refrigerants and Safety classification

ISO 817 (ISO 817:2014) and ASHRAE 34 (ASHRAE 34-2013) assigns a safety class for each refrigerant, for instance “A2L”. The first letter of the safety class describes the toxicity, A for lower level of toxicity and B for higher level of toxicity, while the second part is the flammability of the refrigerant: 1 (no flame propagation), 2L (lower flammability), 2 (flammable), and 3 (higher flammability) (Table 2-2; see the annex to this chapter for addition details).

Table 2-2: Safety classifications

Flammability	**Toxicity**	
	A	**B**
1	A1	B1
2L	A2L	B2L
2	A2	B2
3	A3	B3

As mentioned above, there is a trade-off between GWP and flammability. A low GWP can be achieved by having the refrigerant break down quickly in the atmosphere, however this also means that the refrigerant breaks down easier when subjected to ignition sources. For many applications, flammability is a new aspect to take into account when designing systems.

Although safety standards are not strictly mandatory in most countries, they are one source where the industry looks for guidance for handling the flammability. For instance, ISO 5149 (ISO 5149:2014) Part 1 describes limits to charge amount depending on system type, system location, and accessibility by people unaccustomed with the safety procedures relating to the system. Local legislation will also have an influence, for instance national legislation and building codes. The requirements for flammable refrigerants are very similar across the different flammability classes, the different flammability properties result in different risks (probabilities) and consequences; therefore varying refrigerant charges and thereby system designs for each refrigerant. Further discussion is included in the annex to this chapter.

It is still not clear for all applications whether flammability will be accepted for each level of cooling or heating capacity needed, and how the various markets will split-up with regard to the classes of flammability. The acceptance of flammable refrigerants and the appropriate updates of standards and legislation is clearly a contemporary challenge for the refrigeration air conditioning, and heat-pump industry.

2.1.5 Climate impact metrics for refrigerants

The most popular metric for indicating the climate impact of refrigerant emissions is 100 year GWP, which is the integrated radiative forcing over a 100 year time horizon of 1 kg of refrigerant emitted to the atmosphere. Some parties advocate use of GWP values for shorter or longer integration time horizons or various instantaneous or sustained metrics such as the global temperature potential (GTP) (Shine, 2005; Hodnebrog, 2013; see §8.7 of (IPCC, 2014) for detailed discussions of instantaneous GTP and sustained GTP).

In this chapter both 20 year GWP and 100 year GWP values are listed. The advantage of 20 year GWP over 100 year GWP is that a 20 year time horizon seems more relevant when discussing the climate change in the coming decades and it is also better at differentiating between substances with short life times.

The advantage of using 100 year GWP is that it is more commonly used and the popularity of a metric is important to the efficiency of communicating the climate impact. Also the 100 year GWP is better at differentiating between substances with longer lifetimes, although this seldom applies to currently used non-ODS refrigerants. An example is PFC-116 and HFC-143a; the difference in 20 year GWP is less than 20% while the difference in 100 year GWP is more than a factor of 2. As long lived substances can be used in small amounts in blends with short lived substances to create lower GWP blends, using 20 year GWP may lead to decisions favouring the shorter term at the cost of the longer term.

A classification of 100 year GWP levels which is a slight modification of the proposal in the previous RTOC report (UNEP, 2011) is given in Table 2-3. A complication of naming a substance as low GWP or high GWP is that the climate impact is the product of the GWP and the amount (in kg) emitted, so even though CO2 is classified in Table 2-3 as ultra-low GWP, the amount emitted by the human civilization is large enough to give a significant climate impact. Table 2-3 categorizes using "less than" or "more than" and this enables a refrigerant such as HFC-1234yf to have ultra-low, very low, and Low GWP at the same time. Likewise a refrigerant such as HFC-23 has ultra-high, very high, and high GWP. The purpose of this feature is to allow simple references to all refrigerants below or above a given limits.

Table 2-3: Classification of 100 year GWP levels

100 Year GWP	Classification
< 30	Ultra-low or Negligible
< 100	Very low
< 300	Low
300-1000	Medium
> 1000	High
> 3000	Very high
> 10000	Ultra-high

For gases with lifetimes of a century or more the uncertainties are of the order of ±20% and ±30% for 20- and 100-year horizons. For shorter lived gases the uncertainties in GWPs will be larger (IPCC, 2014). This is one reason why care must be taken when comparing the GWP of refrigerants. For substances with very low GWP the picture is further complicated since, for historical reasons, GWPs for hydrocarbons are indirect GWPs, which include breakdown products such as CO_2, as opposed to the GWPs for HCFCs, HFCs etc., which do not cover breakdown products.

When comparing carbon emissions associated with the use of refrigerants, care must be taken to also include a comparison of energy efficiency of the refrigerant in the given application. Emissions from energy production may have a greater climate impact than the refrigerant emissions only. For further discussion see chapter 11.

2.1.6 ODP and GWP data for regulatory and reporting purposes

The ODP and GWP data presented in this chapter are based on international scientific assessments and reflect the latest consensus determinations on potential impacts. However, the reduction requirements and allocations under the Montreal Protocol, emission reductions and reporting pursuant to the Kyoto Protocol, and provisions in many national regulations pursuant to them use older, adopted values.

Table 2-4 compares the latest consensus ODP data (WMO, 2014) and (WMO, 2011) to the "regulatory" ODPs used in the Montreal Protocol (UNEP, 2012). Table 2-5 similarly contrasts the latest consensus GWPs, for a 100 year integration, with those used for reporting and emission reductions under the Kyoto Protocol from IPCC (1995).

Table 2-4: Scientific and regulatory ODPs for selected BFC, BCFC, CFC, and HCFC refrigerants

Refrigerant	ODP		
	(WMO, 2014)	(WMO, 2011)	Reporting (UNEP, 2012)
CFC-11	1,0	1,0	1,0
CFC-12	0,73	0,82	1,0
BCFC-12B1	6,9	7,9	3,0
CFC-13			1,0
BFC-13B1	15,2	15,9	10,0
HCFC-22	0,034	0,04	0,055
CFC-113	0,81	0,85	0,8
CFC-114	0,50	0,58	1,0
CFC-115	0,26	0,57	0,6
HCFC-123		0,01	0,02
HCFC-141b	0,102	0,12	0,11
HCFC-142b	0,057	0,06	0,065

Table 2-5: Scientific and regulatory GWPs for 100 year integration for selected refrigerants

Refrigerant	GWP			
	(WMO, 2014)	(IPCC, 2014)	(WMO, 2011)	Reporting (IPCC, 1995)
PFC-14		6630	7 390	6 500
HFC-23	12 500	12 400	14 200	11 700
HFC-32	704	677	716	650
PFC-116		11 100	12 200	9 200
HFC-125	3 450	3 170	3 420	2 800
HFC-134a	1 360	1 300	1 370	1 300
HFC-143a	5 080	4 800	4 180	3 800
HFC-152a	148	138	133	140
PFC-218		8 900	8 830	7 000
HFC-227ea	3 140	3 350	3 580	2 900
HFC-236fa		8 060	9 820	6 300
PFC-C318		9 540	10 300	8 700
R-744 (CO_2)	1	1	1	1

2.1.7 Selection of refrigerant

There are several factors that should be considered when selecting an alternative refrigerant for refrigeration, air conditioning and heat pump systems and applications. These include:

- Zero ODP
- Climate Change impact (reduced direct and indirect emissions)
- Performance (capacity and efficiency)
- Safety, including flammability and toxicity
- Impact on product cost
- Availability and cost of the refrigerant
- Skills and technology required to use
- Recyclability
- Stability

The selection of a refrigerant for a given application will be a compromise of the above criteria. Other than zero ODP, the rest of the parameters will to be traded-off against one another to arrive at the optimum for each type of system and application. In particular the carbon emissions include both the “direct” and “indirect” contribution of the product over its life time. A number of approaches have been documented in the literature including: Total Equivalent Warming Impact (TEWI), Life Cycle Climate Performance (LCCP), Multilateral Fund Climate Impact Indicator (MCII) and other methods.

For new refrigerants for existing systems, there are a number of criteria that should be achieved in order for a suitable refrigerant to be selected. In summary, with respect to the refrigerant being replaced, these are:

- As close a volumetric refrigerating capacity over the range of normal operating evaporator and condenser temperatures;
- Does not lead to lower energy efficiency;
- Does not exceed the condensing pressure at maximum condenser temperature;
- As close a match to the temperature glide, or negligible temperature glide if the original was a single component;
- Similar oil solubility and miscibility gap;
- Non-flammable or not higher flammability;
- Lower toxicity or not higher toxicity;
- Commercial availability of refrigerant (with reasonable cost).

There are a number of other parameters that should be considered. However, in practical terms it is unlikely that any of the commercially available refrigerants can meet all of the above criteria and therefore some compromise should be anticipated.

A refrigerant that is capable of replacing an existing refrigerant without changing any major components, including the oil, is sometimes referred to as a drop-in refrigerant. The term drop-in is somewhat misleading, as safety standards require the system to be upgraded to the latest safety requirements for any change of refrigerant type, and the trade-offs mentioned above may affect the performance and durability of the system.

2.1.8 HCFC-22 replacements

The challenge of reducing the use of HCFC-22 has led to the development of refrigerants specifically designed to replace HCFC-22 in existing equipment or replace HCFC-22 in new systems without the need for significant design changes.

A main differentiator between the HCFC-22 replacements is whether the refrigerant is miscible with the mineral oil often used with HCFC-22.

The refrigerants which are more miscible with mineral oil typically contain a minute amount (< 4%) of hydrocarbon to increase the miscibility and help the oil return to the compressor. These refrigerants typically have safety classification A1 and include: R-417A, R-417B, R-417C, R-422A, R-422B, R-422C, R-422D, R-422E, R-424A, R-425A, R-428A, R-434A, R-438A, and R-442A.

The refrigerants that are designed to fit the thermodynamic properties of HCFC-22 refrigerants, but not to be used with the mineral oil often used with HCFC-22 includes: R-404A, R-407A, R-407B, R-407C, R-407D, R-407E, R-407F, R-421A, R-421B, R-427A, R-444B, and R-507A. While they typically have the safety classification A1, some of the more recent HCFC-22-like blends (specifically R-444B) have the safety classification A2L.

When changing refrigerant in a system there is always recommended to check gaskets, elastomeric seals, and other materials for compatibility with the new refrigerant, and there is a risk that exposure to HCFC-22 has changed the properties of polymer materials to the point where they will not function correctly or exasperate leakage after a refrigerant change. There may also be a need for other system modifications to reach an acceptable energy efficiency and capacity. See also the discussion in 2.1.7 on a general discussion about replacing one refrigerant with another in existing systems.

For new systems, there are several other options for replacing HCFC-22 with system designs adapted to e.g. R-717, R-744, HCs, HFCs, or other newly developed molecules.

2.2 Refrigerant descriptions

The most important refrigerants discussed in this report are described briefly below in Table 2-6. The list is in numerical order and is meant to serve as a quick reference as it does not cover all aspects of the selected refrigerants.

The refrigerants are single component for refrigerant designation numbers below 400 and from 600 and up, while designation numbers in the 400’s and 500’s are mixtures of two or more components. The 400 series are blends with a temperature glide, known as zeotropes. If the glide is large then exchangers need to be designed suitably to take this into account. The 500 series are blends, which are azeotropic at some condition, thus inferring with negligible temperature glide and change in composition between the liquid and vapour phases.

The safety class according to ISO 817 (ISO 817: 2014) of each refrigerant is stated, and where ISO 817 does not list the refrigerant, the safety class is taken from ASHRAE 34 (ASHRAE 34-2013). Where dual classification exists, the higher (i.e. more conservative) class is given.

Table 2-6: Description of selected refrigerants

CFC-11	CFC-11 was introduced in 1932 as a replacement to flammable and or toxic refrigerants used at the time and gained popularity in Centrifugal chillers (Calm, 1997) and was widely used as a solvent and a blowing agent. CFC-11 is classed as an A1 refrigerant and is the reference substance for ODP and has a

	defined ODP of 1. It is a low pressure refrigerant, with similar pressure as HCFC-123, and has often been replaced with this refrigerant.
CFC-12	CFC-12 was introduced in 1931 as a replacement to flammable and or toxic refrigerants used at the time (Calm, 1997) and has been popular in both refrigeration applications and chillers for air-conditioning. CFC-12 is classed as an A1 refrigerant, and has high ODP, almost as high as CFC-11. The pressure is similar to HFC-134a, which replaced it in many applications.
HCFC-22	HCFC-22 was originally used for low temperature refrigeration and later air-conditioning, and is today the most popular HCFC refrigerant. It is classed as an A1 refrigerant and is the most used refrigerant in the world for commercial refrigeration, industrial processes, and mainly air-to-air air conditioning systems. The HCFC-22 bank is estimated to be 1,6 million metric tonnes at the global level. The energy efficiency of this refrigerant became a reference for the validation of its substitutes: R-404A in commercial and industrial refrigeration and R-407C and R-410A in air conditioning. HCFC-22 has a medium pressure similar to R-404A and R-407C, and as seen in section 2.2.2 below, alternatives to HCFC-22 has been getting attention in the industry.
HFC-32	HFC-32 was originally used as a component of refrigerant blends such as R-407C and R-410A. Pressure and capacity are around 1.5 times higher than HCFC-22 and slightly higher than R-410A. It is classed as A2L. The efficiency of HFC-32 systems are higher than R-410A but less than HCFC-22. Discharge temperatures are higher than R-410A and HCFC-22 and thus some mitigation device or controls may be necessary for handling the discharge temperature of the compressor especially at high ambient temperatures.
HCFC-123	HCFC-123 is mainly used in centrifugal chillers and is classed as a B1 refrigerant. HCFC-123 is a low-GWP HCFC refrigerant, but since it is an ODS it is being phased-out under the Montreal Protocol.
HFC-125	HFC-125 is used as a component of refrigerant blends such as R-404A and R-410A to lower discharge temperature and reduce flammability from other components.
HFC-134a	HFC-134a is used in a variety of equipment including heat pumps, chillers, mobile air conditioning and domestic refrigeration and has a pressure lower than HCFC-22 and similar to CFC-12. It is classed as an A1 refrigerant. Energy efficiency is good, provided that pipes and heat exchangers are suitably sized.
HFC-152a	HFC-152a has performance characteristics similar to HFC-134a as well as 10% lower vapour pressure and volumetric refrigeration capacity. It is classed as an A2 refrigerant. HFC-152a is used as a component in several new blends.
HFC-161	HFC-161 has with zero ODP and very low GWP of 4 (IPCC, 2014) and it is under evaluation to replace HCFC-22 in small air conditioning unit. It is not yet classified in ISO 817 (ISO 817: 2014) or ASHRAE 34 (ASHRAE 34-2013) but is likely to be classified A3. Performance is similar to HCFC-22 and HC-290. The lower flammability limit is about 4 times higher than for HC-290 allowing for a higher charge to be used and thereby higher cooling capacity to be achieved compared with a system using HC-290.
HFC-245fa	HFC-245fa has found limited use in centrifugal chillers, high temperature heat pumps, and organic Rankine cycle (ORC) power generation cycles and is

	classified as B1. Because the high temperature heat pump and ORC are still emerging markets the use may increase. It has operating pressures higher than for HCFC-123 but lower than for HFC-134a.
HC-290	HC-290 has thermodynamic properties similar to HCFC-22, although slightly lower pressure and capacity. It is classified as A3. Due to its excellent thermophysical properties the efficiency is good under most conditions, including high ambient, as well as having low discharge temperatures. It is the most frequently used hydrocarbon refrigerant in air conditioning applications. It is also used as a major component in many HC blends.
R-404A	R-404A is used widely in commercial refrigeration systems, and is classified as A1. The efficiency is acceptable. A major advantage of R-404A is the low discharge temperature, which makes it possible to have a high temperature lift in a single stage system, hence it being the primary substitute for R-501. R-404A is also used in industrial refrigeration, especially when R-717 is not desired for safety or technical reasons. R-404A and R-507A are very similar in composition and performance parameters.
R-407A	R-407A is a mixture of the same components of other 407 refrigerants but in slightly different proportions. It was originally developed to replace HCFC-22 and is now used as a replacement for R-404A. It is classified as A1. The efficiency is acceptable and better than R-404A. However, its moderate temperature glide and higher discharge temperature needs to be taken into account.
R-407C	R-407C is a mixture of the same components of other 407 refrigerants but in slightly different proportions. 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 A1. The efficiency is acceptable and better than R-404A. However, its moderate temperature glide and higher discharge temperature needs to be taken into account.
R-407F	R-407F is a mixture of the same components of other R-407 refrigerants but in slightly different proportions. It is used as a replacement for R-404A. It is classified as A1. The efficiency is acceptable and better than R-404A. However, its moderate temperature glide and higher discharge temperature needs to be taken into account.
R-410A	R-410A is used widely in air conditioning, chiller and heat pump systems and is classified as A1. The pressure of R-410A is higher than HCFC-22, the R-407 series and R-404A. Generally the efficiency is equivalent to HCFC-22, especially at lower temperatures, although efficiency and capacity deteriorates at a greater rate at higher ambient temperatures.
R-417A	R-417A is mainly designed to replace HCFC-22 as a “drop-in” in air-conditioning systems, but is also utilised in refrigeration and heat pump applications in existing systems as well as in new equipment. It is classified A1 and has a higher GWP than HCFC-22.
R-444A	R-444A is a replacement for HFC-134a and is classified as A2L. It has efficiency, capacity and operating pressures close to HFC-134a.

R-444B	R-444B can replace HCFC-22 in new AC equipment without major modifications as its pressures are similar. It is classified as A2L. R-444B matches the capacity of HCFC-22 with a marginally lower efficiency although relative performance can be better in high ambient climates.
R-445A	R-445A is a replacement for HFC-134a and is classified as A2L. It has been tested in mobile air conditioning systems where its energy efficiency and capacity are close to HFC-134a and HFC-1234yf. Its temperature glide is about twice that of R-407C, which may influence system design.
R-446A	R-446A can replace R-410A in AC equipment and is classified as A2L. Efficiency of R-446A systems is comparable to R-410A whilst the capacity is lower than R-410A and discharge temperatures are slightly higher. Due to its relative higher critical point compared to other refrigerants, R-446A performs well at high ambient temperatures.
R-447A	R-447A can replace R-410A in AC equipment and is classified as A2L. The efficiency of R-447A systems is at the same level as R-410A, the capacity is slightly lower and discharge temperatures are slightly higher than R-410A. Due to its relative higher critical point compared to other refrigerants, R-447A performs well at high ambient temperatures.
R-448A	R-448A can replace R-404A in existing and new refrigeration equipment and is classified as A1. This refrigerant has capacity and efficiency similar to R-404A. However, its notable temperature glide may influence system design.
R-449A	R-449A can replace R-404A in new refrigeration equipment and is classified as A1. This refrigerant has a capacity marginally higher than R-404A and a slightly better efficiency.
R-450A	R-450A can replace HFC-134a in new equipment, where its lower volumetric capacity can be addressed in the design of the equipment. It is classified as A1. When used in reciprocating or scroll compressors, this refrigerant produces efficiency levels comparable to HFC-134a, although the capacity is lower.
R-507A	R-507A is used widely in commercial refrigeration systems, and is classified as A1. The efficiency is acceptable. A major advantage of R-507A is the low discharge temperature, which makes it possible to have a high temperature lift in a single stage system (thus being adopted as a replacement for R-502). It is also used in industrial refrigeration, especially when R-717 is not desired for safety or technical reasons. R-404A and R-507A are very similar in composition and performance parameters.
HC-600a	HC-600a is a low pressure hydrocarbon refrigerant classified as A3. The operating pressures and capacity is less than half that of HFC-134a, whilst efficiency is good. It is used extensively for small refrigeration systems such as domestic refrigeration and small commercial systems. It is also used as a component in many HC blends.
R-717	R-717 (ammonia, NH_3) is classified as B2L. In principle, it has thermo-physical properties that lead to excellent efficiency. The vapour pressure and refrigerating capacity is similar to HCFC-22. However, R-717 has a very high discharge temperature, so for lower temperature applications two-stage-

	compression is normally needed. It is not practically compatible with copper and copper alloys, which limits the system to welded steel or aluminium components and piping. The application of R-717 in small to large absorption systems is also wide spread.
R-718	R-718 (Water, H_2O) is used as refrigerant in vapour compression cycles at very low pressures, high compression ratios and high volumetric flow rates, leading to larger system sizes and a cost premium. It has also been tested for high temperature heat pumps with promising results, especially when it can be integrated in direct vapour compression cycles. It is also used in adsorption chillers, coupled with widely available adsorbents such as silica gel and zeolite, and in absorption systems either with LiBr as absorbent, or as absorbent of ammonia.
R-744	R-744 (carbon dioxide, CO_2) is classified as A1, and has thermo-physical properties that lead to good efficiency for certain levels of temperatures (such as for refrigeration range). The vapour pressure is several times greater than usual refrigerants and the volumetric refrigerating capacity is correspondingly higher for conditions below 25°C. However, with a very low critical temperature, the cycle efficiency declines as the temperature before the expansion device increases and other features are needed to achieve similar (to HCFC-22) efficiency values at higher ambient conditions. Compared to a basic cycle, 10–20% energy efficiency improvement can be achieved by applying an ejector instead of an ordinary expansion device (Hafner, 2012) although using an expander alone can bring the efficiency to within 10% of HCFC-22 (Subiantoro, 2013). Other features to help improve efficiency in high ambient conditions include economiser (parallel compression), liquid-suction heat exchange and mechanical subcooling. Also, discharge temperatures are very high and therefore, where the high temperature cannot be utilised, technology options such as additional compression stages and inter-cooling may be adopted in the system design. These additional features add to the complexity and cost of the system.
HCFC-1233zd(E)	HCFC-1233zd(E) is an unsaturated HCFC and has similar pressure to that of HCFC-123. It is classified as A1. When used with centrifugal compressors, this refrigerant produces efficiency levels similar to HCFC-123, allowing the design of systems with very high energy efficiency.
HFC-1234yf	HFC-1234yf is an unsaturated HFC and can replace HFC-134a in same systems since the pressure-temperature characteristics are almost identical, It is classified as A2L. In general this refrigerant produces efficiency levels comparable to HFC-134a although the theoretical COP is a few percent below that of HFC-134a.
HFC-1234ze(E)	HFC-1234ze(E) is an unsaturated HFC and can replace HFC-134a in new equipment where its lower volumetric capacity can be addressed in the design of the equipment. It is classified as A2L.
HC-1270	HC-1270 is an unsaturated hydrocarbon with a vapour pressure and capacity almost identical to HCFC-22. It is classified as A3 and also has a distinctive odour. Due to its excellent thermophysical properties the efficiency is good under most conditions, including high ambient, as well as having low discharge temperatures.

2.3 Data summary

This section summarizes physical, safety, and environmental data for refrigerants with a safety classification in ISO 817 (ISO 817:2014) or ASHRAE 34 (ASHRAE 34-2013).

Table 2-7 covers single component refrigerants; Table 2-8 is the summary for zeotropic refrigerant blends, while Table 2-9 covers azeotropic refrigerant blends.

Table 2-7: Data summary for single component refrigerants

Refrigerant Designation	Chemical Formula	Chemical Name	Molecular Weight	Boiling Point (°C)	ATEL/ODL (kg/m³)	LFL (kg/m³)	Safety Class	Atmospheric Lifetime (Years)	Radiative Efficiency (W/m/ppm)	GWP 100 Year	GWP 20 Year	ODP
Methane series												
CFC-11	CCl_3F	trichlorofluoromethane	137,4	24	0,006 2	NF	A1	52	0,26	5 160	7 090	1
CFC-12	CCl_2F_2	dichlorodifluoromethane	120,9	-30	0,088	NF	A1	102	0,32	10 300	10 800	0,73
CFC-13	$CClF_3$	chlorotrifluoromethane	104,5	–81	ND	NF	A1	640	0,25	13 900	10 900	1
BFC-13B1	$CBrF_3$	bromotrifluoromethane	148,9	–58	ND	NF	A1	72	0,30	6 670	7 930	15,2
PFC-14	CF_4	tetrafluoromethane (carbon tetrafluoride)	88,0	-128	0,40	NF	A1	50000	0,09	6 630	4 880	
HCFC-22	$CHClF_2$	chlorodifluoromethane	86,5	-41	0,21	NF	A1	12	0,21	1 780	5 310	0,034
HFC-23	CHF_3	trifluoromethane	70,0	-82	0,15	NF	A1	228	0,18	12 500	10 800	
HCC-30	CH_2Cl_2	dichloromethane (methylene chloride)	84,9	40	ND	NF	B1	0,4	0,03	9	33	
HFC-32	CH_2F_2	difluoromethane (methylene fluoride)	52,0	-52	0,30	0,307	A2L	5,4	0,11	704	2 530	
HC-50	CH_4	methane	16,0	–161	ND	0,032	A3	12,4	3,63e-4	30	85	
Ethane series												
CFC-113	CCl_2FCClF_2	1,1,2-trichloro-1,2,2-trifluoroethane	187,4	48	0,02	NF	A1	93	0,30	6 080	6 560	0,81
CFC-114	$CClF_2CClF_2$	1,2-dichloro-1,1,2,2-tetrafluoroethane	170,9	4	0,14	NF	A1	189	0,31	8 580	7 710	0,5
CFC-115	$CClF_2CF_3$	chloropentafluoroethane	154,5	-39	0,76	NF	A1	540	0,20	7 310	5 780	0,26
PFC-116	CF_3CF_3	hexafluoroethane	138,0	-78	0,68	NF	A1	10000	0,25	11 100	8 210	
HCFC-123	$CHCl_2CF_3$	2,2-dichloro-1,1,1-trifluoroethane	152,9	27	0,057	NF	B1	1,3	0,15	79	292	0,01
HCFC-124	$CHClFCF_3$	2-chloro-1,1,1,2-tetrafluoroethane	136,5	-12	0,056	NF	A1	5,9	0,20	527	1 870	0,02
HFC-125	CHF_2CF_3	pentafluoroethane	120,0	-49	0,37	NF	A1	31	0,23	3 450	6 280	
HFC-134a	CH_2FCF_3	1,1,1,2-tetrafluoroethane	102,0	-26	0,21	NF	A1	14	0,16	1 360	3 810	
HCFC-142b	CH_3CClF_2	1-chloro-1,1-difluoroethane	100,5	-10	0,10	0,329	A2	18	0,19	2 070	5 140	0,057
HFC-143a	CH_3CF_3	1,1,1-trifluoroethane	84,0	-47	0,48	0,282	A2L	51	0,16	5 080	7 050	
HFC-152a	CH_3CHF_2	1,1-difluoroethane	66,1	-25	0,14	0,130	A2	1,6	0,10	148	545	
HC-170	CH_3CH_3	ethane	30,1	-89	0,008 6	0,038	A3			5,5	20	
Ethers												
HE-E170	CH_3OCH_3	methoxymethane (dimethyl ether)	46,1	-25	0,079	0,064	A3	0,015	0,02	1	1	
Propane series												
PFC-218	$CF_3CF_2CF_3$	octafluoropropane	188,0	-37	0,34	NF	A1	2600	0,28	8 900	6 640	
HFC-227ea	CF_3CHFCF_3	1,1,1,2,3,3,3-heptafluoropropane	170,0	-16	0,19	NF	A1	36	0,26	3 140	5 250	
HFC-236fa	$CF_3CH_2CF_3$	1,1,1,3,3,3-hexafluropropane	152,0	-1	0,34	NF	A1	242	0,24	8 060	6 940	
HFC-245fa	$CHF_2CH_2CF_3$	1,1,1,3,3-pentafluoropropane	134,0	15	0,19	NF	B1	7,9	0,24	882	2 980	
HC-290	$CH_3CH_2CH_3$	propane	44,1	-42	0,09	0,038	A3	12,5 days		5	18	

Cyclic organic compounds												
PFC-C318	$-(CF_2)_4-$	octafluorocyclobutane	200,0	-6	0,65	NF	A1	3200	0,32	9 540	7 110	
Hydrocarbons												
HC-600	$CH_3CH_2CH_2CH_3$	butane	58,1	0	0,002 4	0,038	A3			4	15	
HC-600a	$CH(CH_3)_2CH_3$	2-methylpropane (isobutane)	58,1	-12	0,059	0,043	A3	6,0 days		~20	74	
HC-601	$CH_3CH_2CH_2$-CH_2CH_3	Pentane	72,2	36	0,0029	0,035	A3	3,4 days		~20	74	
HC-601a	$CH(CH_3)_2CH_2$-CH_3	2-methylbutane (isopentane)	72,2	27	0,0029	0,038	A3	3,4 days		~20	74	
Inorganic compounds												
R-702	H_2	Hydrogen	2,0	-253			A3					
R-704	He	Helium	4,0	-269		NF	A1					
R-717	NH_3	Ammonia	17,0	-33	0,000 22	0,116	B2L					
R-718	H2O	Water	18,0	100		NF	A1					
R-720	Ne	Neon	20,2	-246		NF	A1					
R-728	N_2	Nitrogen	28,0	-196		NF	A1					
R-740	Ar	Argon	39,9	-186		NF	A1					
R-744	CO_2	carbon dioxide	44,0	-78c	0,072	NF	A1		1,37e-5	1	1	
Unsaturated organic compounds												
HC-1150	$CH_2=CH_2$	ethene (ethylene)	28,1	–104	ND	0,036	A3			3,7	14	
HCFC-1233zd(E)	$CF_3CH=CHCl$	trans-1-chloro-3,3,3-trifluoro-1-propene	130,5	18,1	0	NF	A1	26,0 days	0,04	1	5	0,000 34
HFC-1234yf	$CF_3CF=CH_2$	2,3,3,3-tetrafluoro-1-propene	114,0	-29,4	0,47	0,289	A2L	10,5 days	0,02	<1	1	
HFC-1234ze(E)	$CF_3CH=CHF$	trans-1,3,3,3-tetrafluoro-1-propene	114,0	-19,0	0,28	0,303	A2L	40,4 days	0,04	<1	4	
HC-1270	$CH_3CH=CH_2$	propene (propylene)	42,1	-48	0,001 7	0,046	A3	0,35 days		1,8	6,6	

Table 2-8: Data summary for zeotropic refrigerant blends

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight	Bubble Point/ Dew Point (°C)	ATEL/ODL (kg/m3)	LFL (kg/m3)	Safety Class	GWP 100 Year	GWP 20 Year	ODP
R-401A	R-22/152a/124 (53,0/13,0/34,0)	94,4	-34,4/-28,8	0,10	NF	A1	1 100	3 500	0,02
R-401B	R-22/152a/124 (61,0/11,0/28,0)	92,8	-35,7/-30,8	0,11	NF	A1	1 200	3 800	0,03
R-401C	R-22/152a/124 (33,0/15,0/52,0)	101	-30,5/-23,8	0,083	NF	A1	880	2 800	0,02
R-402A	R-125/290/22 (60,0/2,0/38,0)	101,5	-49,2/-47,0	0,27	NF	A1	2 700	5 800	0,01
R-402B	R-125/290/22 (38,0/2,0/60,0)	94,7	-47,2/-44,9	0,24	NF	A1	2 400	5 600	0,02
R-403A	R-290/22/218 (5,0/75,0/20,0)	92	-44,0/-42,3	0,24	0,480	A2	3 100	5 300	0,03
R-403B	R-290/22/218 (5,0/56,0/39,0)	103,3	-43,8/-42,3	0,29	NF	A1	4 500	5 600	0,02
R-404A	R-125/143a/134a (44,0/52,0/4,0)	97,6	-46,6/-45,8	0,52	NF	A1	4 200	6 600	
R-406A	R-22/600a/142b (55,0/4,0/41,0)	89,9	-32,7/-23,5	0,14	0,302	A2	1 800	5 000	0,04
R-407A	R-32/125/134a (20,0/40,0/40,0)	90,1	-45,2/-38,7	0,31	NF	A1	2 100	4 500	
R-407B	R-32/125/134a (10,0/70,0/20,0)	102,9	-46,8/-42,4	0,33	NF	A1	2 800	5 400	
R-407C	R-32/125/134a (23,0/25,0/52,0)	86,2	-43,8/-36,7	0,29	NF	A1	1 700	4 100	
R-407D	R-32/125/134a (15,0/15,0/70,0)	91	-39,4/-32,7	0,25	NF	A1	1 600	4 000	
R-407E	R-32/125/134a (25,0/15,0/60,0)	83,8	-42,8/-35,6	0,27	NF	A1	1 500	3 900	
R-407F	R-32/125/134a (30,0/30,0/40,0)	82,1	-46,1/-39,7	0,32	NF	A1	1 800	4 200	
R-408A	R-125/143a/22 (7,0/46,0/47,0)	87	-45,5/-45,0	0,33	NF	A1	3 400	6 200	0,02
R-409A	R-22/124/142b (60,0/25,0/15,0)	97,4	-35,4/-27,5	0,12	NF	A1	1 500	4 400	0,03
R-409B	R-22/124/142b (65,0/25,0/10,0)	96,7	-36,5/-29,7	0,12	NF	A1	1 500	4 400	0,03
R-410A	R-32/125 (50,0/50,0)	72,6	-51,6/-51,5	0,42	NF	A1	2 100	4 400	
R-410B	R-32/125 (45,0/55,0)	75,6	-51,5/-51,4	0,43	NF	A1	2 200	4 600	

R-411A	R-1270/22/152a) (1,5/87,5/11,0)	82,4	-39,7/-37,2	0,074	0,186	A2	1 600	4 700	0,03
R-411B	R-1270/22/152a (3,0/94,0/3,0)	83,1	-41,6/-41,3	0,044	0,239	A2	1 700	5 000	0,03
R-412A	R-22/218/142b (70,0/5,0/25,0)	92,2	-36,4/-28,8	0,17	0,329	A2	2 200	5 300	0,04
R-413A	R-218/134a/600a (9,0/88,0/3,0)	104	-29,3/-27,6	0,21	0,375	A2	2 000	4 000	
R-414A	R-22/124/600a/142b (51,0/28,5/4,0/16,5)	96,9	-34,0/-25,8	0,10	NF	A1	1 400	4 100	0,03
R-414B	R-22/124/600a/142b (50,0/39,0/1,5/9,5)	101,6	-34,4/-26,1	0,096	NF	A1	1 300	3 900	0,03
R-415A	R-22/152a (82,0/18,0)	81,9	-37,5/-34,7	0,19	0,188	A2	1 500	4 500	0,03
R-415B	R-22/152a (25,0/75,0)	70,2	-23,4/-21,8	0,15	0,13	A2	560	1 700	0,009
R-416A	R-134a/124/600 (59,0/39,5/1,5)	111,9	-23,4/-21,8	0,064	NF	A1	1 000	3 000	0,008
R-417A	R-125/134a/600 (46,6/50,0/3,4)	106,7	-38,0/-32,9	0,057	NF	A1	2 300	4 800	
R-417B	R-125/134a/600 (79,0/18,3/2,7)	113,1	-44,9/-41.5	0,069	NF	A1	3 000	5 700	
R-417C	R-125/134a/600 (19,5/78,8/1,7)	103,7	–32,7/–29,2		NF	A1	1 700	4 200	
R-418A	R-290/22/152a (1,5/96,0/2,5)	84,6	-41,2/-40,1	0,20	0,31	A2	1 700	5 100	0,03
R-419A	R-125/134a/E170 (77,0/19,0/4,0)	109,3	-42,6/-36,0	0,31	0,25	A2	2 900	5 600	
R-419B	R-125/134a/E170 (48,5/48,0/3,5)	105,2	–37,4/–31,5			A2	2 300	4 900	
R-420A	R-134a/142b (88,0/12,0)	101,8	-25,0/-24,2	0,18	NF	A1	1 400	4 000	0,007
R-421A	R-125/134a (58,0/42,0)	111,7	-40,8/-35,5	0,28	NF	A1	2 600	5 200	
R-421B	R-125/134a (85,0/15,0)	116,9	-45,7/-42,6	0,33	NF	A1	3 100	5 900	
R-422A	R-125/134a/600a (85,1/11,5/3,4)	113,6	-46,5/-44,1	0,29	NF	A1	3 100	5 800	
R-422B	R-125/134a/600a (55,0/42,0/3,0)	108,5	-40,5/-35,6	0,25	NF	A1	2 500	5 100	
R-422C	R-125/134a/600a (82,0/15,0/3,0)	113,4	-45,3/-42,3	0,29	NF	A1	3 000	5 700	
R-422D	R-125/134a/600a (65,1/31,5/3,4)	109,9	-43,2/-38,4	0,26	NF	A1	2 700	5 300	
R-422E	R-125/134a/600a (58,0/39,3/2,7)	109,3	–41,8/–36,4		NF	A1	2 500	5 100	
R-423A	134a/227ea (52,5/47,5)	126	-24,2/-23,5	0,30	NF	A1	2 200	4 500	
R-424A	R-125/134a/600a/600/601a (50,5/47,0/0,9/1,0/0,6)	108,4	-39,1/-33,3	0,10	NF	A1	2 400	5 000	
R-425A	R-32/134a/227ea (18,5/69,5/12)	90,3	-38,1/-31,3	0,27	NF	A1	1 500	3 700	
R-426A	R-125/134a/600/601a (5,1/93,0/1,3/0,6)	101,6	-28,5/-26,7	0,083	NF	A1	1 400	3 900	
R-427A	R-32/125/143a/134a (15,0/25,0/10,0/50,0)	90,4	-43,0/-36,3	0,29	NF	A1	2 200	4 600	
R-428A	R-125/143a/290/600a (77,5/20,0/0,6/1,9)	107,5	-48,3/-47,5	0,37	NF	A1	3 700	6 300	
R-429A	R-E170/152a/600a (60,0/10,0/30,0)	50,8	-26,0/-25.6	0,098	0,052	A3	21	77	
R-430A	R-152a/600a (76,0/24,0)	64	-27,6/-27,4	0,10	0,084	A3	120	430	
R-431A	R-290/152a (71,0/29,0)	48,8	-43,1/-43,1	0,10	0,044	A3	46	170	
R-432A	R-1270/E170 (80,0/20,0)	42,8	-46,6/-45,6	0,002 1	0,039	A3	1,6	5,5	
R-433A	R-1270/290 (30,0/70,0)	43,5	-44,6/-44,2	0,005 5	0,036	A3	4	15	
R-433B	R-1270/290 (5,0/95,0)	44	-42,7/-42,5	0,025	0,025	A3	4,8	17	
R-433C	R-1270/290 (25,0/75,0)	43,6	-44,3/-43,9	0,006 6	0,032	A3	4,2	15	
R-434A	R-125/143a/134a/600a (63,2/18,0/16,0/2,8)	105,7	-45,0/-42,3	0,32	NF	A1	3 300	5 800	
R-435A	R-E170/152a (80,0/20,0)	49	-26,1/-25,9	0,09	0,069	A3	30	110	
R-436A	R-290/600a (56,0/44,0)	49,3	-34,3/-26,2	0,073	0,032	A3	12	43	
R-436B	R-290/600a (52,0/48,0)	49,9	-33,4/-25,0	0,071	0,033	A3	12	45	
R-437A	R-125/134a/600/601 (19,5/78,5/1,4/0,6)	103,7	-32,9/-29,2	0,081	NF	A1	1 700	4 200	
R-438A	R-32/125/134a/600/601a (8,5/45,0/44,2/1,7/0,6)	99,1	-43,0/-36,4	0,079	NF	A1	2 200	4 700	
R-439A	R-32/125/600a (50,0/47,0/3,0)	71,2	-52,0/-51,8	0,34	0,304	A2	2 000	4 200	
R-440A	R-290/134a/152a (0,6/1,6/97,8)	66,2	-25,5/-24,3	0,14	0,124	A2	170	590	
R-441A	R-170/290/600a/600 (3,1/54,8/6,0/36,1)	48,3	-41,9/-20,4	0,006 3	0,032	A3	5,6	20	
R-442A	R-32/125/134a/152a/227ea (31,0/31,0/30,0/3,0/5,0)	81,8	–46,5/–39,9	0,33	NF	A1	1 900	4 200	
R-443A	R-1270/290/600a (55,0/40,0/5,0)	43,5	–44,8/–41,2			A3	4	15	
R-444A	R-32/152a/1234ze(E) (12,0/5,0/83,0)	96,7	–34,3/–24,3			A2L	93	330	
R-444B	R-32/1234ze(E)/152a (41,5/48,5/10)	72,8	–44,6/–34,9			A2L	310	1 100	
R-445A	R-744/134a/1234ze(E) (6,0/9,0/85,0)	103,1	–50,3/–23,5			A2L	120	350	
R-446A	R-32/1234ze(E)/600 (68,0/29,0/3,0)	62	–49,4/–44,0			A2L	480	1 700	

R-447A	R-32/125/1234ze(E) (68,0/3,5/28,5)	63	–49,3/–44,2			A2L	600	1 900
R-448A	R-32/125/1234yf/134a /1234ze(E) (26/26/20/21/7)	86,4	–45,9/–39,8			A1	1 400	3 100
R-449A	R-32/125/1234yf/134a (24,3/24,7/25,3/25,7)	87,2	–46,0/–39,9			A1	1 400	3 100
R-450A	R-1234ze(E)/134a (58/42)	108,7	–23,4/–22,8			A1	570	1 600
R-451A	R-1234yf/134a (89,8/10,2)	112,7	–30,8/–30,5			A2L	140	390
R-451B	R-1234yf/134a (88,8/11,2)	112,6	–31,0/–30,6			A2L	150	430
R-452A	R-1234yf/32/125 (30/11/59)	103,5	–47,0/–43,2			A1	2 100	4 000

Table 2-9: Data summary for azeotropic refrigerant blends

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight	Normal Boiling Point (°C)	ATEL/ODL (kg/m3)	LFL (kg/m3)	Safety Class	GWP 100 Year	GWP 20 Year	ODP
R-500	R-12/152a (73,8/26,2)	99,3	-33,6/-33,6	0,12	NF	A1	7 600	8 100	0,5
R-501	R-22/12 (75,0/25,0)	93,1	-40,5/-40,3	0,21	NF	A1	3 900	6 700	0,2
R-502	R-22/115 (48,8/51,2)	111,6	-45,3/-45,0	0,33	NF	A1	4 600	5 600	0,1
R-503	R-23/13 (40,1/59,9)	87,2	–88	ND	NF	A1	13 000	11 000	0,6
R-504	R-32/115 (48,2/51,8)	79,2	–57	0,45	NF	A1	4 100	4 200	0,1
R-507A	R-125/143a (50,0/50,0)	98,9	-47,1/-47,1	0,53	NF	A1	4 300	6 700	
R-508A	R-23/116 (39,0/61,0)	100,1	-87,4/-87,4	0,23	NF	A1	12 000	9 200	
R-508B	R-23/116 (46,0/54,0)	95,4	-87,4/-87,0	0,2	NF	A1	12 000	9 400	
R-509A	R-22/218 (44,0/56,0)	124	-40,4/-40,4	0,38	NF	A1	5 800	6 100	0,01
R-510A	R-E170/600a (88,0/12,0)	47,2	-25,2/-25,2	0,087	0,056	A3	3,3	9,8	
R-511A	R-290/E170 (95,0/5,0)	44,2	-42,18/-42,1	0,092	0,038	A3	4,8	17	
R-512A	R-134a/152a (5,0/95,0)	67,2	-24,0/-24,0	0,14	0,124	A2	210	710	
R-513A	R-1234yf/134a (56/44)	108,4	-29,2			A1	600	1 700	

Note: Yellow highlights in Tables 2-8 and 2-9 show figures that were corrected after the report was issued in February 2015.

2.3.1 Data sources

2.3.1.1 Data sources for Table 2-7

Chemical Formula, Chemical Name, and Boiling Point: ISO 817 (ISO 817:2014) is used as first priority, ISO 5149 (ISO 5149:2014) as second priority and ASHRAE 34 (ASHRAE 34-2013) as third priority.

Molecular Weight: Calculated from the sum of atoms making up the molecule (based on the chemical formula). The atomic weights are from IUPAC (Wieser, 2013).

ATEL/ODL and LFL: Taken from ISO 5149 (ISO 5149:2014).

Safety Class: ISO 817 (ISO 817:2014) is used as first priority, ISO 5149 (ISO 5149:2014) as second priority and ASHRAE 34 (ASHRAE 34-2013) as third priority.

Atmospheric Lifetime: Values are taken from Table 5.1 and Table 5.3 in (WMO, 2014) where available, (IPCC, 2014) is used as 2nd priority, (WMO, 2011) is used as 3rd priority, and (IPCC, 2007) is used as 4th priority.

Radiative Efficiency: Values are taken from (IPCC, 2014) where available and (IPCC, 2007) is used as 2nd priority. (WMO, 2014) and (WMO, 2011) do not give radiative efficiencies.

GWP 100 Year: Values are taken from (WMO, 2014) where available, Table 8.A.1 in (IPCC, 2014) is used as 2nd priority, (WMO, 2011) as 3rd priority (HC-290), Table 2-14 and 2-

15 in (IPCC, 2007) as 4th priority (HE-E170 and hydrocarbons), and for the remaining refrigerant (HC-600a, HC-601, HC-601a) the approximation of ~20 from (UNEP, 2011) is reused. When considering the GWP values for other hydrocarbons, it seems ~20 is likely to be a conservative number. GWPs are direct GWPs except for hydrocarbons, which are indirect GWPs (e.g., including climate impact of breakdown product). Under UNFCCC accounting, only direct GWP is used.

GWP 20 Year: Values are taken from (WMO, 2014) where available, Table 8.A.1 in (IPCC, 2014) is used as 2nd priority, (WMO, 2011) does not contain GWP 20 year numbers for the remaining refrigerants therefor (IPCC, 2007) is used as 3rd priority. Where values are not available from the above sources (HE-E170 and hydrocarbons, all with short atmospheric lifetimes) the GWP 20 year will be calculated from GWP 100 year using the approximation derived here:

Note that for substance x the GWP of time horizon y is $GWP^x(y) = aGWP^x(y)/aGWP^{CO2}(y)$, and for substances with short atmospheric lifetimes note that a GWP (20 year) is close to a GWP (100 year), since the substance will be practically removed from the atmosphere within the first 20 years and no additional radiative forcing will be added between the 20th and the 100th year. This makes it possible to estimate GWP (20 year):

$$\begin{aligned} GWP^x(20\,year) &= \frac{aGWP^x(20\,year)}{aGWP^{CO2}(20\,year)} \approx \frac{aGWP^x(100\,year)}{aGWP^{CO2}(20\,year)} \\ &= \frac{aGWP^{CO2}(100\,year)}{aGWP^{CO2}(20\,year)} \times \frac{aGWP^x(100\,year)}{aGWP^{CO2}(100\,year)} \\ &= \frac{aGWP^{CO2}(100\,year)}{aGWP^{CO2}(20\,year)} \times GWP^x(20\,year) = \frac{9{,}17 \times 10^{-14}}{2{,}49 \times 10^{-14}} \times GWP^x(20\,year) \end{aligned} \quad \text{(eq. 2.1)}$$

GWP for hydrocarbons includes breakdown products (as opposed to the GWP for HFCs), part of the GWP will come from CO_2, where the 20 year GWP is 1, so the above formula will give GWP 20 values that are slightly too high. This is, however, the approach that has been chosen here for these substances.

ODP: Values are taken from (WMO, 2014) where available, (WMO, 2011) is used as 2nd priority (for HCFC-123), (WMO, 2007) as 3rd priority (for HCFC-124), and the Montreal protocol as 4th priority (for CFC-13).

2.3.1.2 Data sources for Tables 2-8 and 2-9

Molecular weight, GWP 100 Year, GWP 20 Year, ODP: Calculated based on data for single components given in Table 2-7. The resulting GWP values are rounded to 2 significant digits, since, as mentioned in section 2.1.5, the uncertainty for the GWP values is on the order of ±20% for very long lived gases and even larger for shorter lived gases.

Refrigerant Composition, Bubble Point/Dew Point (°C), Safety Class: ISO 817 (ISO 817:2014) 1st priority, ISO 5149 (ISO 5149:2014) in principle 2nd priority, ASHRAE 34 (ASHRAE 34-2013) 3rd priority. No information for these tables were simultaneously available in ISO 5149 and not in ISO 817, which is why ISO 5149 is in principle only the 2nd priority. Where dual safety classes are given in the standards, the higher is used.

ATEL/ODL, LFL: Values are taken from ISO 5149 (ISO 5149:2014).

2.4 Concluding remarks

This chapter discussed and provided tabular summaries for identifiers as well as physical, safety, and environmental data for refrigerants including the summary descriptions of refrigerants discussed elsewhere in this report.

Whatever refrigerant is chosen will always have to be a balance between several factors, the availability and cost of the refrigerant (and the associated equipment), the system energy efficiency, the safety and convenience of applicability, environmental issues and many more.

The refrigerants which have emerged since the last assessment report in 2010 address climate concerns, with climate impacts considerably lower than most of the currently used substances, and ozone depletion concerns with the replacement refrigerants for ozone-depleting substances. Among the new refrigerants are several blends based on unsaturated HFCs and a new unsaturated HCFC molecule. Most of these are refrigerants with lower flammability (2L), raising the question of how to handle flammability.

The perfect refrigerant does not exist, and is unlikely to come into existence. The choice will therefore be a selection between the existing low GWP refrigerants (e.g. R-717, R-744 or HCs) and the newly applied and developed chemicals. Many new alternatives are proposed which create a challenge in finding the right refrigerant for each application. One of the important aspects is that refrigerants with low direct impact on climate change are often flammable to some extent.

There is a complex selection process ahead, where the industry will need to find out which of the many proposed new or old refrigerants will be used in each application. In some cases this may be as simple as changing the refrigerant, while in other cases this will require redesign of the system or even change of system topology. The search is a trade-off between cost, safety, energy efficiency, and limiting the need for redesign.

Part of the complexity is that the market is unlikely to be able to support many different refrigerants for the same application. This will leave a period in time, likely to last a couple of decades, where the industry will have to work with both the currently established refrigerants and new refrigerants addressing ozone depletion and/or climate change concerns. In the long run the number of candidates is likely to fall, but it is too early to tell which or even how many of the refrigerant candidates will survive.

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Annex to chapter 2 - safety standards and regulations

With the introduction and potentially wide use of refrigerants that are flammable, have higher toxicity and/or operate at notably higher pressures than the conventional ODS refrigerants or alternative non-flammable HFC refrigerants, consideration of safety matters has become more important. Accordingly, more attention is presently being paid to the requirements of safety standards and regulations that directly relate to refrigerants that exhibit these characteristics. This section summarises the main implications.

Safety classification of refrigerants

The most widely used classification of substances under the UN, where so-called dangerous goods receive a classification according to their main hazards.

Within the RAC industry, a different classification scheme is applied, where most refrigerants are assigned a safety classification, which is a function of toxicity and flammability. The classification scheme is adopted by such standards as, ISO 817 and draft EN 378. An overview of this was given in section 2.1.4, see also Table 2-2.

The toxicity classification is based on whether toxicity has or has not been identified at concentrations of less than 400 ppm by volume, based on data used to determine the threshold limit value – time weighted average (TLV-TWA) or consistent indices. There are two toxicity classes:

- Class A: no chronic toxicity effects have been observed below 400 ppm
- Class B: chronic toxicity effects have been observed below 400 ppm

The flammability classification depends upon whether or not the substances can be ignited in standardised tests, and if so, what the lower flammability limit (LFL) and the heat of combustion are. There are three flammability classes (values according to ISO 817):

- Class 1: do not show flame propagation when tested in air at 60°C and standard atmospheric pressure
- Class 2L: as Class 2 but with a (laminar) burning velocity of less than 0.10 m/s
- Class 2: exhibit flame propagation when tested at 60°C and atmospheric pressure, but have a LFL higher than 3.5% by volume, and have a heat of combustion of less than 19,000 kJ/kg
- Class 3: exhibit flame propagation when tested at 60°C and atmospheric pressure, but have an LFL at or less than 3.5% by volume, or have a heat of combustion that is equal to or greater than 19,000 kJ/kg

Class 2L is now included in ISO 817, ISO 5149 and proposed for inclusion in EN 378. It is primarily intended to differentiate between HFC-152a and the remainder of class 2 refrigerants (such as R-717, HFC-32 and HFC-1234yf), which tend to be more difficult to ignite and is less likely to evolve overpressures that could cause damage.

Typically, a “higher” the classification – that is toxicity Class B instead of Class A, and flammability Class 3 instead of Class 1 – means that the refrigerating system has more onerous design requirements associated with it, in order to handle the higher risk presented by the refrigerant.

Lower Flammability Limit

The lower flammability limit (LFL) of flammable refrigerants is typically applied as a constraint to the amount of refrigerant that can be released into a room or enclosure, as it represents the smallest quantity that, when in the presence of an active source of ignition, could sustain a flame.

Acute Toxicity Exposure Limit

The acute toxicity exposure limit (ATEL) of any refrigerant may also applied as a constraint to the amount of refrigerant that can be released into a room or enclosure, as it represents the smallest quantity that could impose adverse toxicological effects onto occupants.

Practical Limit
There is a further safety measure for the application of refrigerants, termed the practical concentration limit (PL). This represents the highest concentrations level in an occupied space which will not result in any escape impairing (i.e., acute) effects. Thus, it is principally, the lowest “dangerous” concentration of a refrigerant, with a safety factor applied. The estimation of PL is based on the lowest of the following:

- Acute toxicity exposure limit (ATEL), based on mortality (in terms of LC50) and/or cardiac sensitisation, and/or anaesthetic or central nervous system (CNS) effects
- Oxygen deprivation limit (ODL)
- 20% of the lower flammability limit (or 25% in ASHRAE 34)

For class A1 (and A2L) and class B refrigerants, the PL is normally based on the ATEL, whereas for A2 and A3 refrigerants it is normally dictated by the LFL. For some refrigerants the PL is based on historical use experience.

Relevant safety standards
Unlike conventional refrigerants, almost all of the low GWP refrigerants have safety characteristics, which demand greater attention, such as flammability, toxicity and higher operating pressures. Safety standards (and industry codes of practice) provide guidance to offset the additional risks posed by the more hazardous characteristics of the substances.

Safety standards are generated internationally (e.g., ISO, IEC), regionally (e.g., EN) and nationally. Often there are parallels or alignment between standards of similar scope across these different levels, although individual countries elect to adopt alternative requirements than those at international level. The main international and regional standards that affect design and construction of systems as a function of refrigerant selection are listed in Table A2-1 and the scope according to the sections in this report is identified.

Table A2-1: Scope of different international and regional safety standards for AC&R systems

Chapter/Sector	**IEC 60335-2-24**	**IEC 60335-2-40**	**IEC 60335-2-89**	**ISO 5149**	**ISO 13043**	**EN 378**
3 / Domestic refrigeration	×					
4 / Commercial refrigeration			×	×		×
5 / Industrial systems				×		×
6 / Transport refrigeration				[×]		×

7 / Air-to-air air conditioners and heat pumps	×	×	×
8 / Water heating heat pumps	×	×	×
9 / Chillers	×	×	×
10 / Vehicle air conditioning		×	

The three important characteristics that differ amongst refrigerants that have a strong influence over the design and construction requirements are pressure, flammability and toxicity. Typically, the more severe these characteristics (i.e., higher pressure, higher flammability, higher toxicity), the more onerous the requirements are. In principle, these more onerous requirements are intended to offset the potentially worse consequences arising from the more severe characteristics. Table A2-2 provides a summary of the main measures that may require attention when adopting such refrigerants

Table A2-2: Main measures to be considered for substances with greater pressure, toxicity and/or flammability

Greater pressure	Greater toxicity	Greater flammability
Thicker materials/higher pressure rating for pipes and components	Stricter limits on the quantity of refrigerant in occupied spaces	Stricter limits on the quantity of refrigerant in occupied spaces
Additional use of pressure relief devices and/or pressure limiting devices	Limited use in more densely populated areas	Use of gas detection, alarms and emergency ventilation
Higher competencies for workers involved in construction of components and assemblies	Use of gas detection, alarms and emergency ventilation	Prohibition of items that could act as sources of ignition
	Provision of personal protective equipment	Warnings/signage

One critical issue within the various standards, particularly for flammable and higher toxicity refrigerants is the allowable and maximum refrigerant charge. Depending upon the type of occupancy, different approaches are used to determine such values. Table A2-3 provides some indicative charge limits (per refrigerant circuit) based on ISO 5149:2014 for selected situations and a number of commonly discussed refrigerants.

Although these safety standards cover requirements for flammable refrigerants, it is important to highlight that in many countries specific standards for equipment using flammable gases are available and are generally linked to legislation. For example, in Europe products which are placed on the market (except for those that are exempt) and that use flammable gases (including refrigerants) must meet the essential health safety requirements (EHSRs) of the Atex product directive (94/9/EC). By following the Atex harmonized standards, there is a presumption of conformity. Since none of the AC&R safety standards are harmonized to Atex, safety standards such as EN 1127-1 can be used for the evaluation of flammability safety; provided that AC&R equipment meets the requirements of such standards then deviations from the AC&R standards is acceptable if equivalent safety is demonstrated (for example, where larger refrigerant charges are needed.) In addition to meeting the EHSRs, the general approach prescribed by flammable gas standards and regulations is summarised:

- Identification of explosion hazards and determination of the likelihood of occurrence of a hazardous atmosphere;
- Identification of ignition hazards and determination of the likelihood of occurrence of potential ignition sources;
- Estimation of the possible effects of an explosion in case of ignition;
- Evaluation of the risk and whether the intended level of protection has been achieved;
- Consideration of and application of measures to reduce of the risks

Table A2-3 provides the result of calculations for determination of allowable and maximum charge sizes (per refrigerant circuit) for a selection of commonly discussed refrigerants.

Table A2-3: Summary of PL and charge size limits for selected refrigerant and occupancies according to ISO 5149

Refrigerant Class	Example Refrigerant	Practical Limit (g/m^3)	Allowable Charge in a 15 m^2 Occupied Space (comfort)† (kg)	Allowable Charge in a 15 m^2 Occupied Space (general)* (kg)	Max. Charge in an Occupied Space (Occupancy A)	Max Charge in Open Air or Machinery Room	Max Charge for a Ventilated Enclosure
A1	HCFC-22	300	11.3	11.3	PL×RV$^{\delta}$	no limit	no limit
	HFC-134a	250	9.4	9.4			
	R-404A	520	19.5	19.5			
	R-407C	310	11.6	11.6			
	R-410A	440	16.5	16.5			
	R-744	100	3.8	3.8			
A2L	HFC-32	61	1.3 – 4.9	2.3	12 (60‡)	no limit	60
	HFC-1234yf	58	1.2 – 4.5	2.2	11 (56‡)	no limit	56
	HFC-1234ze	61	1.3-4.8	2.3	12 (59‡)	no limit	59
A2	HFC-152a	27	0.5 – 1.7	1.0	3.4	no limit	17
A3	HC-600a	11	0.1 – 0.4	0.3	1.5	no limit	5.6
	HC-290	8	0.1 – 0.4	0.3	1.5	no limit	4.9
	HC-1270	8	0.1 – 0.3	0.3	1.5	no limit	6.0
B2L	R-717	0.35	0.01	0.01	4.5	no limit	23

$^{\delta}$ For systems with multiple indoor heat exchangers a higher charge may be allowed depending on circumstances; ‡ For systems with multiple indoor heat exchangers; † Depending upon installation conditions; * 2.5 m high room

Note: Allowable and maximum charges are per individual refrigerant circuit

Note: The values provided within this table are indicative and determination of refrigerant charge size limits for particular types of systems and installation locations requires the use of the standard and the values within this table should not be taken as a substitute.

References

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EN 378	EN 378-1:2008+A2:2012, EN 378-2:2008+A2:2012, EN 378-3:2008+A1:2012. EN 378-4:2008+A1:2012, Refrigeration Systems and Heat Pumps – Safety and Environmental Requirements
IEC 60335-2-24	IEC 60335-2-24:2010, Specification for safety of household and similar electrical appliances. Particular requirements for refrigerating appliances, ice-cream appliances and ice-makers
IEC 60335-2-40	IEC 60335-2-40:2003+A13:2012, Specification for safety of household and similar electrical appliances. Safety. Particular requirements for electrical heat pumps air-conditioners, and dehumidifiers
IEC 60335-2-89	IEC 60335-2-89:2010, Specification for safety of household and similar electrical appliances. Safety. Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant condensing unit or compressor
ISO 13043	ISO 13043:2011, Road vehicles – Refrigerant systems used in mobile air conditioning systems (MAC) – Safety requirements
ISO 817	ISO 817: 2014, Refrigerants — Designation and safety classification. International Organization for Standardization (ISO)
ISO 5149	ISO 5149: 2014, Refrigerating systems and heat pumps — Safety and environmental requirements. International Organization for Standardization (ISO)

Chapter 3

Domestic Appliances

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3 Domestic appliances

3.1 Introduction

Under the domestic appliance category, the domestic refrigeration sub-sector is the major component and comprises appliances that are broadly used domestically, such as refrigerators, freezers and combined refrigerator/freezer products. Small beverage dispensing machines are similar products and are commonly included in domestic refrigeration, but represent a small fraction of total units. Domestic dehumidifiers have not been considered in this chapter. For domestic wine coolers the same considerations as for domestic refrigerators apply.

Approximately 170 million domestic refrigerators and freezers are produced annually. The vast majority are used for food storage in residential dwellings, with a significant minority used in offices for domestic purposes and small businesses for commercial purposes. Typical storage volumes range from 20 to 850 litres. Various fundamental design approaches and consumer convenience features are included within the product offerings. A typical product contains a factory-assembled, hermetically sealed, vapour-compression refrigeration system employing a 50 to 250 W induction motor and containing 20 to 250 grammes of refrigerant. Some topics discussed below have been covered in earlier reports of this committee. They are briefly included here to provide a more comprehensive perspective. Niche market products in some cases employ alternative technologies to vapour-compression refrigeration. The age distribution of the global installed products is extremely broad (Weston, 1997) with median age estimates ranging from 9 to 19 years at retirement. Long product life and high volume annual production combine for an estimated 2000 to 2300 million unit global installed inventory.

The other domestic appliance covered in this chapter is the heat pump clothe (laundry) dryer (HPCD), which is emerging in the market as an energy efficient alternative to the electric heater dryer. It is included in this chapter for the first time and the title has been accordingly modified as “Domestic Appliances” instead of “Domestic Refrigerators” used earlier (UNEP, 2010). The market for HPCD is fast growing in the EU (while it is very limited in the US and other parts of the world). There are manufacturers from EU and Japan. These dryers mostly use HFC-134a as a refrigerant and charge amounts vary from 200 to 400 g, though the continued use of HFC-134a is under discussion in several global regions. HPCDs using HC-290 have been just introduced. The market share of heat pump clothe dryers in Europe was about 4% in 2009 or about 200,000 shipments per year (out of 4.9 million total clothe dryer sales). The largest market shares in EU are Austria, Germany, Italy and Switzerland. It is projected that in EU, HPCDs would continue to gain market share in the next few years. The total annual sale of heat pump tumble dryers in 2013 is estimated at 1.5 million. An American study has concluded that HPCDs have positive economic benefits only for households with high clothe dryer usage or with high electricity prices and moderately high utilization (Meyers, 2010). The current market share in Article 5 countries for this product is almost negligible.

The ozone depletion potential (ODP) and global warming potential (GWP) values of the refrigerants mentioned in this chapter are given in chapter 2 of this report.

3.2 Options for new equipment

Globally, new refrigerator production conversion from use of ODS was essentially completed by 2008. HC-600a or HFC-134a continue to be the refrigerant options for new production. No other new refrigerant has matured to become an energy-efficient and cost-competitive alternative. Refrigerant migration from HFC-134a to HC-600a is expected to continue, driven either by local regulations on HFCs or by the desire for reduced global warming impact from potential emissions. Excluding any influence from regulatory interventions, it is still projected that by 2020 about 75% of new refrigerator production will use HC-600a (possibly with a small share by unsaturated HFC refrigerants) and the rest will use HFC-134a. This is further discussed in section 3.2.2.

Besides the choice of alternative refrigerants, there are more aspects to consider with respect to the environmental impact of the equipment, such as energy efficiency improvements (see 3.2.5), recycling and end of life issues (see 3.4).

Domestic heat pump clothe dryers have only recently entered the market using mostly HFC-134a, R-407C and HC-290 to a small extent. They do not have any significant historical use of CFCs or HCFCs. The refrigeration circuit differs from domestic refrigeration by its very high evaporation temperature (typical 10 to 30^{o}C) and high condensation temperature (up to 70^{o}C). Rotary as well as reciprocating compressors are being employed.

3.2.1 Alternatives for domestic refrigerators

HC-600a: HC-600a is the main energy-efficient and cost-competitive alternative. Concerns with the high flammability, which existed at the introduction of the refrigerant in 1994 in Europe have been addressed with design features and safety standards, particularly as the charges required for domestic refrigeration are below 150 g. When the safety requirements are met (e.g. IEC 60335-2-24) and adequate risk assessment to address the flammable nature of the refrigerant, HC-600a is the ideal refrigerant for domestic refrigeration products, giving roughly 5 % higher efficiency than HFC-134a while at the same time reducing noise level of the unit.

According to a recent study for a review of the European Regulation (EC) on fluorinated gases (Schwarz et al., 2013), the investment cost for a manufacturing facility for domestic refrigerators using HC-600a is 1.7% higher than for HFC-134a, which represents an incremental product costs of around €7/unit, considering European averages. This is basically due to higher production costs related to the requirements for safety systems. The report also mentions that annual running costs and lifetime cost of HC-600a equipment are lower, resulting in an overall negative life cycle cost differential in case of HC-600a.

In general there are no significant barriers to the use of HC-600a, illustrated by the existence of over 500 million domestic fridges in the market to date. However, in the USA the use of HC-600a is almost non-existent and this can be attributed to a number of factors. These include general concerns regarding public safety (or the perception of), concerns about flammability safety and accidents (which are reflected in the restrictive national standards) and the reluctance to be one of the early movers in the region. However, during recent years this situation is changing which is discussed in section 3.2.2.

HC-600a was the standard refrigerant for European domestic refrigerators and freezers originally and proliferated into other regions, including Article 5 countries. Worldwide over 50 million appliances are produced annually with HC-600a. Increased energy efficiency and the low GWP of the HC-600a refrigerant reduce the climate impact of household refrigerators, due to mitigation of direct (refrigerant) and indirect (CO_2 associated with electricity consumption) GHG emissions, compared to HFC-134a.

In the past, where capital resources were constrained, the use of binary hydrocarbon blends (HC-600a and HC-290) allowed matching the volumetric capacity of previously used refrigerants to avoid investments required to modify compressor manufacturing tools. These blends result in a reduction in thermodynamic efficiency versus pure HC-600a and most of the productions using blends have migrated to the use of pure HC -600a. The use of HC blends has become insignificant and is not further discussed in this chapter.

HFC-134a: HFC-134a was originally the predominant refrigerant for domestic refrigeration since the phase-out of CFC-12. There are no significant safety implications concerning its use. Energy efficiency is similar to that of CFC-12, although with continual optimization, the current HFC-134a refrigeration units are considerably more efficient than those that used CFC-12.

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 for HFC-134a and it has lower flammability characteristics than HC-600a. The lower flammability makes application easier for countries like USA that have limitations with respect to the allowable refrigerant charge for HC-600a. The experience with HC-600a has shown that design changes and investment can abate the risk to an acceptable risk level given the lower flammability of HFC-1234yf.

According to some industrial sources, initial developments to assess the use of HFC-1234yf in domestic refrigeration have begun, but it is not being pursued with high priority, as in automotive applications (see Chapter 10). The preliminary assessment is that HFC-1234yf has the potential for comparable efficiency to HFC-134a, although often slightly worse in practice. Long term reliability tests for capillary tube restriction due to chemical degradation have not been completed. As such, product costs are estimated to be 1% higher than for HFC-134a technology due to the larger surface area of heat exchangers required (to account for poorer energy performance) and an additional 1% due to the higher costs of the refrigerant.

Given the cost disadvantage, flammability and investment requirements for product development, HFC-1234yf suffers significant disadvantages. With the lack of activity by manufacturers, HFC-1234yf is not likely to displace HC-600a or HFC-134a in the foreseeable future.

HFC-1234ze: This refrigerant is still in an early exploration phase (Karber, 2012, Leighton, 2011). The same considerations with respect to flammability as for HFC-1234yf hold. In addition, compressor adaptations are required to match the reduced volumetric capacity compared to HFC-134a. Therefore, also this refrigerant is not likely to displace HC-600a or HFC-134a in the foreseeable future.

R-744: Currently, experience on the use of R-744 is available from a large number of bottle coolers, which have been in use since many years, and are similar, low-charged applications. These are further discussed in Chapter 4.

R-744 application implies an additional cost, which can be attributed to the greater mass of materials necessary to achieve protection against the high pressure level, this in particular for the compressor. Further concerns are the extremely small compressor swept volume requirements and reduced thermal efficiency (Beek and Janssen, 2008). These concerns and the fact that other low GWP alternatives are available make it unlikely that R-744 will become commercialized. Moreover, no major domestic refrigerator manufacturer is actively developing R-744 systems.

3.2.2 Conversion of HFC-134a domestic refrigerators to low GWP alternatives

Current industry dynamics include increasing migration from HFC-134a to lower GWP alternatives. Commercial conversion to date has been restricted to HC-600a. European production of No-frost side by side refrigerators began conversion from HFC-134a to HC-600a in the early 2000's. Initial conversions of automatic defrost refrigerators in Japan from HFC-134a to HC-600a were discussed in the 2006 report of this committee (UNEP, 2006). This conversion, motivated by global warming considerations, has progressed to include more than 90 % of refrigerator production in Japan.

The North American appliance market is dominated by HFC-134a while the conversion to HC continues in the rest of the world. Several factors are uniquely weighted in the North American market that has caused this delay including litigation costs, increased intensity by the Consumer Product Safety Commission, local regulations requiring adherence to ASHRAE 15 and 34 standards, product cost differential for additional safety features, investment costs to meet in plant OSHA safety requirements and the investment cost associated with serviceability of a refrigerant that must be recovered. In the EU, protection is provided by the EU Directive 2001/95/EC on general product safety. North American manufacturers have consequently elected to develop additional costly safety requirements in addition to third party standards prior to introduction of HC-600a to appliances.

Whilst legal concerns have so far limited the use of HC-600a in USA, a major U.S. manufacturer introduced an auto-defrost refrigerators using HC-600a refrigerant to the U.S. market in 2010. This introduction was a significant departure from prior North American practices for domestic refrigeration. In 2011, US EPA approved HC-600a as acceptable alternative under their Significant New Alternatives Policy Program (SNAP) for household and small commercial refrigerators and freezers, subject to certain conditions. Conditions included a limitation on charge to 57 g (note that substitution will be on an equal-molar basis, i.e. 100 grams of HFC-134a will be replaced by 57 g of HC-600a) and the requirement that products comply with the revised UL 250. Concurrently, the number of HC-based refrigerator models offered by manufacturers based in Central and South America are rising as well.

The trend of new production conversion to hydrocarbon refrigerants will continue. Excluding any influence from government regulatory intervention, it is still projected that 75% of new refrigerator production will use HC-600a or any other alternative low GWP refrigerants and 25% will use HFC-134a by 2020 (UNEP, 2010). This estimated migration is shown schematically in Figure 3-1. Estimated conversion extents are based on the following assumptions:

1. All current HC-600a applications will continue.
2. One-half of HFC-134a applications in geographic areas where forced convection, auto defrost refrigerators are the typical configuration will convert to either HC-600a or a new development alternative refrigerant such a low GWP unsaturated halocarbon refrigerants such as HFC-1234yf, e.g. in cases where HC charge limitations are a factor.
3. Three-fourths of HFC-134a applications in geographic areas where natural convection and/or manual defrost refrigerators are the typical configuration will convert to HC-600a or to low GWP HFC alternatives. This is driven by the advantages of HC-600a versus HFC-134a discussed earlier and production rationalization.
4. Use of low GWP unsaturated HFC refrigerants will require successful addressing of numerous application criteria including: thermal stability, hermetic system chemical compatibilities, process fluid compatibilities, contamination sensitivities, etc., in addition to cost implications. Successful closure of any identified issues will be necessary to permit proceeding with confidence for system reliability. Conversions will be influenced by regional market or climate change policy choices. Government regulatory influence was not considered.

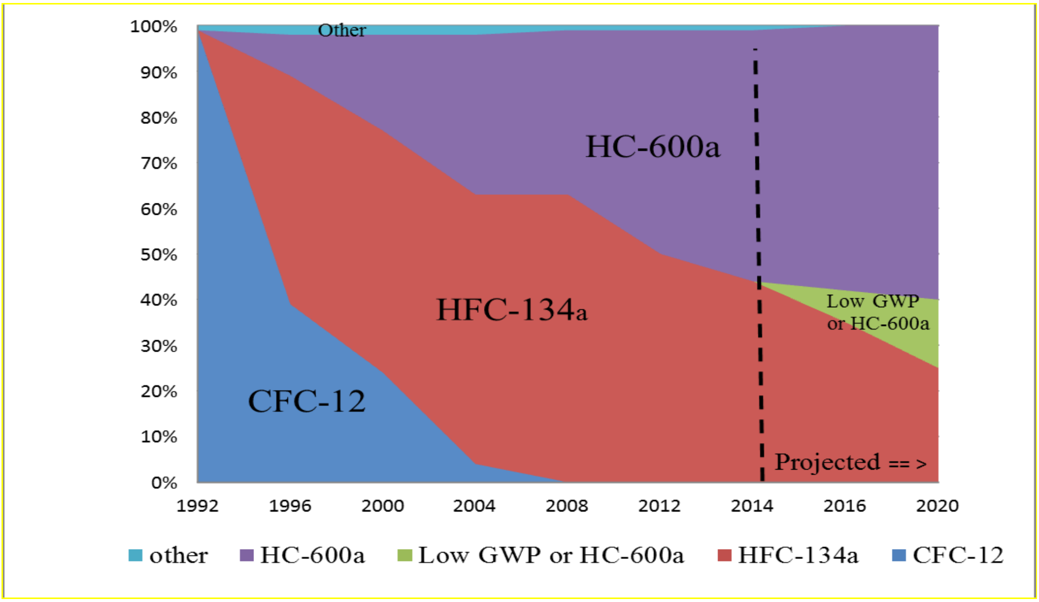

Figure 3-1: New production refrigerant conversion trend

Technologies to accomplish conversions are readily available, though it needs consideration that conversion costs of the production facilities are significant. The rate and extent of conversion will be influenced by premium product cost to maintain product safety with introduction of flammable refrigerants. Premium costs are for modified electrical components, increased use of reduced voltage to avoid electrical arcing and any other safety devices. Cost pressures are more significant on models with lower profit margins. However, lower-end models include fewer components requiring conversions tend to receive priority.

3.2.3 Alternatives for tumble dryers

These dryers typically use HFC-134a as a refrigerant and charge amounts vary from 200 to 400 g. Products using R-407C and HC-290 are also being placed on the market and can potentially make use of the temperature glide, if heat exchangers are optimised for such refrigerants mixtures. Though the continued use of HFCs is under discussion at several global regions, it is also recognised that the use of heat pumps in a dryer lead to significant energy savings of 50% or more and to a substantial reduction in global warming impact of countries using fossil fuel for power generation. Alternative low GWP refrigerant solutions have not yet been introduced in the market, but are being explored. This includes R-744, hydrocarbons and low GWP HFCs.

Low GWP refrigerants currently explored are:

- R-744 (CO_2): The high temperature glide at the gas cooler side can effectively result in an efficient drying process and possibly higher air exit temperatures than possible with subcritical refrigerants. High costs of some components and the probable need of an effective intercooler in order to reduce gas exit temperatures are the challenges currently to be faced.
- Hydrocarbons: In principle various hydrocarbons are suitable. Supply of suitable compressors is currently very limited. Safety hazards due to the refrigerant flammability need careful evaluation as the laundry dryers pose additional risks compared to domestic refrigeration due to the high temperatures involved, the presence of dry textile materials, mechanically moving objects (drum, motor etc.) and the presence of static charges. Further charge minimisation may be needed, considering the relatively high amount of refrigerant required

- Low GWP HFCs: Due to the similar characteristics as HFC-134a, this category may offer potential candidates. However, their flammability results in similar safety hazards as listed for the hydrocarbons, though some of these hazards may be easier to deal with due to the reduced flammability characteristic.

3.2.4 Not-in-kind alternative technologies

Alternative refrigeration technologies for domestic refrigeration continue to be pursued for applications with unique drivers such as very low noise, portability or no access to the electrical energy distribution network. Technologies of interest include Stirling cycle, absorption and adsorption cycles, thermoelectric and magnetic. In the absence of unique drivers such as the examples cited above, no identified technology is cost or efficiency competitive with conventional vapour-compression technology for mass-produced domestic refrigerators.

Absorption refrigeration equipment has been used in hotel mini-bar units due to low noise levels and for mobile, off-network applications such as campers or mobile homes for many years. Thermoelectric or Stirling cycle technologies are used for portable refrigerated chests in applications such as medical transport. Thermoelectric is also used for hotel units and wine storage units with moderate cooling temperature levels.

Magnetic refrigeration is one of the not-in-kind technologies with possible potential for commercialization. Magnetic refrigeration does not use refrigerant and employs an active magnetic regenerator, comprising magneto-caloric materials exposed to an intermittent magnetic field. At lower cooling power, it possibly presents higher efficiency over conventional vapour compression. To decrease the price of the technology, the use of an iron-based alloy to provide the magnetic charge has been considered as an alternative to the rare-earth magnets such as gadolinium used originally.

The remaining specialty niche product areas cited above would each require high capital investment to establish mass production capability. These product technologies will not be further discussed in this report focused on options for mass produced markets.

Not-in-kind laundry dryer technologies are still in an early exploration stage.

3.2.5 Product energy efficiency improvement technologies for domestic refrigerators

The energy efficiency of domestic refrigeration products is a topic of active consumer and regulatory interest. This topic is discussed at length in Chapter 11 of this report. This section contains only a condensed discussion on energy efficiency. A more detailed discussion of efficiency improvement options was included in the 2002 report of this committee (UNEP, 2002). Additional information can be found in various sources, amongst others the reports under the Eco-Design Directive studies (Ecocold, 2006). These studies provided capability background used for updating European Commission minimum energy efficiency standards (EN-643, 2009).

Factors influencing refrigerant selection and product energy efficiency include local, regional and national regulation, Eco-labelling, and third party standards. Globally labelling requirements and minimum standards are reviewed and upgraded on a regular basis, driving the product to reduced power consumption levels with corresponding reductions on global warming impact. Such standards for measurement of product sustainability provide transparency and credibility in the labelling of product impact on the environment, thus driving a more informed decision for the consumer. One example is the recently developed AHAM 7001-2012 Sustainability Standard for Household Refrigeration Appliances, developed and endorsed by multiple stakeholders including environmental, industry, government and consumers. Similar to the EU F-Gas legislation, this standard provides a calculation for the net material GWP impact of a product as the mass weighted average GWP of the product component materials.

Significant technology options to improve product energy efficiency have already demonstrated mass production feasibility and robust, long-term reliability. Both mandatory and voluntary energy efficiency regulation programs catalysed industry product efficiency development efforts. Efforts to develop a universal energy test protocol are in almost completed state (IEC-FDIS 62552-1, 2 and 3, 2014), at present each test procedure is unique and the results from one should never be directly compared to results from another. A number of improved energy efficiency design options are fully mature, and future improvements of these options are expected to be evolutionary. Examples of these options include efficient compressors, high efficiency heat exchangers, improved low thermal loss cabinet structures and gaskets, and less variable manufacturing processes. Extension of these to all global domestic refrigeration would yield significant benefit, but is generally constrained by availability of capital funds and related product cost implications. Similarly, retooling compressor manufacturing facilities facilitated the recovery of the minor efficiency penalties incurred with the use of HC-600a/HC290 blends versus HC-600a.

Design options with less economic justification are sometimes introduced in premium-cost models having incentive subsidies. This provides the opportunity to mature new efficiency technologies and progress them through their individual cost/experience curves. This increases the likelihood for migration of the efficiency technologies to more cost-sensitive model line segments. Options that presently have limited or newly introduced application include variable speed compressors; intelligent controls; system reconfigurations, such as dual evaporators; advanced insulation systems; and Demand Side Management (DSM) initiatives requiring interactive communication with energy providers in order to implement the Smart Grid concept. The premium-cost of these options currently restrict their application to high-end models and constrain their proliferation for general use. A further constraint is the fact that not all energy saving measures results in a reduced energy value during tests according the current test standards. The new universal test protocol mentioned earlier attempts to improve this situation.

- Variable capacity compressors avoid cycle losses and inertial losses through modulating capacity and compressor speed. Use of higher efficiency permanent magnet or linear motors is also enabled by electronic commutation controls.
- Intelligent, adaptive controls allow variable control algorithms that avoid optimising at seldom-experienced worst-case conditions (e.g. variable defrost algorithms).
- Parallel dual evaporators can improve Carnot theoretical efficiency by effectively reducing required pressure ratios of the higher temperature evaporator. Cost–effective, reliable and stable system controls need to be demonstrated.
- Advanced vacuum panel insulation concepts have been selectively used for several years in Japan, Western Europe and the United States. Their premium cost has constrained extension to general use.
- Power line load management (Smart Grid) features of domestic refrigerators reduce energy service provider’s peak load demands. Typically, such a feature on electronic models responds to the power company request for reduced energy consumption. Consequently, the appliances may postpone heated defrost, delay ice harvests or delay the start of a compressor for short periods. The application of such load management features to domestic refrigeration market is ramping up very slowly since the consumer benefit is marginal.

3.2.6 Product energy efficiency improvement technologies for tumble dryers

For HPCDs the inclusion of a heat pump on itself is a major energy saving technology compared to conventional laundry dryers. Current energy saving option is predominantly related to optimisation of the refrigeration system in combination with the air circulation system.

3.3 Options for existing domestic refrigerators

Non-Article 5 countries completed conversions of new equipment production to non-ozone depleting substances (ODSs) more than 15 years ago. Later, a number of Article 5 countries also completed their conversion, e.g. India by 2003. Therefore, most products containing ozone depleting refrigerants are now approaching the end of their life cycle.

Field conversion to non-ODS refrigerants has significantly lagged original equipment conversion. The distributed and individual proprietor character of the service industry is a barrier to co-ordinated efforts to convert from ODS refrigerants. Field service procedures typically use originally specified refrigerants. Refrigerant blends developed specifically for use as drop-in service alternatives have had limited success. The interested reader is referred to the 1998 report of this committee for an extended discussion of field repair and conversion options (UNEP, 1998). Chapter 2 in this current report contains an updated listing of refrigerant blend options.

Limited capital resources also favoured rebuilding service options in Article 5 countries versus replacement by new equipment. Rebuilding has the accompanying consequence of voiding the opportunity to significantly improve product energy efficiency and reduce stress on the power distribution grid.

Field service conversion to non-ODS alternatives e.g. HFC-134a, and HFC and HC blends, is not being done significantly. In some countries, the old units are bartered for new appliances using non-ODS alternatives. The cost of extensive reconfiguration potentially required to properly convert for use of alternative refrigerants is a significant deterrent to this approach.

In the case of conversion to HC blends, safety considerations require that any flammable fluid accumulation within an enclosed volume must avoid the potential within that volume for an electrical spark, electrical arc or surface temperature above the auto-ignition temperature of the leaked gas in air. The extent of in-service product modification to assure this is dependent upon the original product configuration. The original equipment manufacturer is most familiar with the product construction and should be consulted for required modifications prior to decision to proceed.

- Cold-wall-evaporator constructions require leaking refrigerant to diffuse through the refrigerator inner liner or flow by convection through apertures in the liner in order to accumulate within the cooled volume. There is a low probability of significant gas accumulation. Additionally, electrical components located within the cooled volume are limited and consequently there is a low probability of an ignition source within the enclosed volume. Economical drop-in conversion of this configuration is alleged to be viable as per some reports, but procedure definition by the original manufacturer should be sought prior to decision to proceed.
- Thin-wall evaporators positioned within the cooled volume are a common construction for automatic-defrost refrigerators. Leakage of refrigerant can accumulate within the cooled volume and the risk of ignition is dependent on whether the rate of leakage is sufficient to result in a combustible mixture within the cooled volume. Additionally, electrical components are commonly located within the cooled volume, such as, thermostats, convective fans, defrost heaters, lights, icemakers, etc., increasing the probability of an ignition source being present. The viability of a drop-in conversion will depend upon the extent of original construction modification required to achieve an acceptable configuration. Again, conversion procedure definition by the original manufacturer is prudent and should be sought prior to decision to proceed.

3.4 End-of-life disposal

The small unit charge and the geographically dispersed location of these units complicate commercial opportunities to promote recovery and recycling initiatives to manage emissions from disposed units. Regulations for mandatory end-of-life refrigerant handling have existed in many developed countries for several years and are being introduced in Article 5 countries. Chapter 11 of this report addresses this and related conservation approaches. Interest in conservation programmes is leveraged by the 1 to 2 kg of foam blowing agents typically present in a domestic refrigerator.

For HPCDs, similar recovery and recycling technologies apply for refrigerant and lubricant as for domestic refrigeration systems, although there is no adequate experience in this emerging segment.

3.5 Concluding remarks

Conversion of new equipment production to non-ODS refrigerants in Article 5 countries occurred over a span of five to seventeen years ago. Migration to second generation non-ODS refrigerant from HFC-134a to HC-600a in new product production is occurring as a result of the GWP difference between the two alternatives. This migration began in Japan several years ago and is now occurring in Brazil, Mexico and the United States. No new technology is required and the trend will likely proliferate. The rate and extent of proliferation will be influenced by the relative cost for HFC-134a and HFC-600a products. Current estimates indicate that additional cost results from design changes to allow the use of flammable refrigerants in automatic defrost refrigerators.

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Chapter 4

Commercial Refrigeration

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4 Commercial refrigeration

4.1 Introduction

Commercial refrigeration is characterised by storing and displaying food and beverages at different levels of temperature within commercial stores with sales areas varying in size from approximately 10 m^2 to 20,000 m^2. The refrigerating capacities of equipment vary from hundreds of Watts to as high as 1.5 MW. Two main levels of temperatures are generated by refrigeration systems from around 0 °C to 8 °C for the conservation of fresh food and beverages, and around -18 °C for frozen food and ice cream.

Globally, HCFC-22 continues to represent the largest refrigerant bank in commercial refrigeration and is used at all temperature levels. The most used HFC (blend) is R-404A for all temperature levels.

For the past decade, HCs for low refrigerant charge systems, and CO_2 for larger supermarket applications are increasingly used in many developed nations.

In parallel, progress has been made to improve energy efficiency and leak tightness, especially for centralized systems. The progressive phase-out of HCFC-22 in developing countries requires making informed choices on the best replacement options.

AHRI launched a Low GWP Alternative Refrigerant Evaluation Program (AREP) in 2010 (AHRI, 2013). A number of new blends based on HFC-1234yf and HFC-1234ze(E) as well as HFC-32 have been formulated to replace HFC-134a, HCFC-22, and R-404A. So, for the three groups of commercial refrigeration equipment, comparisons are now being made in order to select amongst the most energy efficient options with the smallest environmental impact due to refrigerant emissions.

In commercial refrigeration, as in air-conditioning, high ambient applications require special consideration in selecting and designing components and equipment. However, designers of commercial refrigeration equipment choose components to design systems based on delivering the cooling required at the highest ambient condition.

For moderate and cold climates it is an important option to recover heat from the refrigeration plant for heating purposes in the cold season. Considering the supermarket as an energy system for which energy use should be minimized may give considerable energy savings.

The ozone depleting potential (ODP) and global warming potential (GWP) values of the alternates mentioned in this chapter are given in Chapter 2 of this report.

4.2 Applications

Stand-alone equipment are self-contained refrigeration systems and comprise a wide variety of applications: ice-cream freezers, ice machines, beverage vending machines, and display cases. These systems are found not only in large commercial stores but also restaurants, convenience stores, mini supermarkets and gas stations. For developing countries, domestic refrigerating equipment, refrigerators, and freezers can be found in small shops and used for commercial purposes. Stand-alone equipment are increasingly used in developed countries in medium-size supermarkets because of ease of maintenance of the fully-welded circuit. In Europe, and lately in other markets, this choice is also often related with the use of hydrocarbons or CO_2.

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 typically located external to the sales area. The cooling equipment consists of one or more display case(s) in the sales area and/or a small cold room. Condensing units are typically installed in specialty shops such as bakeries, butcher shops, and convenience stores. In a number of supermarkets, one can find a large number of condensing units (sometimes up to 20) installed side-by-side in a small machinery room. In most of the A5 countries, the use of systems using condensing units is very extensive. Condensing units are easily found in all countries through refrigeration equipment distributors. The global market of condensing units has a strong consequence in terms of refrigerant choices; they are developed based on the most used refrigerants: HCFC-22, R-404A, and HFC-134a.

Centralised and Distributed systems are the preferred options in supermarkets. They operate with racks of compressors installed in a machinery room as in the case of a centralized system or several smaller racks installed in a machinery room or on the roof as in the case of a distributed system. Distributed systems may be thought of as multiple smaller centralized systems which lead to lower charge levels. A number of possible designs exist and will be addressed in Section 4.3 3. 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. In the machinery room, racks of multiple compressors are installed; these utilise common discharge lines to the air cooled condenser and common suction and liquid lines to the refrigerated fixtures. Specific racks are dedicated to low temperature and others to medium temperature. Each refrigerant circuit of each rack is independent. Supermarket centralised systems with long piping circuits have led to large refrigerant charges (100 to 3,000 kg depending on the size of the supermarket) and consequently to large refrigerant losses when ruptures occur. Studies have been conducted which show that low leak rates are possible to achieve in supermarket applications to less than half the typical values, some as low as 3.5% (EPA). Typical emission rates of small supermarkets vary between 15 and 25% and those of large supermarkets between 20 and 35%. These figures represent, in general, the situation of non-Article 5 countries. The emission rates for most of the Article 5 countries are much higher.

Indirect systems are composed of primary heat exchangers where a heat transfer fluid - HTF (also called secondary refrigerant) is cooled and pumped to the display cases where it absorbs heat, and then returned to the primary heat exchanger. HTFs have been receiving interest because indirect systems allow for lower primary refrigerant charge and facilitate the use of flammable or toxic refrigerants when isolated from the sales area.

4.3 Options for new equipment

4.3.1 Stand-alone equipment

Several stand-alone equipment types are described in this section, in order to analyse the trends for refrigerant choices depending on the cooling capacity, the refrigerant charge, and the refrigerant circuit design. Many of stand-alone equipments are owned and installed by global food companies. Those companies develop their own environmental policy and choosing low-GWP refrigerants as well as energy-efficient systems are part of the green positioning of those companies.

Bottle coolers
Glass-door bottle coolers can be found in nearly every supermarket, gas station, and kiosk. The most common type is the one-door 400-liter type, but also bigger (2 or 3 glass doors) and smaller types are on the market.

Hydrocarbon (HC-290) bottle coolers as well as CO_2 bottle coolers show good energy performances and with R&D developments even better compared to the HFC-134a base line. Hydrocarbon bottle coolers showed 28% reduced energy consumption compared to HFC-134a bottle coolers, and for CO_2 12% energy consumption reduction (Pedersen, 2008). The choice of HC-290 is made by several European companies manufacturing those bottle coolers, while CO_2 is preferred by others, based on a different perception of safety risks.

Within the AHRI / AREP test program, laboratory tests have been performed in order to evaluate the two low-GWP HFCs: HFC-1234yf and HFC-1234ze, and HFC-134a based blends designed to replace HFC-134a at nearly the same performances. Tests indicate that those low-GWP refrigerants are in the same range of performances and that refrigeration system optimization is necessary and will be developed in the near future.

Ice-cream cabinets
R-404A and HFC-134a are the refrigerants used in ice-cream cabinets and are progressively being replaced with HC-290 by large food companies. In 2014, the number of HC-290 ice-cream cabinets is expected to be more than one million units as assessed by a leading global company (Refrigerants Naturally, 2014).

Vending machines
Vending machines for soft drinks require a significant cooling capacity to rapidly cool the soft drink container. The usual refrigerant charge of HFC-134a varies between 0.5 and 1 kg leading to the development of CO_2 options to compete with hydrocarbons. High-efficiency CO_2 cassettes have been developed by a Japanese company and are sold to many OEM companies for integration. The CO_2 technology is compact and has passed the tests of energy efficiency defined by soft drink companies. HC-290 vending machines have also been developed to perform satisfactorily from an energy point of view. As for bottle coolers the choice between CO_2 and hydrocarbons is made based on conclusions drawn from the risk analysis and the impact of possible incidents or accidents.

Water coolers
A large number of water coolers for both bottled water and tap water are installed worldwide. The refrigeration capacity is small and the refrigeration circuit is fully brazed. Thus this equipment looks like a small domestic refrigeration system. Many companies have switched from HFC-134a to isobutane (HC-600a). The hydrocarbon charge could be as low as 20 g.

Ice machines
Ice machines are installed in restaurants, bars and hotels, and are dominantly found in North America. Many different refrigeration capacities are found depending on the size of the machine, as well as different technologies depending on the type of ices: cubes, pellets, flakes etc. The usual R-404A charge can vary from 500 g to 2 kg. Within the AHRI/AREP program, an ice-machine dispenser has been tested with a new low-GWP HFC-based blend with a temperature glide of about 7 K at the evaporator. Report #2 indicates lower refrigeration capacity of about 4% without any optimization being done (Schlosser, 2012). In Europe, and in other regions, small ice machines now use HC-290 and are sold as a standard option. More recently, several equipment manufacturers have started introducing ice machines using CO_2 as the refrigerant (Shecco, 2014).

Supermarket plug-in display cases
The use of supermarket cabinets of the plug-in type is increasing in Europe, especially in discounter stores. Many small- and medium-size supermarkets install such units instead of the cabinet cooled by a remote refrigeration system. The plug-in cabinets have lower installed cost, are more flexible and require less system maintenance, because of the fully brazed circuit. Plug-in cabinets are significantly less energy efficient compared to display cases

cooled by condensing units or compressor racks, because small compressors have lower energy efficiency than larger ones.

Moreover, the condenser heat is released into the supermarket sales area where the display cases are installed. For high outdoor temperatures, the heat released in the sales area requires higher cooling capacity for air conditioning. On the contrary, the heat released is a gain in winter in moderate and cold climates. Some installations of stand-alone display cases are designed with water cooled condensers allowing the release of heat outdoor, usually using a small water chiller; in this specific design, energy efficiency can reach acceptable levels.

The refrigerant choice used to be R-404A. Since 2007, hydrocarbon display-cases using HC-290 have been proposed as a standard option in Europe with an energy efficiency gain ranging from 10 to 15% compared to R-404A. CO_2 systems for display cases have also been introduced by several key suppliers.

The first conclusions that can be drawn for standalone equipment are as follows:

- HFC-134a and R-404A will be phased-out progressively in developed countries. Due to multinational companies this phase-out is also beginning in developing countries. There are several low-GWP refrigerant options and hydrocarbons, CO_2 and new low-GWP HFC-based blends can be used depending on commercial availability.
- Addition of glass doors and LED lighting to display cases can reduce the refrigeration load thus enabling the use of flammable refrigerants for these display cabinets within the allowable charge limits.
- Minimum energy standards have been issued or updated in the last years in North America, in Europe and in many other countries, making a new competition between manufacturers in order to reach higher energy efficiency stand-alone systems; the CLASP report (Waide, 2014) estimates the possible gains for the different standalone-equipment types between 30 and 40% compared to the current average energy consumption.
- Eco-labelling taking into account all impacts during the life cycle of product (see Chapter 11) will be soon issued for commercial refrigeration in Europe, energy consumption being the main criterion to be addressed in order to lower significantly the environmental impact of those equipment. In parallel, the amended F-gas regulation will affect refrigerant choices in this equipment.

4.3.2 Condensing unit systems

Condensing units comprises one or several compressors, an air-cooled condenser (usually), a receiver, and a liquid line to be connected to the refrigeration circuit. Condensing units are designed for several capacities and are standardized equipment. Condensing units are commonly used in commercial refrigeration worldwide and especially in developing countries; they are sold by OEMs to installers. The design is as generic as possible and the usual refrigerant is HCFC-22 in developing countries, HFC-134a, R-404A and, to a lesser extent, R-410A in developed countries. 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 all other refrigerants.

Replacement HFC blends

For HCFC-22 replacement, a number of "intermediate" refrigerant blends are proposed, such as R-407A, R-407F, R-448A, and R-449A and others have not yet received their ASHRAE number. Their GWPs are ranging from about 1000 to 1700. They are designed to replace HCFC-22 or R-404A and are used either as retrofit refrigerants or in new equipment. All of them present temperature glides from 5 to 7 K which require special attention paid to the selection and operation of components.

A new set of low-GWP R-404A and HCFC-22 replacement refrigerant blends is also being introduced with GWPs ranging from less than 150 to 300; they are considered to be commercially available before the end of 2016. Some have been tested and results are available in (Schultz, 2013) showing a volumetric capacity either identical or in the range of ±5%, with a COP from 7 to 2% lower compared to HCFC-22. Many low-GWP HFC blends contain HFC-32 and HFC-1234yf and/or HFC-1234ze(E), and they are all low-flammable refrigerants classified as 2L in ASHRAE 34. For HCFC-22, HFC alternative-blend options that are proposed show performances close to the benchmark reference. The results indicate that soft optimization could lead to performances on the level of the baseline refrigerants. Nevertheless, equipment manufacturers have to take into account in the new equipment design that all these refrigerant blends have temperature glides varying from 4 to 7 K.

Ammonia
R-717 is not used much in these systems for cost and safety issues. However it is used in cascade systems with CO_2 in the low stage of the equipment.

CO_2
New carbon dioxide-based condensing units are sold in Northern Europe and Japan. The market penetration is low but increasing. R-744 condensing units require a double-stage design if high ambient temperatures occur frequently. Single-stage systems are designed for cold climates. The additional cost for a double-stage system is significant compared to usual HFC reference condensing units. The cost remains the main barrier for these R-744 condensing units in certain regions, but with increasing production capacities and financial incentives this barrier is expected to overcome soon.

Hydrocarbons
Several hundred indirect condensing units using HC-290 or HC-1270 are operating in Europe with typical refrigerant charges varying from 1 to 20 kg, most of them on the lower charge side, with good energy efficiency.

Direct expansion condensing units from 100 W to 10 kW (up to 1.4 kg charge) are commercially available from major manufacturers operating with HC-600a and HC-290, and for temperatures ranging from -40°C up to 0°C. Costs for these HC-based systems can be up to 15% higher than HFC systems due to safety measures required for flammability mitigation.

4.3.3 Centralized supermarket systems

Centralized systems are the preferred option in medium to large supermarkets, because they usually achieve better energy efficiency than plug-in cabinets and condensing units. This is mainly due to compressor efficiencies being higher for larger compressors (in the range of 60-70%) compared to smaller compressors (in the range of 40-50%) used in plug-in cabinets. The sales area of supermarkets with centralized refrigeration systems varies from 400 m^2 up to 20,000 m^2 for large supermarkets.

Generally, for large supermarkets, the reference design is a direct-expansion centralized system with several racks of compressors operating at the two evaporation temperature levels (-10 °C ± 4 K and -32 °C ± 4 K for example). Several refrigeration system designs exist for medium to large supermarkets; these designs have an impact on refrigerant choices, refrigerant inventories, and energy efficiency. Conventionally, they operate with racks of parallel piped compressors installed in a machinery room, typically using HCFC or HFC in direct expansion refrigeration systems. Typically the compound compressors operate with a common condenser which provides a number of different evaporators with liquid refrigerant. Places to be cooled by the system include refrigerated counters, refrigerated shelves, freezer islands, medium and low temperature storage rooms. Because all cabinets/evaporators are connected to all compressors in one compound system, HFC charges can be quite high – up to 3,000 kg for hypermarkets – with resulting high emissions in the case of component failure like pipe rupture, e.g. due to excessive vibration. In addition, the numerous joints of large systems are prone to frequent leakage (especially mechanical joints), hence such systems often have refrigerant leakage rates in the order of 15 % (Schwarz et al, 2011) or higher, typically 25%. In order to limit refrigerant emissions, some commercial companies have put significant effort in order to limit their annual emissions; some successes have been reported in Germany with reduction of annual emission rates lower than 10% (Kauffeld, 2013).

The different central multi-compressor refrigeration systems offered on the market can be categorized according to

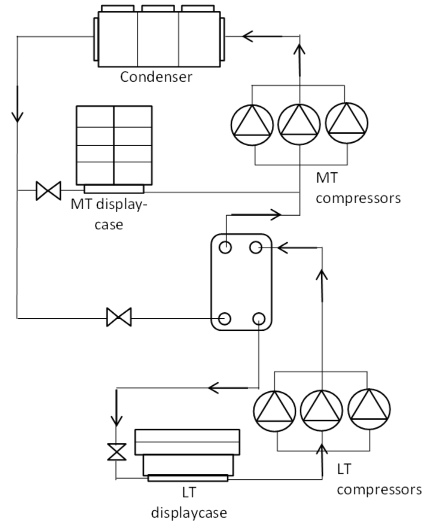
- the choice of refrigerant(s),
    - HCFC or HFC
    - Hydrocarbon (HC)
    - Ammonia (R-717)
    - Carbon dioxide (R-744)
- the type of refrigerant distribution
    - direct expansion or
    - indirect via a heat transfer fluid (HTF) – the HTF can be single phase liquid (mainly used for MT), melting ice slurry (only MT) or evaporating carbon dioxide (MT and LT), and
- the kind of cooling of the condenser/gas cooler
    - Ambient air cooled; in hot climates sometimes with evaporation of water in order to reduce air temperature
    - Water cooled; water cooling by ambient air
    - Water based heat recovery; i.e. condenser is water cooled heating tap water or store
    - Air based heat recovery; heating store room air directly.

Most systems have separate MT and LT systems, but especially systems working with R-744 combine MT and LT in one compound system. Due to safety and technology reasons, not all combinations make sense or are acceptable. For example ammonia by reason of its higher toxicity is excluded from the costumer area and it will therefore never be used in direct expansion systems in the sales area of a supermarket; but ammonia can be used safely as a high-efficiency refrigerant in an indirect supermarket refrigeration system, see below.

The evaporator of direct expansion systems is located in the application (i.e., within the cold room or cabinet). Condensers can be arranged in air-cooled machine rooms in the building or outside of the building. Heat recovered from the condenser can be used for room or tap water heating. Direct expansion systems are worldwide the dominating technology for supermarkets. The direct expansion centralized system is therefore often used as the reference for comparisons of energy performances and refrigerant charges.

The refrigerants for new systems are R-404A and R-744, especially in Europe. To a smaller extent HFC-134a is used for medium temperature applications, as well as R-507A in some countries, e.g. Norway. Direct expansion systems will always have refrigerant-carrying pipes and components inside of the sales area which the public may enter. Therefore, the refrigerant will normally be restricted to lower toxicity, non-flammable safety classification (i.e. class A1 according to EN-378).

For cost reasons and for technical simplicity, commercial centralized systems have usually been designed with a single compression stage even for the low-temperature level (-35°C to -38°C). Two design options, cascade and boosters systems, which are common in industrial refrigeration, have been introduced in commercial refrigeration in order to improve energy efficiency, see Figure 4-1 and 4-2. They can be used for all refrigerants, but the development has been especially made for R-744.



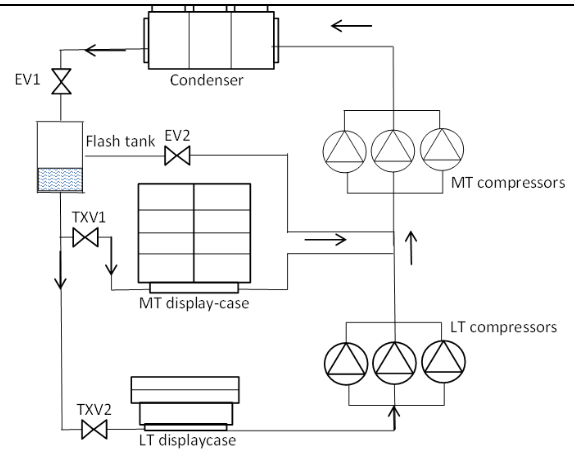


Figure 4-1: Cascade system	***Figure 4-2: Booster system***

Cascade systems
The cascade system, as shown in Figure 4-1 connects the low-temperature compressor rack to the medium-temperature level, via an evaporator-condenser where the heat released by the low-temperature rack is absorbed by the evaporation of the medium-temperature refrigerant. The refrigerants at the two levels of temperature can be either different or identical. In any case two-stage systems are more efficient than single-stage ones; the energy gain is typically of 15 to 20% and is more pronounced for high outdoor temperatures.

Booster systems
Another design, which is simpler and less costly, is also developed and installed now in commercial refrigeration: the booster system presented in Figure 4-2. The low-temperature compressor rack discharges its vapour directly in the suction line of the medium-temperature rack where it is mixed with the medium-temperature vapour. In this design, the refrigerant is the same for the low and medium-temperature levels. The booster system offers several levels of pressure by using a flash tank and several expansion valves. A first expansion valve EV1 expands the refrigerant in the flash tank at a first intermediate pressure; the vapour generated by this first expansion is directly sucked by the medium-temperature compressor rack, and the pressure of the expanded vapour leaving the flash tank is controlled at the medium evaporation pressure by EV2. For CO_2 this design presents a great advantage because above 31°C in the condenser, there is no more condensation and the condenser becomes a gas cooler. In the supercritical region, CO_2 is in dense gas phase at pressure around 90 bars and can be expanded in the flash tank at 40 bars for example, and so a part of the expanded CO_2 changes to liquid phase and feeds both the medium-temperature display-cases via the expansion valve TXV1 and the low-temperature display case via TXV2. For high outdoor temperatures, the booster system offers a efficiency gain for CO_2; however, energy loss for

CO_2 systems due to supercritical operation can be overcome with additional design features like ejectors, parallel compression or subcoolers.

These two designs are now installed in several thousands of stores; cascade systems – with usually HFC-134a at the medium-temperature level – in large supermarkets and full CO_2 booster systems in larger to smaller ones. These stores are currently mostly found in Europe, but are increasing in adoption in the rest of the world.

Distributed systems
In the USA two designs coexist: the centralized and the distributed system. Distributed Systems consist of a number of compact compressor systems / condensing units with – typically - water-cooled condensers. The compressor systems are located in sound-proof boxes, which can be installed in the sales area. Water pipes running through the store remove the condenser heat. The design is compact and the refrigerant lines are short, which makes a gain in terms of reliability and limits the pressure losses. The refrigerant inventory of a distributed system is smaller by about 15% compared to a direct-expansion centralized system while the energy efficiency is in the same range.

R-404A is usually used as the refrigerant of choice although HFC-134a is also feasible for MT applications and HC-1270 is used in some water cooled condensing units (charge always below 1.5 kg). The central chiller can use any kind of refrigerant, many systems use HC-290 or R-404A.

Indirect Systems
Indirect systems include a secondary cycle which transports the heat by means of a heat transfer fluid (HTF) from the refrigerated cabinet to the evaporator of the primary refrigeration system which can be located in a secured machine room or in the open air, i.e. isolated with no public access, see Figure 4-3. During the last 20 years, indirect systems have been developed, mostly for the medium-temperature level, enabling a reduction of the refrigerant charge by at least 50%.

As shown in Figure 4-3, the low-temperature direct expansion system can release the condensation heat to the HTF secondary loop, leading to better energy efficiency of the low-temperature system and allowing also the use of CO_2 in subcritical operation at the low-temperature level. Some other designs are also possible where the condensation heat of the low-temperature system is directly released to the atmosphere

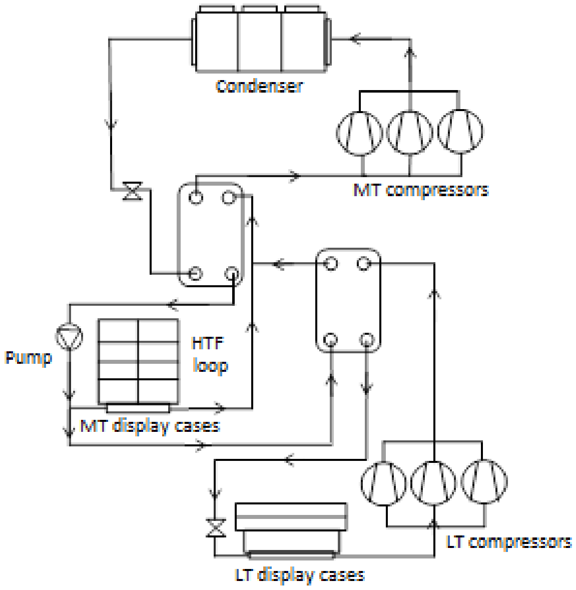


Figure 4-3: Indirect system at the medium-temperature level and direct expansion at the low-temperature level

The use of HTF with phase change offers an energy saving potential: ice slurry for medium temperature or CO_2 for medium and low temperatures (Møller, 2003). Through the selection of the correct additive, ice slurry can also outperform a single-phase HTF (Hägg, 2005; Lagrabette, 2005).

Indirect systems make the primary refrigeration system design very compact. One can use prefabricated units and the assembly of systems can be simplified on site. Indirect systems allow also for providing more stable temperatures and increased humidity at the points of refrigeration (Rhiemeier et al., 2009). The pumping energy of heat transfer fluid, which can be significant, has to be compared with the additional energy consumption due to pressure losses of the long suction lines of direct expansion systems. In order to prevent the energy consumption increase, it is also important to select the appropriate HTF based on liquid viscosity and heat capacity. For indirect systems, the following characteristics have to be mentioned: all piping needs to be insulated; HTF leaks are also possible and difficult to diagnose.

Developing country aspects
In developing countries, supermarkets can be of very different sizes but also have a centralized machinery room as in developed countries; depending on the leadership of companies, one can find CO_2 cascade and booster systems in a country such as Brazil. It has to be taken into account that for cost reasons and ease of installation many small supermarkets and convenience stores in developing countries will be using condensing units.

Refrigerants and systems

HCFCs and HFCs
The dominant refrigerant for centralized systems in the developing countries is HCFC-22 while R-404A is common in developed countries. In Japan R-407C is commonly used, and some stores using R-404A have switched to R-410A in the last years. Now pure HFC-32 is beginning to be used at the medium-temperature level and CO_2 or HFC-32 are under evaluation for the low-temperature level. The flammability of HFC-32 makes it difficult to be used in large direct expansion systems outside of Japan. More recently, lower GWP R-404A alternatives like R-448A, R-449A are undergoing field trials and starting production while

HFC-134a alternative blends like R-450A are also being evaluated. These and other similar lower GWP HFC blends are important as replacements for existing systems that use R-404A and HFC-134a.

HC-290 and HC-1270

Refrigerant changes have begun since the early 2000 in Europe, and especially in Germany, where propylene (HC-1270) has been introduced in supermarkets, using a secondary loop, HC-290 is now the preferred option. For all HCs, the machinery room is located outside of the store. The number of these HC-systems is limited.

Ammonia

Due to its toxicity, ammonia is confined in a ventilated machinery room and ammonia systems are always designed with secondary loops at each temperature level. Several large supermarkets operate with ammonia especially in Luxembourg and Switzerland. Ammonia can be used at the medium-temperature level, together with CO_2 at the low-temperature level.

CO_2 (R-744)

The real breakthroughs using CO_2 as refrigerant began around 2005 with two major new options: CO_2 as the only refrigerant in booster systems and CO_2 in cascade with HFCs or other refrigerants.

For using CO_2 as the only refrigerant in small, medium and large size supermarkets, CO_2 has been introduced in transcritical booster systems (Figure 4-2). The low-temperature rack operates at -33°C ± 3°C evaporation temperature. The medium-temperature rack operates at -9°C ± 3°C evaporation temperature. The heat dissipation occurs up to 30°C depending on the outdoor temperature, and above 27°C outdoor temperature, the operational mode becomes transcritical. Up to now, more than 3000 transcritical CO_2 systems are installed, mainly in Europe (95%) (Chasserot, 2014).

CO_2 systems operate also at the low-temperature level only. The condensation heat is released to the secondary loop, usually at -10°C temperature level as shown in the cascade system (Figure 4-1). The interest of keeping this low level of condensation temperature is to use usual copper tubing designed for maximum pressure of 3 MPa. The medium-temperature compressor rack works with HFC-134a or R-717, those systems are installed in about 2000 stores (Chasserot, 2013). In Brazil, due to the active policy of a European company, more than 50 stores are now operating with CO_2 cascade systems.

The energy efficiency of CO_2 systems is better than that of comparable HFC-systems at ambient temperatures below 22°C, about equal at temperatures between 22 and 26°C, and lower at higher ambient temperatures (Finckh et al, 2011). It should be noted that using electronic expansion valves and similar system enhancements used for CO_2 systems will also have beneficial effects on standard HFC systems. Installation of CO_2 systems has also begun in Asia, the Americas, and Australia. Shifting from HFCs to CO_2 can reduce the carbon footprint of supermarkets by 25% (EPA, 2010) but could be higher depending on the refrigerant leakage and energy recovery utilization

For moderate and cold climates it is an important option to recover heat from the refrigeration plant for heating purposes; e.g. for hot water heating and indoor air heating in the cold season. CO_2 systems are easily adapted to satisfy such demands. Considering the supermarket as an energy system for which energy use should be minimized may give considerable energy savings, e.g. 30% has been demonstrated (Hafner et al, 2014a).

With trials of new developments like booster systems, ejector systems, expander systems, parallel compression and systems with auxiliary mechanical sub-cooling, the efficiency of

CO_2 systems may, in the future, be improved to the extent that such systems will be more energy efficient, even in warmer climates (Huff et al, 2012 and Hafner et al, 2014b).

Low-GWP HFCs and HFC blends for R-404A and HCFC-22 replacement
The AHRI/AREP Report # 21 (Shrestha, 2013) presents several low-GWP HFC blends (from 220 to 300) proposed to replace R-404A in condensing units that are the same as those proposed for centralized systems. The refrigeration capacities of these blends are slightly lower, energy efficiency slightly higher and temperature glides of 4 to 7 K are larger compared to R-404A. The consequence of the temperature glide is a possible distillation of the blend when a leak occurs. Servicing becomes more complex due to the composition change of the refrigerant blend due to the different boiling points of the individual components of the blend. Some contractors recommend the recovery of all the refrigerant remaining in the installation to make a full new charge at the right blend formulation. Such practice could add to running costs of systems due to the anticipated higher costs of low GWP HFCs and associated destruction costs of the remaining refrigerant.

Some of the low-GWP-HFC blends are designed to replace HCFC-22. For the tested blends, the cooling capacity is 2 to 7% lower and the efficiency is from 5 % lower to 10% better. Some of the blends formulated to replace R-404A are the same as those formulated to replace HCFC-22.

The results of the AHRI / AREP reports show that soft optimization of refrigeration systems using those blends may lead to the same level of performances. Three issues are still to be addressed: safety rules for low flammability refrigerants, servicing of refrigerant blends with possible distillation due to leaks and commercial availability.

A new set of low-GWP R-404A refrigerant blends is also being introduced with GWP less than 150.

Summary for centralized systems
In summary, for centralized systems a number of options are available and proven; some of them require a higher technical training of contractors especially for two-stage CO_2 systems.

The replacement of R-404A is underway and will lead to several families of technical options with either CO_2 at all temperature levels or low-GWP HFCs at the medium temperature operating in cascade with CO_2 at the low temperature. R-404A replacements that are non flammable and lower than 2000 GWP will grow in use both in existing and new systems. Low GWP and mildly flammable HFCs at all temperature levels will also be considered but flammability concerns might limit the types of systems due to the current standards.

4.4 Options for existing equipment

This section covers the retrofit options for the installed base of equipment. For stand-alone equipment, there is no real incentive to change the refrigerant because the refrigeration circuit is totally brazed and hermetic, and this type of equipment will be changed based on its current lifetime, if no heavy leaks occur. However, a few options for stand-alone equipment are: R-448A or R-449A for R-404A and R-450A for HFC-134a. This list can be expected to grow as more manufacturers release alternates for existing refrigerants and equipment.

The R-407 series of refrigerants like R-407A, R-407F and R-427A are now used in many developed countries as retrofit refrigerants for R-404A depending on individual manufacturers' approvals. These refrigerants, including R-407C, are commercially available and are also formulated to replace HCFC-22. Other HFC blends with GWP lower than 2000, such as R-448A and R-449A (and others not yet assigned ASHRAE numbers) will be also commercially available in 2015 and will be candidates to replace HCFC-22 and R-404A. In fact, the most important issue for the replacement of HCFC-22 in developing countries will be to find replacement options at acceptable costs; given the fact that developing countries will lag the developed nations in adopting these changes, the cost of these changes can be expected to be better when Article 5 countries are ready to make the change

Depending on the lifetime of refrigeration systems, the retrofit option is part of the refrigerant management plan required to follow the phase-down schedule. Recovery and recycling of existing refrigerants represent a strong option in order to smooth the transition from present day refrigerants to a series of lower GWP options.

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Chapter 5

Industrial Systems

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5 Industrial systems

5.1 Introduction

The industrial sector has not changed significantly since the publication of the last RTOC report (UNEP, 2011). Ammonia continues to be the preferred solution in most markets and new development refrigerants have not gained a significant market share in this period. There have been several major accidents involving R-717 in article 5 countries since the last report, resulting in multiple fatalities. These events have emphasised the need for system design to conform to recognised safety standards as these levels of fatality are unprecedented in traditional market sectors using ammonia and they have increased the emphasis on the education of technicians and engineers. In all cases the accidents would have been avoided if current international safety standards had been followed.

The chapter has been expanded to include more information on process cooling, industrial air-conditioning and heat pumps. Several examples from different regions including many article 5 countries have been added. The ozone depletion potential (ODP) and global warming potential (GWP) values of the refrigerants mentioned in this chapter are given in chapter 2 of this report.

Industrial systems are characterised primarily by the size of the equipment (physical size and heat transfer capability) and the temperature range covered by the sector. This chapter includes discussion on Industrial Heat Pumps (heating systems similar in scale and application to Industrial Refrigeration systems) and Industrial Air-Conditioning (systems for controlling air temperature in production factories, computer centres and other process areas). In addition to size of installation the distinguishing traits of Industrial Air-Conditioning systems are that the cooling is not purely for human comfort, the load is not primarily seasonal and the operation of the facility would be jeopardised by failure of the cooling equipment. Such systems are sometimes called “Mission Critical” and have special design requirements, including the need for uninterrupted service, which are not typically provided by traditional HVAC practices (ASHRAE, 2009). Large chillers used for air cooling in offices, hotels, convention centres and similar installations are not covered by this chapter. Detailed information on those systems will be found in chapter 9 on chillers. A brief overview of the use of HFCs in Rankine cycle electrical generation is also given.

5.1.1 Background

Thirty years ago chlorofluorocarbons were widely used in the industrial sector in many European countries, particularly blends, such as R-502. The particular advantage of these substances was their low index of compression which permitted single stage operation over a wider pressure ratio than could be achieved with R-717 or even HCFC-22. Other countries, notably the United States and Canada had not moved away from R-717 to the same extent as some European countries. In the heat pump sector CFC-12, which has a critical temperature of 112°C, was common for systems of all sizes. It is now replaced by HFC-134a for temperatures up to about 75°C. R-717 is also used in some large systems up to about 85°C. For higher temperatures up to about 120°C, and for ORC's, the market is still limited, but HFC-245fa is being used. Industrial Air-Conditioning was less common at that time, and tended to use standard chillers with CFC refrigerants. The move away from CFCs in the late 1980s prompted by the Montreal Protocol presented particular problems in the industrial sector because the replacement fluids with lower or no ozone depleting potential were not as suitable over the wide operating range required. In some places this resulted in a swift return to R-717 technology, for example in the United Kingdom (Brown, 1992). In other countries the re-adoption of R-717 was more widely resisted and the adoption of low ODP refrigerants was coupled with widespread use of secondary refrigerant systems. For example R-502 had been common in Japan. The industrial sector there responded to its removal by the development of compact, low charge R-717 systems and the use of secondary systems with a limited charge of the more expensive HFC fluids (Kawamura, 2009). In Article 5 countries where R-717 was already used for refrigeration these systems were retained and extended (Tarlea, 2013) (Gulanikar, 2013), but the designs used tended to be old-fashioned and not as efficient or safe as the new Japanese or European innovations. In countries with no history of R-717 use, or with no support infrastructure the solution was often to use large numbers of smaller light commercial systems to satisfy a large cooling load (Pietrzak, 2011). This is expensive to install and maintain, and it is also much less efficient in operation.

5.1.2 Efficiency and sustainability

With increased emphasis on climate change in recent years the importance of energy efficiency is now far greater than before. This has led to a reappraisal of previous policies, for example in the growing trend for central systems with R-717 rather than multiple commercial systems with HCFCs. There is also a greater focus on integration of industrial heating and cooling systems to make better use of waste heat recovery (Pearson, 2011).

In Europe regulation on the use of fluorinated gases has also encouraged users to consider R-717 and other developments such as the use of R-744 in cascade systems, similar to those shown in Figure 4-4. The motivation seems to be primarily based on concern about possible restrictions on HFCs rather than the immediate effect of the current rules (CGF, 2010), which are mainly aimed at commercial and mobile air-conditioning. In the industrial sector it is likely that the adoption of R-717 and R-744 by users who previously deployed HCFC-22 and HFC blends will reduce the energy-related global warming potential through increased efficiency as well as eliminating the direct global warming potential caused by refrigerant leakage. Further discussion of sustainable manufacture is provided in chapter 11.

5.1.3 Refrigeration

Industrial Refrigeration systems are characterised by heat extraction rates in the range 100 kW to 10 MW, typically at evaporating temperatures from –50°C to +20°C. There is some overlap at the lower end of the capacity scale with commercial refrigeration for shops, restaurants and institutions: industrial systems in this sub-sector are characterised by the complexity of the design and the nature of the installation. The size of the industrial refrigeration market is difficult to assess because it covers such a broad range of applications. Some useful insights can be gained from consideration of the market for evaporative condensers, as they are used for heat rejection in the majority of large installations. Data for 2009 was analysed for three global regions; Europe / Russia, North America and India / China. It is assumed that the value of the condenser accounts for 5% of the selling price of the refrigeration system – analysis of a wide range of projects showed that the value of the condenser was in the range 3% - 7% of the total refrigeration contract value.

Table 5-1: Estimated market value (2009) for large industrial refrigeration installations

	Total Condenser Sales (US$m)	**Estimated Total Market (US$m)**	**Proportion of R-717 use**
Europe/Russia	42	830	90%
North America	77	1,500	95%
India/China	45	900	90%

Evaporative condenser manufacturers also report that 90% of the condensers sold in Europe, Russia, India and China are for R-717 systems. In North America the proportion is even higher, at 95%. The balance that is used concerns HCFC-22, R-404A, R-507A or occasionally HFC-134a. The results are shown in Table 5-1.

Smaller industrial systems more often use air-cooled condensers, and in these cases the refrigerant is more likely to be a fluorocarbon, although air-cooled condensers with stainless steel tubes are used in smaller R-717 systems. Table 5-2 shows the estimated value of the refrigeration market for the same regions with the split between R-717, HCFC-22 and HFCs. It should be noted however that there may be significant variations within the regions from country to country or state to state due to legislation or tradition. For example the use of R-717 in small industrial systems is quite common in Germany, but not in France, and is virtually unknown in Canada and some states in the USA, such as New Jersey. Typically if HCFC-22 is still permitted, for example in Article 5 countries, it will be used for these smaller systems. If ozone depleting substances have already been prohibited then the likely refrigerants will be R-404A and R-507A for low temperature systems and HFC-134a for high temperature systems. Experience of accelerated ODS phase out in Europe showed that HCFC-22 systems continue to be deployed right up to the phase-out deadline. The same pattern of behaviour has been observed more recently in the United States which followed the Montreal Protocol phase-out schedule.

Table 5-2: Estimated 2008 market value for small industrial refrigeration installations

	Estimated Total Market (US$m)	Proportion of R-717 use	Proportion of HCFC-22 use	Proportion of HFC use
Europe/Russia	200	25%	10%	65%
North America	300	10%	60%	30%
India/China	500	5%	90%	5%

This table shows that the transition in smaller industrial systems when HCFC-22 is removed is mainly to HFC blends. For Article 5 countries it is possible that a different pattern will emerge. Concern about a possible “phase-down” of HFCs and associated price increases might result in a switch directly from HCFC-22 to R-717 for larger new systems provided trained staff are available and the inherent fear of R-717 is overcome. In many ways this is simpler than switching to HFCs and then to R-717 at a later date. For example the traditional lubricants used with HCFC-22 can also be used with R-717, whereas alternatives (typically polyol ester) are required for HFCs and are not compatible with R-717. The use of R-717 as a replacement for HCFC-22 for small capacity systems will only be feasible if technician training is prioritised and system designs incorporate low refrigerant charge. Uptake of R-717 in smaller systems would also be helped by the development of reliable semi-hermetic compressors suitable for R-717.

In the Middle East, Saudi Arabia and Egypt have a relatively large bank of refrigerants in industrial refrigeration applications. Saudi Arabia has an estimated bank of HCFC-22 of about 2,500 tonnes, in 2008. This constitutes 80% of the total refrigerant bank in Saudi Arabia for industrial refrigeration applications. The remaining 20% is distributed between R-717, CFCs, R-404A and HFC-134a. The phasing-out of R-502 and the harsh high ambient temperatures in the region for a large part of the year coupled with the scarcity of water have resulted in the use of small capacity air-cooled condensing units operating on HCFC-22 in many industrial systems. R-717 systems are few and are used for large applications such as food processing plants, large cold stores and large industrial cooling processes. CFC refrigeration systems are still in operation although most are near the end of their operational life and need to be replaced.

In Southern Africa almost all large systems use R-717 and although R-744 has been trialled in some supermarkets it has not been used in industrial applications. In smaller industrial systems HCFC-22 is almost universally used, and the most common alternative is R-404A.

5.1.4 Heat pumps

The industrial heat pumps sector is growing quickly because it addresses several sustainability issues simultaneously: energy savings, reduction of GHG emissions and increased use of renewable energy. Industrial heat pump systems have heat delivery rates from 100 kW to over 100 MW, with the heat source usually at ambient temperature or the waste heat temperature of an industrial process. These systems are usually required to deliver higher temperatures than domestic or commercial heat pumps used for space or water heating as described in chapters 8 and 9. Typical temperatures are in the range 60°C to 90°C, although if the recovered heat is to be used for steam raising then it needs to be at least 120°C. Heat recovered from large industrial systems is usually transferred to water or a heat transfer fluid and used for process heating or for supply to district heating systems. Direct heating of air from large systems is unusual because of the large volume of air that would be involved.

There is no single component of the system that can be identified and tracked to give an indication of the overall market size, because the compressors could equally be used in other industrial systems and the condenser will be a bespoke design suited to the heating application – most probably a fluid heater such as a plate and frame heat exchanger or shell and tube pressure vessel. The market is probably around 5% of the industrial refrigeration market in Europe, and less in North America, India and China.

5.1.5 Air conditioning

Industrial air-conditioning systems cannot be differentiated from commercial systems on size alone, as many commercial office buildings have large cooling loads. An industrial system requires a higher level of reliability and is subject to year-round high loads. These systems may provide human comfort in highly populated areas with large heat loads, for example in trader rooms or dealer floors with a lot of computing equipment. Other industrial air-conditioning systems are primarily required to maintain acceptable processing conditions for equipment such as computer servers in data centres. In some cases the mission-critical part of a total cooling load may be supplied in conjunction with a comfort cooling system, configured so that, in the event of partial failure of the system, the mission-critical cooling is maintained at the expense of the comfort of the occupants of the rest of the building. Often the chillers used for industrial air-conditioning are the same type as described in Chapter 9 – the market information and options for future change are described there. However many other industrial systems are custom designed for the application.

5.1.6 Rankine cycle

A further use of HFCs not covered elsewhere in this report is in a closed evaporation and condensation cycle for the generation of electrical power (or other useful work) from the expansion of high pressure gas. The basic system, called the Rankine cycle, is similar to the process used for power generation in steam turbines, but operates at lower temperatures (dependent on the working fluid properties) and so can make use of heat from geothermal sources or rejected from industrial processes. When HFCs are used as the working fluid these systems are called Organic Rankine Cycles (ORC) (Zyhowski, 2003). The Rankine cycle uses heat to evaporate the working fluid at relatively high pressure. The resultant gas is passed through an expansion engine which does useful work, usually driving an alternator to produce electrical power. The low pressure gas at the expander outlet is condensed, usually by rejecting heat to atmosphere in a cooling tower, and the resultant liquid is pumped up to evaporating pressure by a liquid pump. The conversion rate from thermal to electrical power varies with the pressure differences and the expansion engine efficiency, but typically is between 10% and 15%, including the electrical power required to drive fans and pumps in the system (Leslie, 2009).

Some ORC systems use HFC-134a as the working fluid. It has the advantage of being relatively cheap and available, but has a low critical temperature and so cannot take full advantage of higher temperature heat sources. Other systems use HFC-245fa or HFC-236fa, which have significantly higher critical temperatures. The GWP of HFC-245fa is approximately 858, whereas for HFC-236fa it is approximately 8060, so it is likely that future commercial systems will be based on HFC-245fa (unless severe restrictions are placed on all high GWP HFCs). A fluorinated ketone, perfluoro-2-methyl-3-pentanone $CF_3CF_2COCF(CF_3)_2$, has been used as an alternative (Brasz, 2008). It has zero ODP and near-zero GWP (Hodnebrog, 2013) but less favourable thermodynamic properties than HFC-245fa. Other new compounds have also recently been proposed, such as R-1336mzz (Z) (Kontomaris, 2014). Rankine cycles have also been produced using R-744 (Persichilli, 2012), R-717 and ammonia-water mixtures as the working fluid, although strictly speaking these cannot be described as "organic". The R-744 power generation systems either operate with the heat input above the critical point (transcritical) or with both heat input and heat output above the critical point (supercritical). The relatively high investment cost and relatively low rate of return mean that these systems are generally limited to use in large process plants, although a few systems have been installed in commercial buildings.

5.2 Applications

5.2.1 Food processing

Refrigeration is used for chilling and freezing food during processing, in order to prolong shelf life, but it can also be used to make handling or processing easier. For example hams are temporarily frozen to enable them to be sliced more thinly. Chilling also plays a part in the pasteurising process where the product is rapidly cooled after heat treatment to minimise spoilage. A wide variety of chilling and freezing techniques are used, including immersion in liquid, air blast freezing in batches or in a continuous process and contact freezing on tables or in blocks between metal plates. The choice of process depends on the form that the product takes, whether it is wrapped or unwrapped, robust or fragile, processed or raw. Some fruits and vegetables such as potatoes, apples and most soft fruit are notoriously difficult to freeze as the expansion of water destroys the cell walls, leading to mushiness when thawed. Other produce, such as peas, corn and beans, can be frozen in very small pieces using a fluidised bed of air to allow each individual piece to freeze without agglomerating.

There is a negative public perception of frozen food, which is that thawed food will always be inferior quality to fresh. In fact if good quality food is frozen professionally immediately after harvest, catch or cooking it should offer increased shelflife and superior quality when thawed. Spoilage rates could be substantially reduced if a greater proportion of food were frozen before shipment. If the public perception of frozen food is improved then there could be a significant increase in this sector of the market. Freezing food requires a lot of heat transfer compared to storage, so refrigeration systems are large capacity and require a large power input although the freezing chamber may be physically quite small. There is a trade-off between the time required to complete freezing and the operating efficiency. Running the system at very low temperature is less efficient but results in a shorter freezing time

Some food processes require careful control of humidity and temperature to ensure product quality and in these cases a cooling system is not enough. Examples include bakeries producing cakes and bread, fruit and vegetable storage and fruit ripening. The rate of fruit ripening is controlled by maintaining low ethylene levels in the atmosphere through the use of high rates of ventilation with fresh air. In periods of high ambient temperature the cooling load for the incoming air can be substantially higher than the product cooling load. Failure of the cooling system would cause the product to ripen too quickly resulting in a large loss of product value before it reached the point of sale. In some cases the air-conditioning system is connected to a central plant cooling system using R-717 or HFCs but in others a custom designed stand alone system in an air-handling unit serves the humidity control requirement.

5.2.2 Cold storage

Cold storage facilities usually operate at two temperature levels, frozen (well below 0^oC) and chilled (above 0^oC). Frozen produce must be stored below -18^oC, and it is usual to maintain the store between -22^oC and -26^oC to provide a factor of safety in the event of major equipment failure. Some products require lower temperatures, for example ice-cream and similar produce is stored between -26^oC and -29^oC, and some niche market products such as some types of sushi must be kept significantly colder, even down to -60^oC, in order to retain product quality. Chilled produce is typically held between 0^oC and 4^oC, although fruit, bakery products and vegetables are stored between 8^oC and 12^oC. Some stores offer long term storage contracts, in order to stock produce until it is "out of season" and therefore more valuable. Stock may be held for months in these warehouses. Other sites provide marshalling facilities in order to restock supermarkets on a daily basis; in these plants the product is not usually in the building for more than 24 hours. The cooling load on such a building is high because of the amount of traffic through the temperature controlled chambers, although product load is typically low because the residence time is not long enough for the air temperature to have any appreciable effect on the product.

5.2.3 Industrial cooling in buildings, power plant and IT centres

Some production processes require tight control of the surrounding temperature, for example microchip production, paint spraying or injection moulding. These loads are relatively constant all year, and production output is affected if the chilling plant is inoperative, so both the reliability and the efficiency of the equipment are more important than for office air conditioning. This can sometimes lead to the specification of uniquely designed site-constructed systems to deliver the cooling in order to provide the high level of reliability required, or to achieve lower energy use. Where heat loads are too high to be handled by air- or water-based cooling systems, for example in some high density data centres and other IT cooling applications, other fluids including R-744 have been used in direct systems (Hutchins, 2005, Solemdal, 2014). Typical loads for these applications may be up to 2 kW per m^2 in comparison to a typical office load of 40 W per m^2.

The industrial cooling load is typically almost entirely "sensible" cooling – reducing the air temperature without reducing the moisture content, in contrast with a typical commercial air conditioning load which is likely to involve more dehumidification, or "latent" cooling. Latent cooling requires lower temperatures to bring the air to its dewpoint. If an industrial cooling load is 100% sensible cooling, or if the cooling can be split into separate systems for sensible and latent cooling, then the operating temperature for the sensible cooling can be raised, making the system more efficient. In these cases it may also be possible to use indirect evaporative cooling to reject some or all of the process heat load.

There is a significant benefit in pre-cooling the inlet air to gas-fired turbines in higher ambient climates. For example reducing the air inlet temperature from 40°C to 8°C will increase capacity by 28% (Kohlenberger, 1995). These systems usually use large chillers with R-22, R-134a or R-717, cooling glycol.

5.2.4 District cooling

In the Middle East since the 1990's district cooling applications have become common with the rapid rate of economic development in the Gulf area. Those applications serve office complexes, shopping malls, airports and call centres (Sarraf, 2012). Because of the high ambient temperatures throughout most of the year, the uninterrupted operation of those systems is “mission critical”. District cooling providers design multiple redundancies in their systems, since stoppage will necessitate vacating those premises incurring heavy fines on the operators.

There is an estimated district cooling installed capacity of about 13.2 GW in the Middle East. The UAE have the largest share of this capacity at about 8.8 GW. Qatar is the second with the single largest district cooling plant with an installed capacity of 420 MW. Saudi Arabia has about 400 MW district cooling capacity and is the fastest growing market. All those systems use vapour compression technology and predominantly HCFC and HFC refrigerants. In Egypt, with an estimated 350 MW total installed capacity of district cooling, natural gas fired absorption chillers are mostly used. Some older district cooling applications in the region still use CFC-11 and CFC-12 but the majority of systems are now HCFC-22, HCFC-123 or HFC-134a.

In the Gulf Cooperation Council countries (GCC), the total cooling demand is expected to triple between 2010 and 2030 (when HCFC are phased-out) reaching approximately 350 GW. This would be the equivalent to 60% additional power generation requirement in the region if the same mix of cooling technologies were used. The additional power generation required for this mix would consume the equivalent of 1.5 million barrels of oil per day so discussions are undergoing to increase the use of district cooling to enable electric power peak shaving and therefore reduce oil consumption for generating electricity. The potential for district cooling in the GCC counties between 2010 and 2030 is over 100 GW, existing capacity in GCC countries is 11.7 GW, and thus an increase of about nine folds of existing capacity is expected. This increase between 2012 and 2030 is divided as shown in Table 5-3 (Olama, 2012)

Table 5-3: Estimated change of district cooling capacity in GCC countries, 2012 - 2030

Kingdom of Saudi Arabia	+44.75GW
United Arab Emirates	+31.12GW
Qatar	+10.18GW
Bahrain	+2.63GW
Kuwait	+10.95GW
Oman	+3.65GW

District cooling systems are not restricted to the extreme tropical climate of the Middle East. Similar systems are installed in the United States serving business districts, hospitals and university campuses, and such systems are becoming more common in Scandinavia where the district heating network makes it easier to incorporate cooling into the existing infrastructure. Helsinki for example has a 120 MW district cooling system (Vartiainen, 2011), which is projected to grow to 280 MW by 2030. Several large systems have been installed in China, including steam-driven absorption. Where absorption chillers are used the district cooling system can be integrated with a combined heat and power plant, using the excess heat from generators to drive the cooling system. In some coastal sites, for example in Hawaii and Mauritius, deep seawater is being considered for district cooling offering a significant reduction in demand on an electrical infrastructure which might already be overloaded.

5.2.5 Industrial heat pumps and heat recovery

Many industrial processes including brewing, dairies, food factories and chemical processes require large amounts of heat in addition to a cooling load. Even if the primary use of heat, for example for cooking food, cannot be achieved by heat pumps or recovery there may be many uses for lower grade heat, such as pre-heating boiler feed water or heating wash water for the production area. When the application is collecting and redirecting waste heat from a refrigerating system it is called heat recovery. When it is performing a non-productive chilling process on a source of heat, whether it is at ambient temperature or is the waste heat stream from another process such as a cooker flue, it is a heat pump.

Large heat pumps have also been used for heating public buildings, for example in Gardermoen Airport, Norway (8100 kW heating capacity) and Akershus hospital, Norway (8000 kW heating capacity). These systems are custom-designed, using R-717 as the refrigerant (Stene, 2008).

Even larger systems are used for district heating systems, with many examples in Scandinavia. The smallest of these systems are about 5 000 kW. Most installations use HFC-134a in centrifugal compressors, with some (up to 15 000 kW) using R-717. The largest is in Stockholm, with a total capacity of 180 000 kW (180 MW) using HFC-134a in centrifugal compressors. This system takes heat from sea water to provide the thermal source; other similar installations have used waste water from the sewage system (Bailer, 2006).

Steam-fired absorption systems (as described in section 5.3.6) can be used to raise condenser water temperature in power plants to provide heat to district heating networks and some industrial processes. Absorption can also be used to boost the temperature of a proportion of a medium temperature process stream by cooling the remainder of the stream. In this way a small part of a stream at 70°C could be raised to 120°C by cooling the rest of the stream and rejecting its heat to atmosphere at, say, 35°C.

5.2.6 Leisure

The principal use of refrigeration in the leisure market is for ice rinks, extended also to indoor ski-slopes, ice climbing walls and other ice features. Many older ice rink systems used direct CFC-12 or direct R-717. To change to an indirect system would require replacement of the floor slab, which is a considerable capital expenditure. Some CFC-12 systems have been converted to HCFC-22 despite the increased pressure. Similarly some R-717 systems in Central Europe have been converted to R-744. A few very large systems have been installed for bobsled and luge runs, typically associated with winter Olympics. These systems usually use pumped R-717. A recently installed cross-country ski track in Finland used R-744 for the track cooling, with circuits up to 1 km long.

5.2.7 Process Refrigeration

Cooling is used in a wide variety of process applications (in addition to food industry applications covered in section 5.2.1). The cooling can be applied by a direct refrigeration system with a coil in the process tank, or a jacket around the outside of a chemical reactor vessel or storage tank. Alternatively, a secondary fluid such as water, brine solution or glycol may be used. In these cases standard chillers as described in chapter 9 might be used, although there may still be other reasons for requiring the chiller to be specially designed for the project, for example location of the equipment within a hazardous area.

In refineries refrigeration is used to remove light hydrocarbons from the process stream. Such systems can be extremely large and may use HCFC or HFC in centrifugal chillers. It is also possible to use the feedstock, particularly ethylene or propylene as the refrigerant, either in a closed-loop system or as part of the process flow. In very large systems, the use of HFC-134a enables centrifugal compressors to be used whereas ethylene typically requires screw compressors, which, at that size, are significantly more expensive.

Some specialist processes including plastic forming, paper milling and precision machining require multiple small capacity systems and are typically constructed on site using HCFC or HFC. The use of multiple flexible hoses to connect to the moving parts of these machines presents a particular challenge due to high refrigerant leak rates.

Where processes produce high grade waste heat, for example flue gases from glass production, power stations, steel mills, incinerators or cement factories, the heat can be used to drive absorption chillers, either directly or by raising steam which is fed to the chiller. Such systems require to be tailored to the application to ensure that the heat production and cooling demand are well matched.

The cooling of deep mines presents another challenge because the operating conditions are arduous and the available space is severely constrained. Typical systems used centrifugal chillers underground. An alternative to the use of CFC-12 or HCFC-123 in centrifugal chillers was to produce cooling at the surface, either as cooled ventilation air or as chilled water or ice. However the depth to which surface cooling is effective is limited and for mines deeper than about 2,000m some form of underground cooling is required to counter the effects of air compression and the power required to transport the cooling effect from the surface to the workface. There is currently no acceptable alternative to HCFC-123 for underground applications to a depth of up to 4,500m (Calm, 2011). Some of the new fluid blends currently under development for other applications (see for example chapter 2, chapter 4 and chapter 9) may also be suitable for this application but it is unlikely that a fluid will be developed solely for this use.

5.3 Options for new equipment

Where its use is still permitted in new systems, particularly in article 5 countries, HCFC-22 is still common as an alternative to R-502. It has not been supplanted by HFC blends because it is cheaper than any of the blends and usually offers better system efficiencies. The most common alternative to HCFC-22 as a replacement for R-502 in new systems is R-404A, although it has a significantly higher global warming potential and is less efficient.

5.3.1 R-717 (Ammonia)

The analysis of evaporative condenser use shown in Table 5-1 indicates that R-717 is by far the most common refrigerant used in industrial systems. The major hazard presented by R-717 is its acute toxicity, although its pungent odour ensures that low, relatively harmless concentrations are obvious and provide an early warning of danger.

R-717 is flammable in relatively high concentrations, but it is difficult to ignite and as a result R-717 conflagrations are extremely rare. The products of combustion are nitrogen and water, so there are no toxic consequences. The lower flammable limit is 16%; about 5,000 times higher than the short term exposure limit, and almost 50,000 times higher than the lowest level which can be detected by smell.

R-717 systems can be designed for very high efficiency, particularly with higher condensing temperatures, so in recent years it has been used more often in smaller systems with air cooled condensers, condensing at about 50 °C (IIR, 2008). Compression of R-717 produces relatively high compressor discharge temperatures compared with most fluorocarbons, but if oil injected screw compressors are used then the heat of compression can be removed by oil cooling. R-717 also produces relatively high heat transfer coefficients and requires a low massflow due to its high latent heat. The high critical temperature of 133°C makes R-717 very suitable for high temperature heat pumps. It is at atmospheric pressure at -33°C, a relatively high temperature for industrial freezers. This means that many freezers operate at sub-atmospheric pressure, so air and moisture are drawn into the system if it is not pressure-tight on the low pressure side. This unfortunate consequence is generally tolerated because the moisture is soluble in ammonia liquid so does not immediately cause unreliability and because both air and water can be relatively easily removed from the system while it is in operation. However excessive water build up will eventually impair operating efficiency and therefore increase electrical consumption, so system contamination should not be left uncorrected (Nielsen, 2000).

5.3.2 Hydrofluorocarbons

When the first HFC refrigerants, particularly HFC-134a, were introduced in the late 1980s to replace CFC-12 there was no obvious successor to the most common CFC blend in the industrial market, R-502. This had been introduced to enable single stage compression plants to be used for low temperature applications without excessive discharge temperatures. When it became clear that R-502 could no longer be used, because it contained CFC-115, most system designers either used HCFC-22 or R-717, both of which produced higher discharge temperatures and therefore required additional cooling or two compression stages for freezer applications.

Saturated: Saturated hydrofluorocarbons include fluids such as HFC-134a and HFC-125 and blends of fluids, mixed to provide specific advantages for particular applications. HFC-134a is used in small high temperature systems; it is at atmospheric pressure at -26^{o}C, and it requires larger compressors than R-717. Sub-atmospheric operation is less common with HFCs because traces of moisture are liable to freeze and block the expansion valve.

HFC-134a is also widely used in centrifugal compressors, including some very large systems used for district heating. A trial system using unsaturated HFC-1234ze(E) as an alternative to HFC-134a in district heating has been tested in Norway (Nørstebø, 2013).

There is no single fluid alternative to HCFC-22 for use in industrial systems. HFC-125 has approximately the right pressure temperature relationship, but has an extremely low critical temperature of 66^{o}C, and would therefore be extremely inefficient if used in industrial systems, unless the condensing temperature was very low. It is used as a component of several of the most popular blended refrigerants, where the deficiencies in its physical properties can be offset by careful selection of the other components of the blend. The most common blends used in the industrial sector are R-404A and R-507A, which are primarily mixtures of HFC-125 and HFC-143a; with the latter providing a higher critical temperature and hence improved efficiency. Many industrial systems use flooded evaporators, where the refrigerant boils in a pool. Zeotropic blends (with a temperature glide during evaporation) are not suitable in these systems because the blend components may fractionate, so R-407C and service replacement blends such as R-417A have not been much used in the industrial sector.

It is surprising that R-410A has not been more widely used in industrial systems because it has a low boiling point at atmospheric pressure (-51.4 ^{o}C), very low glide (less than 0.2K at -40 ^{o}C) and the critical temperature is almost the same as R-404A. The compressor swept volume required for R-410A is about 30% less than for R-404A, so equipment costs, including installed pipework should be less, although operating pressures are higher. The main barrier to its use is the high price of the refrigerant, particularly compared to R-717 and R-744. When the refrigerant inventory in a system is in tonnes the cost of the charge may be a significant part of the total cost of the installation. Typical installations are therefore low capacity, low temperature, for example blood freezing and small pharmaceutical systems. The introduction of rules and guidance for the use of flammability class 2L refrigerants (those that have a burning velocity less than 10 cm s^{-1} and therefore do not explode) might result in an increase in the use of HFC-32 as an alternative to R-717 in industrial systems.

Unsaturated: unsaturated hydrofluorocarbons such as HFC-1234yf and HFC-1243ze have not to date been used in industrial systems. The low global warming potential may give the impression that they could be a suitable alternative to R-717 and R-744, but it is very likely that they will be even more expensive than R-410A, with the further disadvantage of being flammable. It is therefore likely that none of this family of chemicals will achieve any significant market penetration in the industrial sector, even if blended with other compounds to reduce price or flammability. An exception may be found with centrifugal compressors for industrial chillers and heat pumps where HFC-1234ze(E) might provide an alternative to HFC-134a (Nørstebø, 2013). The unsaturated HFC-1336mzz(Z) and the unsaturated HCFC-1233zd(E) may also prove to be suitable in heat pumps with centrifugal compressors, particularly in very large systems.

5.3.3 Hydrocarbons

Hydrocarbons are not widely used in industrial refrigeration except where additional safety measures to ensure that leaking refrigerant cannot be ignited are required anyway, for example 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 R-717 systems, although the whole system cost may be comparable. HC- 290 is generally similar in performance to HCFC-22 and R-717 in terms of operating temperatures and pressures, and requires similarly sized compressors.

5.3.4 R-744 (Carbon dioxide)

R-744 cannot be used in exactly the same way as other industrial refrigerants. It needs to be coupled with a higher temperature refrigerant in a cascade system due to the low critical temperature of 31^{o}C or else used in a transcritical system. Transcritical systems have been used in commercial and small systems, but there are no compressors on the market to provide the necessary high operating pressures to run an industrial R-744 system in this way. A medium-sized distribution centre with an installed capacity of 1500kW has been operating in Denmark since 2008, using multiple commercial-sized compressors (Madsen, 2009).

R-744 is particularly suitable for use in freezer systems because it is liquid at positive pressure down to -56^{o}C and the gas is extremely dense, giving very high rates of heat transfer. The pressure drop characteristics are also very favourable at low temperatures, so R-744 freezer systems have been found to be significantly more efficient than any other alternative, even R-717 (Pearson, 2009). In slightly higher temperature applications, such as cold storage, R-744 cascade systems are likely to be slightly less efficient than two-stage R-717, but still on a par with a single stage economised system, and more efficient than any system using a secondary fluid due to the much lower pumping cost for R-744 compared to glycol, brine or other heat transfer fluids (ASHRAE, 2010).

In Article 5 countries, Saudi Arabia has one cold store application where a cascade system utilises R-744/R-717.

In higher temperature applications, for example IT cooling, R-744 is attractive as an alternative to chilled water because it is electrically non-conductive, does not cause fabric damage in the event of a small leak and enables smaller heat exchangers to be used. The major challenge in these systems is that the operating pressure is approximately 50 bar.

5.3.5 R-718 (Water)

In general R-718 is not suitable for most industrial applications because the triple point is very slightly above 0^{o}C, and because, despite the very high latent heat, the swept volume required for a typical cooling duty is extremely high. There are a few notable exceptions: R-718 has been used for a few deep mine cooling projects where a vacuum system is used to create a mix of solid and liquid water (ice slurry) at the triple point. Similar systems have been used for large plastics moulding coolers, but these systems have not yet been fully commercialised.

5.3.6 Absorption

Absorption systems using aqua-ammonia can be used for low temperature applications, easily reaching cold storage temperatures. This is because the ammonia is used as the refrigerant, with water as the absorbent. Water-lithium bromide (LiBr) systems can only be used above freezing because the water is the refrigerant, and the LiBr is the absorbent. Absorption systems are only effective if there is an abundant source of heat at high temperature to drive the system. It is not normally economic to burn fossil fuel for the sole purpose of driving the regenerator of an absorption system, particularly in low temperature systems, because the heat rejection plant is significantly larger than for an equivalent duty, electrically driven vapour compression system.

Absorption systems are primarily used for process cooling in food, beverage, chemical and pharmaceutical plants where waste heat to drive the system is readily available. Countries with a shortage or unreliable electric supply use direct fired chillers in industrial cooling. Examples are in India, Pakistan, Bangladesh and China. Those units are generally fuel oil fired or gas fired. There is an increase in the food industry, when local on-site power generation is used, and provides a source of waste heat. This has been particularly noted in developing countries such as India and China, where increased food production is being achieved but the electrical infrastructure is still relatively unreliable. In these cases chilling is normally achieved with a vapour compression plant, but with some absorption cooling available to augment the cooling capacity when the generator is running. In countries where natural gas downstream piping infrastructure exist and where gas prices are reasonable compared to electricity, direct fired chillers are used to produce chilled water for industrial applications. Those are normally double effect units.

Indirect fired absorption units are used primarily in applications where excess boiler capacity is available in summer months and where steam or hot water are generated by a co-generation application. Those units are normally single effect and are fired at water or steam temperatures of 90 °C to 120 °C. The efficiency of those units is compared to those of vapour absorption in chapter 9. The Lithium Bromide-water chillers are all water cooled.

5.4 Options for existing equipment

Systems using HCFC-22 have been converted to zero ODP refrigerants, but it is difficult to replicate the operating conditions of HCFC-22 and so conversions often involve an element of equipment replacement. Before committing to any large scale retrofit project consideration should be given to the age of the plant, the cost of replacement with a modern, more efficient system and the risks to continued operation of retrofit.

5.4.1 Conversion to HFC blends

There are numerous blends for the replacement of HCFC-22 in DX (superheat controlled) systems, but there is none that replicates the pressure temperature relationship of HCFC-22 without significant glide, and so these blends are much less common in flooded systems where fractionation of the blend is a concern. Where industrial systems are converted to a blend it may also be necessary to change from mineral or alkyl benzene lubricant to a synthetic ester. Some blends are formulated with hydrocarbons in the mix so that, although still non-flammable, the lubricant is more miscible and less likely to accumulate in the evaporator of the system. For a large flooded system it might be appropriate to convert the compressors and condensers to an HFC blend, but convert the low pressure side to a secondary fluid, or even R-744 as a volatile secondary. Retrofitting of HCFC-22 plant in Article 5 countries is very uncommon to date.

5.4.2 Conversion to R-744

The high operating pressure of R-744 systems makes it highly unlikely that an existing HCFC-22 system could be converted to operate on R-744. Conversion to a cascade system is possible, greatly reducing the inventory of fluorocarbon refrigerant in the system. It may even be possible to reuse the low pressure pipework and evaporators in the system if they are suitably rated. A cold storage or freezing system operating as a cascade on R-744 could be limited to an allowable pressure of 25 bar gauge, however this is a complex retrofit and it may well be more economic to replace the whole plant, especially if it is already more than ten years old.

5.4.3 Conversion to R-717

In a very few cases a pumped HCFC-22 plant has been converted to R-717 (Jensen, 1996). In some cases the compressors and evaporative condensers are suitable for either refrigerant, and pipework is probably welded steel in large applications. If the evaporators are copper tube then they need to be replaced. It is imperative that the system is carefully cleaned during the conversion because any residual traces of HCFC-22, for example in lubricant will react with R-717 to produce a solid foam which can block all the internal components. Triple evacuation with nitrogen purging is probably necessary – this is time-consuming and expensive and again plant replacement should be considered. In the majority of cases, in all countries, equipment using HCFC-22 is not suitable for this conversion.

5.4.4 Conversion to hydrocarbon

Unlike R-744 and R-717 it is technically feasible to remove HCFC-22 from existing systems and replace it with HC-290, however it is highly likely that the resultant system will not comply with safety codes on the use of hydrocarbons because the refrigerant quantity will not comply with charge restrictions and the electrical infrastructure will not be suitably protected. A conversion of this type is believed to have been responsible for a fatal accident in New Zealand in 2008 (NZFS, 2008). A consequence of rapid phase out of HCFCs in Article 5 countries might be an increase of this type of conversion without adequate controls. There is however a case for a controlled conversion from HCFC-22 to HC refrigerant (HC-290 or HC-1270) where the system efficiency can be improved. In this case it is essential that suitable safety measures are ensured.

5.5 Service requirements

Given the difficulty of converting from HCFC-22 to zero ODP refrigerants, many users with multiple systems have planned a replacement strategy to conserve their stock of refrigerant. Setting priorities for which system to replace or convert first includes consideration of age of the plant, likelihood of leakage and ease of conversion. Refrigerant which is recovered from converted systems can be recycled and stored on site to be used in the remaining plants. In Europe, where service with "virgin" HCFC-22 was prohibited from the beginning of 2010, some users have banked additional refrigerant by overcharging their plants with new HCFC-22 prior to the end of 2009 and then recovering the excess refrigerant, which is then classed as recycled. This practice is not strictly outside the law, but it is not in the spirit of the regulation. It probably accounted for some additional sales of HCFC in the two years leading up to the prohibition, keeping sales artificially high at a time when many plants were being converted or decommissioned. If other regions implement similar regulations for the phase out of HCFCs they should consider ways to plug this loophole, for example by limiting the time that recovered HCFC can be stored before it is used, and requiring it to be sent for destruction or reprocessing if it is not used within the timeframe. This was done in Ireland, and greatly improved the effectiveness of the restriction on virgin HCFC-22.

5.6 Concluding remarks

The majority of large industrial systems in some parts of the world use R-717 as the refrigerant. When R-717 is not acceptable in direct systems in these countries, options include R-744 or glycol in secondary systems or HCFCs or HFCs in direct systems. In countries where R-717 has not been the preferred solution, or in market segments with smaller systems, the transition from HCFC-22 is not straightforward. It requires acceptance of higher cost fluorocarbons in systems similar to the types used with HCFC-22 or the adoption of more expensive systems with the cheaper refrigerants R-717 and R-744. This transition is slow and is constrained by a lack of trained personnel and lack of experience of the local end-users. It has been facilitated by corporate policy from multinational food and beverage manufacturers exemplified by the policy statement from the Consumer Goods Forum (CGF, 2010).

The industrial sectors covered by this chapter are too diverse to facilitate the level of development expenditure required to bring a new fluid to market. It therefore follows that if any new development gains market share in industrial systems it will be a fluid developed for some other purpose, either as a refrigerant in smaller mass-market systems or as a foam-blowing agent, solvent or other specialty chemical. Apart from absorption systems there is no significant growth of other not-in-kind cooling or heating solutions.

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Chapter 6

Transport Refrigeration

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6 Transport refrigeration

6.1 Introduction

Transport refrigeration is a small but vital segment comprising delivery of chilled or frozen products by means of trucks, trailers, vans, intermodal containers and boxes. It also includes the use of refrigeration and air conditioning on merchant, naval and fishing vessels above 100 gross tonnes (GT) (over about 24 m in length).

Most development has taken place in the intermodal container industry since 2010. Although many of the lessons are applicable to road transport, differences between containers and road vehicles should not be neglected, and may lead to different system solutions and (possibly) to different refrigerant choices. The three top candidates in the container industry are R-744, hydrocarbons and low-GWP HFCs.

In contrast to the 2010 report, more insight is provided on eutectic and cryogenic systems which may be attractive for some types of transport routes. Porthole container ships, which do not exist any longer, are omitted, as are dedicated railway systems where trailer units or intermodal containers units are now utilized. The niche segment of airfreight containers is added.

New information about vessels in terms of type and refrigerant charge is provided based on the 2012 IMO study. It appears that the differences in type are large and segmentation is needed in the future. Analyses on refrigerant options are limited in this chapter, and the reader is advised to consult the chapters dealing with industrial and air-conditioning systems.

Based on research, the road vehicle fleet size previously estimated at 4 million in the 2006 and 2010 RTOC Reports has been downsized to 2 million. This changes the overall picture in that the refrigerant banks in vessels almost double the banks in other transport sub-segments.

While CFCs and HCFCs can be found in older equipment, virtually all new transport refrigeration systems continue to utilize HFCs, with a prevalence of HFC-134a and R-404A. Some systems aboard vessels utilize HCFC-22 in both non-Article 5 and Article 5 countries. R-717 and R-744 systems are being installed on fishing vessels.

Appendix A contains a general overview and technical progress information, further, the ozone depletion potential (ODP) and global warming potential (GWP) values of the refrigerants discussed in this chapter are given in chapter 2 of this report.

6.2 Options for new equipment

6.2.1 Intermodal containers and road vehicles

6.2.1.1 Hydrocarbons

While hydrocarbons offer superior thermodynamic properties which lead to high energy efficiencies, the possible leakage of the refrigerant inside the box and other failure scenarios present a safety challenge, since these refrigerants are flammable.

Due to the lack of specific safety standards applicable to transport refrigeration, the design usually relies on safety standards for adjacent applications, such as ISO 5149 (ISO, 2014a) or EN 378 (2008). For example, according to the scope, ISO 5149 (ISO, 2014a) covers transport refrigeration but the detailed safe design and operation for all the mentioned applications are not described (König, 2013a). Most standards rely on the concept of “lower flammability limit” combined with a maximum charge and safety factor. In a traditional concept of a transport refrigeration unit, even assuming a significant charge reduction compared to today’s typical charge levels, leakage inside the box would inevitably lead to concentrations above the flammability limit.

The use of higher amounts of refrigerant charge over the thresholds established by the existing standards would require the adoption of provisions covering safe system design and safe operations. These higher amounts can be permitted only when special measures are taken to limit the refrigerant concentrations in case of leakage and the presence of sources of ignition. To justify such special measures, a risk analysis shall be performed to include all foreseeable uses (König, 2013a). All this may increase complexity and may introduce an additional risk that manufacturers must consider.

Measures can include ventilation and shut-off valves, combined with refrigerant detectors and alarm systems. Ventilation may be realized using explosion-proof fans, sensors, etc. Or, as alternative, the flammable refrigerant maybe isolated in a separate circuit and placed outside of the cargo box. A secondary fluid can be used to provide cooling inside the cargo box. The above measures either do not eliminate completely the flammability risk, or make the system very complex, or increase power consumption.

Refrigeration units with direct expansion using HC-290 and HC-1270 have been tested to date in a small number of trucks in the UK and Germany. One European manufacturer has developed a road vehicle system operating on HC-1270, the safety issues being addressed by having a jointless evaporator and installing a detection system. However, this unit is not commercially available. One intermodal container manufacturer (MCI, 2014) announced a possible market introduction of a refrigeration system with HC's in 2018-19 subject to the boundaries of future legislation.

In summary, specific research on the use of flammable refrigerants in transport refrigeration should continue but (as it is the case today) their use would most likely require the implementation of safety measures that could increase the complexity of the system and/or, in case of indirect system, could penalize their efficiency.

6.2.1.2 R-744

R-744 is a promising alternative to HFC refrigerants and its widespread use in transport refrigeration will only come when systems using R-744 can exhibit efficiencies comparable to the efficiencies that are obtained at present from systems using HFC refrigerants.

R-744 is undergoing a renaissance and the technology and learning curve in transport refrigeration is at an early stage. All major manufacturers have displayed concepts of units with R-744 at trade shows or have demonstrated an interest in R-744 solutions through research publications. One manufacturer has been testing an intermodal container unit with customers across the globe, and is now offering the unit. Since 2013, a supermarket chain in the UK has been conducting a trial with an urban distribution trailer fitted with a modified version of the intermodal container system.

The annual energy consumption and the efficiency depends on the ambient air temperature and the cargo box air temperature (refer to appendix A 4.1 for details). Systems using R-744 are more efficient than systems using HFC refrigerants under low-medium ambient temperature conditions. At the same ambient temperature, systems using R-744 are more efficient for chilled cargo and less efficient for frozen cargo than systems using HFC refrigerants.

Literature mainly published for commercial refrigeration and mobile air conditioning application (see Table 6-1) show "crossover temperatures" (= ambient temperatures below which R-744 is more efficient) ranging between 21°C and 40°C. Data for transport refrigeration is limited.

Table 6-1: Crossover temperature with regard to energy consumption/efficiency

Source	**Segment**	**Baseline Refrigerant**	**Tevap, °C**	**Tcrossover, °C**
Shimada, 2011	Commercial refrigeration	R-404A	5	32
			-25	38 to 40
Finckh, 2011	Commercial refrigeration	R-404A	-5 to -7	21 to 26
Hrnjak, 2013	Mobile air conditioning (Summary of SAE MAC program)	HFC-134a	about 5	25 (on the road) 35 (idling)
Möhlenkamp, 2014	Transport refrigeration	R-410A	-20	25 to 40 comparable

Figure 6-1 shows a comparison between the R-744 reefer container unit and the incumbent HFC-134a unit (with comparable technology level) in terms of efficiency. Data was provided from a large manufacturer. Based on typical total cost of ownership of models used in the industry, approx. 15% of the time is estimated to be spent in full load conditions, moderate - high ambient (an ambient temperature of 38 °C is normally used to represent this condition), while an estimate 85% of the time is spent at medium-low ambient, part load (an ambient temperature of 25 °C). The results show a disadvantage of R-744 at the 38 °C full load point, but an advantage at the 25 °C ambient point, with chilled cargo and in part load conditions.

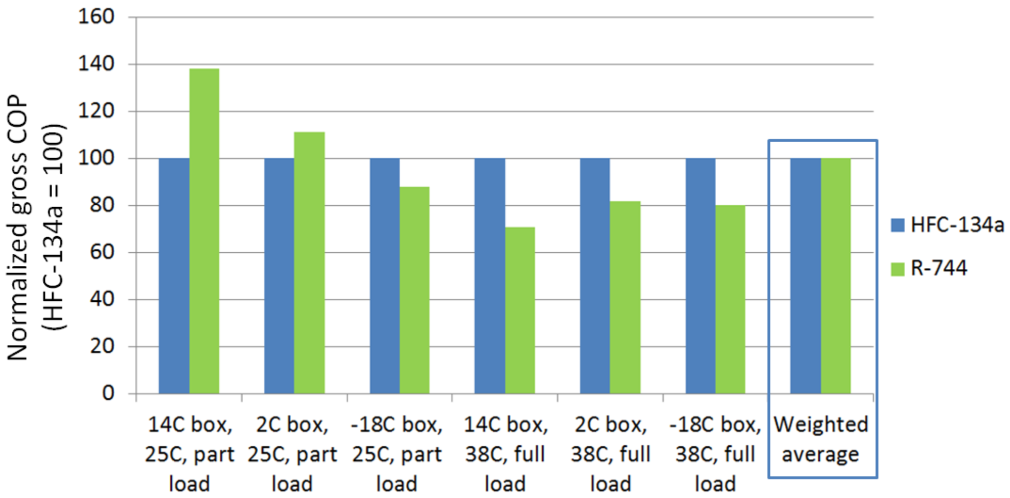

Figure 6-1: Container refrigeration, comparison between HFC-134a and R-744 for typical test conditions.

Note 1: The two systems have different optimization logic (the R-744 system is mostly optimized for part load conditions, not full load conditions).
Note 2: At -18°C box temperature, the R-744 system has tighter air temperature control than the HFC-134a one.

R-744 in general requires dual stage compression. R-744 open shaft compressors have technological challenges in the transport refrigeration pressure range, and are not available today. On the other hand, semi-hermetic reciprocating compressors are available today, and scroll compressors may become available in the future. This may, for the time being, adversely impact the application of R-744 in sub-segments where open shaft compressor and scroll technologies are being utilized (for example vehicle powered truck refrigeration systems).

6.2.1.3 HFC refrigerants

Refrigerant manufacturers are developing low-GWP HFC alternatives of which several have the potential to match the cooling capacity, power consumption and pull-down expected from today's standard R-404A or HFC-134a systems. The flammability of these refrigerants is one of the major concerns for their use in transport refrigeration and the same principals of safety have to be fulfilled in transport refrigeration as described above for use of hydrocarbons (UNC, 2011). At the moment, there are no non-flammable very low-GWP HFC candidates (below GWP 150).

Changes to refrigerant classification have been proposed to mitigate the flammability concern of the medium and low-GWP HFC refrigerants. For example, ASHRAE Standard 34 (2013) (since 2010 edition) and ISO 817 (ISO, 2014b) recognize subclass 2L (= 2 low) refrigerants that are defined as class 2 refrigerants with a maximum burning velocity of =10 cm/s. The most recent revision of standard ISO 5149 (ISO, 2014a) recognizes the fact that A2L and A3 refrigerants need to be treated differently, and proposes more relaxed charge limits for A2L refrigerant when compared with A3. Still, even the more relaxed A2L limits appear not to be compatible with the charge levels / volumes typical of transport refrigeration applications. In addition, for transport refrigeration applications, due to the flammable nature of refrigerants classified as A2L, A2 and A3, a risk assessment should be carried out to ensure compliance with occupational health and safety requirements and other regional standards and requirements.

A calculation assuming a release of 4 kg HFC-1234yf in a 25 m^3 trailer box (80% loaded by cargo) yields concentrations that are at best comparable to the refrigerant concentration limit (RCL) of the ASHRAE Standard 34 (2013), and above the lower flammability limit, using the recommended safety factor of 4. The opening of the box and the consequent leakage of oil or other contaminants in presence of a source of ignition or self-ignition conditions could create an ignition risk. On the other hand, in personal cars, a sudden leakage in case of collision is usually associated with the collapse of the cabin and the consequent ventilation through the broken windows; therefore it is considered a lower and acceptable safety risk for mobile air conditioning systems.

A side-by-side "drop in" comparison of three state-of-the-art low-GWP 2L flammable fluids (GWP ranging from 200 to 400) was conducted as part of AHRI Alternate Refrigerant Evaluation Program (Kopecka, 2013). The evaluation showed that although these 2L flammable fluids were not suitable for retrofit in the field (drop in), they did show potential for increased efficiency and capacity with respect to R-404A.

System manufacturers are also testing low-GWP HFCs to assess the impact of other concerns such as stability, risk of clogging valves and expansion devices and other aspects.

Recent studies identified various non-flammable blends that offer different combination of GWP (ranging between 1300 and 2200), ease of retrofit, properties, performance and consistency with R-404A. These blends have important benefits: they are non-flammable (A1), and in some cases they can be retrofitted in the field. The main limitation is the GWP: significantly lower than R-404A, but still higher than so-called natural or unsaturated HFC (HFO) refrigerants.

The list includes and is not limited to R-407A, R-407F, R-448A, R-449A and R-452A (Mota-Babiloni, 2014, Minor, 2014).

In this group of non-flammable blends, R-448A and R-449A stand out as lower GWP (both approx. 1400) alternatives to R-404A, but have higher discharge temperatures, requiring system changes such as liquid injection in order to achieve comparable capacity, efficiency and reliability. This makes them especially suitable for new systems using liquid injection devices. On the other hand, R-452A has the GWP of approx. 2100 and it stands out as easiest direct drop, allowing it to achieve equivalent performance as R-404A without additional system changes.

Overall, it is likely that each of these blends will have a role to play in the general move towards more environmentally friendly alternatives.

While in transport refrigeration the majority of the attention is currently focused on R-404A due to the higher GWP level, several non-flammable, lower GWP blends have also been developed as alternative / retrofit to HFC-134a. Their GWP is in the 600-700 range, approximately 50% lower than HFC-134a.

6.2.1.4 Cryogenic systems

Liquid nitrogen or carbon dioxide open cooling systems entail low noise levels and low emissions of air pollutant due to the elimination of diesel powered refrigeration. This can bring benefits at the local scale, in addition to lower greenhouse gas (GHG) emissions in the use phase, and therefore of benefit for heavily populated areas. However, the energy required to produce the liquefied gases is substantial and therefore, if fossil fuels are employed during production, GHG emission would rise proportionally. Other options for reducing GHG emissions might be using alternative energy sources in production of liquefied gases such as off-peak nuclear or wind power or, in the case of nitrogen, ensuring that it is a by-product of oxygen production.

Technologies currently under development include systems for recovering mechanical energy from the expansion of liquid nitrogen, leading to a potentially low-GWP nitrogen economy.

Use of cryogenics systems will continue to be determined by the availability of liquefied gas charging stations (see a parallel with liquefied natural gas, or LNG, in some regions). Where available, cryogenic systems can provide an alternative to traditional diesel powered trucks and trailers on a case by case basis.

6.2.1.5 Eutectic systems

There are a limited but important number of applications where eutectic systems represent, and will continue representing, an option for the future: small vans, dedicated to a specific cargo, and with a predictable and repetitive duty cycle. Also, eutectics will continue to be an important solution in some applications in developing countries, where precision of temperature control is less relevant compared to the overall fuel and system cost.

Eutectic systems generally require the use of a refrigerant to “freeze” the eutectic. Some applications use an external system to freeze the eutectic, and the vehicle can be regarded as “refrigerant free”. The external system has a different safety, space, etc. requirement and allows for deployment of R-744 or flammable refrigerants that may otherwise have constraints for application in vehicles.

Technology in eutectics is also moving ahead, and some manufacturers are developing new “phase change” materials that offer high capacity/weight ratio.

6.2.2 Vessels

HFC-134a has been the most often used alternative to HCFC-22 in new vessels for provision refrigeration. New ships may also use R-407C or R-407F for air-conditioning going forward, as it is becoming widespread in other sectors. R-744 in cascade with R-717 is used for freezing down to -50 °C (mainly with fish as the cargo).

Some shipyards utilize HCFC-22 for small fishing vessels in Article 5 countries, but not for international commercial vessels.

Large industrial systems can use R-717 or R-744 where it makes sense. R-717 systems are limited to ships that do not carry passengers but professional crew only (due to toxicity consideration), and ships with a relatively high refrigeration capacity. This makes it suitable for large fishing vessels.

R-744 has been used as a refrigerant with own compressors (second stage in a cascade) or a secondary coolant being circulated by pumps. When used in the second stage, it can cover the temperature range between -10 and -50 °C. HFCs or R-717 is used in the first stage. Further, R-744 Refrigerated Sea Water (RSW) systems have been developed and may be used for replacing HCFC-22 systems to be taken out of operation. Again, these systems are limited to the fishing industry.

Cruise ships use chillers mostly with HFC-134a and it is foreseen that they will continue with this as long as possible due to the safety of the refrigerant hence the passengers. In 2014, a large manufacturer launched a 50 Hz water-cooled centrifugal chiller that utilizes HCFC-1233zd(E) as an alternate technology to HFC-134a.

For commercial vessels and for the off-shore business there is a potential for HC-290 to be a substitute for HCFCs and HFCs as most of the fleet already have Zone 1 or 2 onboard. HC-290 can be used for air conditioning as well as for provision plants, but most systems will be indirect secondary systems using a heat transfer fluid.

The classification companies have to approve a given refrigerant before it can be used onboard ships. The procedure of approval takes time and costs money and therefore only refrigerants requested by the owners are approved. This comes on top of the normal procedures on land. This also slows down the process of changing from one refrigerant to another.

6.3 Options for existing equipment

6.3.1 Road equipment and intermodal containers

The lifetime of road equipment and intermodal containers usually does not exceed 12 to 18 years, respectively. It is determined by their heavy duty and in Europe by the ATP scheme, which has a 3-year recertification period after the first 6-year in operation. HCFC refrigerants, if any are still in use, are being fast replaced by HFCs. Eutectic and cryogenics systems on vehicles are not limited by safety, space and other requirements of transport application, and so can use a variety of refrigerants in their stationary systems.

Of the HCFC and CFC containing fluids, R-502 was widely used in the road transport industry after 1960, to overcome issues with HCFC-22. The retrofit options include R-408A, R-402A (both contain HCFC-22), R-404A or R-507A which, however, require a component change.

Testing of low-GWP alternatives (below GWP 150, usually containing unsaturated HFCs) to the most widely used R-404A is in progress elsewhere. An AHRI AREP participant conducted side-by-side “drop in” comparisons of three state-of-the-art low-GWP 2L flammable fluids (Kopecka, 2013). The evaluation showed that these 2L flammable fluids were not suitable for R-404A retrofit in the field.

Recent studies identified various non-flammable blends that offer different combination of GWP (ranging between 1300 and 2200), ease of retrofit, properties, performance and consistency with R-404A. These blends are safe, they have GWP significantly lower than R-

404A, and in some cases they can be directly dropped into existing units. This makes them a likely solution for the R-404A installed population as well as new systems.

The list includes and is not limited to R-407A, R-407F, R-448A, R-449A and R-452A (Mota-Babiloni, 2014, Minor, 2014).3

In this group of non-flammable blends, R-452A stands out as easy and direct drop in, able to achieve equivalent performance as R-404A without additional system changes. The GWP is at approx.2100. On the other hand, R-448A and R-449A stand out as lower GWP (approx. 1400) options, requiring system changes with various degree of complexity (typically addition of liquid injection to limit discharge temperatures).

At present between 3.5 and 6% of the refrigerated ISO container fleet has been found to contain counterfeit refrigerants, many containing chlorine with an ODP (Lawton, 2012). It is assumed that refrigerant cost and limited availability put a pressure to adopt inexpensive counterfeit refrigerants with the subsequent environmental damage. Taxing of existing HFCs (for instance based on GWP) will likely increase the use of counterfeit refrigerants.

6.3.2 Vessels

The lifetime of vessels is considerably longer than that of the road equipment and intermodal containers. Vessels are in operation for 30 years on average. Merchant and cruise ships are among the newer equipment. The average age of a merchant vessel has been decreasing from 18.9 years in 2008 to 16.7 years in 2012 (ISL, 2012). The number of cruise ships and their size has about doubled in the last decade (ISL, 2011).

HCFC-22 has been the dominant refrigerant in many marine applications. Now it is being phased out gradually and many plants are retrofitted. R-417A, R-422D and R-427A have mainly been used to retrofit HCFC-22 which remains the most common refrigerant in the existing fleet. As discussed in previous chapters, retrofit with the zeotropic refrigerant may not be possible where flooded evaporators are used.

In large passenger ships/cruise liners, large chillers are being used. The most used refrigerant in new ships used to be HFC-134a but also R-410A has been used frequently. For retrofit of existing AC systems other HFC alternatives such as R-407C and R-427A require modifications to the equipment to reach a reasonable efficiency. HCFC-123 never became a real option aboard ships, possibly because of higher toxicity.

It is anticipated that marine AC systems will follow the development of new solutions seen in on-shore systems, perhaps with a small delay of some years due to the long expected life of the systems onboard ships.

6.4 Concluding remarks

It is clear that, in the transport refrigeration application, a unique, low-GWP or natural solution which would be ideal for new and field retrofit applications does not exist.

In the case of a regulation banning the use of refrigerant above a certain GWP level as in the EU, HFC blends will likely play a role as a retrofit to R-404A and (possibly) HFC-134a systems in the installed base: their GWP is significantly lower than R-404A and performances are relatively close. The level of system change in the field depends on the refrigerant choice.

For new systems, hydrocarbons offer high energy efficiency, but the safety risks in transport refrigeration application appear significant, with possible exceptions. On the other hand, R-744 has been tested in the field since the 2010 RTOC report. The non-flammable characteristics make R-744 attractive, but the gap in efficiency in high ambient temperatures and the limited component supply base are limiting its penetration into the market.

Recently there has been an initiative to consider the design and service best practices for flammable and high pressure refrigerants which it is hoped will lead to a fast track ISO standard on how these refrigerants can be applied to intermodal container refrigeration. The framework of this initiative has not yet been set.

We are also seeing "non-conventional" systems such as cryogenic systems or eutectic systems. These technologies offer specific advantages in specific applications, and the fact that they are HFC free will continue making them attractive.

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Annex to Chapter 6

The following sections describe technical progress and general characteristics of the transport refrigeration sector. Differences from other sectors are discussed. Fleet size and refrigerant charge estimates are provided in order to assess the relative importance and contribution of the various sub-sectors to the refrigerant banks and emissions.

A6.1 Requirements

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 cargoes with different temperature needs and even different temperatures simultaneously in different compartments.

All transport refrigeration systems have to be very robust and reliable to withstand vibrations and shocks. At the same time, the systems must be compact to maximise cargo space, and lightweight to reduce the energy required to move the vehicle.

It is imperative that spare parts (including refrigerant) are available along transport routes world-wide. Returning to a port can be a major issue for marine vessels in case of a refrigeration plant breakdown. This must be considered when design changes and improvements are made and introduced. Rigorous testing must be carried out so that only proven reliable systems are commissioned for field use.

Despite these efforts, refrigerant leaks inevitably occur within the refrigeration systems because of vibrations and shocks, and sometimes because of collisions with other objects. In addition, the harsh environmental conditions tend to accelerate the equipment aging. The equipment lifetime is usually between 10 and 15 years for road vehicles, railcars and intermodal containers, or less than 10 years in case of intensive use, and 20 to 25 years for merchant, naval and fishing vessels.

Safety is a number one priority in all transport refrigeration systems, because trained and certified service personnel may not be available along transport routes. Safe operation is particularly essential in the case of marine vessels, where evacuation is difficult or impossible. Safety must be either inherent in the fluids, or must be ensured through a number of technical measures.

A6.2 Vessels

It is assumed that nearly all vessels above 100 GT have refrigeration systems for their provision rooms and air conditioning for the occupied cabin space. IHS Fairplay, the sole global issuing body of the IMO Ship, Company and Registered Owner numbering system, claims to register nearly 180,000 ships of 100 GT and above (IHS, 2013). Of those, refrigeration is used more extensively for process or cargo cooling in several vessel types, namely cruise ships, refrigerated cargo ships and fishing vessels. Refrigerated cargo ships consist of specialized refrigerated ships (reefers), LPG carriers, nuclear fuel carriers and juice carriers. According to Lloyds Register porthole ships no longer exist and they have removed the survey requirements from their notation.

HCFC-22 has been the dominant refrigerant used aboard ships (estimated 80% of present fleet). HFC-134a has been the most often used alternative to HCFC-22 in new vessels for both air conditioning and refrigeration. R-404A and R-407C have been used mainly to retrofit HCFC-22. New ships may also use R-410A going forward, as it is becoming widespread in other sectors. HFC-23 is used for freezing at -60 °C and below (mainly fish as cargo). Natural refrigerants have been used in a relatively few vessels; primarily larger fish trawlers.

The typical charge size for different types of vessels is provided in Table A6-1 reprinted from the 2012 Lloyd's report (IMO, 2012). Although the refrigerant charge of cruise ships can be as high as 4,000 kg or more, their fleet is small. In 2011, the total passenger and passenger/roll-on roll-off cargo fleet for ships of 300 GT and over was composed of 4,131 ships, including only 426 and 35 large cruise ships and liners, respectively (ISL, 2011). The number of reefers, LPG and LNG carriers, porthole container ships, nuclear fuel carriers and juice carriers is also very low. The only growing sector may be the LPG carriers, while cargo containerization has increased, this has removed cargo from reefer ships and which have therefore declined, porthole containers and their ships have disappeared.

Table A6-1: Average refrigerant charge size in kg (IMO, 2012)

	Cruise Ship	**Refrigerated Cargo**	**Fishing Vessel**	**Other**
Air Conditioning	1800	110	60	90
Provision Room	300	15	10	15
Cargo Cooling	0	825	1500	0
Engine Control Room	12	6	5	7
Wheel House	0	8	8	8
Spare Refrigerant	700	317	785	35
Total	2812	1281	2368	155

The ODS inventory is difficult to estimate. The 2012 Lloyd's report quantified the inventory of ozone depleting refrigerant for 41 flag administrations, which estimated stock was greater than 100 t, at 17,696 t. Provided that these 41 countries made up over 82% of the estimated ozone depleting potential refrigerants used in the marine sector as stated in the report, the total inventory could be 21,580 t. Using a much less sophisticated approach, the 2012 TEAP Progress Report (TEAP, 2012) arrived at the total inventory estimate of 27,650 t.

The 2012 Lloyd's report provided also a type-specific estimate of refrigerant leakage rates. The percentages were lower (5 to 15%) for cruise and refrigerated cargo ships, and higher (on average 50%) for the fish factory and trawlers. Regardless of type, the 2012 Progress Report provided an estimated leakage rate of 30% for HCFC-22. Based on the refrigerant charge size and the fleet size, the annual usage quantity (leakage) was estimated at 4.858 t in the Lloyd's report and 8,420 t in the 2012 TEAP Progress Report.

The pieces of information collected so far on the estimated refrigerant charges, leakage rates and fleet sizes suggest that the fishing sector shall be consulted for more details.

Refrigeration systems have to comply with legislation of the state whose flag they are entitled to fly. In the case of servicing, refrigerant sales to vessels operating under a foreign flag are generally considered national exports and imports, and hence restrictions may apply.

A6.3 Trucks, trailers and rail cars

The road refrigeration market comprises several vehicle segments: small trucks and vans with a cargo volume below roughly 19 m3, large trucks with a volume between 20 and 59 m3, and trailers and semi-trailers with a box volume up to more than 100 m3. Small trucks and vans are used predominantly for distribution in urban and sub-urban areas, while long haul transport favors large trucks and trailers.

It is common to state the maximum refrigeration capacity at two or three operating conditions that represent frozen cargo and chilled (perishable) cargo. The exact rating conditions vary slightly for different markets and countries: the North American market prefers to rate at box temperatures of –17.8 ºC and 1.7 ºC at an ambient temperature of 37.8 ºC (AHRI, 2013), while the countries committed to the ATP Agreement (ATP, 2013) prefer the box temperatures of –20 ºC and 0 ºC at an ambient temperature of 30 ºC.

The flexibility required by the carriers of perishable food has brought up the need for multi temperature compartment box in all categories of vehicles, from small vans to the largest trailer. Multi-temperature equipment has been developed for nearly two decades to optimize different logistic scenarios. They allow the same vehicle with only one refrigeration unit to carry products at different temperatures in 2 or 3 compartments. They represent 25% of the French market (Cavalier, 2013) (25% is a weighted average of 9% vans, 44% trucks and 41% trailers). Some operators purchase only the multi-temperature equipment even if they often operate in mono-temperature mode.

If the exact rating conditions and the vehicle type are neglected, the maximum refrigeration capacity ranges from less than 500 W up to 10 kW at the frozen cargo temperatures and from less than 1 kW up to 20 kW at the chilled cargo temperatures. The refrigeration capacity during transportation varies with the actual heat load. Most units are able to provide heating in the cargo box, usually by means of hot gas (compressor discharge), electricity, or independent gas heating equipment.

Majority of road and rail equipment utilizes the vapour compression cycle. The systems for small trucks and vans are typically vehicle powered (direct drive). Large trucks and trailers are self-powered; they contain a power source independent of the vehicle, usually a diesel engine. So called multi temperature units can serve up to 3 compartments at different temperature levels in one vehicle. Single temperature units are traditional and more frequent.

The total world fleet size is difficult to estimate. The new published data suggest that the total fleet size is 2,000,000 vehicles and so is considerably smaller than anticipated previously in RTOC reports. Cavalier and Devin (Cavalier, 2013) analyzed UNECE, IIR, EU and expert's figures and estimated the European Union fleet at some 1,100,000 vehicles. In China and India, the fleet size was estimated at 100,000 and 6,000 vehicles, respectively.

Of the road transport equipment, about 25% are trailers, 25% are large trucks and 50% are small trucks and vans (Cavalier, 2013). These data represent a shift if compared to the estimates presented in the RTOC 2010 report, where it was assumed that trailers and trucks represent, each, 30% of the fleet, and vans covered the remaining 40%. The portion may vary from region to region.

The refrigerant charges ranged typically between several hundred grams and 10 kg, usually less than 6 kg for small and large trucks. Micro-channel condenser technologies have become available because of technical progress in the last few years. Innovation reduced the refrigerant charge by approx. 30%: for example, in new trailer units, the charge has been reduced from around 7.5 kg to 5 kg.

Refrigerants typically used are R-404A and HFC-134a, in some cases R-410A. Cavalier and Devin reported that R-404A is present in more than 95% of equipment and HFC-134a in about 4% of equipment in the European Union.

There is an ongoing effort in the industry to reduce the greenhouse gas emissions. Technologies and designs applied today in vapour compression systems include: micro-channel condensers to reduce refrigerant charge, hermetic solutions to reduce leak rates, reduced number of joints and better process controls and leak testing for joint integrity. In addition to the above, many solutions are being tested in a limited volume base such as alternative propulsion systems (hybrid, electric, etc.) instead of diesel engines.

There are two systems other than the vapour compression cycle and diesel engine system that are available in the market and used in road transport today. Their fleet size is currently, however, small.

Eutectic systems rely on the concept of latent heat. When the unit is plugged in, the eutectic solution is frozen; in operation and delivery, the system is unplugged and the eutectic solution changes state, absorbing heat and cooling the cargo. Eutectic systems have a fundamental advantage: they do not require a diesel engine, so they are noiseless, produce no emissions during operation, and need low maintenance. At the same time, some key limitations apply: they operate at a single temperature (they are not thermostatically controlled), and they have limited pull down, capacity and autonomy.

Cryogenic systems carry liquid nitrogen R-728 or carbon dioxide R-744 in an insulated tank. When needed, the liquid is expanded in a heat exchanger, absorbing heat and cooling the cargo, and then released to the atmosphere. Earlier technologies, where R-728 was supplied directly to the cargo box are not used any longer. Cryogenic systems are noiseless, reliable and offer fast pull down and high capacity regardless of the vehicle speed. On the other hand, they require periodic refilling and infrastructure for liquefied gases. The carbon emissions from liquefying the gas need be considered.

The principles of the cryogenic and eutectic systems are illustrated in Figure A6-1.

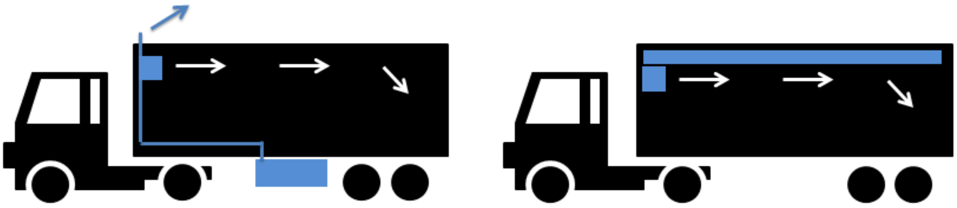

Figure A6-1: Schematic of a cryogenic system (left) and an eutectic system (right)

Refrigerated railcars have become very rare. There is a clear and definite trend to replace them with intermodal refrigerated containers that can be placed on a flat car. There is a small market of refrigeration systems built to handle severe rail and intermodal duty.

A6.4 Intermodal containers

The intermodal containers category includes refrigerated ISO containers (reefers), air freight containers, and small containers and insulated boxes.

Refrigerated ISO containers generally come in 20 ft and 40 ft lengths. Non-standard sizes exist as do swapbodies. The fleet size numbers are fairly accurate. It is estimated that, in 2013, there were approximately 100,000 units of 20 ft containers and 1,000,000 units of 40 ft containers in use. There are about 100,000 new refrigerated containers built annually.

The vapour compression cycle has been the only technology used in refrigerated ISO containers. Because the equipment lifetime is around 12-15 years (up to 18 years in new equipment), and the last HCFC units were produced in 2000, only a few HCFC units may be still in use in ocean traffic today. Current systems utilize HFC-134a or R-404A.

Approximately 60% of new units are fitted with hermetic scroll compressors, about 40% of the units are equipped with reciprocating, single or 2-stage compressors. The current technology features have resulted in reduced refrigerant charges and reduced emissions. The typical charge is approximately 4.5 kg, some manufacturers reporting charge of 2.8 kg HFC-134a.

All container units are electricity driven due to availability of electric grid on ships. When used on land (trailers, flat railcars, etc.), electricity is supplied from the electric grid or from a diesel engine generator set (gen-set) that is mounted on the unit front or the trailer.

The refrigeration performances can be tested according to ISO 1496-2:2008. The maximum refrigeration capacity is commonly stated at three operating conditions that represent frozen cargo and chilled (perishable) cargo. The maximum refrigeration capacity is around 4 kW at a box temperatures of –29 ºC, around 6 kW at a box temperatures of –18 ºC, and it is around 12 kW at a box temperatures of 2 ºC, all rated at the ambient temperature of 38 ºC. All units are able to transport any type of cargo in any climates. This means that both refrigeration and heating must be supplied.

Reducing energy consumption has been a continuing effort in reefer container industry. Manufacturers have focused on compression technology, technologies to part load operation of compressor (such as digital or variable speed by frequency inverters), and improving the control logic, mainly looking for an optimized balance between air temperature control range and energy consumption.

The safety requirements are most complex for intermodal equipment because of the various modes of transport (ship, terminal, road, rail, public events), including air freight. Therefore the reefer industry and operators have established a full operation control technology reporting and documenting the different states of reefer container positions, locations, forwarding information, as well as refrigeration system related information such as cargo temperature.

Dry ice (solid carbon dioxide) and gel packs are the most common types of coolants used for air freight transport. Dry ice is classified as "dangerous goods" and subject to IATA regulations – mass is declared. A small number of air freight containers use HFC-134a in a battery-powered vapour compression cycle. The cooling capacity as well as the refrigerant charge is low.

Small containers and insulated boxes are usually used in road transport. They are refrigerated mainly with dry ice, but also with eutectic plates, ice slurry or small vapour compression units. Boxes are generally not reusable and refrigerated with eutectic sticks or solid carbon dioxide. They are widely used for transport of pharmaceutical products and samples of food products.

A6.5 Temperature profiles

Both ambient temperature and cargo temperature vary during the operation of a refrigerated ISO container. Figure A6-2 presents the average annual ambient temperature profile collected by Maersk Container Industry (König, 2013b). It covers random container operations in a representative container fleet during a period of three years. The data include operations on vessel (including systems using both water-cooled and air-cooled condensers), rail and road, as well as operations in terminals. Temperatures between 17 and 33 °C represent 73% of the time.
Although ambient temperature profiles may vary from shipping line to shipping line, they peak most frequently between 21 and 33 °C. Temperatures around 29 °C are the most frequent and close to the ATP rating temperature of 30 °C (ATP, 2013).

Most frequent cargo temperatures are as follows: -18 °C (41%, frozen), 0 °C (28%, chilled) and 15 °C (17%, banana). The other temperatures represent 14% of the refrigerated ISO container fleet operation (König, 2013b).

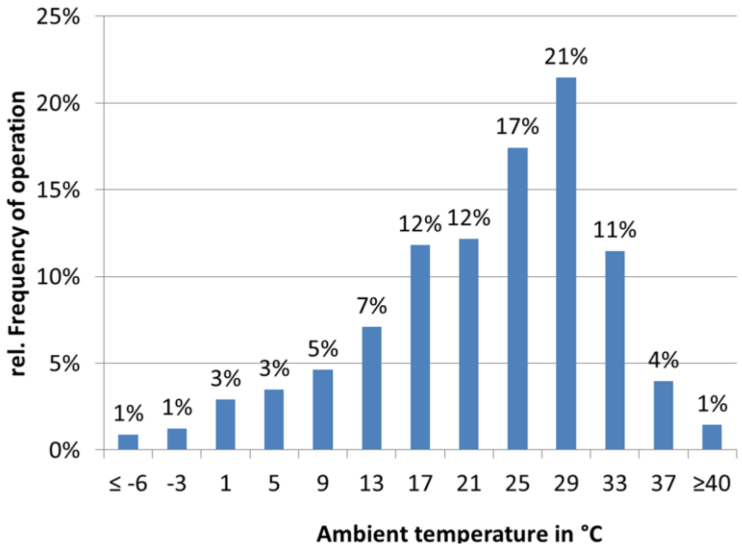

Figure A6-2: Average annual ambient temperature of reefer container fleet (König, 2013b)

Chapter 7

Air-to-air air conditioners and heat pumps

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7 Air-to-air air conditioners and heat pumps

7.1 Introduction

On a global basis, air conditioners (ACs), including reversible air heating heat pumps (generally defined as “reversible heat pumps”) ranging in size from 1 kW to 750 kW comprise a vast majority of the air conditioning market (the majority are less than 70 kW). In the remainder of this chapter the term air conditioning will be used to apply to both air conditioners and air-to-air heat pumps that directly heat air. This broad category is sometimes referred to as air-cooled or unitary equipment. These systems cool and/or heat enclosed spaces ranging from single rooms to large exhibition halls. Essentially, most are electrically driven vapour-compression systems using hermetic rotary, reciprocating or scroll compressors for units with capacities up to about 100 kW, and single or multiple semi-hermetic reciprocating, scroll or screw compressors for units with capacities up to 750 kW. Air in the space is drawn over a coil containing evaporating refrigerant. Heat transfer occurs between the air and the circulating refrigerant. With systems that provide heating and cooling, the role of the evaporator and condenser can be reversed to provide either heating or cooling. In the heating mode, air from the conditioned space passes over the same coil that contains refrigerant undergoing condensation thereby transferring heat to the air.

Nearly all air conditioners manufactured prior to 2000 used HCFC-22. The transition away from HCFC-22 is nearly complete in non-Article 5 countries. The phase-out of HCFC-22 in the manufacturing and import of new products in the EU and Japan was completed between 2004 and 2010, whilst North America and Australia and New Zealand are now also completing the process. However, it is important to note that technical options available at the time of the phase-out in these countries were environmentally focused on the protection of the ozone layer and not on the reduction of global warming potential (GWP). Some Non-Article 5 countries began the transition to non-ODP alternatives ahead of the Montreal Protocol commitment dates (primarily within Europe and Japan). In addition, certain Article 5 countries such as South Korea also pursued an accelerated phase-out similar to non-Article 5 countries.

Globally, in 2014, the majority of the installed unit population currently uses HCFC-22 and approximately around one half of the units produced globally use non-ODP refrigerants. An estimated two-thirds of a billion HCFC-22 air conditioners were operating worldwide, representing approximately one million metric-tonnes of HCFC-22.

The scope of this Chapter includes an overview of the common types of air conditioning equipment, their characteristics and where they are normally applied. Sections also highlight the alternatives refrigerants currently being used and anticipated for use, examining factors such as safety, climate impact, performance, cost implications and lubricants and commercial availability. In addition, issues related to refrigerant charge reduction and not-in-kind technologies applied to air conditioners are also covered. Alternative refrigerants for existing equipment, options for refrigerant replacement (only) and retrofit are summarised and implication of refrigerant choice for new systems used in high ambient temperatures is also addressed. The ozone depletion potential (ODP) and GWP values of the refrigerants mentioned in this chapter are given in Chapter 2 of this report.

The main developments compared to the last assessment report is related the increased substitution of HCFC-22 and the greater consideration of use of medium and low GWP alternatives. Regarding the use of HCFC-22, in 2010 many non-Article 5 countries were approaching the final phase-out of HCFC-22 in new systems; this has now been completed and most major Article 5 countries have initiated their transition from HCFC-22. Previously, medium and low GWP alternatives were not being given major consideration (except hydrocarbons (HCs) such as HC-290) whereas now additional manufacturers are adopting HCs and there is also uptake of HFC-32, whilst others are also considering the variety of new HFC/unsaturated HFC blends. China has made a decision to convert some production lines to HC-290 as part of their HPMP, whilst in India there is at least one plant where HC-290 air conditioners are being produced. There are also new additions to information relating to different alternatives performance under high ambient conditions.

7.2 Equipment types

Air conditioners generally fall into four distinct categories, based primarily on capacity or application: small self-contained air conditioners (window-mounted and through-the-wall air conditioners); non-ducted split residential and commercial air conditioners; ducted, split residential air conditioners; and ducted commercial split, multi-split (including variable refrigerant flow, VRF) and packaged air conditioners (commercial air cooled). In each of these categories, the term “air conditioner” includes systems that directly cool or heat the conditioned air.

Table 7-1 summarises the typical physical and installation characteristics of each type of air conditioner.

Table 7-1: Typical configurations of air conditioner type

Type		**Primary configuration**	**System layout**	**Capacity range (kW)**	**HCFC-22 charge range (kg)**
Small self-contained	Window	Small self-contained	Self-contained	1 – 10	0.3 – 3
	Portable	Small self-contained	Self-contained	1 – 10	0.3 – 3
	Through-the-wall	Small self-contained	Self-contained	1 – 10	0.3 – 3
	Packaged terminal	Small self-contained	Self-contained	1 – 10	0.3 – 3
Split (non-ducted)		Non-ducted split	Remote	2 – 15	0.5 – 5
Multi-split		Non-ducted and ducted split	Remote	4 – 300	2 – 240
Split (ducted)		Ducted split	Remote	4 – 17.5	1 – 7
Packaged rooftop		Ducted commercial	Self-contained	7 – 750	5 – 200
Ducted commercial split		Ducted commercial	Remote	10 – 750	5 – 250

7.2.1 Small self-contained air conditioners

Small Self-Contained (SSC) air conditioners are small capacity units 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 (having an average size of 2.7 kW). This category of products includes the following common configurations:

- Window Mounted Room Air Conditioner,
- Through-the-Wall Air Conditioner
- Portable Air Conditioner [1]
- Packaged Terminal Air Conditioner (PTAC).

Small self-contained air conditioners are designed to heat or cool single spaces, such as bed-

[1] Portable air conditioners are a special class of room air conditioners that can be rolled from room to room. They exhaust their condenser air through a small flexible conduit, which can be placed in an open window. Some portable air conditioners use a separate outdoor condenser, which connects, to the indoor section with flexible refrigerant piping.

rooms, small shops, restaurants and offices. Small self-contained air conditioners, because of their size and relatively low cost, have often been the first individual comfort electrically driven vapour-compression systems to appear in emerging air conditioning markets. However, duct-free, split type room air conditioners are being selected more frequently as the first comfort air conditioning option in most countries resulting in a global decline in the demand for window mounted and through-the-wall air conditioners.

These systems have average refrigerant charge levels of approximately 0.25 kg per kW of cooling capacity, for example, 0.75 kg of HCFC-22. The majority use hermetic rotary compressors, with the remainder employing reciprocating or scroll compressors.

Most small self-contained air conditioners historically used HCFC-22. As non-ODP refrigerants have been applied to these products-the majority have used HFC blends, R-407C and R-410A. A small proportion of units are using HC-290.

Globally there are about 17 million SSC air conditioners currently produced (Gloël, 2014). With service lives over 10 years, it is estimated that more than 170 million SSC air conditioners remain in operation globally.

7.2.2 Split (non-ducted) residential and commercial air conditioners

In many parts of the world, residential and light commercial air-conditioning is done with non-ducted split air conditioners. Non-ducted split air conditioners are widely applied in commercial buildings, schools, apartments and freestanding residences and range in capacity from 2.0 kW to 20 kW (average size of 3.8 kW).

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. Single splits often position the expansion device also within the condensing/outdoor unit. Compressors are typically hermetic rotary, scroll or reciprocating type; high energy saving potential comes from introducing inverter technology and technology is currently used in about half of new units.

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. These units are designed to provide high efficiency and capacity at low ambient temperatures; typically down to -30°C. Reversible air conditioners can reduce indirect CO_2 emissions by providing an efficient and cost effective alternative to electric resistance and fossil fuel heating. Heat pumps designed for cold climates utilize one or more technologies to improve their low ambient performance. These technologies include, multi-stage or variable speed compression, larger heat exchangers and enhanced control strategies.

The vast majority of mini-split residential and commercial air conditioners manufactured prior to 2000 used HCFC-22 refrigerant. Mini-split air conditioners have average HCFC-22 charge levels of approximately 0.25 to 0.30 kg per kW of cooling capacity. The majority of non-ODP refrigerants that have been applied to these products are HFC blends such as R-410A and R-407C, whilst HFC-134a has been more dominant in regions that experience high ambient conditions.

The current global market for these types of split systems is around 80 million units per year (Gloël et al, 2014).

7.2.3 Multi-split air conditioners for commercial and residential

A second type of products are multi-split; essentially the same as a single split (as described above) but a single condensing unit may feed two or more indoor units, although 50 indoor units can be used with 1 km of piping. Whilst dual indoor unit models may be used for residential applications, this category of split systems is more often used in commercial buildings. Specific refrigerant charges tend from around 0.3 kg/kW upwards, depending upon the installation characteristics. As with single splits, non-ducted and ducted multi-splits also offer reversible (heating) options.

Variable Refrigerant Flow (VRF) systems are a sub-category of the multi-split 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. The outdoor air conditioning unit can adjust the refrigerant flow in response to the demand from each indoor unit. In some configurations, these systems can have independent cooling or heating functionality for each indoor unit thus simultaneously heat and cool separate indoor spaces. The outdoor unit modulates the total refrigerant flow using various compressor capacity control methodologies, with compressor types generally being rotary or scroll type. VRF systems have capacities ranging from 10 kW to over 150 kW. Although systems produced before 2000 tended to use HCFC-22, there has since been a growing increase in the use of R-407C and R-410A even in Article 5 countries, with typical charge levels of 0.30 – 0.70 kg/kW of cooling.

Cooling capacities range from about 4 kW to about 150 kW, with an average (module) capacity of 20 kW (noting that modules are often multiplexed to provide greater capacities). Approximately 1 million systems are produced each year (Gloël et al, 2014).

7.2.4 Split ducted air conditioners (residential and commercial)

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), 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. Compressor types typically include hermetic rotary, reciprocating and scrolls. The most common refrigerant in these systems was HCFC-22 until the period 2005 – 2010, although over the past few years the majority has transferred to R-410A and R-407C. For residential systems, capacities range from 5 kW to 17.5 kW (average size around 10 kW) and each has an average HCFC-22 charge of 0.26 to 0.35 kg per kW of capacity. For commercial systems, capacities range from 7 to 750 kW with a current annual output of about 10 million units (Gloël et al, 2014).

7.2.5 Ducted commercial packaged (self-contained) air conditioners

Ducted commercial packaged air conditioners and heat pumps are single self-contained units which comprise an integral fan and heat exchanger assembly which is connected by means of ducting to the air distribution system of the commercial structure. The other part of the package is the condensing unit, normally with an air cooled condenser and compressors, which are often hermetic scrolls, although hermetic and semi-hermetic reciprocating and screw machines are sometimes employed.

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.

They are offered in a wide range of capacities from around 7 kW to over 700 kW and have specific refrigerant charges of around 0.3 to 0.5 kg per kW of cooling capacity. Most ducted systems historically used HCFC-22, whilst in non-Article 5 countries R-410A is mainly used and to a lesser extent R-407C, which is used more frequently in regions with higher ambient conditions. Annual market is currently about 1 million units (Gloël et al, 2014).

7.3 Options for new equipment

As discussed in Chapter 2, there are several factors that should be considered when selecting an alternative refrigerant. Accordingly, this section provides a summary of the most viable HCFC-22 replacement candidates for new air-conditioners, based on the current information available to the RTOC.

Several single component HFC refrigerants have been investigated as replacements for HCFC-22, although previously, HFC-134a was the only single component HFC that has been commercially used in air conditioning systems to a limited extent. Recently air conditioners have become available with HC-290 and HFC-32 as single component refrigerants. A number of HFC blends have emerged as replacements for HCFC-22 in air conditioning systems. Various compositions of HFC-32, HFC-125, and HFC-134a are being offered as non-ODS replacements for HCFC-22. The two most widely used HFC blends are R-407C and R-410A. Both R-407C and R-410A have GWP values close to that of HCFC-22 (Table 2-7 and 2-8).

More recently, new low- and medium-GWP blends are being proposed, which comprise unsaturated HFCs (such as HFC-1234yf, HFC-1234ze(E), HFC-1243zf, etc.) with other non-ODP refrigerants such as HFC-32, HFC-134a and R-744. These blends are mixed in order to more closely match the performance of the refrigerants currently being used in these products such as HCFC-22 and R-410A (Minor, 2008, Spatz et al., 2010). Due to their compositions, most of these blends exhibit various levels of temperature glide (being the difference in dew- and bubble-point temperature at a given saturation pressure) and in most cases are flammable. There are a large number of such blends proposed by manufacturers, but to date few have been assigned an R-number (although this is expected to change in the next two to three years).

Whenever an alternative refrigerant is selected, there must be a corresponding choice of lubricant (i.e., the base oil and appropriate additives) and this choice is also affected by the compressor technology and the anticipated range of operating conditions of the system. The selection of the lubricant to be used with a particular HFC is generally made by the compressor manufacturer which makes the selection after extensive material compatibility and reliability testing.

Considering the various alternatives with medium and lower GWP, the majority of these are flammable to some extent. If flammable refrigerants are selected they present hazards not historically associated with safety concerns with air conditioners. In the event of ignition of a refrigerant leak, possible consequences can result in overpressure and thermal radiation, leading to further secondary consequence (secondary fire, fragments, high toxicity decomposition products, etc.). Furthermore, the societal tolerance of consequences from flammables tends to be lower than with other hazards. Therefore appropriate measures have to be applied in order to mitigate the risk, for example, minimising the amount of refrigerant that can leak into occupied spaces or removing the refrigerant from the occupied space entirely, ensure that probability of ignition is greatly reduced through risk assessment and at a minimum, meet the requirements of national regulations and/or appropriate safety standards (where they exist); such rules are continuously under development.

7.3.1 HFC-134a

Whilst HFC-134a is a potential HCFC-22 replacement in air-cooled systems, it has not seen broad use because manufacturers have been able to develop substantially lower cost air-cooled air conditioning systems using HFC blends such as R-407C and R-410A.

To achieve the same capacity as an HCFC-22 system, the compressor displacement must be increased approximately 40% to compensate for the lower volumetric refrigeration capacity of HFC-134a. Similarly, significant equipment redesign is necessary to achieve efficiency and capacity equivalent to HCFC-22 systems. These design changes include larger heat exchangers, larger diameter interconnecting refrigerant tubing, larger compressors and re-sized compressor motors.

Although it is seldom a cost-effective alternative, it has been used widely in regions that experience high ambient temperatures for a variety of different types of air-to-air systems.

7.3.2 R-407C

Since R-407C requires only modest modifications to existing HCFC-22 systems, it has been used as a transitional refrigerant in equipment originally designed for HCFC-22. However, since around 2004 many of the R-407C systems have been redesigned for R-410A to achieve size and cost reductions. An exception is when the target market’s standard conditions are high ambient temperatures, such as above 40-55°C.

There are currently R-407C air conditioning products available in Europe, Japan and other parts of Asia. Because of its low saturated pressure, R-407C is chosen as an alternative to HCFC-22 by some manufactures in the Middle East where ambient temperatures can be high. R-407C has also seen some limited use in the North America, primarily in commercial applications. Generally, R-407C has little chance to replace widely HCFC-22 in the air conditioning sector in future, at least where standard temperatures apply.

Performance tests with R-407C indicate that in properly designed air conditioners, this refrigerant will have capacities and efficiencies within ± 5% of equivalent HCFC-22 systems (Li and Rajewski, 2000). Linton et al (2000) found that for a fixed capacity, R-407C resulted in a 5-11% lower cooling COP.

As R-407C is a zeotropic blend, temperature glide is significant but has been manageable through many years of use and experience. Counter flow design of heat exchangers can mitigate the negative impact of refrigerant glide. However, with reversible heat pumps it is difficult to employ counter flow heat exchanger designs because the refrigerant has opposite flow directions in the heating and cooling modes unless complex reversible refrigerant heat exchanger circuiting is employed.

Polyolester (POE) or polyvinylether (PVE) lubricants can be selected for R-407C. Of these, POE is the most widely used lubricant in HFC refrigerant applications. A recent tendency is for compressor manufacturers to use POE oils in compressors so the system manufacturers can use the same compressor for both HCFC-22 and R-407C systems.

7.3.3 R-410A

R-410A can replace HCFC-22 in new equipment production, since the operating pressures are around 50-60% higher than HCFC-22. Due to its thermophysical properties, the design of R-410A units can be more compact than the HCFC-22 units they replace. In addition, R-410A can have better performance in inverter type air conditioner than HCFC-22.

R-410A air conditioners are currently commercially available in the US, Asia and Europe. A significant portion of the duct-free split products sold in Japan and Europe now use R-410A as the preferred refrigerant.

System designers have addressed the higher operating pressures of R-410A through design changes such as thicker walls in compressor shells, pressure vessels (accumulators, receivers, filter driers etc.). In addition, the considerations for lubricant requirements are as described for R-407C; POE or PVE have to be used.

As concerns over GWP have increased, with it high value, R-410A is becoming seen as a less viable alternative for HCFC-22 in the longer term, although it currently remains the first choice for new air conditioning equipment. Another concern is its low critical temperature that can result in degradation of performance at high condensing temperatures (see Section 7.5.1).

7.3.4 HFC-32

HFC-32 is seen as a replacement for R-410A due to its medium GWP and slightly higher capacity and similar efficiency. Due to lower density the specific refrigerant charge (per kW of cooling capacity) is around 10-20% less (Piao et al, 2012, Yajima et al., 2000). R-410A systems can be redesigned for HFC-32 with modifications and with additional safety considerations given its class 2L flammability (see Annex to Chapter 2); appropriate design, application and service changes will be required for it to be safely applied. Another factor that must be considered with flammable refrigerants is refrigerant reclaim and recovery requirements during servicing and at the end of the product's life to protect those servicing or recycling the product. The current POE and PVE lubricants used with R-410A have insufficient miscibility with HFC-32 (Ota and Araki, 2010) and therefore modified oils are selected.

HFC-32 has comparable efficiency to that of R-410A and HCFC-22 in many mini-split ACs, as shown recently by a number of performance evaluations. Barve and Cremaschi (2012) tested HFC-32 in an R-410A reversible AC, with various optimization modes. In cooling mode, the COP varied by 0% to -2%, but with up to +8% higher capacity. Pham and Rajendran (2012) reported on tests with HFC-32 in an R-410A system gave about +3% higher cooling capacity with -1% lower COP and in heating mode capacity was about 4% higher with negligible change in COP. Three different R-410A units were tested with HFC-32 by Guo et al. (2012). The capacity increased by about +5 to +6% whilst COP was -3% to 0% lower. As part of the AHRI "low GWP AREP" programme, HFC-32 was tested against R-410A in two reversible heat pump air conditioners (Crawford and Uselton, 2012). Depending upon the conditions, the cooling capacity ranged from -1% to +3% of R-410A with cooling COP and heating COP varying by -1% to +2% and -6% to +4%, respectively. In a subsequent report (Li and By, 2012), HFC-32 was shown to have an increased cooling capacity ranging from +2% to +4% and a COP of 1% to 2% higher. Piao et al (2012) showed in a split air conditioner a 4% higher cooling COP and 1% higher heating COP compared to an R-410A system. Yajima et al. (2000) reported 10% higher cooling COP and 7% higher heating COP in a commercial split system.

In 2014, HFC-32 systems have been presented to the market in Japan, Europe, India and Australia, amongst others. One Japanese manufacturer reported that although there are some million split-type units installed there have been no incidents reported so far.

7.3.5 HFC-152a

HFC-152a has performance characteristics similar to HFC-134a as well as 10% lower vapour pressure and volumetric refrigeration capacity. As such, significant redesign of existing HCFC-22 systems would be required, similar to that described for HFC-134a. Application of HFC-152a demands that systems must be designed, constructed and installed with due consideration of its class 2 flammability (see Annex to Chapter 2), as well as due consideration to reclaim and recovery requirements during servicing and at end of life.

It is unlikely that HFC-152a will be commercialised in air conditioning systems primarily because its low volumetric refrigerating capacity implies increased costs relative to an HCFC-22 system, added to the considerations required to handle flammability.

7.3.6 HFC-161

HFC-161 is also being evaluated as a replacement for HCFC-22 in air conditioning systems. It has similar thermodynamic properties to HCFC-22 and is flammable and therefore systems have to be designed, constructed and installed accordingly (see Annex to Chapter 2), as well as due consideration to reclaim and recovery requirements during servicing and at end of life. One potential obstacle exists in that the toxicity classification has still not been assigned under the relevant standards (see Annex to Chapter 2).

In terms of performance, the volumetric refrigerating capacity is close, around 5% lower, to that of HCFC. Tests comparing the efficiency have found that the COP of HFC-161 is about 10% higher than HCFC-22 (Padalkar et al., 2011). Furthermore the refrigerant mass can be decreased to about half of the HCFC-22 charge. Wu et al. (2012b) reported on tests in split air conditioners, showing that both cooling and heating capacity was about 5% lower than HCFC-22, whilst cooling and heating COP was between 5 – 10% higher. As the ambient temperature increases (towards 48°C), the difference in cooling capacity reduced and the improvement in COP increased. Discharge temperature was consistently about 5 K lower than with HCFC-22. Han et al (2012) measured efficiencies of about 10 – 15% higher than R-5410A and HFC-32.

Either mineral oil or POE can be used for HFC-161. There have also been some questions raised regarding the thermal stability of HFC-161; one recent study has shown it can degrade under elevated temperature and pressure conditions, forming acids and thus corrosion (Leck and Hydutsky, 2013).

7.3.7 HFC-1234yf

Since the thermodynamic characteristics of HFC-1234yf are very similar to HFC-134a, the same general observations about its applicability in air-to-air systems are as stated previously, i.e., it has a much lower volumetric refrigerating capacity and cannot be used as a direct replacement. Compressors would need a significantly larger displacement and experimental studies indicate is should be 40% larger than HCFC-22 systems (Fujitaka et al., 2010; Hara et al., 2010). Additional design changes include increased heat exchanger areas and larger diameter interconnecting tubing. As with HFC-134a, HFC-1234yf is therefore likely to suffer from cost issues, although possibly more so given the anticipated higher fluid costs. Although it is unlikely that unitary air-conditioners using pure HFC-1234yf will be commercially viable in most cases, there may be interest in some cases, such as for regions that experience high ambient temperatures. However, HFC-1234yf is being successfully demonstrated as a beneficial ingredient in refrigerant blends for use in air conditioning and refrigeration applications.

Given the class 2L flammability classification, systems should be designed, constructed and installed with due consideration of its flammability (see Annex to Chapter 2), as well as due consideration to reclaim and recovery requirements during servicing and at end of life.

7.3.8 HC-290

HC systems are commercially available in low charge air conditioning applications, such as small split, window and portable air conditioners. HC-290 is the most frequently used HC refrigerant in air conditioning applications. When used to replace HCFC-22, HC-290 has performance characteristics which tend to yield higher energy efficiency and slightly lower cooling and heating capacity. In terms of improvements in system COP in split type and window air conditioners with HC-290, values range from around -4% to +20%, such as: 4-7% (Chinnaraj et al, 2010); up to 8% (Devotta et al, 2005b); 4-12% (Jin et al, 2012); 10-15% (Li et al, 2010); 10-20% (Liu, 2007); up to 14% (Padalkar et al, 2010); up to 11% (Park et al, 2008); up to 2% (Park et al, 2007); 1-4% (Teng et al., 2012);12-19% (Wang et al, 2004); up to 12% (Xiao et al, 2006); up to 10% (Xiao et al, 2009); around 7% (Xu et al, 2011); up to 10% (Yan, 1999); up to 12% (Zhang et al, 2002); up to 9% (Zhou and Zhang, 2010). Amongst these studies, capacity varies within -10% to +10%.

Since HC-290 has lower density and higher specific heat, the charge quantity is about 45% of HCFC-22; typically around 0.05 – 0.15 kg/kW of rated cooling capacity. In addition, HC-290 has reduced compressor discharge temperatures and improved heat transfer due to favourable thermo-physical properties. Compressor manufacturers indicate that both mineral oil-based and POE lubricants are being used in HC compressors (Chen and Gao, 2011, Suess, 2004, Bitzer, 2012), however they should be optimised, for example with certain additives.

The main difficulty with HC-290 is its class 3 flammability, which creates safety concerns in application, installation and field service. European and international standards limit the charge of HC-290 (see Annex to Chapter 2). Such charge size limitations can constrain the use of HC-290 to smaller capacity systems that need to achieve a certain efficiency level, depending upon the specific heat load (i.e., kW/m^2) of the application; in order to extend the capacity range, charge reduction techniques can be applied. Charge reduction technologies and correct oil selection can be used to minimise the amount of refrigerant, which can increase the capacity range. Similarly, control strategies can be applied to restrict the amount of refrigerant that can leak into the occupied space can be applied, which may prevent up to 80% of the charge being released (Colbourne et al., 2013). Furthermore, systems (such as centralised/packaged) can use two or more independent refrigerant circuits or reboiler loop, although this implies a cost increase.

Leak, ignition and fire tests demonstrated that even with catastrophic refrigerant leaks, only sources of ignition present in the immediate vicinity of the indoor unit have the possibility to ignite a leak of refrigerant and consequences are insufficient to damage doors or windows (Zhang et al., 2013). Similar findings for developed concentrations were reported by Li (2014a). Risk analyses on the use of HCs in air conditioners suggest that when the requirements of safety standards are met, the probability of ignition during normal operation is extremely low (Colbourne and Suen, 2004). A recent study demonstrated that the flammability risk associated with split air conditioners is around 100 times lower than with HC-600a domestic refrigerators (Colbourne, 2014). The situation leading to highest risk is sudden leaks, refrigerant handling, and servicing activities, thus, installation and service practices must be modified to avoid exposing occupants and field technicians to the additional risks associated with flammable refrigerants.

Another factor that must be considered with flammable refrigerants is refrigerant reclaim and recovery requirements during servicing and at the end of the product's life to protect those servicing or recycling the product. Current recovery and recycling practices depend largely upon national or regional regulations. For example, in Europe waste legislation implies that HCs must be recovered, whereas in many Article 5 countries, venting of HCs may be considered an acceptable option, but should only be done subject to a risk assessment.

Some major Chinese and Indian manufacturers have had commercially available HC-290 products since 2012 and have been available in Europe and Australia for several years. To date, whilst output is limited, conversion of production capacity from HCFC-22 to HC-290 of approximately four million units per year has been completed in China (Zhou, 2014).

7.3.9 HC-1270

HC-1270 has favourable characteristics from the point of view of both thermodynamic and transport properties, but is a class 3 flammable refrigerant. It has a similar cooling capacity to HCFC-22 but higher (about 4%) efficiency (Lin et al., 2010). Wu et al. (2012a) measured the performance of a split type air conditioner with HC-1270 and HC-290 whilst exchanging the compressor to match the original HCFC-22 capacity. For both refrigerants, improvements of 1-5% in COP were observed. Chen et al. (2012) and Chen et al. (2011) compared HC-290 and HC-1270 in a split air conditioner and found that despite a drop in cooling capacity of 8% and 4% respectively, COP was always higher than HCFC-22. Park et al. (2010) measured the performance of a split type air conditioner in heating mode and results showed that the capacity of HC-1270 was 3-10% higher than that of HCFC-22 and the COP was 3% higher. HC-1270 also has a lower discharge temperature than HCFC-22.

The charge mass is about 40% of HCFC-22 and compared with HC-290, HC-1270 has a larger capacity which is useful to reduce the specific charge. Similarly, the obstacles and flammability risk for use of HC-1270 in air conditioners are similar to those of HC-290 (see Annex to Chapter 2).

Some manufacturers of room air conditioners are developing products using HC-1270.

7.3.10 R-744

R-744 has a low critical temperature, which results in significant efficiency losses when it is applied at the typical indoor and outdoor air temperatures of air-to-air air conditioning applications. This is particularly the case in high ambient climates, which could result in higher system costs (Elbel and Hrnjak, 2008; Hafner et al., 2008; Johansen, 2008). R-744 air conditioning systems typically operate above the critical temperature of R-744 during heat rejection.

R-744 air conditioners operating in warmer climates (design temperatures greater than 30°C) could have efficiencies approaching best in class HFC based designs (Neksa et al, 2010); tested prototypes at 36°C ambient had COPs between 6% and 21% lower than the best R-410A models. However, a number of design enhancements can be made to improve their efficiency. The efficiency of R-744 systems can be improved through multi-stage compression, addition of oil separators, use of refrigerant ejectors and expanders, various inter-cycle heat exchangers, and cross-counter-flow heat exchangers, which take advantage of the favourable thermophysical properties of R-744 (Xie et al., 2008; Wang et al., 2008; Koyama et al., 2008; Li and Groll, 2008; Peuker and Hrnjak, 2008; Kasayer et al., 2008). The addition of efficiency enhancing components can improve the efficiency of R-744 systems, but will also increase the cost of R-744 systems.

Gas cooler operating pressures for R-744 systems are high; typically up 50 140 bar, with a mean system pressure near 50 bar (Ibrahim and Fleming, 2003). The required hydrostatic burst strength of systems operating at these high pressures would have to be approximately 300 (Bosco and Weber, 2008) to 400 bar (see Annex to Chapter 2). The higher operating pressures contribute to high specific cooling capacity, thus allowing the reduction of inner diameters of tubes and lower compressor displacement or swept volume. The smaller component diameters result in comparable wall thickness to address the high operating pressures of R-744. Design changes required to address the burst pressure requirements of R-744 systems may also result in manufacturing cost increases. The high cost of R-744 systems, unless resolved, is expected to substantially hinder the adoption of R-744 technology in air-to-air air conditioning applications.

Air-cooled R-744 air conditioners are available in capacities from about 3 to 300 kW. Experimental results show that R-744 systems may compete in energy efficiency with high efficiency R-410A systems for moderate climates in both cooling and heating mode; however, improvements are needed to significantly increase the capacity, efficiency and reduce the peak electrical power requirements during the cooling mode in high ambient conditions (Jakobsen et al., 2007).

The solubility of R-744 in lubricant is relatively high at the crankcase operating pressures of R-744 compressors (Dorin, 2001). The knowledge base of information on lubricant compatibility in R-744 refrigeration systems is expanding as more researchers conduct studies of R-744 compressors (Hubacher, 2002; Li et al., 2000; Youbi-Idrissi, 2003; Muller and Eggers, 2008). Some of the lubricants being considered for R-744 systems are POEs, PAO, and naphthenic mineral oil or alkyl benzene lubricants (Youbi-Idrissi, 2003; Seeton, 2006). It is very likely that an oil separator will be needed in R-744 systems because of the large detrimental impact oil circulation has on the heat transfer performance of R-744 (Muller and Eggers, 2008).

7.3.11 R-446A and R-447A

The blends R-446A and R-447A have similar pressure and capacity characteristics to R-410A and are feasible for use in most types of air conditioning. Since they have class 2L flammability, the maximum charge is constrained for larger capacity systems (see Annex to Chapter 2). As with other flammable refrigerants, systems should be designed, constructed and installed with due consideration of its flammability, as well as due consideration to reclaim and recovery requirements during servicing and at end of life.

The efficiency is comparable to that of R-410A for moderate ambient temperatures. Both R-446A and R-447A have higher critical temperature of around 84°C and 83°C, respectively, compared to 71°C for R-410A. This higher critical temperature enables them to have a higher efficiency at high ambient temperature (Sethi, 2013).

The cost implications should be comparable to those of R-410A, although marginally greater due to the higher refrigerant price at present.

Currently there is testing and trials on going and manufacturers in Japan, Korea, China and New Zealand are developing prototypes.

7.3.12 R-444B

Use of the R-444B is feasible in split ACs, for example, where HCFC-22 or R-407C is already used. Since it has class 2L flammability, the appropriate safety standards should be followed (see Annex to Chapter 2). As with other flammable refrigerants, systems should be designed, constructed and installed with due consideration of its flammability, as well as due consideration to reclaim and recovery requirements during servicing and at end of life.

The efficiency is comparable to that of HCFC-22 and the liquid density indicates that the charge should be about 10-15% lower than HCFC-22. R-444B has a critical temperature similar to HCFC-22 and thus substantially higher than R-410A, which implies that it should show performance at high ambient temperatures similar to HCFC-22. Preliminary test results indicate that R-444B shows similar capacity and efficiency to HCFC-22 (Sethi et al, 2014).

The cost implications should be comparable to that of HCFC-22 although probably greater due to the higher refrigerant price at present.

Currently there is testing and trials on going and manufacturers in Japan, Korea and China are developing prototypes.

Table 7-2: Refrigerant options for existing HCFC-22 and new equipment

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Options for new equipment</th><th colspan="2">Options for existing equipment</th></tr>
<tr><th>Refrigerant replacement (only)</th><th>Retrofit</th></tr>
<tr><td>Window</td><td rowspan="6">R-410A, R-407C, HC-290, HC-1270, HFC-32, R-444B, R-446A, R-447A</td><td rowspan="10">R-417A
R-417B
R-422A
R-422B
R-422C
R-422D
R-424A
R-425A
R-428A
R-434A
R-438A
R-442A</td><td rowspan="10">R-407A
R-407B
R-407C
R-407D
R-407E
R-421A
R-421B
R-427A</td></tr>
<tr><td>Portable</td></tr>
<tr><td>Through-the-wall</td></tr>
<tr><td>Packaged terminal</td></tr>
<tr><td>Split (non-ducted) smaller</td></tr>
<tr><td>Split (ducted)</td></tr>
<tr><td>Split (non-ducted) larger</td><td rowspan="4">R-410A, R-407C, HFC-32, R-444B, R-446A, R-447A</td></tr>
<tr><td>Multi-split</td></tr>
<tr><td>Packaged rooftop</td></tr>
<tr><td>Ducted commercial split</td></tr>
</table>

NOTE: All the options are not universally applicable in the listed equipment types and this list is not exhaustive.

7.3.13 Charge reduction

In general, there is a tendency for an increase in specific refrigerant charge due to increasing efficiency implications. When the design of a system remains principally the same (such as heat exchanger configuration), an increase in system efficiency is typically coupled with a greater specific charge due to the need of larger heat exchanger surfaces to reduce approach temperature differences, thus larger internal volumes and refrigerant amount (ICF, 2006). As an example, in the United States, the minimum efficiency of residential air conditioners that can be manufactured was increased in 2006 from “10 SEER” (2.93 kWh/kWh) to “13 SEER” (3.81 kWh/kWh), by approximately 30%. Products meeting the new minimum efficiency levels have specific charges some 20 to 40% greater than the products meeting the prior minimum efficiency levels (ICF, 2006).

Contrarily, the object of refrigerant charge reduction is becoming an increasingly important consideration in the design of air conditioning systems. There are several reasons for this and these mostly depend upon refrigerant types.

- Cost reduction. A smaller refrigerant charge means less expenditure on refrigerant, which is likely to be of greater importance as newer substances are likely to demand much higher costs. Furthermore, since a lower charge often corresponds to smaller component volumes, less expenditure of materials is implied.
- Reduction in environmental impact. A smaller charge corresponds to a smaller potential contained impact (in terms of mass × ODP or mass × GWP). Moreover, the degradation of system performance arising from a loss of refrigerant is likely to be observed sooner and remedial action can be taken to minimise further leakage.
- Risk mitigation. For all refrigerants, but moreover for flammable substances, a smaller quantity of refrigerant equates to a smaller risk (assuming no other differences in conditions). So in situations where it is desirable to reduce the risk associated with a particular refrigerant, a reduction in charge can bring the interpretation of risk to a more acceptable level. Furthermore, certain safety standards

impose charge size limits for refrigerants in different situations (see Annex to Chapter 2) and through a process of charge reduction, the extent of use of a given refrigerant in a particular situation can be extended.

A reduced refrigerant charge can have both positive and negative effects on system efficiency (for a given capacity) (Poggia et al., 2008). In addition, a disadvantage of reducing the charge size is that the performance of systems tends to be more sensitive to leakage, i.e., greater degradation of efficiency and capacity can occur for the same amount of refrigerant lost. It is important to carry out charge reduction commensurate with system performance optimisation, also considering the impact on reverse mode operation and defrosting (if relevant). Considerable research has and continues to be conducted into reducing refrigerant charge levels (Fernado and Lundquist, 2005). Most large system manufacturers actively pursue developments in charge reduction and there are regular IIR conferences on the topic.
In carrying out charge reduction, consideration of the typical refrigerant quantities within different components can be useful to help identify target areas; for most air conditioners, condenser, compressor, evaporator and liquid line should be approached. Techniques include use of mini- or micro-channel heat exchangers, evaporative condensers, flat tube heat exchangers and/or pipework, smaller tube diameters, oil selection for low solubility, small internal volume compressors and avoidance or careful selection of liquid receivers and accumulators (GIZ, 2010). Further discussion on this topic is in Chapter 11.

7.3.14 Not-in-kind alternative technologies

In past assessment reports, a number of potential new technologies were presented as options that could have a positive impact on the phase-out of ODS refrigerants. Some of the technologies presented in prior assessments were: absorption, desiccant cooling systems, Stirling systems, thermoelectric and number of other thermodynamic cycles. However, a search of the literature published since the previous assessment has continued to confirm that most of these technologies have not progressed much closer to widespread commercial viability for air-cooled air conditioning applications than they were at the time of the 1990 and the four subsequent assessment reports and will therefore not be discussed further.

7.4 Options for existing equipment

As the HCFC phase-out proceeds in non-Article 5 or Article 5 countries, there remains a need to service the installed population of products until the end of their useful lives. When servicing these products the treatment of refrigerant can fall into the following categories:

- Use existing refrigerant
- Refrigerant replacement only[2]
- Retrofit (refrigerant change and system components)
- Conversion (to flammable refrigerant)

Most of these categories are likely to be important for Article 5 countries because systems are often repaired several times in order to extend their useful lives. There are a large number of Low Volume Consuming (LVC) countries, which import rather than manufacture air-conditioners where most of the HCFC consumption is used to service the installed base of air-conditioners. In these countries, HCFC consumption can be reduced by the use of service refrigerants or by retrofitting existing equipment to non-ODP refrigerants. An additional less desirable option because of cost would be to replace the existing equipment before the end of its useful life. In non-Article 5 countries, unit replacement is more common because the costs

[2] Usually the term "drop-in" is used for this type of replacement. However, since there are no alternatives with identical thermophysical, safety and chemical properties as the existing refrigerant (e.g., HCFC-22) then the phrase "refrigerant replacement only" is used to substitute the term "drop-in".

associated with performing a major repair or retrofit can often be greater than the cost to replace the product. The need for retrofit and replacement refrigerants will largely be determined by the size of the installed population of HCFC-22 products, HCFC phase-out schedule, allowed "service tail"[3], the availability of HCFC-22 and the recovery and reclaim practices in place leading up to the phase-out. The installed population of air conditioners and heat pumps has an average service life in non-Article 5 countries of 15 to 20 years and may be longer in Article 5 countries. Therefore, implementing recovery and reclaim programmes coupled with the availability of replacement and retrofit refrigerants could help reduce the demand for HCFC-22.

Using the existing refrigerant following a repair, one can follow normal practices using virgin, recycled or reclaimed refrigerant (i.e., typically HCFC-22).

For refrigerant replacement only, HCFC is replaced with a blend, but without changing the lubricant used in the original equipment or any other system component. Refrigerants used for this activity are sometimes referred to as "service blends" or "drop-ins". Such a change in refrigerant in most cases results in a lower capacity and/or efficiency, different operating pressures, temperatures and compressor power compared to HCFC.

Retrofit refers to not only changing the refrigerant, but also system components such as lubricant (although not always necessary), filter dryer (if required) and more extensive modifications which could include the replacement of the compressor, refrigerant, lubricant, dryer, expansion device, and purging and flushing the system to remove all residual lubricant from the system. Retrofitting can be substantially more costly than using existing refrigerant, replacing the refrigerant without additional changes or even unit replacement; it is probably not cost effective if either the compressor or heat exchangers have to be replaced.

Conversion is where the existing refrigerant is replaced with another without necessarily having to address the refrigeration circuit components and lubricant in the same way as retrofit, but because the replacement refrigerant is flammable, the external aspects of the equipment, such as potential sources of ignition, have to be addressed. However, since this is a complex process and can lead to unforeseen safety risks, it is not normally recommended. Again, such a change in refrigerant can affect capacity and/or efficiency, operating pressures, temperatures, lubricity, etc., to HCFC.

In the case of refrigerant replacement and retrofit in HCFC systems, the GWP of the new should also be given consideration as many blends have a GWP higher than HCFC.

In all cases, before changing the refrigerant it is recommended that the system manufacturer be consulted.

7.4.1 Replacement refrigerants only

There are several refrigerants currently introduced to replace HCFC-22 for servicing. They generally combine two or more HFC refrigerants with a small amount of HC (or certain HFC refrigerants, such a HFC-227ea), which are added to the blend to enable the refrigerant to work with the naphthenic mineral-oil-based and alkyl benzene lubricants used in nearly all HCFC-22 air conditioning systems. Thus these refrigerants attempt to mimic the performance of HCFC-22. However, they seldom perform as well as HCFC-22; having either lower capacity, efficiency or both. For example, in a split air conditioner Spatz and Richard (2002) showed that R-417A exhibited a 10% drop in both capacity and COP at standard test conditions, compared to HCFC-22. Calorimeter tests of Allgood et al. (2010) showed that R-438A has a capacity and COP around 7% and 2% lower than HCFC-22, respectively. A study

[3] The term "service tail" is used to describe the time between when a refrigerant has been phased out for use in new equipment and the date at which the refrigerant may no longer be produced.

by Messineo et al. (2012) found that none of the HFC blends, R-417A, R-407C and R-404A performed better than HCFC-22 when measured in field trails in an air conditioning system.

Although not conventionally used for air conditioners, Bolaji (2011) compared R-404A and R-507A against HCFC-22 in a window air conditioner. The average refrigeration capacities of R-507A and R-404A were 4.7% higher and 8.4% lower than that of HCFC-22, respectively, while the average COP were increased by 10.6% and reduced by 16.0%.

In addition to the performance and efficiency impacts the blends may not perform the same for oil return. HCs are added to allow for the oil return, but it may not be as effective and problems could result at lower loads and extreme operating point seen during high ambient temperatures and heat pump operation.

A selection of the many commercially available HCFC-22 replacement blends is listed in Table 7-2. Compressor and system manufacturers often carry out evaluations of such refrigerant options and provide recommendations as to which they believe are suitable for use in their equipment. Information on the application of these blends can be obtained from manufacturers. It may also be recognised that since some HCFC-22 compressors are now supplied with POE oils, R-407C or similar HFCs could in principle be used as a direct replacement.

There are a number of criteria that should be achieved in order for a replacement only refrigerant to be selected and these are discussed in Chapter 2.

7.4.2 Retrofit refrigerants

A number of the HFC blends proposed for alternatives to HCFC-22 in air conditioners, are also deemed as suitable retrofit refrigerants for HCFC-22 systems; examples of such HFC blends are listed in Table 7-2.

Whilst many of the proposed blends are seldom used, R-407C has been demonstrated to be an acceptable retrofit refrigerant and has seen widespread use in some regions. This is especially the case in regions with high ambient temperatures as the capacity drop at elevated temperatures is relatively lower than that of R-410A, although there is some loss in capacity and efficiency compared to HCFC 22. Devotta et al. (2005a) found a 2-8% drop in capacity and 8-14% increase in COP when a window type HCFC-22 air conditioner was retrofitted with R-407C. Conversely, a drop of about 7% in COP was observed by Raghavan and Pss (2010). Gopalnarayanan and Rolotti (2000) tested a reversible split system in both cooling and heating mode and found that in cooling mode R-407C capacity matched that of HCFC-22 and there was a marginal increase in COP when the oil was changed from a mineral to a POE oil. However, in heating mode, there was a capacity and COP drop of less than 5%. Fathouh et al. (2010) found that the cooling capacity and COP was around 8% and 6% lower, respectively for R-407C. Judge et al (1995) tested two different units and showed that in one, the cooling capacity was marginally lower than HCFC-22 with 10% loss in COP, whereas in another unit there was a marginal increase in capacity and a 5% drop in COP.

As indicated, provided that the compressor already uses a mineral oil, a change from HCFC-22 to R-407C requires that the existing naphthenic mineral oil or alkyl benzene synthetic oil lubricant be replaced and filter driers that are able to absorb breakdown products from synthetic lubricants should also be installed. The disadvantage of using high glide blends is the need to remove and replace the entire charge during servicing to avoid substantial composition shift. However, because R-407C has a moderate glide, laboratory and field experience indicates R-407C can be serviced without replacing the entire refrigerant charge with minimal impact on performance. The other HFC blends will tend to have similar practical implications as R-407C.

The criteria for selecting a suitable retrofit refrigerant are discussed in section Chapter 2.

7.4.3 Conversion to flammable refrigerants

HC refrigerants such as HC-290, HC-1270 and blends including these as well as HC-170 and R-E170 (e.g., R-433A, R-433B, R-433C, R-441A and R-443A) are being used as conversion replacements for HCFC-22 in some regions, typically in small systems (such as window and single splits). Some countries are including this approach in their HCFC phase-out strategies, whilst the practice is not legal in other countries (such as in USA). While these refrigerants may provide capacity and efficiency close to HCFC-22 (see examples in section 7.3), this practice can create a significant safety hazard because of the flammability of these refrigerants. In general, HCs are not recommended for use in systems that have not been specifically designed appropriately. If HCs are being considered then the applicable safety standards and codes of practice should be strictly followed. The GIZ Handbook for Hydrocarbon Safety (GIZ, 2010) is one source of information on the utilisation of these refrigerants.

In addition to the above, there are also some other mixtures with class 3 flammability being marketed, which in addition to HCs also comprise R-E170 (dimethyl ether) and HFC-152a. For example, Park et al. (2009a) measured performance of R-431A and HCFC-22 under air-conditioning and heat pumping conditions. Results showed that the COP of R-431A is 4% higher than that of HCFC-22 while the capacity of R-431A is similar under both conditions. Comparing the performance of R-432A and HCFC-22, Park et al. (2009b) showed that the COP and capacity of R-432A are 9% and 2 – 6% higher for both conditions.

7.5 High ambient considerations

The objective of this section is to summarise the performance of the various HCFC-22 options for high ambient air conditioning applications; “high ambient” is considered to be between 40°C and 55°C (which represents the maximum rating conditions for the Middle East region).

The governing thermodynamic properties and principles result in a declining capacity and efficiency for all refrigerants as the heat-rejection (refrigerant condensing) temperature increases, including HCFC-22. However, some of the HCFC-22 replacements exhibit greater degradation in capacity and efficiency than HCFC-22 under high ambient conditions. Another consideration is with regards to the possible impact on required refrigerant charge, where hotter regions can imply greater head loads, larger system capacity and thus larger refrigerant charge. Therefore where limits on refrigerant charge apply, those limits may be approached at smaller capacities; in these cases additional (safety) measures may need to be applied to the equipment.

Currently, the most widely applied replacements for HCFC-22 in these air conditioning applications are HFC blends, primarily R-410A and R-407C. HCs are also being used in some low refrigerant-charge applications. R-410A and R-407C both have lower critical temperatures than HCFC-22 (refer to Chapter 2 for values) because HFC-125 (a component of both R-407C and R-410A) has a comparatively low critical point temperature; this is an important parameter since such refrigerants will exhibit a steeper decline in capacity with increased ambient (outdoor) temperatures than refrigerants having higher critical temperatures. This steeper decline in capacity is of particular importance in geographic regions, which have condensing design temperatures approaching the critical temperature of the refrigerant.

As well as the use of high efficiency components, the optimum selection of compressor, airflow, condenser design (i.e., tube diameter, fin design, coil circuitry, etc.) and expansion device can reduce the performance losses at high ambient temperatures (Bitzer, 2012). If the curve is steep something must be done about the starting point. i.e., the reference efficiency should be set at a higher level in order to compensate for the possibility of lower efficiency at high ambient conditions. Thus for most refrigerants, by taking measures to appropriately optimise the system, similar efficiencies to HCFC-22 can be achieved at higher ambient temperatures.

Systems using low-GWP refrigerants are not currently available for large capacity systems in most regions with high ambient temperatures.

7.5.1 Performance of alternatives under high ambient temperatures

Table 7-3A: Comparative theoretical cycle volumetric refrigerating capacity of selected alternatives relative to HCFC-22

	Condensing temperature			
	40°C	50°C	60°C	70°C
HCFC-22	100%	100%	100%	100%
HFC-32	100%	99%	99%	98%
HFC-134a	100%	98%	96%	94%
HFC-152a	100%	100%	101%	102%
HFC-161	100%	100%	101%	103%
HC-290	100%	98%	96%	93%
HFC-1234yf	100%	96%	91%	85%
HC-1270	100%	99%	97%	94%
R-407C	100%	98% (97%)	96% (94%)	92% (90%)
R-410A	100%	97%	93%	86%
R-444B	100%	99%	98% (97%)	96% (94%)
R-446A	100%	99%	97%	95% (94%)
R-447A	100%	99% (98%)	97% (96%)	94% (93%)

NOTE: Condenser subcooling = 5 K; evaporating temperature = +10°C; evaporator exit superheat = 5 K; suction line superheat = 0 K; volumetric efficiency = 100%; properties from Refprop9; reference condition for blends: dew point and mid-point (in parentheses, if different)

Table 7-3B: Comparative theoretical cycle COP of selected alternatives relative to HCFC22

	Condensing temperature			
	40°C	50°C	60°C	70°C
HCFC-22	100%	100%	100%	100%
HFC-32	100%	99%	97%	95%
HFC-134a	100%	99%	99%	97%
HFC-152a	100%	101%	102%	104%
HFC-161	100%	101%	102%	103%
HC-290	100%	99%	98%	95%
HFC-1234yf	100%	98%	94%	90%
HC-1270	100%	99%	98%	95%
R-407C	100%	99%	97%	94% (93%)
R-410A	100%	97%	93%	86%
R-444B	100%	100% (99%)	99% (98%)	97%
R-446A	100%	99%	97%	95% (94%)
R-447A	100%	99%	97%	94%

NOTE: Condenser subcooling = 5 K; evaporating temperature = +10°C; evaporator exit superheat = 5 K; suction line superheat = 0 K; global compressor efficiency = 100%; properties from Refprop9; reference condition for blends: dew-point and mid-point (in parentheses, if different)

As an initial reference point, Table 7-3A and 7-3B provide the results of theoretical refrigerant performance calculations for various alternative refrigerants at elevated condensing temperatures, when compared against HCFC-22 at a reference condition of 40°C.[4] Performance in real systems and measures to design and optimise systems for high ambient conditions are discussed in the following sections.

R-410A

R-410A systems have been demonstrated to operate acceptably at ambient temperatures up to 52°C. The performance (capacity and efficiency) of R-410A air-conditioners falls off more rapidly than HCFC-22 systems at high ambient temperatures (above 40°C). At a condensing temperature of 70°C, both capacity and COP of R-410A degrades by around 14% relative to HCFC-22, as shown in Table 7.3. Very few studies are available in the literature to illustrate the extent of performance depredation in real systems. In one, Domanski and Payne (2002) report on measurements of an air conditioner comparing HCFC-22 and R-410A but with two different compressors. With one compressor, R-410A indicated a 7-8% reduction in capacity at 52°C and around 14 – 20% drop in COP.

Even with optimised designs, systems that will operate a significant number of hours at high ambient temperatures, the system designer should take into consideration the reduced high ambient capacity when sizing the equipment. For cases where the base capacity of the unit would need to be increased to meet the building load at extreme ambient temperatures the cost impact can be approximated as proportional to the respective capacity degradation.
A few studies where made to enhance the performance of the R-410A refrigerant in high ambient conditions. Chin and Spatz (1999) also conducted simulations comparing HCFC-22 against R-410A, showing a 6% and 7% drop in capacity and COP, respectively, at 52°C ambient. Another study by Wang et al. (2009) for a two-stage heat pump system with special vapour-injected scroll compressor showed an enhancement on the cooling capacity of R-410A at high ambient conditions as high as 15% and an enhancement of the COP between 2 – 4%.

R-407C

R-407C systems will typically perform in nearly the same way as HCFC-22 systems at typical ambient temperatures. At ambient temperatures above 40°C, R-407C systems show less degradation of capacity and efficiency than R-410A systems. However, an R-407C system will still exhibit a capacity approximately 8% less than an HCFC-22 system at a condensing temperature of 70°C and 6% reduction in COP (Table 7-3).

Even though the R-407C is in most cases more preferable to be used in air conditioning systems than HFC-32 and R-410A because the thermodynamic characteristic are much closer to HCFC-22, the effect of the high temperature glide of R-407C only has a minor effect in the new systems. As such R-407C can be considered better option than R-410A for high ambient regions.

HFC-134a

HFC-134a has a relatively high critical temperature. However, theoretical cycle calculations show that the performance degradation relative to HCFC-22 at high ambient temperature shows 6% lower capacity and 3 % lower COP.

HC-290

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[4] (To put these values into context, it must be noted that the capacity of HCFC-22 falls by 25% and its COP reduces by 60% as the condensing temperature rises from 40°C to 70°C. Thus, degradation of (for example) 10% of one alternative relative to HCFC-22 represents only 2½% and 6% further absolute reduction, respectively.)

HC-290 has performance characteristics similar to HCFC-22 and the characteristics are close enough that the current products that employ HCFC-22 could be re-engineered to employ HC-290. HC-290 has successfully been demonstrated as an HCFC-22 replacement in low charge, room and portable air-conditioners applications (Devotta et al., 2005; Padalkar et al, 2014) for regions that experience high ambient conditions.

HC-290 shows a 4% reduction in capacity at 70°C based on theoretical calculations (Table 7-3). Some recent studies at ambient temperatures up to 54°C (Chen, 2012; Rajadhyaksha et al, 2013; Li, 2014b) showed the degradation of capacity and COP of HC-290 relative to HCFC-22 at high ambient temperature to be within 3%. An intensive study by Wu et al. (2012a) showed results at high ambient temperatures as similar to HCFC-22. The use of special design heat exchangers like micro channel aluminium type showed favourable results and the refrigerant charge can be reduced as low as 0.07 kg/kW or even less (Rajadhyaksha et al, 2014).

HC-1270

HC-1270 has performance characteristics similar to HCFC-22 and the characteristics are close enough that the current products that employ HCFC-22 could be re-engineered to employ HC-1270. Based on theoretical cycle calculations, HC-1270 shows a 7% reduction in capacity at 70°C and a 3% reduction in COP relative to HCFC-22 (Table 7-3).

HFC-32

HFC-32 is being considered as an alternative to R-410A with a higher efficiency and capacity at high ambient temperatures, although worse than HCFC-22, where the capacity is approximately 2% less and COP 5% in theoretical cycle calculations (Table 7-3). Discharge temperature can be from 5 K to 30 K higher than R-410A and HCFC-22. However, this can be managed by injection technology or wet suction control, although this implies at a cost and/or performance penalty to the AC. It can also be tackled by adjusting the viscosity of oil (Piao et al., 2012), although this impacts reliability.

A performance comparison of R-410A and HFC-32 in vapour injection cycles (Xu et al., 2012) shows HFC-32 is slightly better than R-410A at higher ambient conditions. In Piao et al. (2012), HFC-32 achieves the same COP as HCFC-22 at 52°C if the COP of HFC-32 at rating conditions is 9.4% higher than HCFC-22. Consistent with this, Chen (2012) showed that HFC-32 has a small relative drop in capacity compared to HCFC-22, yet at 52°C it exhibits a 10% relative reduction in COP. Again, as with other alternatives, this loss in performance can be managed through system and/or compressor technology, which may or may not incur cost implications. The use of an injection circuit (to reduce excessively high discharge temperature, in excess of 137°C), whilst not affecting COP results in a 5% drop in capacity relative to HCFC-22. The injection yields the benefit of reducing discharge temperature to 115°C, although this is still about 5 K above both HCFC-22 and R-410A.

R-744

The desirable characteristics of R-744 are offset by the fact that it has a very low critical temperature (31°C) and will operate above the critical point conditions in most air-conditioning applications. Operation at these conditions results in a significant degradation in both capacity and COP at high ambient temperatures. These losses can be partially offset by the addition of internal cycle heat exchangers and expanders or ejectors. However, R-744 systems are not expected to provide a cost effective alternative to HCFC-22 or HFC refrigerants when being applied in high temperature regions (> 40°C).

HFC-161

At a 70°C condensing temperature HFC-161 has a theoretical capacity and COP approximately 3% greater than HCFC-22 (Table 7-3) and exhibits a considerably better high ambient performance than R-410A. Practical measurements by Wu et al. (2012b) support these theoretical characteristics, where the relative COP and capacity of HFC-161 improve relative to HCFC-22 as the ambient temperature increases. As such, this implies interesting possibilities for countries, which experience hot climates.

HFC-152a

HFC-152a has performance characteristics similar to HFC-134a. Although activities within industry indicate little interest in this substance currently, HFC-152a has performance better than that of HCFC-22, showing a 3% increase in capacity at 70°C and a 4% increase in COP relative to HCFC-22 (Table 7-3).

HFC-1234yf

HFC-1234yf ordinarily has performance characteristics similar to HFC-134a. However, considering behaviour at high ambient conditions, the degradation of performance is closer to R-410A, where there is a 15% reduction in capacity at 70°C and a 10% reduction in COP relative to HCFC-22 (Table 7-3) based on theoretical cycle calculations.

R-444B

R-444B systems are expected to perform similar to HCFC-22 systems at high ambient temperatures; theoretical cycle performance indicates that the capacity and COP are about 5% and 3% lower, respectively, relative to HCFC-22 (Table 7-3). Tests on a split air conditioner (with modified capillary tube and evaporator circuitry to account for the temperature glide) achieved identical capacity and COP as HCFC-22 at both 46°C and 52°C ambient (Sethi et al, 2014). The discharge temperature is also the same as with HCFC-22.

R-446A and R-447A

R-446A and R-447A systems are expected to perform slightly worse compared to HCFC-22 high ambient temperatures; theoretical cycle performance indicates that the performance is around 5-7% lower relative to HCFC-22 (Table 7-3). Tests on a split air conditioner, showed a degradation of both capacity and COP about 5% worse than R-410A at 46°C ambient from a baseline of 35°C (Alabdulkarem et al, 2013).

7.5.2 Measures to design and optimise air-conditioners for high ambient conditions

There are several aspects that can be considered important when adapting equipment for use in high ambient conditions.

The evaporator coil design should be reselected to adopt the new pressure and pressure drop characteristics at high ambient conditions for the replacement refrigerants. Also the tube diameter can be reduced to enhance the heat transfer for the evaporator coils; typically using ¼ inch OD tube diameters will enhance the performance and can bear higher pressures for high pressure refrigerants like R-410A and HFC-32.

The condenser coil design should also be reselected to accommodate the new pressure drop characteristics for the replacement refrigerants. Micro channel aluminium coils can be used in order to enhance the heat transfer and to reduce the condensing temperature at high ambient conditions, whilst larger condenser coils and special condenser fans also can be used to reduce the condensing temperature at high ambient conditions. Controlling the subcooling by using condensers with dedicated subcooling circuits is vital in high ambient conditions to enhance the efficiency (Qureshi et al., 2012).

Special types of compressors are needed for the high pressure refrigerants such R-744. While normally the same compressor design can be used for R-407C and HC-290, larger displacement compressors (~10%) can be used to compensate for the lower capacity resulting from using these refrigerants. It should also be considered to add vapour and/or liquid injection to an intermediate pressure area in the compressor to enhance the performance at high ambient conditions. Additionally techniques can be applied to the compressor, such as oil flooding or vapour injection, which can yield significant benefits (Bahman et al, 2014).

Another consideration is the use of a thermostatic expansion valve instead of a capillary tube. In fact the use of capillary tubes for small air conditioners is not recommended, especially at high ambient conditions (Chinnaraj et al, 2011; Zhou and Zhang, 2010). The wide range of temperatures make the use of capillary tubes impossible for sufficiently accurate control of superheat where subsequently compressor discharge temperatures will affect the performance of the whole system (Chen et al, 2009) and is also useful to accurately control both suction gas superheat, discharge temperature and subcooling in the circuit.

7.6 Concluding remarks

HCFC-22 remains the dominant refrigerant in use, where the refrigerant bank for unitary air conditioners is estimated to be in excess of 1 million tonnes. In new systems, HCFC-22 is only being used in Article 5 countries. The HFC blend R-410A is the most common alternative and to a limited extent R-407C along with HFC-134a are used in regions with high ambient temperatures. HC-290 is being used in split systems, window and portable air conditioners. HFC-32 is being used in split systems and is being proposed for larger ducted and multi-split systems. These various alternatives highlighted have also been found to achieve performance approaching, as good as or better than HCFC-22.

In general there is still a significant proportion of the sector throughout almost all Article 5 countries that remains to be shifted from HCFC-22 to a zero ODP alternative. R-410A is increasingly becoming considered unacceptable because its high GWP and so investigations into medium and low GWP alternatives is continuing. In cooler climates, R-744 is available for commercial sized systems and the technology is further being explored. There are a large number of new mixtures being considered for air conditioning systems primarily consisting of HFCs and unsaturated HFCs, such as R-444B, R-446A and R-447A. Although there is concern over the use of R-410A in high ambient temperatures, appropriate design measures can be used to help remedy the relatively greater degradation in performance; nevertheless, work is underway to investigate this refrigerant and others further.

The forthcoming direction remains unclear in terms of which alternatives this sector, sub-sectors and regions will settle upon. It is likely that different manufacturers and countries will opt for a variety of alternatives before any single option is chosen (if at all). In the meantime, investigations will continue into medium GWP flammable HFCs, HFC/unsaturated HFC blends and HCs for normal operating conditions as well as high ambient.

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Chapter 8

Water Heating Heat Pumps

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8 Water heating heat pumps

8.1 Introduction

Heat pumps are able to upgrade (“pump”) heat from a lower temperature to a useful higher temperature level. The heat is used for space heating, service (including domestic) water heating, and manufacturing process heating. The heat sources are generally ambient air, water or ground-source heat. The heat sink can be air, water or a process fluid. This chapter covers only systems where water is the sink (grey zone indicated in Table 8-1). The products for industrial process heating, large capacity systems, typically MW capacity, are covered in chapter 5 “Industrial systems”. Air-to-air heat pumps are the most widely used heat pumps. Their construction and refrigerant use are similar to air conditioners; therefore they are covered in chapter 7 “Air-to-air air conditioners and heat pumps”.

The temperature difference between the source and sink has a direct impact on the pressure difference the compressor must meet for a specific refrigerant. In general, heat pump systems will be less efficient under higher temperature difference condition. The required compressor power input is a fraction of the total useful energy delivered. The required input power to the heat pump is mainly dictated by the heating capacity required from the heat pump, the temperature difference between the source and sink, the effectiveness of heat exchangers and compressor/driver efficiency. Required power input to water pumps and fans must be included to determine the power consumption of the total heat pump system. The heat pump overall coefficient of performance (COP) is defined as the useful heat delivered divided by the total power input. Recent standards and regulations are referring to a seasonal coefficient of performance (SCOP) defined as the useful heat delivered during the heating season divided by the corresponding power input.

Heat pumps are in most applications an alternative to fossil fuel gas or oil combustion boilers, often resulting in a significant reduction in CO_2 emission and primary energy consumption. The cost of the equipment and efficiency are most important to compete with fossil fuel solutions.

In 2012 the global air to water heat pump market increased by around 5.4 % to 1,37 million units. Both Europe and China had an increase of respectively 7% and 11%, while Japan had a drop of 12.8% (JARN, 2013/08).

The Ozone Depleting Potential (ODP) and Global Warming Potential (GWP) values of the refrigerants mentioned in this chapter are given in chapter 2 of this report.

8.2 Heat pump types, implications and trends

8.2.1 Heat pump types

Heat pumps are classified by heat source (air, water, and ground) and heat sink (air, water), resulting in the following naming of heat pumps used in this chapter as given in Table 8.1.

Table 8-1: Heat pump classification

			Heat source (direct expansion or indirect expansion system)		
			Air	Water	Ground
Heat sink	Air		Air to air	Water to air	Ground to air
	Water	Water heater	Air to water	Water to water	Ground to water
		Space heating			
		Combined			

Air-source heat pumps are equipped with air-to-refrigerant evaporator coils and fans to obtain heat from the ambient air. Water-source heat pumps are equipped with water-to-refrigerant evaporators and a water circulation pump to obtain the heat from a water source. Ground source heat pumps are generally equipped with a brine-to-refrigerant evaporator and brine to ground tubes combined with a circulation pump or, refrigerant-to-ground evaporator tubes to obtain heat from the ground. The tubes in the ground are installed horizontally one to a few meters below ground level or installed in a vertical drilled hole, typically 50-150 m deep.

Most heat pumps are driven by electric motors, but gas engine drives are also used to a small extent. Heat pumps may also be thermally driven, using a sorption or ejector concept.

It is also possible to classify heat pumps by types depending on the usage:

1) Heat pump water heaters (HPWH)
2) Space heating heat pumps
3) Combined water and space heating heat pumps

Heat Pump Water Heaters (HPWH)

Heat pump water heaters (HPWH) are a category of heat pumps designed to heat domestic and other service hot water to temperatures between 50 and 90 °C. These operating temperatures must be considered when selecting the refrigerant.

A HPWH basically 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 city water supply is heated by the condenser or, for trans-critical cycles using R-744 the gas cooler of the refrigerant circuit or, for absorption cycles by both condenser and absorber, and then returned to the storage tank or used directly for service. Stored hot water is supplied to each tapping point, in response to the demand.

The basic components of the heat pump unit are: a compressor driven by an electric motor or gas engine, a condenser or a gas cooler for heating water, an evaporator to absorb heat from the heat source, refrigerant, a refrigerant expansion device, and a control unit. Heat pump units that use R-744 as a refrigerant typically use an additional internal heat exchanger, and in some cases, an ejector or expander to improve energy efficiency. Different from mechanical compression type heat pumps, there is not any mechanical compressor for absorption types. Instead one or two generators, one or two solution heat exchangers, one or two solution valves and a solution pump are used.

Space Heating Heat Pumps

A space heating heat pump is optimised for comfort heating. Comfort heating heats the room by heating water for distribution to an air handling unit, radiator or under floor panel. The required water temperature depends 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 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.

A space heating heat pump using water for distribution generally consists of a heat pump unit and often an additional heat exchanger unit and a water storage tank. Several different configurations are used. The basic components of a heat pump space heating unit are similar to those of heat pump water heaters.

In most cases air source heat pumps are used for space heating. Ground and water source heat pumps are also used, especially in colder regions, but they represent a smaller segment of the total heat pump market.

Combined Space and Hot Water Heat Pumps

Combined water heating and space heating heat pumps have two functions, supplying hot tap water and providing space heating. Several configurations of combined space and water heating heat pumps exist in order to optimise the seasonal energy efficiency for a specific application. In most configurations a water storage tank is used to store the domestic hot water and also to act as a small heat buffer for the space heating function.

In order to obtain high water temperatures at low outdoor ambient temperatures, air to water heat pump systems can utilise a multistage compression system or a cascade refrigerating system with different refrigerants for each stage in the cascade.

Capacity Ranges of Water and Space Heating Heat Pumps

Table 8-2 lists the most common heating capacity range offered by single units of each type of heat pumps.

Table 8-2: Heat pump capacity ranges

Heat pump type	**Capacity Range (kW)**
Heat pump water heater	1.5 – 50
Space heating heat pump	4 – 400
Combined water and space heating heat pump	6 – 45

8.2.2 Heat pump implications and trends

Most of the space heating and water heating systems globally use fossil fuels. Since fossil fuel burning systems generate CO_2 during combustion, they contribute to global warming. Heat pumps also contribute to global warming, but in a different way. The contribution to global warming is only related to CO_2 emissions in the generation of the electricity to drive the compressor and possible direct contributions due to refrigerant emissions. Therefore, the heat pumps energy efficiency is the primary environmental consideration. Efficient heat pumps can reduce global warming impact compared with fossil fuel burning systems significantly, typically in the range of 50-80% whilst inefficient heat pumps can lead to a significant increase in global warming impact. The reduction depends on the efficiency level of the heat pump and the carbon emission per kWh of the electricity generation.

The tendency of decarbonisation of electricity strengthens this positive effect. Also the efficiency levels of heat pumps are being improved year by year. However, the investment in a heat pump is in most cases more expensive than a fossil fuel system because they employ complicated refrigerant circuits, compressors, larger heat exchangers and other special features. The majority of purchasers have not yet accepted the significantly higher first costs of heat pumps as a means to reduce running costs, compared to lower first cost fossil fuel based space and water heating systems, especially in colder regions.

In 2013 the EU commission decided upon a common energy label (commission delegated regulation No 811/2013) for hydronic heating systems comparing the primary energy efficiency of all major heat generators. This may have a positive impact on the heat pump applications in Europe. Minimum efficiency requirements are set separate for heat pumps. Both the energy label and minimum efficiency requirements will have a major impact on the refrigerant choice. Air source heat pumps have become the most popular heat pump type in

Europe. They have experienced strong growth over the last several years because of their economic benefits and recognition as renewable energy source. The positive environmental aspects and potential market growth of heat pumps must be taken into account when refrigerant options and limitations are considered

In Japan, heat pump water heaters using the refrigerant R-744 have become very popular in recent years under the trade name "Eco-cute" and are also introduced in Europe. These heat pump water heaters were launched in 2001. Between 2008 and 2011, there were annual sales of around 500,000 units (JARN, 2013/08). An evaluation method for defining the annual performance factor of heat pump water heaters has been established in Japan. This method considers the typical Japanese life style usage of hot tap water.

In the USA, commercial interest for combined water and space heating heat pumps resumed in late 2009 and 2010. Three major and several additional manufacturers began marketing newer, more efficient integral designs in 2010. These new products use either HFC-134a or R-410A as the refrigerant, but the split between them is uncertain. Predicated on the new efficiency standards and analyses used in development of national requirements, estimated HPWH shipments in the USA are 10,000 units per year in 2010, 260,000 units per year by 2015, and - though somewhat speculative - 270,000 or more units per year by 2020.

The general trend when taking new building standards into account is that the relative importance of tap water heating will increase compared to space heating. It is expected that this will be reflected in future systems.

8.3 Options for new equipment

In most non-article 5 countries the transfer to non-ODS refrigerants was completed several years ago. But, based on its favourable thermodynamic properties and high efficiency in heat pump applications, HCFC-22 is still in use for high and moderate temperature water and space heating heat pumps in the A5 countries.

When selecting refrigerants, both the direct and indirect climate impacts must be considered (see chapter 2 and chapter 11). For heat pumps, the reduction in emission resulting from replacing fossil fuel burning may be the most important factor regarding greenhouse gas emissions.

Options for new heat pumps include HFC-32, HFC-134a, R-407C, R-410A, R-417A, HFC-1234yf, new HFC blends, HC-290, HC-600a, R-744 and R-717.

Studies of new low-GWP fluorochemicals (notably unsaturated HFCs – see Chapter 2 "*Refrigerants*") in heat pumps are ongoing, notably in several European countries, Japan and the USA. Similar studies are underway to evaluate use or broader use of R-744 and hydrocarbons as refrigerants in several types of heat pumps, though actual product development and commercialization are limited to Europe and Japan at present.

8.3.1 HFC-134a and HFC blends R-407C, R-417A and R-410A

HFC-134a, R-407C and R-410A are used widely in heat pump systems and are well commercialised globally. R-417A is used in heat pump application in existing systems as well as in new equipment.

These refrigerants are being used in high to low temperature water and space heating heat pumps, in countries where HCFC-22 consumption reduction started in advance of the Montreal Protocol. These refrigerants are used mainly in Europe. In Japan R-410A is used and HFC-134a and R-410A are used in Canada and USA and to a lesser extent in Mexico and the Caribbean countries. R-407C has been used to mainly replace HCFC-22 in existing product designs because minimal design changes are required. However, the use of R-407C is declining in favour of the higher efficiency of R-410A and lower system cost. To use R-410A design changes are necessary to address its higher operating pressures and to optimise the system to its properties and thereby achieve a higher performance. Cascade heat pumps using HFC-134a and R-410A are commercialised in high temperature combined space and hot water heating heat pumps in Europe. These heat pumps have a relatively good performance and can operate without auxiliary electrical heaters. The heat pump can supply water at temperatures approaching 80 ºC.

Most new heat pump products are using refrigerant R-410A because it results in more compact and efficient systems when they are optimised.

Air to water split cascade systems are put on the market using R-410A for the low temperature and HFC-134a for the high temperature circuit. They guarantee high seasonal COP for colder climates even at high water sink temperatures, while keeping the required heating capacity without auxiliary electrical heaters. They are most used for combined space and hot water heating to replace existing boiler systems.

Energy efficiency of R-407C systems is typically poorer than HCFC-22, although similar COPs can be achieved if the system is carefully designed. R-407C shows a pronounced temperature glide in practice, which can lead to operational difficulties.

R-417A has been used by some manufactures for heat pump water heaters. R-417A provides lower capacity than HCFC-22 but has demonstrated its effectiveness at higher temperatures.

As the cost of the refrigerant itself is minor in the total system cost, limited differences in refrigerant cost have a minor effect. The cost of components has a major impact. A more compact design results in general in a lower cost. For larger systems the design pressure has a larger impact on the cost than for small systems. For small and medium size systems R-410A is the most cost effective, while for large systems HFC-134a is most effective.

There are no significant barriers to their use at the moment, but the high GWP of the refrigerants may put them under pressure to changes for lower GWP fluids.

8.3.2 HFC-32

The use of HFC-32 in water heating heat pumps is not commercialized yet on a larger scale.

HFC-32 has a higher operating efficiency than HCFC-22 and R-410A (Shigehara, 2001). It has saturation pressures slightly higher than R-410A which is approximately 60% higher than HCFC-22. The system refrigerant charge can be up to 43% less than for HCFC-22 while the energy efficiency is the same or higher (Yajima, 2000). It has better heat transfer and transport properties than R-410A due to lower molar mass. Since it has higher discharge temperatures than R-410A more accurate control of temperature is necessary especially for high temperature water heating heat pumps and low temperature heat source.

The direct cost of the pure HFC-32 substance is lower than R-410A, but this has limited effect on the system cost. Based on the refrigerant properties, the equipment is more compact and consequently potentially cheaper, while mitigation devices for high discharge temperature may add some cost.

The main barriers are related to the safe use of the lower flammable refrigerants (class 2L by ISO 817); see chapter 2. Standard ISO-5149 is updated in 2014 and IEC-60335-2-40 is in process of update to accommodate this new class. In general safety aspects during the lifecycle of the equipment are limited. However, some building codes do not allow the use of flammable refrigerants in certain type of buildings. If the refrigerant water heat exchanger is located in outside occupancy, the safety issue is easier to solve but frost prevention becomes an issue.

8.3.3 HFC-1234yf and other low-GWP HFC blends

HFC-1234yf is similar in thermophysical properties to HFC-134a.

A number of other unsaturated chemicals are being identified in the patent literature as possible low-GWP refrigerants for heat pumps. Blends with HFC-32 or HFC-125 may make it possible to approach the properties of HCFC-22 or R-410A, but it results in a higher GWP than pure HFC-1234yf. As sample supply of these refrigerants is very limited, it is too early to judge whether any of these chemicals will be commercialised and will show acceptable performance and competitiveness in heat pump systems. Due to the price competitiveness pure HFC-1234yf is not considered as a future solution.

For water heating and space heating heat pumps using HCFC-22, R-410A, R-407C, significant design changes would be required to optimise for HFC-1234yf. Some of the required changes include larger displacement compressors, larger diameter interconnecting and heat exchanger tubing and additional heat exchanger surface to offset lower heat transfer and higher flow resistance.

The heat transfer is expected to be lower than for R-410A systems because of its lower saturation pressure. The relatively higher pressure drop in the refrigerant pipes and heat exchanger will result in poor efficiency at high temperatures typical for heat pump water heaters.

As a new molecule due to a different manufacturing process, the HFC-1234yf and other Low-GWP HFC blend refrigerants has significant higher cost than that of HFC-134a. Components cost will be similar to HFC-134a, but the flammability will have effect for larger systems due to the pressure vessel codes.

The same restrictions as for HFC-32 apply (see Annex to Chapter 2).

8.3.4 R-744 (carbon dioxide)

In the past, R-744 was not used in water and space heating heat pumps because of its high pressure characteristics (Fernandez, 2008).

Development of R-744 heat pumps started around 1990 (Nekså, 1998). R-744 heat pump water heaters were introduced to the Japanese market in 2001, with heat pumps for heating of bath or sanitary water as the main application. Space heating heat pumps that operate at lower water temperatures in combination with hot water heating have also been developed, but the numbers sold are less. R-744 operates at very high pressures; approximately 5 times higher than HCFC-22 and 3.5 times higher than R-410A. This is an advantage enabling more compact system designs. The low critical temperature of R-744 results in trans-critical operation. R-744 refrigerant has been used primarily in storage type heat pump water heater applications.

Continued growth of market for domestic hot water heat pumps is expected in Japan, Asia and to some extent in Europe. Recently, R-744 heat pumps for domestic space heating application have been developed in Europe for use in cold climates if combined with very high temperature radiator type space heating. For commercial buildings with combined radiator and air heating systems, R-744 is a very promising refrigerant (Nekså, 2002). This also holds for new low energy buildings where the domestic hot water demand is large compared to the space heating requirement. It is not known what level of market penetration R-744 space heating heat pumps will experience. The ultimate market acceptance will be determined by the system economics, energy labelling and minimum energy efficiency requirements.

R-744 as refrigerant enables domestic water heating up to temperatures as high as 90 ºC without use of an auxiliary electrical heater. R-744 may give a high performance when it is used with low temperature sources and high temperature sinks with a certain temperature difference between inlet and outlet water temperature (Steene, 2008). This makes it well suited for use in storage type heat pump water heaters in which low temperature inlet water is heated to a high temperature for thermal storage of domestic hot water.

Compared to HFC refrigerants design modifications are required to get equivalent performance with R-744 for space heating alone (Nekså, 2010). To obtain high efficiency for domestic space heating application is challenging if the difference between the high and low water temperature of the heat sink is low. System designs enabling a low water return temperature are then required (Nekså, 2010) or introduction of work recovery components, e.g. ejectors or expanders may overcome the energy efficiency barrier, but the cost for it may make the product less competitive.

The cost of the working fluid is low. 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.

The main barrier is cost of the system and energy efficiency in some applications.

8.3.5 Hydrocarbons

Hydrocarbons (HCs) include three main refrigerants, HC-290 (propane), HC-1270 (propene) and HC-600a (iso-butane).

At present HC-290 systems are sold in a limited number of low charge level heat pump water heater installations in Europe. While, for hydronic systems, with ventilated enclosures configuration, larger refrigerant charges are allowed. Use in Europe has declined due to introduction of the Pressure Equipment Directive (Palm, 2008) but some compressor manufacturers are now offering compressors for HC-290 applications.

The efficiency of HC-290 and HC-1270 in heat pumps is known to be good (Palm, 2008).

The direct cost of the substance is favourable. Based on the refrigerant properties the equipment cost is similar to HCFC-22 while mitigation devices for safety add some cost.

The main barriers are related to the safety. For systems with parts, which are located in occupied spaces, the allowable charge quantity is limited, whereas for systems located outside, there are no major restrictions. The necessity to ensure that technicians are appropriately trained to handle the flammability of hydrocarbons is a main barrier. For equipment manufacturers the liability aspects combined with the costs for safety measures are the main barriers to extend the use of hydrocarbons.

8.3.6 R-717 (ammonia)

R-717 is used mainly for large capacity systems. It has also been used in a small number of reversible heat pumps and sorption ones. It is not expected to be used in small capacity water and space heating heat pumps.

The energy efficiency of R-717 heat pumps is known to be very good. Crucial problems in commercial ammonia direct expansion system is oil return so as to achieve good heat transfer in the evaporator. These problems can be solved by use of oil which is soluble in ammonia (Palm, 2008).

The cost effectiveness is unfavourable for non-industrial process use due to equipment and/or installations costs.

The main barriers are related to safety aspects (see Annex to Chapter 2) during the life cycle of the equipment and the minimal capacity required for cost-effectiveness and certain national regulations controlling installation, even though it has been shown that small capacity heat pump systems can be designed to operate with very low charge of ammonia (100 g of ammonia for 9 kW heating capacity (Palm, 2008).

The main obstacle for the commercialization of small capacity heat pump systems is the limited supply of components. Particularly, there are no hermetic or semi-hermetic compressors for ammonia available and ammonia is incompatible with copper.

8.4 Refrigerant charge Levels

Table 8-3 shows approximate charge levels for HPWHs and space heating heat pumps for several typical refrigerants.

Charge levels may vary over a range of values for each refrigerant and type of heat pump depending on capacity levels, target energy efficiency levels, types of heat exchangers used in the system, etc.

Table 8-3: HPWH and space heating HP refrigerants; average charge levels given

Refrigerant	kg/kW
HCFC-22	0.30
HFC-134a	0.40
HFC blends R-410A and R-407C	0.30
Hydrocarbons	0.15
R-744	0.15

8.5 Options for existing systems

Replacing an ODS refrigerant, mostly HCFC-22, by a non-ODS refrigerant has similar considerations as described in Chapter 7. As for most water heating heat pumps there is no refrigerant field piping involved the option to replace the total unit is in many cases the better economical solution. For larger units located in places where the replacement of the total unit may be difficult, sometimes the option is taken to replace components such as the compressor, expansion device, gaskets, safety devices and oil. For that purpose manufacturers of the equipment sometimes provide special retrofit packages.

8.6 Concluding remarks

Most heat pumps commercialised today make use of non-ODS refrigerants. Refrigerants used are R-410A, HFC-134a, R-407C, HC-290, HC-600a, R-717 and R-744. The majority of new equipment use R-410A. In some Article 5 countries, HCFC-22 is being used as it has favourable thermodynamic properties and high efficiency. To replace HCFC-22 by a non-ODS there are no technical barriers. The technical and process changes related to pressure, lubrication and contamination control are well known. Replacements are commercially available, technically proven and energy efficient. All replacements have a similar or lower environmental impact. R-410A has a slightly higher GWP but the required charge is less than HCFC-22. The issue in high ambient is of less or no importance for water heating heat pumps. The main parameters to select the alternatives and the main issue to switch over from HFCF-22 are the efficiency, cost effectiveness, economic impact, safe use and easiness of use.

Replacements such as HFC-32 and other low-GWP HFC blends are under way to become commercial available.

HFC-134a, R-744 and HFC blends R-407C, R-417A and R-410A are commercial available solutions that have the highest grade of safety and easiness to use. R-410A is most cost effective for small and medium size systems, while for large systems HFC-134a is most efficient. R-407C and R-417A are from design point of view the easiest alternatives for HCFC-22, but cannot compete with the other HFC-solutions.

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Chapter 9

Chillers

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9 Chillers

9.1 Introduction

Comfort air conditioning in large commercial buildings and building complexes is commonly provided by chillers. The chillers that serve these systems cool water or other heat transfer fluid 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 centers, electronics fabrication, precision machining, molding, and mining (particularly in deep mines with high thermal gradients). District cooling is another application that provides air conditioning to multiple buildings through a large chilled water distribution system. Chapter 5 provides additional information on chillers used in these applications.

Chillers commonly employ a vapour compression cycle using reciprocating, scroll, screw, or turbo (centrifugal or mixed axial/centrifugal flow) compressors. Heat typically is rejected through air-cooled or water-cooled heat exchangers. Evaporatively-cooled condensers and dry coolers also can be used for heat rejection. Though less common, an absorption refrigeration cycle is used in absorption chillers, especially where a low-cost source of hot water or steam is available.

Chillers tend to stay in service for long periods in the range from 20 to 40 years. Even though CFCs were phased out for new equipment in 2010, a significant number of CFC-11, CFC-12, and HCFC-22 chillers are still operating. HCFC-123 also is used, but will be phased out in 2020. Article 5 countries may still use all these refrigerants. The change-over to zero ODP refrigerants required a very high investment and was a lengthy process. However, the current generation of chillers has proven to be highly reliable and has resulted in higher performance, no small feat.

The zero ODP refrigerants used today generally have GWPs greater than 1000. Climate change concerns are driving efforts to seek lower-GWP refrigerants to replace the refrigerants currently in use, mainly HFC-134a and R-410a. Also, Article 5 countries are expressing interest in “leap-frogging” to the next generation of refrigerants in order to avoid investing in technology that may become obsolete.

While manufacturers, consumers, and regulators alike have an interest in low GWP refrigerants, a number of things stand in the way. This chapter presents refrigerants under consideration and factors affecting their success. In the end, the time and expense to change to another generation of refrigerants likely will be required again.

All other considerations aside, to be acceptable, new refrigerants should result in products with energy efficiencies that are equal to or better than the refrigerants replaced. This is because the global warming effects from chillers are dominated by the energy-related component from their power usage. Life Cycle Climate Performance (LCCP) models typically show that more than 95% of the climate effect is due to energy consumption. The direct global warming effects from refrigerant emissions are significantly smaller. Emissions have been significantly reduced in recent years through lower charge systems, low-leak designs, manufacturing and testing improvements, and improved service practices. At the same time, chiller energy efficiency has been enhanced in today’s systems by adding features such as variable speed drives, economizers, suction line heat exchangers, and increased subcooling. The use of higher performing chillers is more important to climate change than prematurely changing to another intermediate refrigerant solution.

Fortunately, the consumer can make intelligent choices when alternatives are explored. The annual energy consumption can be calculated with computer simulation programs using the chiller(s) load profile, building loads, and weather data. For large and complex chiller systems, extensive modeling can provide systems and chiller solutions that minimize total energy consumption. However, smaller machines are commonly sold on the basis of full and/or part load rating, a simplified representation of energy consumption. Rating standards and rating certification programs exist in most countries. AHRI Standard 550/590 (AHRI 2011) and EN 14825 are among the rating standards in use.

Other methods used to describe the environmental effects of chiller operation are Total Equivalent Warming Impact (TEWI) or Life Cycle Climate Performance (LCCP). These methods are defined in Chapter 2, *Refrigerants,* and further discussed in Chapter 11, *Sustainable Refrigeration*. The ozone depletion potential (ODP) and global warming potential (GWP) of the refrigerants mentioned in this chapter are given in Chapter 2. Chapter 2 includes other refrigerant properties and a description of the issues associated with changing refrigerants, including safety aspects.

9.2 Types of equipment and applications

9.2.1 Mechanical vapour compression chillers

Vapour-compression chillers use either centrifugal or positive displacement compressors. The positive displacement category includes reciprocating piston, rotary, screw, and scroll compressors. Not all refrigerants can be used in all compressor types because compressors generally are designed for specific refrigerants and applications.

Water-cooled positive-displacement chillers below 700 kW commonly employ direct-expansion (DX) shell-and-tube evaporators with chilled water on the shell side, or brazed plate evaporators. Chillers above 700 kW typically use flooded/pool-boiler type, falling film, or spray evaporators with the refrigerant on the shell side of the tubes. Similar to compressor technology, heat exchangers are designed for particular refrigerants and applications.

For flooded evaporators or falling film evaporators there is a limit on refrigerant selection. Zeotropic refrigerants such as R-407C with high temperature glide can fractionate during evaporation and during condensation in shell-side condensers, creating significant performance issues (see Section 9.3.1).

9.2.2 Absorption chillers

Absorption chillers utilize heat provided by a fuel-fired burner, steam, or hot water as the main energy source. Electricity still is required for internal solution pumps and controls. Large absorption systems commonly use water and lithium bromide. Small absorption chillers may use an alternative fluid pair, R-717 and water where water is the absorbent. Other working pairs are proposed and see very limited use. Chillers with lithium bromide and water all are water-cooled. Chillers using R-717 and water can be water-cooled or air-cooled.

Absorption chillers are identified by the number of heat input levels they employ (e.g., single-effect or double-effect), and whether they are direct-fired with a burning fuel, or use steam or hot water as the heat source.

Single-effect absorption applications, with lower efficiency, typically are limited to sites that can utilize waste heat in the form of recovered hot water or steam as the energy source, or where boilers must be run year-round such as in hospitals. Other sites include co-generation systems where waste engine heat or steam is available.

Double-effect machines have an additional heat recovery heat exchanger and can be driven by hot water or steam, or can be direct-fired. Double-effect absorption chillers can have primary-energy-based efficiencies that are 35 – 45% of those of vapour-compression systems. For example, double-effect absorption chillers can have a cooling coefficient of performance (COP) of 0.9 to 1.2 on a seasonal basis based on source energy input. Electrical vapour-compression systems can have a COP as high as 7.8, which must, in the case of thermal power plants, be multiplied by the heat-source-to-electricity delivery efficiency of the power plant and distribution system - around 35% for heat-driven generators that are predominant. Triple-effect machines have been commercialized but are not used widely. A fluid pair other than water/lithium bromide must be used in the high stage generator.

9.2.3 Chiller capacity ranges

Table 9-1 lists the cooling capacity range offered by single units of each type of chiller. (Most applications, particularly in larger capacities, use multiple chillers)

Table 9-1: Chiller capacity ranges

Chiller Type	Approximate Capacity Range (kW)	Typical Refrigerants
Scroll, rotary, and reciprocating water-cooled	10 - 1,200	R-410A, HCFC-22, R-407C Less commonly, HC-290
Screw water-cooled	100 – 7,000	HFC-134a, HCFC-22 R-717
Screw, scroll, rotary, and reciprocating air-cooled	10 – 1,800	HFC-134a, R-410A, HCFC-22, R-407C
Centrifugal water-cooled	200 - 21,000	HFC-134a, HCFC-123
Centrifugal air-cooled	200 – 7,000	HFC-134a
Absorption (R-717-water, air or water cooled)	17 – 85	R-717
Absorption (R-717-water, water cooled)	700 – 3500	R-717
Absorption (water-lithium bromide – shell and tube)	140 -18,000	R-718
Absorption (water-lithium bromide – shell and coil)	17 – 120	R-718

9.3 Options for new equipment

9.3.1 Evaluation of experimental refrigerants for vapour compression chillers.

Many of the refrigerants in Table 9-1 have GWPs greater than 1000, which is considered to be undesirably high. Lower-GWP refrigerants have been tested and evaluated for several years. With interest growing to find replacements for existing refrigerants, refrigerant manufacturers are proposing new chemicals and blends with lower GWP. As stated in Chapter 2, the perfect, inexpensive, energy efficient, non-toxic, non-flammable, and broadly applicable refrigerant does not exist and is highly unlikely to come into existence. There is a complex selection process ahead where the industry will need to find out which of the many proposed new refrigerants are appropriate for each chiller system. The selection process is a trade-off among GWP, energy efficiency, safety, applied cost, and limiting the need for redesign.

In 2011 the U.S. Air-Conditioning, Heating, and Refrigeration Institute (AHRI) launched an industry-wide cooperative research program to identify and evaluate promising alternative refrigerants for major product categories including chillers (Johnson 2012). The program, referred to as the Low-GWP Alternative Refrigerants Evaluation Program or Low-GWP AREP, was desired by the industry to assess the research needs, accelerate industry's response to environmental challenges raised by the use of high GWP refrigerants, and avoid duplicative work. Many refrigerant blends as well as single-component refrigerants were candidates for chiller applications. A number of the proposed alternatives have vapour compression cycle characteristics that are close to those of the chiller refrigerant being replaced, namely HFC-134a, R-410A, HCFC-22 (and R-407C), and HCFC-123.

Test results from the Low-GWP AREP program are available from an AHRI website (AHRI, 2013). Tests of alternative lower-GWP refrigerants also have been conducted in Japan under the auspices of the Ministry of Economy, Trade and Industry (METI), and in China. Industry has not yet selected any preferred candidates for commercialization from this work.

Additional information on non-fluorinated and low-GWP refrigerants for chillers is given in Section 4 of the TEAP XXIV/7 Task Force Report (TEAP, 2013). The energy efficiency, efficacy, costs, cost effectiveness, and extent of commercialization are presented for a number of selected ODS refrigerant alternatives.

When evaluating a new refrigerant there are many characteristics to consider beyond operating pressure levels, cooling capacities, and energy efficiencies. Chapter 2.1.7 presents these characteristics. The Annex to Chapter 2 includes application and safety standards for refrigerants and systems employing them. Flammable refrigerants, Class 2L, 2, and 3, are part of the mix of potential choices, Class 2L is a new classification that was defined in 2010. Timelines for introduction of A2L refrigerants will vary by country, and their application in large chillers where system charges are unlimited likely will not come until experience is gained in smaller limited-charge systems.

Several limitations for refrigerant selection, unique to chillers, are important to note. A limitation on the application of blended non-azeotropic refrigerants exists in large chillers with flooded evaporators and shell and tube condensers. “Glide” in heat exchangers is a change in refrigerant temperature at constant pressure during evaporation. Flooded evaporators used in larger chillers are essentially isothermal and isobaric, so the "glide" tendency is exhibited as a composition change between the liquid and vapour phases in the evaporator. Glide also occurs during condensation. Glide can be at least partially accommodated in the traditional cross-flow air-side condenser heat exchangers of air-cooled chillers. Refrigerants with little or no temperature glide (1 K or less) are required for use in shell and tube heat exchangers with refrigerant on the shell side. Refrigerants with temperature glides up to around 5.6 K can be used in DX systems, but designs must be modified to account for glide which otherwise may handicap chiller efficiency and tends to increase heat exchanger size. Zeotropic refrigerants with glide also require special consideration of service practices that avoid composition changes resulting from separation and differential leakage of blend components

Other unique refrigerant parameters that chiller designers must take into account in choosing a refrigerant include heat transfer coefficients in large pool boiling evaporators and compressor discharge temperatures, particularly at low suction temperature or high ambient conditions. Heat recovery and heat pumping applications for chillers are increasing. A refrigerant’s performance in these higher-temperature conditions will be important for these applications. Another consideration is operating pressure level and the related need for pressure vessel code redesign

Unlike small systems that predominately use coils, refrigerant cost is an additional important factor. Centrifugal chillers of an average size (e.g., 1400 kW) hold a refrigerant charge of the order of 500 kg. Refrigerant cost may be affected favorably by increased production volumes if a new low-GWP refrigerant can be used as a retrofit in existing chillers or if there are high-volume applications for a refrigerant such as use as a foaming agent.

9.3.2 Options for new vapour compression chillers

9.3.2.1 Fluorinated refrigerants

Options to replace HFC-134a in new chillers

HFC-134a is used in positive displacement chillers and centrifugal chillers. Heat exchangers with refrigerants on the shell side vs. inside the tubes and plate heat exchangers with refrigerant inside differ in their sensitivity to temperature glide which can occur with zeotropic refrigerant blends (see section 9.3.1).

Zeotropic mixtures offer the greatest flexibility in blending refrigerants to approximate the physical and thermodynamic properties of HFC-134a - particularly the general trend of the pressure/temperature relationships. There are a number of A1 refrigerant candidates with low glide and capacities close to HFC-134a with GWPs around 600. Candidates with low GWP (150 or less) all are in safety classes A2L or A3.

Earlier studies based on thermodynamic properties suggest that the COP of chillers using one candidate, unsaturated HFC-1234yf refrigerant, is not as good as for HFC-134a (Kontomaris, 2009) and (Leck, 2010). However, a recent study based on chiller measurements indicates that the performance of R-513A, an azeotropic blend, is equivalent to HFC-134a (Kontomaris, 2013). Other evaluations of unsaturated HFCs for chillers have been done (Kontomaris, 2010a), (Kontomaris, 2010b), (Kontomaris, 2010c), and (Spatz, 2008).

In Europe chillers are on the market using unsaturated HFC-1234 ze(E) as the refrigerant. The efficiency is found to be better than HFC-1234yf and equivalent to HFC-134a. Testing has shown that HFC-1234ze(E) has a capacity reduction of approximately 25% compared to HFC-134a (Schultz, 2012). The choice of refrigerant in Europe will be influenced by the F-gas regulation and the pressure equipment directive, amongst many other parameters such as end user specifications.

It is not possible at this time to know which particular low-GWP refrigerants or blends will find significant acceptance for use in chillers.

Options to replace R-410A in new chillers

R-410A is used primarily in positive-displacement water-cooled and air-cooled chillers. Although it operates at higher pressure levels and lower volume flow rates, R-410A became the successor to HCFC-22 in the capacity ranges where hermetic reciprocating and scroll compressors commonly are used. Chillers with R-410A generally employ DX heat exchangers, microchannel heat exchangers, or plate heat exchangers.

One of the alternatives tested as a possible successor to R-410A is HFC-32. This refrigerant is used as a component in blends including R-410A. HFC-32 can be used in positive displacement chillers by itself and as a component in blends with HC-600 (n-butane), HC-600a (isobutane), and other low GWP components because it has a moderate GWP, good energy efficiency, and high capacity in the vapour-compression cycle. Disadvantages include flammability and operating pressure levels higher than for HCFC-22. HFC-32 is classed as an A2L refrigerant. Chillers using HFC-32 (other than as a blend component) have not been widely commercialized yet and will require changes to meet still-to be-developed safety codes and building standards.

Other alternatives identified during the Low-GWP AREP program are blends that have similar or lower cooling capacities than R-410A. Several of the blends have temperature glides of 5.6 K or less. All of the alternatives have higher estimated COPs than R-410A. None of the alternatives have a GWP <150. All of the alternatives are in the A2L safety class.

Options to replace HCFC-22 in new chillers

HCFC-22 was favored for many years as a refrigerant for positive displacement chillers. HCFC-22 also was used in some centrifugal chillers produced before 2000. It was phased out in 2012 for use in new equipment in developed countries. HCFC-22 still is offered for chillers in some Article 5 countries.

The zeotropic mixture R-407C served as a transition refrigerant. It allowed manufacturers to offer chillers with a zero ODP refrigerant by making modest changes in their HCFC-22 products. R-407C has an appreciable temperature glide (5 K) so is not suitable for use in flooded evaporators that predominate in larger chillers. R-407C still is used in Europe, on a more limited basis in Japan as a replacement for HCFC-22, and elsewhere as one of a number of zero-ODP aftermarket drop-in options for retrofits. The retrofit list includes R-421A, R-422D, R-427A, R-438A, and others.

The low-GWP AREP program alternatives for HCFC-22 include five A1 refrigerants. Three others are A2L refrigerants. The remaining candidates are A3, or in the case of R-717, B2L A1 and A2L refrigerants have temperature glides so system designs optimized to use R-407C are more appropriate than systems designed for HCFC-22. The COPs of the A1 and A2L refrigerants are estimated to be lower than for equivalent HCFC-22 systems. Only one A2L alternative has a GWP <150. The selection of a preferred candidate for further development in chillers has not been made.

Refrigerant options for new centrifugal chillers

Centrifugal compressors are the most efficient technology in large units, those exceeding 1700 kW capacity. Water chillers employing these compressors are designed for specific refrigerants.

HFC-134a is a popular choice for large centrifugal chillers. Two other refrigerants are also used. These refrigerants have particularly high thermodynamic efficiency and operate at lower pressure levels and higher volumetric flow rates than HFC-134a. They are HCFC-123 and HFC-245fa. HCFC-123 is a low-GWP HCFC refrigerant which is subject to phase-out under the Montreal Protocol in 2020. Large chillers using HCFC-123 likely will continue to be produced in North America and China until the phase out occurs. HFC-245fa is an HFC which has found limited use in centrifugal chillers, heat pumps, and organic Rankine cycle (ORC) power generation cycles. HFC-245fa has operating pressures higher than for HCFC-123 but lower than for HFC-134a. Chillers employing HCFC-1233zd(E) have recently been introduced on the European market.

9.3.2.2 Non-fluorinated refrigerants

R-717

Chillers employing R-717 as a refrigerant have been available for many years and are widely used in industrial and central chiller plant systems (see Chapter 5). There are a number of installations in Europe, the Middle East, China, and the U.S.A. R-717 chillers are available with open drive screw compressors in the capacity range 100-7000 kW. Chillers with open drive reciprocating compressors are available in the capacity range 20-1600 kW.

R-717 chillers are manufactured in small quantities compared to HFC chillers of similar capacity. Different materials of construction are used because R-717 causes rapid corrosion of copper, the most widely used heat exchange surface in HFC chillers. Plate-and-frame steel heat exchangers are common in R-717 systems.

R-717 is better suited to water-cooled chillers because of higher costs of air-cooled R-717 condenser coils. Information on R-717 chiller applications in building air conditioning is given in (Pearson, 2008a), (Pearson, 2008b), and (Pearson, 2012).

R-717 is not a suitable refrigerant for centrifugal chillers because it requires four or more compressor stages to produce the pressure rise ("lift" or "head") required.

If the use of R-717 refrigerant in chillers is to expand in the capacity range served by positive displacement compressors, particularly outside Europe, several impediments must be addressed:

- Chiller costs typically are higher than for HCFC and HFC chillers.
- Safety concerns with R-717 in comfort cooling applications can increase installation costs. Building codes in some countries heavily restrict applications.

None-the-less, the market for R-717 chillers is growing in regions where concerns about the control of high-GWP refrigerants are strong.

Hydrocarbons

Hydrocarbon refrigerants all are flammable and are classified A3. A discussion of safety aspects is given in the Annex to Chapter 2. Chillers employing hydrocarbons as a refrigerant have been available for many years, though typically only in small capacities (up to 200 kW) per refrigerant circuit and for outdoor applications. HC-290 s used in chillers in air conditioning and industrial applications. HC-290 and another hydrocarbon, HC-1270, are used in a limited number of small (<1200 kW) air-cooled chiller installations in Denmark, Norway, the United Kingdom, Germany, Ireland, the U.S.A., and New Zealand. Some Article 5 countries such as Indonesia, Malaysia, and the Philippines are applying hydrocarbon chillers to large space cooling needs. The current market for hydrocarbon chillers is larger than for R-717 chillers on a global basis but still very small compared to the market for HCFC-22 and HFC chillers.

Apart from safety considerations, HC-290 and HC-1270 have properties similar to those of HCFC-22. This allows their use in new equipment of current design after appropriate adjustments for safety aspects and different lubricants. Chillers employing hydrocarbon refrigerants are somewhat higher in cost than HFC chillers though modification of equipment originally designed for HCFC-22 is fairly straightforward.

All safety codes impose strict requirements on hydrocarbons in large refrigerant charges in chillers, particularly for indoor chiller installations in machinery rooms. Accordingly, hydrocarbon chillers have not been adopted in all regions. In regions supporting-hydrocarbon solutions the safety concerns have been addressed by engineering design, technician training, and changes in building codes and safety standards. If experience is successful, the use of hydrocarbon chillers may grow in the future. However, in countries such as the U.S.A., regulations, building codes, and legal environments make it unlikely that hydrocarbons will be used in commercial chillers in the foreseeable future.

Hydrocarbon refrigerants are in limited use in centrifugal chillers in petrochemical plants where a variety of very hazardous materials are routinely used and the staff is highly trained in safety measures and emergency response (see Chapter 5). Hydrocarbon refrigerants have not been used in centrifugal chillers for air conditioning due to safety code restrictions, concerns with large charges of flammable refrigerants, liability, and insurance issues.

R-744

R-744 air-cooled chillers have been introduced in the northern European market. Both air- and water-cooled gas cooler versions are available. Models with cooling capacities from 40 to 500 kW are offered. In climates where the dominant cooling requirement is at an average ambient temperature of 15^0C or less, these systems can be equivalent in energy efficiency and LCCP with systems employing HFCs, R-717, or HCs. R-744 chillers are less attractive at higher ambient temperatures due to decreasing efficiency with increasing ambient temperature.

There heat recovery to generate hot water at temperatures of 60^oC or higher can be employed in a total energy strategy for a building, R-744 chillers offer the advantage of being able to use waste heat to raise water to higher temperatures with higher efficiency than other refrigerants. Chilled water can be used to sub-cool the refrigerant before expansion. For this application, R-744 heat recovery chillers provide good efficiency.

R-718

The very low pressures, high compression ratios, and high volumetric flow rates required in water vapour compression systems require high volumetric flow axial compressor designs that are uncommon in the chiller field. However, several research projects are active and developmental companies have attempted their commercialization. A product was announced in 2014 using water as the refrigerant. Applications for water as a refrigerant can chill water or produce an ice slurry by direct evaporation from a pool of water. R-718 systems carry a cost premium above conventional systems. The higher costs are inherent and are associated with the large physical size of water vapour chillers and the complexity of the compressor technology. Several developmental chillers and commercial vacuum ice makers have been demonstrated in Europe, the Middle East, and South Africa including deep mine refrigeration (Jahn, 1996), (Ophir, 2008), (Sheer, 2001), (Calm, 2011).

9.3.2.3 Alternatives to mechanical compression systems (absorption and adsorption chillers)

Absorption water chillers are a viable alternative to the vapour-compression cycle for some installations. Absorption chillers have been described in Section 9.2.2.

Adsorption chillers using water and zeolite also are an alternative (Boone, 2011).

9.4 Options for existing chiller equipment

When CFC and HCFC refrigerants are phased out (and in several countries that phased out HFCs), the functions performed by chillers employing those refrigerants have to be supported in one of the following ways:

Retain/Contain: continued operation with stocked and/or reclaimed inventories in conjunction with containment procedures and equipment modifications to reduce emissions.

Retrofit: modification to allow operation with alternative refrigerants (HFCs where permitted) depending on applicable regulations.

Replace: early retirement/replacement with new chillers (preferably having higher efficiency which reduces energy-related climate impact) using allowed refrigerants or not-in-kind alternatives,

The retrofit options depend on the specific refrigerant for which the chiller was originally designed. When any retrofit is performed, it is recommended that the machinery room be upgraded to the requirements of the latest edition of safety standards such as ASHRAE 15 (ASHRAE, 2013), and EN 378 (EN, 2008) or international standards such as ISO 5149 (ISO, 2014). It is also recommended that the manufacturers of the equipment be consulted in any retrofit program.

9.4.1 Positive displacement chillers

A positive displacement compressor inherently can be applied to handle a number of different refrigerants and pressure ratios in a chiller if its motor has adequate power, the compressor, tubing, heat exchangers, and other components can meet pressure codes and regulations with the refrigerants, and the system materials and lubricant are compatible with the refrigerants. Despite this flexibility, there remain a number of issues in retrofitting positive displacement chillers to operate with new refrigerants. These issues were discussed in the 2010 RTOC report.

9.4.2 Centrifugal chillers

Centrifugal compressors by nature must be designed specifically for a particular refrigerant and a particular set of operating conditions for the refrigerant cycle in which they are used. Direct refrigerant substitution in centrifugal chillers can be made only in cases where the properties of the substitute refrigerant are nearly the same as those of the refrigerant for which the equipment was designed, or when the impeller speed and/or impeller geometry can be changed easily. In the past this has been accomplished by gear changes in open drive chillers and with variable speed drives in both open and hermetic compressor chillers. The compressor surge margin must be checked using the properties of the substitute refrigerant.

9.4.3 Non-vapor compression chiller replacements – absorption

The most common absorption chiller is the water-lithium bromide solution type, both direct and indirect fired versions. When comparing the size of a mechanical vapour compression chiller with an absorption chiller of similar capacity, the absorption chiller is about 25 to 50 % bulkier. This factor may be crucial when retrofitting existing systems because of the size of access ways and corridors. Another important factor is the cooling tower requirement of an absorption chiller. Because absorption chillers require cooling for their condenser as well as their absorbers where the mixing of the refrigerant and absorbent occurs, resulting in the emission of heat of mixing and heat of solution that need to be removed, the cooling tower of an absorption system can be 30 to 60 % larger than that of a mechanical vapour compression system of a similar capacity.

On the other hand, the replacement of a mechanical vapour compression system with an absorption system saves a portion of the electric consumption of the building. This reduces the capacity requirements for the transformer, electric switchboards, and electric conduits. Provision has to be made for suitable gas piping and train when a natural gas fired system is used. Absorption systems do not require anti-vibration mounting since they have few moving parts.

9.5 Alternatives for high ambient conditions

Chiller rating points commonly involve ambient air temperatures of 35°C (95°F). However, in very warm climates there is interest in knowing how chillers will perform when air temperatures reach 47°C or even 52°C, and also, how the design of chillers can be modified to improve high ambient operation.

This section focuses on air cooled chillers. The design of water cooled chillers for high ambient conditions involves the same approaches as for air cooled chillers but is less challenging because condensing temperatures are lower for a given ambient temperature.

Air-cooled chillers with positive displacement compressors (rotary, reciprocating, scroll, screw) designed for an ambient of 35°C will operate at high ambient conditions but with reductions in capacity and COP. An illustrative example is given for actual 3 ton residential air conditioners in the May 2010 TEAP XX/8 Task Force Report. For HCFC-22, capacity was reduced by 15% and COP was reduced by 35% when the ambient temperature increased from 35°C to 52°C. For R-410A the reductions were 18% and 40 % respectively. Design changes that can improve chiller performance at high ambient temperatures include applying a compressor with proper capacity and compression ratio for the ambient condition, adjusting the compressor built-in volume ratio for scroll and screw compressors, increasing condenser size, and providing a properly-sized expansion device. Features such as economizers are more effective in high ambient conditions than for lower condensing temperatures. HFC-134a has less performance degradation than R-410A, and HFC-32 (an A2L refrigerant) has even less performance degradation. These refrigerants are not interchangeable because of their differing capacities, pressure levels, and lubricant requirements. Chiller design must be tailored for the specific refrigerant selected.

Chillers with centrifugal compressors require a different approach. Typically, additional compressor stages may be required. If condensers cannot be water-cooled because water is scarce or expensive, dry coolers are used. Air-cooled condensers with tubes and fins or microchannel heat exchangers are not commonly used with centrifugal compressors because they are sensitive to the increased pressure drop on the refrigerant side of these types of condensers as compared to dry coolers. The refrigerants used in centrifugal chillers for high ambient conditions typically are HFC-134a and HCFC-123.

HFC-32, an A2L refrigerant, is being considered as a lower-GWP alternative to R-410A or HFC-134a for high ambient applications. R-444B has been shown to perform well at high ambient conditions (Schultz 2014). It is too early to know whether or when other lower GWP refrigerants will be available as alternatives to R-410A, HFC-134a, and HCFC-123 for chillers operating in high ambient conditions.

9.6 Concluding remarks

- This chapter shows that no “ideal” low-GWP replacements for HFC-134a, R-410A, and HCFC-22 have been identified for chiller applications. An “ideal” refrigerant would have nearly-zero ODP, a zero or low GWP, an A1 ASHRAE/ISO safety classification, near-zero temperature glide, energy efficiency equivalent to or better than the refrigerant being replaced, and acceptable cost for the quantity used in typical chillers. Additionally, the cost of conversion of compressors and heat exchangers should not be prohibitive to manufacturers.
- Global warming effects from chillers are dominated by their energy use. There continues to be consumer and regulatory pressure to improve full and part load or seasonal energy consumption which will have a positive climate impact.
- Direct global warming effects from refrigerant emissions from chillers are-significantly smaller than the climate effect from the energy consumed during the lifetime of

operation. Emissions have been significantly reduced in recent years through lower charge systems, low-leak designs, manufacturing and testing improvements, and improved service practices.

- Thus, chemical producers and chiller manufacturers will continue to focus their efforts on refrigerant candidates that provide energy efficiencies that are equal to or better than the refrigerants being replaced.
- A1 refrigerants with GWPs up to 675 offer performance and safety benefits for some applications.
- The ultimate goal is to choose alternative solutions that are the most energy efficient while remaining viable to chiller manufacturers, regulators, and users.

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Chapter 10

Vehicle Air Conditioning

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10 Vehicle air conditioning

10.1 Introduction

Vehicles (cars, trucks, buses and trains – this chapter does not cover ship air conditioning) built before the mid-1990’s used mostly CFC-12 as the refrigerant with some HCFC-22 use in trains. Since then, in response to the Montreal Protocol, new vehicles with air conditioning (AC) have been equipped with systems using HFC-134a. By the year 2000, the transition from CFC-12 to HFC-134a as an Original Equipment Manufacturer (OEM) refrigerant, for factory installed AC systems, was complete in all developed countries. The transition to HFC-134a in developing countries was completed by approximately 2007. In addition, since the mid-1990’s, development of alternatives to HFC-134a has been underway due to the high Global Warming Potential [GWP] of HFC-134a.

In this chapter, mobile air conditioning systems are those used in passenger cars, light duty trucks, buses and rail vehicles that are generally based on vapour compression cycles. This chapter also addresses the heat pump mode of the air conditioning cycle, for example systems used for heating battery-driven electric vehicles (BEVs). Annex C (Not-In-Kind Alternatives) provides a brief overview of other refrigeration techniques which might become important for vehicle air conditioning systems in the future (beyond 2020).

Chapter 10 covers the new developments in the field of mobile air conditioning systems since the RTOC 2010 Report. For more details on the system design and the history of refrigerant system development for these vehicles prior to 2010, see that and all preceding RTOC reports.

It should be mentioned that the development in this field is strongly driven by legal guidelines and regulations (probably much stronger than in other fields). So, Annex B provides a partial overview of the legal situation worldwide.

The ozone depletion potential (ODP) and global warming potential (GWP) values of the refrigerants mentioned in this chapter are given in chapter 2 of this report.

10.2 Description of systems and current and future applications of mobile air conditioning systems

Detailed descriptions of direct and indirect (secondary loop) systems can be found in the 2002, 2006, and 2010 RTOC Reports. As noted above, due to the transition from CFC to HFC's in the mid-1990's, HFC-134a quickly became the refrigerant of choice for new equipment as well as retrofits of CFC-12 designs. Most non-Article 5 countries phased in HFC-134a in new vehicles similarly to the U.S., starting in the early 1990s and completing this transition by the mid-1990s. Article 5 countries followed with some models offered during the 1990s and full transition by the following decade.

HFC-134a systems have become increasingly more leak tight taking benefit in part from the technology developed in the study of R-744 (carbon dioxide) and in part from regional leak reduction programs, e.g., US light-duty vehicle regulations, the Improved Mobile Air Conditioning (I-MAC) program, etc. Correspondingly, hose materials and coupling designs for hoses have also been improved in a relevant way. In addition to that, compared to earlier designs, HFC-134a systems today show improved energy efficiency and lower fuel consumption to meet new regulatory requirements in the USA (USEPA, 2011b) and driven by increased awareness of fuel consumption of mobile air conditioners (MACs) in the EU.

10.2.1 Refrigerant cost and recharge

Passenger cars and light duty trucks have refrigerant charge amounts from 0.3 kg to 1.4 kg. Bus and rail vehicles can have refrigerant charge amounts from 2 kg to 15 kg and some even higher amounts.

The rise in counterfeiting is probably due to production and use restrictions on some refrigerants in accordance with the 1987 Montreal Protocol and the 1997 Kyoto Protocol and to the higher cost associated with more environmentally friendly refrigerants than what they are replacing (Velders, 2009). Hence, counterfeited HFC-134a is infiltrating the refrigerant bank in Asia, and affecting also other countries.

Today, even if the relative cost of HFC-134a is low, i.e. 5 US$/lb or 11 US$/kg (or even less), counterfeit HFC-134a is still appearing in the automotive market. Counterfeit HFC-134a containing multiple CFC, toxic, or corrosive components is a serious threat destroying equipment and injuring end-users. It also has an increasing opportunity to enter the supply chain. The issue is even more relevant in non-European countries (Coll, 2012).

So, in case that a drop-in or nearly drop-in but more expensive refrigerant will be chosen to replace HFC-134a worldwide, the counterfeit risk will become even more relevant and this, beside all the other impacts, could strongly reduce the expected environmental benefit.

The commercial expected price of HFC-1234yf (Weissler, 2013) is estimated at US$ 40-45/lb or US$ 88-99/kg (retail prices could be 2 to 3 times higher). The expected price of R-445A probably will be lower but there exist questions that have been raised on patent issues. Cost and availability are crucial issues that have to be considered in identifying replacement(s) for HFC-134a, currently widely adopted in car air conditioning systems.

10.2.2 Future Trends

The European Union and the United States already have in place regulations that influence mobile air conditioning designs while the other countries with a high density of road vehicles are rapidly moving in the same direction (for example Brazil, Inovar Auto, 2012).

This drives to more efficient on-board systems including MACs and to the replacement of high GWP fluid with lower GWP substances.

Meanwhile the same regulations are leading to a progressive diffusion of hybrid vehicles in the short-medium term (3 - 10 years) that in the medium-long term (5 - 15 years) will be further integrated with fully electric vehicles. These vehicles require highly efficient mobile air conditioning to minimise the impact on the pure electric range and, as additional evolution, to be able to operate also as a heat pump. These challenges will be met by developing and adopting technical solutions that will have to represent the best trade-off among economic and environmental sustainability issues.

In this framework the thermal systems and especially the MAC systems have a relevant role and will likely undergo a deep change where the system integration will represent a relevant evolution guideline.

It is expected that the passenger cars and light duty vehicle domain will rapidly move toward downsized turbocharged engines often coupled with different levels of hybridization to make the overall powertrain more efficient and to reduce CO_2 emissions, with effects on MACs as described below. Increased levels of transmission gears are also occurring, moving vehicles from 4/5/6 levels to 7/8/9 levels leading to a reduction of average compressor speeds so implying AC capacity concerns at low speeds in some cases or to the increase of the compressor displacement or finally to the adoption of electrically driven systems.

To answer to the increased demand of capacity and reduction of GHG emission, the car air conditioning systems using HFC-134a have to become increasingly more leak tight and efficient.

The adoption of improved components (compressor and heat exchangers) and the introduction of internal heat exchangers as well as improved control strategies allowed a significant increase of system efficiencies.

New sealing concepts and improved hose materials have also been developed to reduce refrigerant direct emissions and to reduce the frequency of required maintenance or service.

The trend in the MACS service profiles over the last 10 years (2003-2013) indicates that with reduced refrigerant emissions, the system is being serviced later in the vehicle's life, indicating more years of useful life from the system. With this extended lifetime, service is more likely to be purchased by the vehicle's second owner as compared to previous surveys of earlier vehicles (Atkinson, 2014).

Stop & Start and Hybrid Vehicles

The diffusion of vehicles able to carry out part of their mission with the combustion engine off (e.g. Stop & Start, extended Stop & Start, and hybrids) asks for new solutions for the air conditioning system to guarantee the summer and winter thermal comfort in all the operational conditions.

The majority of these vehicles will have 12 V to 48 V electric energy sources and only part of them will have higher voltage network (e.g. up to 350 V), while all will have an additional on-board electric energy storage unit with a capacity ranging from 0.2 kWh (low voltage) up to 5 kWh (high voltage).

This implies that only a small portion of the future vehicles will have an electric compressor while a large part will be equipped with mechanically driven compressors as today due to energy balance and cost, so measures will be adopted to maintain the required comfort and guarantee the safety performance (i.e. de-fogging), as for example:

- cooling energy storage unit based on phase change materials
- secondary loop system taking benefit from its thermal inertia to store cooling power
- additional electric compressor, downsizing the belt-driven compressor

The increase of on-board electric power and the diffusion of turbocharged engines together with the need to at least maintain the aerodynamic drag will presumably lead to a low temperature cooling loop integrating the charge air cooler, air conditioning condenser, power electronics and generator in the case of hybrid powertrain.

In synthesis, the evolution will produce a deeper integration of the on-board thermal systems and the air conditioning will become part of it.

Plug-in Hybrids and Battery-driven Electric Vehicles

For Plug-in Hybrids (PHEV) and Battery-driven electric vehicles (BEV), vehicle air conditioning systems for cooling as well as heat pump systems for heating need to have very high energy efficiency to minimize the impact on the vehicle driving range.

MAC systems, when operating as a heat pump with HFC-refrigerants currently used can take benefit of the on-board outdoor heat sources (battery, power electronics, etc.) to enhance their effectiveness in case of very low ambient temperatures partially compensating for their low efficiency and capacity. This can be achieved adopting a secondary loop that by collecting the heat from the on-board electronics can raise the temperature of the heat source. In this framework, dual loop systems (with liquid cooled condensers and liquid heated evaporators) offer the highest flexibility level and at the same time allow the OEM to minimize the refrigerant charge, the leak rate, and the risk of dispersion in case of an accident. However, these secondary loop systems do increase the vehicle mass due to the additional coolant and components which might adversely affect vehicle fuel economy at all times of vehicle usage.

For some applications the MAC system will be also used for battery thermal control as well as power electronics (i.e. cooling and heating).

New Refrigeration Systems

The need to progressively increase the energy efficiency requires the exploitation of all available waste energies, heat included. The application of heat driven refrigeration systems (e.g. adsorption, absorption, etc.) can be foreseen for the heavy duty vehicle domain (e.g. trucks and coaches) which often operate at near constant speed (highway) and where the weight and packaging constraints are less severe than in the passenger cars field.

Waste Heat Recovery

The adoption of a Rankine Cycle to convert part of the combustion waste heat of a thermal engine into mechanical or electric energy could allow manufacturers to increase dramatically the vehicle energy efficiency (see section 5.1.6 of this report, and for example Horst et al. 2014 or Hartmann 2014).

These systems are under investigation for diesel heavy duty truck applications in Europe and the US and for gasoline light trucks in the US.

As a working fluid, the Rankine cycle can use water, ethanol or a mixture of both, or an organic fluid like HFC-245fa, hydrocarbons, or carbon dioxide.

The fluid HFC-245fa has good properties for the application but has a GWP of 1050, higher than the threshold of the MAC Directive in Europe.

Studies are ongoing to evaluate the application of fluids with similar properties but with a lower GWP, as for example HCFC-1233zd(E) and HFC-1336mzz(Z) (Kontomaris, 2014).

10.3 Options for New and Future Mobile Air Conditioning Systems

10.3.1 Passenger Car and Light Truck Air Conditioning\

As already mentioned in the introduction, this report concentrates on vapour compression refrigeration cycle technology for vehicle air conditioning.

Improved HFC-134a Systems

With the introduction of the credit system in the USA, and also upcoming legislation in Europe, more vehicle OEMs are introducing technologies to reduce energy consumption with HFC-134a refrigerants. Many efficiency-improving technologies are now being used in current production HFC-134a systems, for example, internal heat exchangers, oil separators in compressors, increased use of externally controlled compressors, etc.

HFC-1234yf Systems

HFC-1234yf systems are able to reach the same system performance and fuel efficiency as HFC-134a system if they use either an internal heat exchanger (IHX) or a condenser in which the subcooling area is enlarged by about 10% while keeping the same total exchange area (Zilio, 2009). In the latter case, HFC-1234yf charge amounts could increase by a maximum of 10% depending on the system layout. The addition of an IHX also generally increases charge amount but some suppliers are reducing the liquid-side volume to minimize this and in some cases there are issues with pressure drop on the liquid side of the IHX. Thus, manufacturers are working now on ways to compensate for this and to reduce refrigerant charge further due to the higher (i.e., more than 10 times expected) cost of HFC-1234yf as compared to HFC-134a. Due to increased density of HFC-1234yf versus HFC-134a, it might be possible to reduce the charge amount depending on the system layout.

HFC-1234yf is designated as an A2L refrigerant, meaning that it is flammable under prescribed testing conditions but exhibits a lower burning velocity than other flammable refrigerants designated as class 2 or 3 flammability refrigerants (ASHRAE, 2013). The flammability potential has led to high scrutiny surrounding the safe use of the refrigerant and possible ways to mitigate any risks.

The US EPA has studied the potential use of HFC-1234yf as a MAC refrigerant under the US Clean Air Act's Significant New Alternatives Policy (SNAP) Program and has SNAP-listed HFC-1234yf as an acceptable refrigerant with the following additional use conditions (USEPA, 2011a):

- HFC-1234yf MAC systems must meet the requirements of the 2011 SAE J639 standard version („Safety Standards for Motor Vehicle Refrigerant Vapor Compression Systems“), describing the safety requirements for the use of R-1234yf in MAC systems.

- Manufacturer for MAC systems and vehicles have to conduct and keep records of a risk assessment and Failure Mode and Effects Analysis according to the SAE J1739 standard („Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA)“) for at least three years from the date of creation

Further requirements outside the US are based on ISO 13043:2011.

Some car manufacturers currently have new vehicles equipped with the HFC-1234yf on the European market (Mandrile, 2013) and in the United States (McAvoy, 2014 and Moultanovsky, 2014). Atkinson, 2014 provides a list of 9 car types which use HFC-1234yf in the US market.

A SAE Cooperative Research Project (CRP) set up to assess the HFC-1234yf systems safety concluded that HFC-1234yf is acceptable for market without concentration limits. Even the German VDA stated in a 2012 publication (Hammer, 2012) that flammability and toxicity of the refrigerant or possible decomposition products do not lead to higher level of risks for vehicle occupants or helpers at accidents, e.g. fire fighters, and cars using HFC-1234yf are as safe as those using HFC-134a. SAE standards have been developed to cover service best practices, safety practices, technician training, and refrigerant purity of HFC-1234yf (SAE J2845, 2013).

Further analyses, however, have disputed these earlier findings that the flammability and toxicity of HFC-1234yf do not lead to higher level of risks. A German car manufacturer carried out a series of additional tests on HFC-1234yf as part of a new test scenario developed in-house which goes above and beyond the legally prescribed requirements. Under these conditions, described by the manufacturer as real-life, the reproducible test results demonstrate that HFC-1234yf, which is otherwise difficult to ignite under laboratory conditions, mixed with lubricant can indeed prove to be flammable in a hot engine compartment. Similar tests of the current HFC-134a refrigerant and lubricant did not result in ignition. Based on these new findings, the German car manufacturer concluded that HFC-1234yf will not be used in its products (Daimler, 2012).

Some EU countries are starting to ask for additional safety evaluation and preventive safety measures to assure the higher safety standards. Nevertheless, the EU, in agreement with the Regulation that does not indicate any specific substance, decided to not change the regulation or allow any delay or derogation.

In response and to address the safety concerns of the German car manufacturer, a new SAE CRP (1234-4: SAE press rel., 2013) was formed and continued its process of carefully reviewing the use of HFC-1234yf by using universally accepted engineering methods, including analysis of recent OEM testing from actual vehicle crash data, on-vehicle simulations, laboratory simulations, bench tests, and over 100 engine compartment refrigerant releases. Based on this testing the CRP has found that the refrigerant is highly unlikely to ignite and that ignition requires extremely idealized conditions, even when mixed with the lubricant as normally happens in real world conditions. The SAE CRP team has also identified that the refrigerant release testing completed by the German car manufacturer was unrealistic by creating the extremely idealized conditions for ignition while ignoring actual real world collision scenarios. These conditions include specific combinations of temperature, amount and distribution of refrigerant, along with velocity, turbulence, and atomization, which are highly improbable to simultaneously occur in real-world collisions. The SAE CRP team included European (but no German), North American, and Asian OEMs (SAE, 2013).

According to a report (Reuters, 2013), the accuracy of which has been disputed, five German OEMs and (only for the European market) one Japanese OEM made the decision (temporarily) not to use HFC-1234yf in their cars but to use old type approval schemes for extending the use of HFC-134a. This development is slowing down the introduction of HFC-1234yf globally.

To review and address the safety concerns of the German car manufacturer, Germany's Federal Motor Transport Authority (Kraftfahrt-Bundesamt, KBA) commissioned tests based on a variation of the R94 crash test with standard cars equipped with HFC-134a and HFC-1234yf air conditioning systems. The German Technischer Überwachungsverein (TÜV) tested four cars on behalf of KBA. The general test condition employed were the following: 40 km/h, 40% vehicle off-set simulated crash, hot engine test, refrigerant leakage varied in the various test stages:

- Stage 1: simulated 40% off-set, vehicle crash where components were checked for refrigerant leakage

- Stage 2: non-leaking A/C parts that were damaged in simulated crash, were manually made to leak refrigerant

- Stage 3: further changes made to A/C parts to change direction of refrigerant leakage flow by turning lines and adding plate or fish mouth aperture.

Two realistic scenarios have been evaluated (stage 1 and 2). The second stage intended to evaluate the dispersion of the refrigerant in the engine bay because of breaches that have not been created during the crash test but that could be possible. In all of the situations no ignition and no hydrogene fluoride (HF) production have been observed. A third scenario (stage 3) has been considered where the components have been manually modified in order to simulate further breaks and underhood situations that could be possible. For HFC-1234yf, Stage 3 showed higher hydrogene fluoride values. At that level a fire occurred in one of the four cars. The test was repeated twice more; a fire occurred in one of those two tests. In the test where the refrigerant ignited, peak HF concentrations of more than 3000 ppm were measured briefly (a few seconds) in the engine compartment. No HF concentration was found at the measurement point in the vehicle interior (at the sun visor near the driver's head). In a comparative test with HFC-134a under those same conditions (level 3 test of this one model) no fire occurred. .

Based on these tests KBA found that compared to cars with HFC-134a air conditioning systems the safety level of a car is decreasing if the car is equipped with a HFC-1234yf air conditioning system. Based on this, KBA recommends further investigation and asks for a specific legislation that defines tests for the type approval (KBA, 2013).

The Joint Research Centre (JRC) of the EU was holding discussions with relevant stakeholders during the review of the safety of HFC-1234yf. This consultation process was essential to provide for transparency and confidence in the process, but did not entail the approval by the stakeholders of the JRC report. Therefore, on behalf of the European Commission, DG ENTR and the JRC requested industry stakeholders and institutions which have conducted relevant test procedures and risk assessments and could provide further information useful for the process, to participate in this process and communicate the relevant information available.

Following this consultation process, in March 2014 the JRC completed its final report with the following conclusions (EU, 2014a and EU, 2014b):

1. Regarding the general approach to the testing by KBA, the report acknowledges that there is no "Standard" or "Regulatory" testing procedure available for the purpose. Therefore the KBA has legitimately used the experts' judgments and engineering judgments for selecting the test conditions.

2. Regarding the pre-tests that the KBA carried out to determine the desired test temperature for the refrigerant release tests, the testing of the vehicles followed the objective to reach the highest possible temperatures. The derived scenarios were extreme, but justifiable and reasonable ones, covering urban, extra-urban and highway driving conditions, and fully justified within the scope of the vehicle testing for the purpose of product safety investigations.

3. Regarding the crash tests, the JRC considered that the approach taken by the KBA was justified.

4. Regarding the Level 1 and Level 2 tests, the KBA concluded that "results do not provide sufficient supporting evidence of a serious risk within the meaning of the Product Safety Act (ProdSG) with the vehicle types tested hereto warrant the taking of any immediate measures by the KBA pursuant to that Act". The JRC underlined that these tests showed no ignition of refrigerants and very low hydrogen fluoride (HF) release despite the very high temperatures in the engine compartment. Consequently the results as such with the vehicles tested under the conditions as described provided no evidence of a serious risk. The JRC hence supports the evaluation of the KBA that there were no grounds for the authorities to take measures under the European general product safety legislation. Therefore, according to this legislation, the products tested have to be considered safe products.

5. Finally, regarding the refrigerant release tests under Level 3, these were not taken into account by KBA as relevant input "for the assessment of a possible risk within the scope of the statutory tasks as product safety authority". This approach is supported by the JRC. One driving force behind the tests carried out under Level 3 is exploring what could happen under assumed extreme conditions not yet covered in Level 1 and Level 2 testing. The research character is also confirmed by going beyond the boundaries and limitations set for Level 1 and Level 2 tests, to verify if the worst case was chosen in the test setup, and considering in Level 3 also the "development of engines which can be expected for the future". Whilst Level 1 and Level 2 tests were realistic and were considered by KBA for their conclusions on risks with respect to the product safety regulations, the Level 3 tests could not be associated with the necessary concrete probability of occurrence, but serve as a general appraisal of the risk. Compared to the scenarios for the realistic Level 1 and Level 2 testing, the probability of Level 3 scenarios must be assumed to be far lower, and not reflecting "normal or reasonably foreseeable conditions of use" under which the General Product Safety Directive 2001/95/EC applies.

6. Although not being part of the working group's mandate, during the meetings some measures to further improve MAC safety were presented. Examples such as release valves in MAC circuits, fire extinguisher, reduction of hot surfaces (thermal insulation) and additional ventilation were discussed in different occasions during the working group meetings.

As other methods to mitigate the flammability risks of HFC-1234yf MACs, studies are on-going in industry on flame arrestors (Koban, 2013) and on the adoption of a liquid cooled condenser.

Carbon Dioxide (R-744) Systems

R-744 refrigerant charge amounts are typically reduced by 20-30% as compared to HFC-134a systems. The US EPA has studied the potential use of R-744 as a refrigerant under the US Clean Air Act’s Significant New Alternatives Policy (SNAP) Program and has SNAP-listed R-744 as an acceptable refrigerant with the following additional use conditions (USEPA, 2012a):

- Engineering strategies and/or mitigation devices shall be incorporated such that in the event of refrigerant leaks the resulting R-744 concentrations do not exceed the short term exposure level. Vehicle manufacturers must keep records of the tests performed for a minimum period of three years demonstrating that R-744 refrigerant levels do not exceed the STEL (short-term exposure limit) of 3% averaged over 15 minutes in the passenger free space, and the ceiling limit of 4% at any time in the breathing zone.

- The use of R-744 in MAC systems must adhere to the standard conditions identified in SAE J639 Standard.

Outside of the US, ISO Standard 13043:2011 may be employed which provides additional exposure limits which deviate from the SNAP values listed in the first bullet: an acute toxicity exposure limit (ATEL) of 4% averaged over 30 minutes, an acute toxicity exposure limit of 5.5% averaged over 5 minutes, and a peak limit of 9%.

SAE standards are being developed to cover service best practices, safety practices, and refrigerant purity of R-744 (SAE J2845, 2013). However, many of the R-744 standards were not completed and published due to the interest by the industry in HFC-1234yf. With the renewed interest in R-744 the SAE ICCC is currently reviewing standards for its use.

R-744, with appropriate system design and control, has been shown to be comparable to HFC-134a systems with respect to cooling performance and total equivalent CO_2 emissions due to MAC systems, and qualifies for use in the EU under the current regulation (Directive 2006/40/EC). In a generic study which does not depend on an actual state of development, Strupp (2011) compared the required energy input (which is proportional to the CO_2 emission) of typical R-744 air conditioning systems with low, medium and high energy efficiencies to a typical HFC air conditioning system. With a high resolution, his comparison takes into account the climatic region, the local population density, and the user behavior (how many cars are at a particular time on a particular road). He did this comparison for the typical climatic regions China, Europe, India, and USA, with the result that the differences between the required annual energy inputs to drive the different air conditioning systems in a particular climatic region are in a margin of plus/minus seven percent.

R-744 heat pumps are available from one German supplier as compact cooling and heating systems for the particular application in hybrid and battery driven electric vehicles (Hinrichs, 2011). In comparison to electric resistance heaters (positive temperature coefficient (PTC) heaters), which reduce significantly the vehicle fuel efficiency and hence driving range, R-744 heat pumps operate at a substantial higher level of efficiency and offer the advantage of reducing only moderately the vehicle fuel efficiency and hence driving range (Steiner, 2014).

Currently, technical hurdles (noise, vibration, harshness (NVH) reliability, and leakage) and commercial challenges (infrastructure development, handling, aftermarket servicing, additional costs, etc.) exist that will require resolution prior to the implementation of R-744 as a general refrigerant for car air conditioning. As a consequence of the safety concerns of one German OEM regarding HFC-1234yf, in March 2013, four additional German car manufacturers proclaimed that they will also develop R-744 (see for example Volkswagen, 2013).

Together with suppliers the German OEMs are working seriously (several working groups, standardization, etc.) to achieve the aim of serial-produced R-744-systems in the year 2017 (see for example Geyer, 2013; Pelsemaker 2013; and Leisenheimer, 2013).

Carbon dioxide has also the potential to be used as working fluid in future car Organic Rankine Cycles (ORC) which could help improve the overall fuel efficiency of vehicles (see, for example, Chen, 2010 as well as Mitri, 2013).

HFC-152a Systems

Because of its flammability, HFC-152a would require additional safety systems. Most development activity has been focused on using this refrigerant in a secondary loop system but more probably in a double secondary loop system as a means of assuring safe use. Refrigerant charge amounts in a direct expansion system could be reduced by 25-30% in mass as compared to HFC-134a and with a secondary loop system, typically 50%. Industry experts have discussed using HFC-152a, but only in a secondary loop type system. A secondary loop system uses glycol and water as the direct coolant in the passenger compartment with this coolant being cooled under-hood by the refrigerant. A double secondary loop system uses glycol and water as the direct coolant passenger compartment and another glycol and water loop being used with the condenser. The use of two loops prevents refrigerant leaking into passenger compartment or leaking during breach of condenser during an accident. Prototype HFC-152a MACs and prototype vehicles using them have been demonstrated in the past years (for example, Craig, T, 2007 or Lemke, 2014). The obstacles to the implementation due to the additional cost, weight increases and size constraints are in part compensated by the advantages in case of Stop & Start thanks to the additional inertia of the system and the possibility to store cooling power.

The US EPA has studied the potential use of HFC-152a as a refrigerant under the US Clean Air Act's Significant New Alternatives Policy (SNAP) Program and has SNAP-listed HFC-152a as an acceptable refrigerant with the following additional use condition (USEPA, 2008):

- Engineering strategies and/or devices shall be incorporated into the system such that foreseeable leaks into the passenger compartment do not result in HFC-152a concentrations of 3.7% v/v or above in any part of the free space inside the passenger compartment for more than 15 seconds when the car ignition is on.

As already mentioned in the RTOC 2010 Report, HFC-152a in a secondary loop system has been shown to be comparable to HFC-134a with respect to cooling performance and equivalent CO_2 emissions due to MAC systems and qualifies for use in the EU under the aforementioned regulations.

At present, only one car manufacturer has expressed a certain interest in adoption HFC-152a as the refrigerant for MAC serial production, due to NVH and cost (for dual evaporator systems) advantages related to the secondary loop system (Andersen, 2013).

With many new vehicle designs, using a secondary loop system may have advantages for idle stop, cooling batteries or on-board electronics cooling. It also reduces the amount of refrigerant and leak rate for multi-evaporator installations since chilled coolant is circulated throughout the vehicle not refrigerant.

An Italian and a German OEM jointly completed an EU financed project with a double loop (liquid cooled condenser and chiller) whose concept has been presented on a light duty commercial demo vehicle (Malvicino, 2012); the same concept has been proposed also for hybrid and electric vehicles (Leighton, 2014).

In China, some of the vehicle companies are using R-415B as refrigerant, which was developed as alternative refrigerant for CFC-12 and HFC-134a. It consists of 75% by mass HFC-152a and 25% HCFC-22.

Unsaturated Fluorinated Hydrocarbons and Blends containing Unsaturated Fluorinated Hydrocarbons

In addition to HFC-1234yf, some zeotropic blends are still considered as possible candidates in vehicle air conditioning systems by many researchers. Two mildly flammable blends were introduced by a large chemical company, which has a history that traces its roots to HFC-134a and other fluorochemical production in England. This chemical company registered the lesser flammable of the two blends at the January 2013 ASHRAE meeting with a nominal mass composition of 6% (±1%) R-744, 9% (±1%) HFC-134a and 85% (±2%) HFC-1234ze(E). It is designated R-445A. The other blend, designated R-444A, is 12% HFC-32, 5% HFC-152a and 83% HFC-1234ze(E) by mass and is also registered with ASHRAE. Presentations regarding these two blends were made at the annual SAE symposiums in Scottsdale, AZ and Troy, MI (see for example Peral-Antunez, 2011; Atkinson and Hope, 2012; Peral-Antunez, 2012; and Peral-Antunez, 2013).

Both blends are below the European Community regulated global warming limit of 150. Both blends exhibit some flammability, with a designated A2L safety rating under ASHRAE Standard 34-2013. The blends are being evaluated by a Cooperative Research Program (CRP) under SAE rules. The more flammable blend (R-444A) matches the LCCP (life cycle climate performance, a measure of environmental impact) of HFC-1234yf, whereas the lesser flammable blend (R-445A) needs some improvement in efficiency to reach LCCP equality. However, engineering approaches to reach this point are believed to have been identified, and if the significant temperature glide (20K and more) also proves to be manageable, R-445A would be the preferred blend because of its lower potential flammability than HFC-1234yf.

The CRP reports said that the more flammable blend R-444A has a pressure-temperature curve and cooling efficiency close to both HFC-134a and HFC-1234yf, that its flammability is similar to HFC-1234yf, and that the glide is similar to zeotropic blends in stationary cooling.

Atkinson and Hope (2012) as well as Peral-Antunez (2012, 2013) report of significant different leakage rates of the three components which could lead to a concentration shift after some operating time or due to servicing. However, the team around Peral-Antunez (2014) encountered no significant leakage problems during a four month/50,000 km on-the-road test of two new cars equipped with R-445A MAC systems. Compared to HFC-134a, R-445A has a higher high-side pressure (about 2bar) and a higher compressor discharge temperature (about 10K). Due to the high temperature glide it has the risk of ice formation in the evaporator (Koehler et al. 2013, and Li 2013). Owing to the high temperature glide R-445A has the potential to be used as a heat pump fluid. Overall toxicity was described in promising terms for both blends and a preliminary toxicology estimate for the Occupational Exposure Limit, assigned by the CRP, shows that both are higher than the 500 ppm of HFC-1234yf and close to the 1000 ppm for HFC-134a.

Hydrocarbons and Blends containing Hydrocarbons

In Australia and the USA, hydrocarbon blends, sold under various trade names, have been used as refrigerants to replace CFC-12 and to a lesser extent for HFC-134a. The retrofits with HCs are legal in some Australian states and illegal in others and in the USA. US EPA has forbidden the uses of HCs for retrofit but has considered the possible use of HCs for new systems, but is awaiting proof that safety issues have been mitigated.

HCs or HC-blends, when correctly chosen, present suitable thermodynamic properties for the vapour compression cycle and permit high energy efficiency to be achieved with well-designed indirect systems (same systems as the secondary loop system presented above for HFC-152a). Nevertheless, even with indirect systems, HCs are so far not seen by the largest part of vehicle manufacturers as replacement fluids for mass-produced AC systems due to safety concerns.

The combined needs of advanced thermal systems and air conditioning for hybrid and electric vehicles and lower GHG emissions makes promising the introduction of a compact refrigeration unit incorporating an electric compressor and fully sealed and pre-charged design. The compact refrigeration unit being constituted by two liquid cooled exchangers (chiller and condenser and where requested of an internal heat exchanger) is able to produce hot or cold coolant, normally a water-glycol mixture, and to minimize the refrigerant charge and leak.

With this perspective, the use of hydrocarbons or blends of them becomes once again interesting, being such fluids are worldwide available, cheap and with a very low environmental impact.

The use of a compact refrigeration unit with a double loop enables the opportunity to mitigate the issue related to refrigerant leak allowing very low charge (-50%). Furthermore it enables also the use of the air conditioner as heat pump without the need of a 4 way valve, making easier the thermal management of the batteries and electronics. This approach is under development in Italy and Germany and the components are already available from different leading suppliers in Italy, France, as well as in Germany and US.

Hydrocarbons have also the potential to be used as working fluid in future car Organic Rankine Cycles which could help improve the overall fuel efficiency of cars (Preißinger, 2012 and Mitri, 2013).

10.3.2 Bus and Rail Air Conditioning

Mass transit vehicles involve buses, coaches and rail cars, which can further be segmented to conventional trains, high speed trains, trams, subways, etc. As compared to passenger cars, their air conditioning systems are larger in size, have a higher cooling capacity, and in general use modified commercial components. They are usually packaged specifically for each application.

The mass transit vehicle fleet is smaller than that of passenger cars. The latest statistical data for the 27 European countries show that per 1000 inhabitants, there are approx. 1.6 buses and coaches, 0.1 locomotives and rail cars, and 477 passenger cars (Statistical Handbook, 2012). The number is assumed to be different elsewhere (in the North America and Japan, more passenger cars than mass transit vehicles; in developing countries, the reverse). It may be assumed that, on average, at least 50% of the current EU mass transit vehicle fleet is air-conditioned. Both climate and economic conditions would determine the likelihood of air conditioning in transit vehicles in other regions.

Today, most buses and coaches have the entire air-conditioning system mounted in the roof, except for the compressor, which is driven from the vehicle engine. The air conditioning units for rails cars can have a similar concept, especially if powered by diesel engines. But more often, in about 75% of cases, the air conditioning systems in rail cars are self-contained and electrically powered. The self-contained concept reduces both the charge and the leakage rate.

The predominant refrigerant used in new buses and coaches is HFC-134a. While several years ago the refrigerant charge used to be in the excess of 10 kg per unit (Schwarz, 2007), the introduction of microchannel condensers as well as component downsizing reduced the current refrigerant charge below 5 kg in the new systems. The air conditioning units for rail cars use HFC-134a and R-407C in about equal share. A small fraction of rail cars use R-410A. The refrigerant charge is about 10 kg.

In China, heat pump systems are used for thousands of electric buses, which utilize the refrigerant blends R-407C and R-410A. As train air conditioning units usually are hermetic systems with hermetic or semi-hermetic compressors, their system design is based more on stationary air conditioning than on mobile air conditioning. Here R-410A is preferred.

Older systems in developing countries still utilize HCFC-22. According to the European statistics, the average age of a European bus or coach is 16.5 years. Although the rail car units are designed to last for more than 30 years, technological progress and fleet upgrades determine their lifetime to about 20 years. Even before a rail car reaches its end-of-life, a major overhaul is often performed wherein the air conditioner is replaced.

Although limited by its volume, the mass transit vehicle industry follows closely the developments in passenger cars and other fields. A large German manufacturer has on-going fleet tests of R-744 systems in buses since 2003 (see for example Eberwein, 2011; Schirra, 2011; and Sonnekalb, 2012). In the year 2012 a Polish bus manufacturer started selling battery-driven electric busses with reversible R-744 heat pump systems for heating and cooling (Solaris, 2012). The significant potentials of energy efficiency improvements of R-744 bus air conditioning systems, due to measures like cylinder bank shut-off controls, ejectors, and two-speed planetary gearbox compressor drives, were investigated by Kossel (2011) and Kaiser (2012).

The Low-GWP Alternative Refrigerants Evaluation Program of AHRI investigated the use of drop-in alternative refrigerant blends in bus air conditioning (N-13a [R-450A] and AC5 [R-444A] as alternatives for HFC-134a, and L-20 [by mass 45% HFC-32/20% HFC-152a/35% HFC-1234ze(E)] and D52Y [by mass 15% HFC-32/25% HFC-125/60% HFC-1234yf]as alternatives for R-407C). They found mostly comparable or lower energy efficiencies for bus air conditioning systems which used the alternative blends (Kopecka, 2013a and 2013b).

Environmental and fuel price concerns lead bus and coach manufacturers to pursue development of hybrid and battery driven electric vehicles. The concept makes traditional engine-driven compressors obsolete and favors self-contained hermetic systems, where the refrigerant charge and leakage rate are lower. The electric power is supplied either from the on-board sources, or engine-driven generators. These systems are not limited to electric vehicles, but can be applied also in traditional buses and coaches. Installations can be found in trolleybuses.

10.4 Options for existing Systems

10.4.1 Retrofit of CFC-12 systems

There are 12 blend refrigerants that are approved by the USEPA under the SNAP regulation for retrofit of CFC-12 systems (USEPA, 2013); however, many of these have seen only minimal use and some were never fully commercialized. Retrofit to HFC-134a was approved by the OEMs and was more commonly used if a retrofit was deemed appropriate. In a 2013 MAC survey about 6% of all cars were still operating with CFC-12 and about 10% of all cars had been retrofitted to HFC-134a (Atkinson, 2014). However, retrofitting of CFC-12 vehicles has declined significantly primarily due to the declining fleet of vehicles with CFC-12 MACs and in part due to the continued availability of reclaimed CFC-12. In the USA, the sale of CFC-12 is restricted only to certified technicians.

10.4.2 Hydrocarbon retrofits

Retrofit of HFC-134a and CFC-12 systems to hydrocarbons is still occurring in various regions, particularly in Australia and to some extent in North America even though vehicle OEMs and some regulatory bodies do not approve of this process due to inadequate safety mitigation

10.5 Concluding Remarks

Currently, more than one refrigerant are being used for car and light truck air conditioning: HFC-134a will remain largely adopted worldwide, while HFC-1234yf is currently implemented in some models and likely will be used in more models in the near future. Development of R-744 continues and will also likely be used. Possibly some new low GWP synthetic refrigerant or refrigerant blend (e.g. R-445A) will also be used. In existing systems (designed for CFC-12 or HFC-134a), even hydrocarbons (e.g. HC-290) are used in some regions (e.g. Australia).

At the moment, it cannot be foreseen whether or not all these refrigerants will remain for a long period of time parallel in the market. If the bus and train sector will follow these trends is also unclear.

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Annex to Chapter 10

Annex B: Regulatory actions affecting vehicle air conditioning and refrigerants

This annex summarizes for several, but not all, different regions the legal situation for vehicle air conditioning systems.

Light-Duty Cars and Trucks

Brazil and Latin America: No specific regulations are in place in Brazil regarding mobile air conditioning. The current most important regulation (Resolução 267_00 CONAMA) states that the current gas refrigerant has to comply with the Montreal Protocol and to have low ozone depletion potential (ODP).

The refrigerant currently used not only in Brazil but in whole Latin America is HFC-134a.

China: In China, the refrigerant in Mobile Air Conditioning (MAC) systems had been completely changed to HFC-134a since June 30, 2007. The consumption of HFC-134a in MAC in 2012 can be estimated to be about 20,000 tons. The Chinese government also realizes the importance of reducing the emission of greenhouse gas (GHG) since HFC-134a has a high GWP value. For the refrigerant in the vehicle, the work of Chinese government is mainly focused on refrigerant recovery and reducing the refrigerant charge amount since the substitute of HFC-134a is still not so clear.

Europe: European Union (EU) regulations, which control MAC system direct emissions, fall into two groups:

- controlling leaks
- phasing out high-GWP fluorinated GHG's.

Directive 2006/40/EC (EU Directive, 2006) applies to passenger cars and light commercial (categories M1 and N1) and covers both the emissions from air-conditioning systems in motor vehicles and the ban on use of refrigerants with a GWP greater than 150 in new type vehicles from January 1, 2011 and all new vehicles from January 1, 2017.

Due to the shortage of the low-GWP refrigerant R-1234yf, which had apparently been chosen by most if not all OEMs, the European Commission decided not to enforce the Directive until the end of 2012. Although the MAC systems of new types of vehicles to be type approved had to be compatible with MAC directive 2006/40/ EC requirements, manufacturers were allowed to fill new type approved production vehicles with R-134a until 31 December 2012. The European Commission (EC) has confirmed several times that this situation of refrigerant shortage has been resolved to its satisfaction and therefore the MAC Directive has been in full effect since 1 January 2013.

The type-approval authorities of the Member States are responsible for the monitoring of the implementation of the measures above and for verifying the conformity of production after 31 December 2012.

EU Commission Regulation (EC) No 706/2007 (EU Regulation, 2007) includes a harmonized test for measuring leakages from mobile air conditioning systems.

EU Commission Directive 2007/37/EC (EU Directive 2007) limits refrigerant emissions from mobile air conditioning, using refrigerants with GWP>150, to 40 g/y for single evaporator systems and 60 g/y for dual evaporator systems beginning with new type vehicles in June 2008 and all vehicles in June 2009.

The European Regulation (EC) No 443/2009 (EU Regulation 2009) sets emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicle. The Regulation limits CO_2 emissions per kilometer to 130 gCO_2/km from 2012 to 2019 and 95 gCO_2/km from 2020 onwards. The regulation includes off-cycle credit for innovative technologies reducing the fuel consumption, so-called eco-innovations (chapter 12 of the Regulation), but for mobile air conditioning systems that will be regulated by a specific procedure. The EU is currently cooperating with the stakeholders to develop this procedure.

It is possible that the Regulation will be extended to all the other motor vehicle categories once the application transient on passenger cars and light commercial vehicles is completed

India: India has comprehensive Ozone Depleting Substances (Regulation and Control) Rules, 2000 which were put in place from July 19, 2000 under the Environment (Protection) Act 1986. These rules set the deadlines for phasing-out the ozone depleting substances. There is a mandatory requirement of registration for ozone depleting substances producers, consumers, importers, reclamation centers, destruction facilities, etc. with a designated authority. The unique feature of these rules is banning of use of CFCs in manufacturing of new products and equipment including refrigeration and air-conditioning equipment for cars, busses and trains as early as January 1, 2003. This not only achieved the phase-out of CFCs earlier than the Montreal Protocol schedule but also reduced the inventory of CFC based equipment which resulted in the lowering of servicing requirements of CFCs. As a consequence of ozone depleting substances rules in India all light-duty vehicle Mobile Air Conditioning manufacturing was converted to HFC-134a from January 1, 2003 and all new manufacturing capacities were put up with HFC-134a and same is continuing. The busses and trains use either HFC-134a or HCFC-22. Most of the old MAC and train air-conditioning CFC based systems were retrofitted to HFC-134a. The Ozone Depleting Substances (Regulation and Control) Rules, 2000 have been amended from time to time to align with the Montreal Protocol phase-out schedule and internal policies of the country. These rules have been amended in 2014 to align with accelerated phase-out of HCFCs and amendment has been notified as Ozone Depleting Substances (Regulation and Control) Amendment Rules, 2014.

Japan: In August 2009, Japanese government allowed the import of HFC-1234yf into Japan without the limitation of usage amount, aspects and any special monitoring. This decision was made after HFC-1234yf was examined by Japan's Ministry of Health, Labor, and Welfare, Japan's Ministry of Economics Trade and Japanese Ministry of the Environment based on "Toxic Chemicals Control Law".

USA: Motor Vehicle Air Conditioning refrigerants must be submitted to the U.S. Environmental Protection Agency (USEPA) and found acceptable under its Significant New Alternatives Policy (SNAP) Program. So far (2014), approximately 17 different refrigerants, and 3 alternative technologies, have been found acceptable under the SNAP Program (USEPA 2013). The majority of these refrigerants were aimed primarily at the retrofit of CFC-12 cars and found very little, if any, use. HFC-134a was until recently the only refrigerant accepted by the OEMs and quickly became the only refrigerant used in new equipment, with a few model year 1992 vehicle types using HFC-134a and all types by model year 1995 (MACS, 2003).

Three of the refrigerants found acceptable have GWPs less than 150: HFC-152a, HFC-1234yf and R-744 (CO_2). All are subject to certain use conditions (for details see the particular sections covering these refrigerants). The use conditions that apply to all substitute mobile AC refrigerants are required by the USEPA to reduce the flammability and/or toxicity risks from these refrigerants as well as to avoid mixing of different refrigerants.

Joint regulations from the USEPA and the National Highway Traffic Safety Administration set requirements for corporate average fuel economy (i.e., average miles per gallon or liters per 100 kilometers) and tailpipe emissions (i.e., grams CO_2-equivalent per mile or kilometer). Although these regulations do not require specific choice of refrigerants, utilizing low-leak designs and/or low-GWP refrigerants offer additional pathways to comply partially with the requirements. In addition, credits were offered for (1) improvements in air conditioning systems that reduce tailpipe CO_2 through efficiency improvements, and (2) for reduced refrigerant leakage through better components and/or use of alternative refrigerants with lower global warming potential. These regulations were enacted first for model years 2012 through 2016. That rule allowed OEMs to achieve credits in advance of the regulations for design changes in model years 2009 through 2011, a stipulation that helped spur more leak-tight and fuel-efficient systems. The second set of regulations applies to model years 2017 through 2025. USEPA expects that the credits offered in this program will incentivize the uptake of low-GWP refrigerants; USEPA estimated that uptake of HFC-1234yf would reach 20% in model year 2017 vehicles, rising linearly to 100% by model year 2021 vehicles (USEPA and NHTSA, 2012b). One U.S. OEM committed to convert some models to HFC-1234yf refrigerant by MY2013 (General Motors, 2010); one of these models has been sold in the U.S. and elsewhere since 2012. A Japanese OEM also offered one MY2013 model with HFC-1234yf, and other models are expected with MY2014 designs (Automotive News, 2013). Atkinson, 2014 provides a list of 9 car types which use HFC-1234yf in the US market.

In June, 2013, U.S. President Obama announced a Climate Change Action Plan. Amongst other initiatives, the President committed the USEPA to "use its authority through the Significant New Alternatives Policy Program to encourage private sector investment in low-emissions technology by identifying and approving climate-friendly chemicals while prohibiting certain uses of the most harmful chemical alternatives" (US President, 2013). One prohibition proposed by USEPA is to prohibit the use of HFC-134a in light-duty motor vehicles beginning with MY 2021 (USEPA, 2014). This proposal has not been finalized as of December 2014.

USEPA has a new drive schedule that is required to be run from 2016. Initially the credits are determined strictly by a menu driven formula, but from 2017, the new AC17 test schedule must be run and the resulting CO2 emissions must support the credit before it can be applied. This drive schedule is a dynamic one with solar load applied in a test chamber. (Nelson, 2012 and Brakora, 2013).

Buses and Trains

There are no particular legal restrictions on Buses and Trains refrigerant, apart from those discussed above. However, the bus industry follows closely the developments in passenger cars and the trains industry has to date followed closely the development of hermetic and semi-hermetic systems similar to the stationary air-conditioning market. Given possible safety implications of the low-GWP alternatives, however, it may be that bus and train MAC systems will eventually use a different set of refrigerants than those used in light-duty vehicles.

Annex C: Not-In-Kind Alternatives

The refrigeration technologies described in this annex are all far away from a serial-production status. However, OEMs and suppliers do work on the development of these systems because they have a certain potential to become interesting alternative options for a time horizon which goes beyond 2020. For some even that seems unlikely considering the long history of effort for them.

Air cycle (Brayton cycle)**:** These systems have the advantage of using air as refrigerant which is environmentally very benign. However, they have comparatively very low energy efficiencies and cooling capacities (see Liebherr, 2010).

Thermoelectric heating and cooling: Thermoelectricity (TE) is one of the simplest technologies applicable to energy conversion based on the properties of couples of materials that can use electric energy to operate as heat pumps providing active cooling or heating.

Small pieces of thermoelectric material (TE elements) are connected to form a Peltier couple: one element is of p-type, the other one of n-type; they are electrically connected in series (by means of a copper plate) and thermally in parallel. A set of such couples forms a TE-module. Cost and efficiency (maybe also capacity) are currently the main issues limiting the application of thermoelectric heat pumps only to specific uses like, for example, the automotive seats air conditioning.

Magneto caloric heating and cooling: Since 1975, many experimental prototypes of magnetic refrigerators at room temperature have been developed with different configurations and operating conditions (see for example Vasile, 2005, Yu, 2010, and Sciullo, 2011). Recently relevant progresses have been achieved both for applications in the automotive domain as well as for stationary application (e.g. vending machines and domestic refrigerator).

The magneto caloric effect results in a temperature increase within a magneto caloric material when a magnetic field is applied owing to a reversible energy transfer from the magnetic field to the material; the material reaches the initial lower temperature once the magnetic field is removed.

Thermo acoustic heating and cooling: Although the phenomenon that temperature gradients along a tube can provoke (pressure) oscillations in gases has been known for more than 150 years, it was the work of Rott (1980) which brought about the breakthrough for further investigations.

The corresponding thermodynamic cycles are the Brayton (standing wave machine) and Stirling (travelling wave machine) cycle. As working fluid often helium is applied (Swift 2002).

The environmentally benign working fluid as well the possibility to use the waste heat from the engine could lead to future applications of thermo acoustics in MAC systems (see for example Zink, 2010, and Zoontjens, 2005). Although recent investigations show the feasibility of these refrigerators (Bassem, 2011), significant further research and development of this technique are necessary.

Sorption heating and cooling: Sorption cooling based on the re-use of waste heat (e.g. exhaust gas or cooling jacket) has been evaluated within several projects in the last decade (see for example Tamainot-Telto, 2009 and Vasta, 2012).

The heavy duty truck application has a higher potential due to higher waste heat amount and less severe constraint in terms of weight and size.

In addition to that, sorption systems offer the opportunity of long-term thermal storage.

Chapter 11

Sustainable Refrigeration

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11 Sustainable refrigeration

11.1 Introduction

Sustainability of refrigeration and air conditioning systems is a major factor affecting the choice of alternative refrigerants. In this chapter both equipment and systems from concept to end-of-life are described. It includes sections on the direct and indirect impact of refrigerants on emissions and the tools used to assess such impact; equipment lifetime considerations and the regulations covering equipment design, installation, and operation; as well as energy management considerations for systems, buildings, and processes.

By discussing all aspects of refrigeration systems affecting sustainability, the chapter tackles aspects that affect the environment globally and hence have become crucial in the search of alternative refrigerants. Care was taken to include examples from many countries and regions since sustainability refers to the biosphere and human society as a whole.

11.2 Sustainability applied to refrigeration

Refrigeration impacts the ability of global sustainability in many ways. Economic, environmental and social impacts - some positive, other negative – are produced throughout the life cycle of the refrigeration equipment, from the extraction of its raw materials until end of life.

While keeping focus on possible environmental impacts of refrigeration treated throughout the report - namely the depletion of the stratospheric ozone layer and global warming - a wider range of relevant environmental, as well as social considerations, are briefly described in this section, for consideration by decision makers.

Sustainable manufacture of systems is gradually becoming part of the decision making process for manufacturers who used to base their design on cost grounds rather than for environmental compliance leading to the acceptance of lower efficiency systems in some cases. Designers today are faced with dilemma of designing smaller units for sustainability reasons vs. larger ones for efficiency purposes. For example, a 15 to 20 K design temperature difference used for air-cooled condensers results in, smaller heat exchangers which use less material; however, it is possible to get improved efficiency by using larger heat exchangers which use more raw material and are more expensive. There is no clear guidance on optimizing these design decisions, even though there are today some best practices like the use of recycled aluminium in heat exchangers, greater use of plastics and other synthetic materials from renewable sources.

11.2.1 Sustainability principles

The most widely known definition for sustainable development is the one presented by the Brundtland report: "to meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987). The same overall goal can be expressed in more specific terms: four necessary and sufficient conditions for a sustainable society were proposed (Holmberg, 1996), and submitted to extensive peer review. These conditions are stated as follows:

"In a sustainable society, nature is not subject to systematically increasing of:

1. Concentrations of substances extracted from the Earth's crust
2. Concentrations of substances produced by society
3. Degradation by physical means, and, in that society...

4. People are not subject to conditions that systematically undermine their capacity to meet their needs." (Ny, 2006)

These general principles are affected by environmental and social aspects.

11.2.2 Environmental aspects

Some ecological aspects related to refrigeration derived from the principles i, ii, and iii, disclosed in section 11.2.1, are:

i. Extraction of resources: energy from fossil fuels, mining of materials such as copper, (used in tubing, heat exchangers, and winding of electric motors), zinc, fluorite (European Commission, 2011) and other scarce materials (here understood as proportional to the rate a substance is being extracted, relative to its natural concentration in the environment), aluminum, iron, rare earth products, use of fossil substances as raw materials for refrigerants (virtually all refrigerants except water and ammonia), use of fossil fuels and mineral oil in compressors and other moving parts. Despite of recycling efforts, the combined production levels of copper, zinc, and fluorite reached 30.4 Mt in 2006, representing an increase of 20 % over the production levels in 1999 (Lottermoser, 2010).
ii. Emission of man-made substances: emissions of refrigerants, solvents, paints & other surface treatment materials, and the incineration of materials are a major part the direct emissions of greenhouse gases. Indirect emissions related to the lifecycle of refrigeration systems form the other part.
iii. Degradation of fertile ecosystems: Examples are food conservation, metals and non-metals mining, water usage, oil extraction, landfill of waste materials.

11.2.3 Social aspects

Refrigeration and air conditioning relate mainly to the social need of physical and psychological wellness, from health and safety conditions prevailing along the value chain, including consumer safety, to the availability of healthy food and reduction of food waste by appropriate refrigeration, thermal comfort and avoidance of thermal stress provided by air conditioning.

However other social needs should also be considered when coupling the refrigeration business to the sustainability imperative, such as:

- Learning through: awareness, education, proper training of employees and technicians; and
- Equity and fairness, supported by: ethical conduction of business, fair trade, fair marketing, low cost equipment coupled with high energy efficiency to the extent commercially feasible.

11.2.4 Assessment tools

The following assessment tools treat of particular aspects related to sustainability:

Total Equivalent Warming impact (TEWI) is a measure of the global warming impact of equipment based on the total related emissions of greenhouse gases during the operation of the equipment and the disposal of the operating fluids at the end-of-life. TEWI takes into account both direct fugitive emissions, and indirect emissions produced through the energy consumed in operating the equipment. TEWI is measured in units of mass in kg of carbon dioxide equivalent (CO2-eq.). The TEWI equation can be found in (EN, 2008) and (Fischer, 1991). It can be evaluated in conjunction with seasonal profiles of temperatures and capacity.

Life Cycle Climate Performance (LCCP) is a concept that incorporates the TEWI considerations and additionally includes direct and indirect greenhouse emissions from the manufacture of the active substances. Active substances are components and the working fluids such as the refrigerants (IPCC, 2005). Various studies of LCCP have included for instance the fugitive emissions of a refrigerant from production until installation in equipment, the embodied energy or GHG emissions associated with producing the refrigerant, and the GHG emissions associated with extracting materials and producing components of an air-conditioning or refrigeration system.

Both LCCP and TEWI include a measure of the efficiency of the product and give a better indication than a simple GWP reference of what the greenhouse gas emissions associated with the use of air-conditioning and refrigeration equipment will be. LCCP and TEWI calculations provide more information on the sustainability of air-conditioning and refrigeration equipment than GWP or energy efficiency alone; therefore, these methodologies should be used when comparing products and systems.

Social and Socio-Economic Life Cycle Assessment (S-LCA) is a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal. S-LCA complements the more usual environmental Life Cycle Assessment (E-LCA) with social and socio-economic aspects. It can either be applied on its own or in combination with E-LCA. S-LCA assesses social and socio-economic impacts found along the life cycle (supply chain, including the use phase and disposal) with generic and site specific data. It differs from other social impact assessment techniques by its objects: products and services, and its scope: the entire life cycle. Social and socio- economic aspects assessed in S-LCA are those that may directly affect stakeholders positively or negatively during the life cycle of a product. They may be linked to the behaviour of enterprises, to socio-economic processes, or to impacts on social capital. Depending on the scope of the study, indirect impacts on stakeholders may also be considered. S-LCA provides information on social and socio-economic aspects for decision making, instigating dialogue on the social and socio-economic aspects of production and consumption, in the prospect to improve performance of organizations and ultimately the well-being of stakeholders (UNEP, 2009).

Sustainability Life Cycle Assessment is a qualitative technique to determine the degree of conformity of an actual product or system to sustainable conditions, through the identification of gaps in knowledge or potential impact, which would need focused quantitative assessments (NY, 2006).

11.2.5 Opportunities for improvement

Some relevant opportunities for the industry aiming to achieve sustainability improvements along the lifecycle of a refrigeration system are:

- Close progressively the production-consumption loop of materials manufactured from minerals, especially scarce materials such as copper, zinc and fluorine;
- Reduce the emissions of GHG while reducing the dependence on oil. This can be achieved by focusing on energy efficiency, and by increasing the share of fossil-free energy during life cycle;
- Reduce progressively the use of virgin raw materials, minimize emissions, upcycle waste, reuse water, and check responsible management of substances along the value chain;
- Manage and progressively phase out persistent, bio accumulative and other hazardous substances to the environment and health from the materials inventory;

- Establish codes of ethical conduct for suppliers along value chain and use them as effective management tools;
- Reduce the use of packaging materials;
- Ensure refrigerant conservation.

Such improvements may be facilitated with:
- Development of standards that measure and report the relative sustainability of products and processes
- Awareness raising through the value chain
- Education on sustainability and its implications
- Regulations and political actions defining technical conditions
- Integration of social and environmental externalities into corporate governance and reporting
- Financial incentives to take account of environmental damage

11.3 Direct impact of refrigerants

Most of the halocarbon refrigerants including CFCs, HCFCs and HFCs are either ozone depleting or global warming or both. Therefore, emissions of these refrigerants have direct impact on the environment. Refrigerants are not only used in new equipment and appliances but there is a recurring consumption in servicing during the useful working life of the equipment. Consumption of refrigerants for servicing is more than what is being used in the manufacturing of new equipment. In the worst cases, the entire refrigerant charged and used for servicing over the useful working life of refrigeration and air-conditioning equipment is gradually emitted to the environment. Efforts are being made to reduce the impact of these refrigerants on the environment by refrigerant management and conservation techniques.

11.3.1 Design criteria for charge minimization and leak tightness

Charge minimization

Charge minimization is one important factor for conservation of refrigerant. Minimization of the refrigerant charge would not only reduce the global consumption of refrigerants but it would also reduce their impact on climate by reducing the quantity of possible emissions that could be emitted during catastrophic leak events, during the working life of equipment and end of life of equipment. Historically, little attention has been given to minimize charge quantities. The charge amount is only specified for small equipment especially for capillary fitted units where the performance of the unit is highly affected by the charge quantity. Other systems are charged on the site and charge quantity is rarely pre-calculated or specified.

Recognizing the importance of the charge minimization, industry is paying attention to this aspect by employing designs for lower storage of refrigerant. In case of unitary air-conditioning systems with hermetic compressors, the majority of refrigerant is banked in the compressor and heat exchangers, especially in the condenser. Systems are designed with mini channel heat exchangers to reduce the internal volume of the condenser, and compressors are designed for reduced oil. Significant efforts are also being made to design and develop supermarket refrigeration equipment by using secondary loop and cascade systems that use a much smaller refrigerant charge than traditional refrigeration system. It should be noted that there may be negative effects of charge minimization: some systems may be sensitive to a charge deficit leading to an increase in energy consumption and even a system failure. Another typical trade-off situation is the choice between direct and indirect systems. The latter systems tend to minimize the direct emissions of fluids, but might increase the indirect emissions due to the increased losses. There is a balance to ensure good efficiency despite minor leakage and reduced direct emissions.

Overcharging of equipment is common, especially in systems with receivers, as the amount of refrigerant contained in refrigerant receivers is not always known. Refrigerant receivers are equipment components that contain excess refrigerant that migrates through the system as a result of changes in ambient conditions. Therefore, refrigerant receivers should be designed or selected in a proper way. On the other hand design criteria's for varying ambient conditions and operation parameters are often not commonly known. For such equipment, field charging is often continued until the charge is considered satisfactory. Without the check of weighing the charge, the circuit could be overfilled with two harmful consequences: (1) a potential release of refrigerant, and (2) the possibility of transferring the entire charge into the receiver. The receiver-filling ratio, therefore, has to be limited during nominal operation, and an inspection tool (indicator, level, etc.) must be provided.

More detailed information has been published recently by IIR-IIF (IIR, 2014)

There is a trend in the market to move towards what is referred to a critically charged. In these systems it is very important not to charge more on the system than it is designed for. This helps not overcharging the system but it also requires more skills from the persons working on the system.

Another trend from legislation side is the move from look more on the leak potentials rather than look at the charge size. The potential leak can come from any connections, flanges, valves, compressor and motor assemblies etc. The likelihood of a pipe or a vessel should become leaky is minimal in a well-designed system. Leaks, however, tend to come when valves or flanges have been serviced. The authorities like to look at potential leak and the advantage is that you can deal with it already at the design phase. You can count the flanges and you can calculated all sealings and connections and in this way determine what leak rate you can have and where the leaks might be.

Reduction of emissions through leak tightness

Leak detection of the equipment in production or assembly is a basic element, both in constructing and servicing of cooling equipment, as it makes it possible to measure and improve conservation of refrigerant. Leak detection must take place at the end of construction by the manufacturers, at the end of assembly in the field by contractors, and during regularly scheduled maintenance of equipment by service technicians.

Beside other code of good practice and refrigeration standards covering requirements for leak testing and tightness, there are three general types of leak detection methods:

1. Global methods indicate that a leak exists somewhere, but they do not locate the leaks. They are useful at the end of construction and every time the system is opened up for repair or retrofit;
2. Local methods pinpoint the location of the leak and are the usual methods used during servicing;
3. Automated performance monitoring systems indicate that a leak exists by sensing changes in equipment performance and alerting operators.

Industry both in developed and developing countries, in recent years, have improved design for leak tightness in the air-conditioning and refrigeration equipment manufactured after the Montreal Protocol. In addition existing equipment/appliances have often been modified with new devices, such as high-efficiency purge devices for low-pressure chillers that have significantly lowered refrigerant emissions. Design changes have been made with regard to leak tightness in response to growing environmental, regulatory, and economic concerns associated with refrigerant emissions.

11.3.2 Reduction of emissions through installation, servicing and maintenance

The installation of refrigeration equipment plays a very important role in terms of equipment life, energy consumption, trouble free operation, and refrigerant conservation. Use of proper installation techniques should be followed to ensure joints that can withstand vibration, temperature and thermal cycling stresses. Proper cleaning of joints and evacuation to remove air and non-condensable gases will minimize the future service requirements. For non-hermetic equipment, the installer should ensure the proper charge is provided. The installer should also seize the opportunity to find manufacturing defects before the system begins operation.

The Montreal Protocol has globally sensitized the servicing community as well as the end-users to use good servicing practices and reduce the emissions of refrigerants through awareness programmes. Servicing practices have improved especially in some of the sectors mainly because of training of servicing personnel engaged in these sectors. Unsustainable servicing practices—such as topping-up refrigerant without repairing leaks, or leak testing with high-ODP or high-GWP refrigerants—are avoidable. Instead, refrigerant recovery, recycling, reclamation and destruction, discussed below, should be practiced.

Technicians must study the service records to determine the history of leakage or malfunction and energy consumption trends. Technicians should also measure performance parameters to determine the operating condition of the cooling system. Fixing leaks and defects early will help avoid catastrophic failures that may contaminate or release the entire refrigerant charge. Technicians should determine the best location from which to recover the refrigerant and assure that proper recovery equipment and recovery cylinders are available. Proper maintenance documents like logbooks enable the user to monitor the frequency of repairs as well as the amount of refrigerant recovered, added and emitted.

In addition, periodical cleaning of refrigeration equipment not only enhances the proper operation of the system but also reduces the frequency of system failure.

Training of technicians is essential for the proper handling and conservation of refrigerants, the optimized operation of the equipment, the control or reduction of energy consumption, and avoids loss of stocked food when refrigerant and lubricant come in contact with it due to improper handling. Such training should include information on the environmental and safety hazards of refrigerants, the proper techniques for recovery, recycling, reclamation and leak detection, and local legislation regarding refrigerant handling. The European standard EN 13313 describes the competence developments necessary for all levels, from system design to commissioning and servicing.

11.3.3 Refrigerant recovery, recycling, reclamation and destruction

This section provides an overview of refrigerant conservation. Additional details can be found in previous RTOC report (UNEP, 2011).

In the last few decades, there has been an increasing emphasis on conservation of refrigerants and reduction of emissions that has led the industry to develop a specific terminology which is used in this report (ISO, 1999):

- Recover: to remove refrigerant in any condition from a system and store it in an external container.
- Recycle: to clean the extracted refrigerant using oil separation and single or multiple passes through filter-driers which reduce moisture, acidity, and particulate matter. Recycling normally takes place at the field job site.

- Reclaim: to reprocess used refrigerant to virgin product specifications. Reclamation removes contaminants such as water, HCl and HF reaction products, other acids, high boiling residue, particulates/solids, non-condensable gases, and impurities including other refrigerants. Chemical analysis of the refrigerant is required to determine that appropriate specifications are met. The identification of contaminants and required chemical analysis are specified by reference to national or international standards for new product specifications. Reclamation typically occurs at a reprocessing or manufacturing facility.
- Destroy: to transform used refrigerant into other chemicals in an environmentally responsible manner.

Refrigerant recovery

Recovery of refrigerant, especially CFC-12 and H-CFC-22, has become an integral part of servicing practices in most of the countries, especially for systems having relatively large charge quantities. The incentives for refrigerant recovery are the cost of refrigerants and environmental protection. The regulatory framework is also a driving force for recovery of refrigerant especially in non-Article 5 countries. In developing countries, the continuing replacement of old CFC-based refrigerators in favour of new ones, many of them containing HFC as refrigerant, and the rapidly growing market of HFC-based room air conditioners, increases the importance of regulations aiming to avoid venting of refrigerants during equipment repair.

Refrigerant recovery equipment reduces emissions by providing a means of temporary storage of refrigerants that have been removed from systems undergoing service or disposal. Such equipment is used to temporarily store recovered refrigerant until the system is ready to be recharged. The recovered refrigerant may also be used in other equipment or sent for destruction. Refrigerant recovery equipment may have the added capability of recycling of refrigerants.

Refrigerant recovery equipment has been developed and is available with a wide range of features and prices. Some equipment with protected potential sources of ignition also exists for recovery of flammable refrigerant. Although liquid recovery is the most efficient, vapour recovery methods may be used alone to remove the entire refrigerant charge; however, in order to reach the vacuum levels that are required in some countries for larger systems, vapour recovery is used after liquid recovery (Clodic, 1994). Testing standards have been developed to measure equipment performance for automotive (SAE, 1990) and non-automotive (ISO, 1999) applications. Such standards, as a part of common service procedures, should be adopted by regulating authorities.

Refrigerant recycling

Refrigerant recycling conserves refrigerant during the service, maintenance, repair, or disposal of refrigeration and air-conditioning equipment. Refrigerant recovery and recycling equipment should be made available to service technicians in every sector. The logistic process should be easy to understand and cover all players from point of sales to the customer, and back to point of return. It may be noted that due to incompatibility issues and the array of refrigerants used that refrigerant recovery/recycling equipment intended for use with one refrigerant and/or type of air-conditioning system may not be adequate to service other refrigerants or sectors.

Recycling reduces oil, acid, particulate, moisture, and non-condensable (air) contaminants from used refrigerants. The recycling performances can be measured on standardized contaminated refrigerant samples according to test methods (AHRI, 2012). Since the quality of recycled refrigerant cannot be proven by analysis, restrictions are imposed on the use of recycled refrigerants.

Currently, the automotive air-conditioning industry typically reuses recycled refrigerant without reclamation in a different owner's system. Acceptance in other sectors depends on national regulation, recommendation of the system manufacturers, existence of reclamation services, variety and type of systems, and the preference of the service contractor and owner. Reuse of recovered refrigerant requires strict adherence to good practices including identifying the refrigerant type. Mixed refrigerants are often costly to separate which may result in the sale of cross-contaminated refrigerants. For most refrigerants there is a lack of inexpensive field instruments available to measure the contaminant levels of recycled refrigerant after processing; hence in countries where access to qualified laboratories is limited and shipping costs are prohibitive, caution is required to prevent unintentional mixing of refrigerants.

Refrigerant reclamation

Recovery and reclamation of used refrigerants can, to a certain extent in some countries, meet the servicing requirements as well as conserve refrigerant and reduce emissions to the environment. Reclamation is the processing of used recovered refrigerant back to almost virgin specifications. Reclamation also extends the lifespan of the refrigerant as well as the equipment and decreases the dependency on virgin refrigerant by placing it back into service. Reclaimed refrigerants are tested and verified to meet specifications that are similar to newly produced refrigerants product specifications, such as those provided in (AHRI, 2012). The reclaimed refrigerants can be repacked and sold to new users.

Reclamation is essentially a market-driven industry. If there is no demand for a particular refrigerant, the costs to send recovered refrigerant to reclamation facilities will be a disincentive to reclaim. Efforts must be initiated early with refrigerant supply companies to take back refrigerant for reclamation. Many service establishments will not be able to afford storage for recovered refrigerants yet the cost of sending small quantities of recovered refrigerant to reclamation facilities is also a disincentive to reclamation efforts. Such disincentives promote venting or reuse of stockpiled refrigerant. Care should be taken by policy makers to eliminate parallel (and potentially illegal) routes to market. Such avoidance of improperly reclaimed used refrigerants requires strict auditing of the refrigerant distribution chain. Enforcement is required to insure that these refrigerants do not contain incompatible components such as R-40, methylchloride. Documented refrigerant control through its life cycle can avoid illegal trade of counterfeit refrigerants.

Small capacity portable refrigerant reclamation equipment have also been developed and are available with varying features. Such equipment is capable of reclaiming about 80 kg of refrigerant per hour.

The use of reclaimed refrigerant has the advantage of avoiding possible system breakdowns, as a direct result of contaminated refrigerant, which might lead to refrigerant emissions. As reclaimed refrigerant meets new product specifications, it may have the support of equipment manufacturers who maintain warranties on their equipment. Another advantage is that the quantification of refrigerant recovered are easily obtained. However, reclamation does require a costly infrastructure, which may only prove viable when the potential for financial return of recovered refrigerant is sufficient to overcome the initial investment of the enterprise performing reclamation.

Refrigerant destruction

There is worldwide recognition of the need for destruction of unwanted ODS refrigerants because of ozone and climate benefits from the avoided emissions of ODS. The destruction of ODS banks has the potential to earn carbon credits through global carbon markets, broadly divided into the compliance market and the voluntary market. The compliance market for GHGs is based on a legal requirement where, at an international (e.g., Clean Development

Mechanism) or national and regional level (e.g., European Union Emission Trading Scheme), those participants must demonstrate that they hold the carbon credit equivalents to the amount of GHGs that they have emitted in order to meet their GHG reduction obligations. In some of these markets, the carbon credits resulting from ODS destruction are not considered for compliance generally because ODS are not included in the Kyoto Protocol and are being phased out.

The voluntary markets have also been in operation where individual organisations voluntarily commit to actions and projects to offset their GHG emissions. The voluntary carbon market also established standards for ODS destruction as carbon offset projects. Standards such as The Climate Action Reserve (CAR) and the Verified Carbon Standard (VCS) provide carbon credits for ODS destruction (CAR, 2013; VCS, 2014). Since 2010, there has been a relatively low demand for carbon credits in the voluntary markets.

Normal conditions where recovery, recycling, and reclamation under a good logistical system are prevalent should lead to fairly low requests for destruction in the refrigeration industry. This is especially the case where the demand for ODS remains high. A need for destruction facilities may be created in instances where regulations forbid the service use or export of ODS. The general method of destruction is based on incineration of refrigerants and on scrubbing combustion products that contain particularly aggressive acids, especially hydrofluoric acid. Mainly, their resistance to hydrofluoric acid limits the number of usable incinerators. CFCs and more particularly halons, burn very poorly. In order to be incinerated, they must be mixed with fuels in specific proportions.

The Parties to the Montreal Protocol, recognizing the benefits of destruction of unwanted ODS in an environment friendly manner, approved processes, through decision IV/11 as early as in 1992. Since then, the list of approved destruction processes has been updated a number of times. Presently, there are 16 destruction processes approved.

There are a number of destruction facilities based on the approved destruction processes by the Montreal Protocol, especially in non-Article 5 Parties and in some Article 5 Parties. Currently, there are limited facilities to destroy unwanted ODS refrigerants in most developing countries.

11.4 Indirect impacts due to energy use

By its very nature, the use of energy to accomplish refrigeration draws a valuable resource as the power generation systems consume fuel and, in many cases emit CO_2 and other pollutants. The refrigerant selection impacts the energy consumption of the refrigeration system due to its thermodynamic nature in many ways. The indirect emissions operating the refrigeration systems during its lifetime contribute in many cases far more compared to the direct impact. The more important is the participation of renewable sources to the power grid, the less prevalent is the indirect impacts from energy use.

Designing and efficiently maintaining HVAC&R systems contributes by a large factor to the reduction of GHG related to the air conditioning and refrigeration industry through cutting “indirect emissions”. Consequently, using measurement for the global warming effect of refrigerants that take into consideration indirect emissions is a more representative way for selecting environment friendly refrigerants than a simple comparison by direct emissions alone. Also the introduction of minimum energy performance standards (MEPS) has helped drive energy efficiency to higher levels than if those standards had not been applied, and that the cost of not complying with those standards will have an adverse effect on cutting GHG emissions.

Energy efficiency is the measure of the amount of energy input to a machine to deliver a required output. It is measured in units of energy output or work done by the machine vs. the power input to the machine. However, energy efficiency for the HVAC industry can be measured at different levels: individual components, cooling and heating systems, or a building as a whole. The efficiency at each level contributes to that of the other level up and depends on the proper design and application of components at the particular level.

Energy efficiency parameters are measured at certain conditions at which the machine is working and will have different readings if those conditions change. For most air-source air conditioning machines, this includes the ambient air conditions and the room temperature that the machine is expected to deliver. An air conditioner operating in a high ambient temperature condition will generally be less efficient than one working in an outside temperature of 35°C or below.

11.4.1 Energy efficiency improvements

The discussion around energy efficiency is closely related to the one on alternative refrigerants. The guidelines from paragraph 15 of Decision XIX/6 require countries benefiting from investment projects, to implement conversion technologies that minimise the effects on climate. By converting to more energy efficient products, countries will minimise the consumption of electric power leading to a reduction in the carbon emissions from power plants. Emissions of CO_2 in grams per kWh of electric power generated vary by fuel type or amount of renewable energy as well as plant design; emission factors are approximately 443 for natural gas, 778 for oil and 960 for coal. Depending on the sources of electric power in a particular country, each kWh saved will contribute to a reduction of up to a kilogram of CO_2.

An analysis by the European Commission on residential air conditioners reckons that "most of the environmental impacts (and life cycle costs - LCC) are attributable to the use-phase." (European Commission, 2009b). This shows the importance of understanding energy efficiency in any discussion about climate impact of air-conditioning and refrigeration equipment. Moreover, it is important to note that climate impact may also be reduced by the use of renewable energy sources; however, this does not mean that countries with low-carbon electric grids do not have to keep the pressure on higher energy efficiency standards especially when electric grids are regionally interconnected.

11.5 Equipment life cycle considerations: equipment design, operation, maintenance, and end-of-life

Concepts and selection criteria for alternative refrigerants in various applications for each sector of the HVAC&R industry are presented in other chapters of this Assessment Report. The common criteria among the different sectors are the necessity to design, operate, and maintain efficient systems that operates with minimized emissions, both direct and indirect.

For refrigeration and air-conditioning systems, the most important design criteria in an optimized operation is reducing indirect emissions due to energy efficiency measures over the lifetime of the equipment. In the design phase, the optimization process is a result of product innovation (such as part load design considerations of compressors, heat exchangers, and components), integration of the refrigeration equipment into the heating system for heat recovery, and utilization of power grid based controls. Those technical design criteria are linked to regulations and standards as well as voluntary agreements by industry.
In U.S. buildings, space cooling and refrigeration accounted for 13.7% of the site and 21.3% of the primary energy use, in 2010 (USDOE, 2011). Additional energy is consumed for heating via reversible heat pumps, primarily in the residential sector. 16% in Germany have been reported (Arnemann, 2013), while the EU estimates that 55% of the primary energy in used by heating (Hudson, 2014). Buildings account for 40% of the world’s energy use with the resulting carbon emissions substantially more than those in the transportation sector

(WBSCD, 2009). Estimated energy saving potential with available state-of-the-art technology is around 35-40% (FKT, 2009) per annum. A study by the German Research Council shows that it will be technically possible to achieve potential energy savings of 40% until 2020, if accompanying political measures are taken (FKT, 2012). In emerging markets like Brazil, RAC sales rocketed from 1 million units in 2003 to 3.3 million units in 2012 (Eletrobras Procel, 2013).

As examples, the following energy savings achieved by voluntary agreements have been documented:
- Supermarket refrigeration: 5.5%/year (period 2004-2012 (Heinbokel, 2011)
- Domestic refrigeration: 27% over 10 years (Preuß, 2011); 40 % over 7 years (Silva, 2003)
- Refrigeration in air conditioning systems: 2%/year (Brinkmann, 2009)

In the position paper (FKT, 2012) by the German Research Council it is stated that considerable energy savings can be achieved through the optimum design of a system rather than just optimizing the design of components. Other savings can be obtained from the control, operation, and maintenance of the system.

The same study found that savings up to 40% can be achieved through:
- Efficient control, operation and design of systems (around 10%)
- Reduction of effective temperature differences on heat exchangers (around 12%)
- Use of efficient drives (around 3%)
- Reducing cooling / heating demand (around 7%)
- System improvement by designing in compliance with the annual temperature profile, use of heat recovery, thermal storage (around 8%)

In Europe, the successful implementation of energy savings through commitments by the industry and by Eco-Design Requirements (European Commission, 2009b) in relation to the foreseeable requirements from the legislature led to a significant competitive advantage for manufacturers undertaking those voluntary commitments.

As for the direct effect of the refrigerants used, here too there are opportunities to improve the life-cycle sustainability of refrigeration systems. As discussed in Section 11.6, if a refrigerant with poor environmental properties is used, careful management of that refrigerant is necessary throughout the lifecycle of the equipment. This entails designing equipment for low leaks, maintaining and operating equipment to prevent emissions, and finally properly recovering the refrigerant when the equipment is disposed or replaced.

11.5.1 Equipment design

From an engineering point of view, the design of components such as compressors or electrical drives has a possibility for limited improvement of a few percentage points in terms of efficiency compared to ideal theoretical efficiency. Main improvements can be made through controls and smart electronic integration, minimized heat exchanger temperature differences and other measures described above. To address the direct effect, equipment can be designed to use alternative low-GWP refrigerants and/or to reduce emissions. These types of improvements are either driven by cost, product innovation or by enforced standards requirements.

Environmental sustainability, including efficiency and refrigerant management considerations, can be achieved at different levels in the design phase by taking the following technical and regulatory criteria into consideration:

Technical considerations:

- Meeting customer design requirements, including the proper specification of annual cooling/heating demands;
- Minimizing refrigerant usage and choosing alternative refrigerants that meet energy efficiency requirements;
- Integrating the technical design of equipment into larger system or whole-building design;
- Eliminating competing targets in the decision making process: low first cost versus high efficiency.

Regulatory considerations:

- Refrigerant regulations specifically for those refrigerants targeted for a phase-down, for example the European Union F-Gas (European Union, 2012) regulations;
- Agreements for achieving high energy efficiency and/or low consumption and emissions of refrigerants, for example the German agreement VDMA 24247 for energy efficiency in supermarket refrigerating systems" (VDMA, 2011);
- Equipment energy efficiency ratings, for example "eco design" Directive 2009/125/EC, "establishing a framework for the setting of ecodesign requirements for energy-related products (European Union, 2009);
- Standards provided by global organizations or industry associations, for example International Standards Organization (ISO), European Committee for Standardization (CEN) or the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE)[5].

The decision of which equipment to use during the design stage is often faced by competing targets: low first cost investment versus high energy efficiency affecting the cost of energy over the lifetime of the system and the GHG emission. To resolve this conflict between low first cost, operating cost and refrigerant emissions, new financing methods and evaluation criteria for the technical operation of systems in terms of their contribution to the environment are being developed. These financial mechanisms can contribute significantly to the reduction of energy consumption and refrigerant emissions and thus to system design. To be really relevant, these mechanisms must be able to account for an adequate balance between life cycle cost and LCCP.

Refrigerant selection

Sustainability aspects are being included as regulatory requirements (EU F-gas law) and third party standards such as the US AHAM Refrigerator Sustainability Standard (AHAM, 2012). A lifecycle approach is typically used to provide a complete analysis of the impact on the environment over the expected lifetime of the product containing refrigerant.

Many of the factors that influence energy efficiency are included in Table 11-1 "Refrigerant Selection Criteria". The efficiency of components, as well as efficiency losses such as pressure drops, have a large effect on the overall energy efficiency of the application. Energy efficiency in turn has a significant impact on the Total Equivalent Warming Impact (TEWI), the mass of refrigerant needed, the use of resources such as fuel, and end of life disposal requirements. Energy consumption is greatly affected by the selection of refrigerants, especially considering the lifetime of the equipment.

For example, a typical 10 kW cooling capacity system with a SEER of 13 in the USA will use over 44000 kWh over its lifetime based on the life cycle cost estimator proposed by the U.S. Energy Star Program (Energy Star, 2014). This system will typically have 2 kg of refrigerant charge. The CO2 emissions due to the energy consumption of 44000 kWh are **30.3** metric

[5] www.iso.org and www.ashrae.org

tonnes of CO_2, based on the USA power grid, which is 45 % coal-based. The equivalent CO_2 emissions due to the direct release of the refrigerant charge are **2.7** metric tonnes, which is less than 10 % of the lifetime CO_2 emissions.

Design considerations for safety can sometimes counter the design for energy efficiency and lead to more CO_2 emissions. For example, isolating heat exchangers for sake of safety or toxicity can affect the heat transfer efficiency either positively or negatively.

Refrigerant criteria and properties provide a basis for the selection of a refrigerant in an application in support of the intermediate factors. Properties and selection criteria of significance are shown in Table 11-1.

Table 11-1: Refrigerant selection criteria

Selection criteria	**Factors / Properties and Impact**	**Expected development**
Climate impact	refrigeration systems contribute to global warming by energy consumption and emissions of refrigerants	higher acceptance for products and technologies with lower TEWI; stronger regulations might lead to phase out of high GWP fluids
Energy efficiency	More than 80% of emissions are related to operation (depending upon the conditions).	Higher full load and annualized efficiency requirements resulting in stricter regulations and better adjustment to local requirements and conditions. Industry transition from prescriptive full-load efficiency to a systemic approach.
Refrigerant Cost	Cost and design factor	Market price reduction
Commercial availability	Market penetration driven by local demand	availability globally is limited by local phase-out regulations; global manufacturer will develop local solutions with different refrigerants
Technological level	Increase of energy optimized operation, leak reduction, safe handling and use, education and training	Development of “smart” products which requires less know-how by operators
High ambient temperature fitness	Design factor and operation requirement, reduction in energy efficiency related to refrigerant critical temperature	system adjustment to ambient conditions (larger HX, refrigerants with low compressor discharge temperatures), optimization for annual operation or local conditions by "intelligent" design
Safety	Related to adjustments of the technical design of products and to user know-how. Cost and design factors. Lack of local regulation	Increasing “intelligence” of the technical system including handling of risks and operation, result to increase of safety level as lower safety might not be accepted by society.
Flammability	Risks associated with the use of flammable refrigerants are due to the concurrent existence of: 1. leakage, 2. flammable concentration and 3. Source of Ignition (SOI). In general these risks can be reduced to acceptable levels by means of	Increase of flammable refrigerants’ market share and know how to use them Due to flammable nature of new (unsaturated HFC) and known refrigerants (such as HFC-32, HFC-152a, HC-290, HC-600a, NH_3) it is expected that the application, design know-how, service practices and

	technical adjustments which might result in higher costs. Lack of local regulation.	procedures, education, training, as well as adoption of technical standards for safe use of these flammable refrigerants will be developed within the next 3-5 years[6].

[6] Safety requirements for flammable refrigerants classified as A2L, A2, and A3 are described in chapter 2 of this report

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