MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

2010 REPORT OF THE REFRIGERATION, AIR CONDITIONING AND HEAT PUMPS TECHNICAL OPTIONS COMMITTEE

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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 Annex I.

The opinions expressed are those of the Committee and do not necessarily reflect the views of any sponsoring or supporting organisations.

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Key messages

- The required global phase-out of HCFCs, and the need to manage the lifetime operation of CFC- and also HCFC-based equipment, coupled with concerns to reduce global warming, drive transition from ozone depleting substance (ODS) refrigerants. The technical options are universal, but local laws, regulations, standards, economics, competitive situations and other factors influence regional and local choices.
- More than 60 new refrigerants, many of them blends, were introduced for use either in new equipment or as service fluids (to maintain or convert existing equipment) since the 2006 assessment report. The primary focus for examination of new refrigerants is on unsaturated hydrofluorocarbons and unsaturated hydrochlorofluorocarbons. The overarching climate change issue as well as changing refrigerant options for refrigeration and air conditioning will continue to advance equipment innovations. HFCs and non-fluorochemical options are increasingly used in most sectors, with emphasis on optimising system efficiency (expressed as Coefficient of Performance - COP) and reducing emissions of high Global Warming Potential (GWP) refrigerants.
- There are several low and medium GWP alternatives being considered as replacements for HCFC-22. These include lower GWP HFC refrigerants (HFC-32, HFC-152a, HFC-161, HFC-1234yf and other unsaturated fluorochemicals, as well as blends of them), HC-290 and R-744 (CO_2). HC-290 and some of the HFC refrigerants are flammable and will need to be applied in accordance with an appropriate safety standard. A high degree of containment applies to all future refrigerant applications, either for decreasing climate impact or for safety reasons. The latter aspect will also increase the need to advance charge reduction technologies.
- In commercial refrigeration stand-alone equipment, hydrocarbons (HCs) and R-744 are gaining market shares in Europe and in Japan; they are replacing HFC-134a, which is the dominant choice in most countries. In many developed countries, R-404A and R-507A have been the main replacements for HCFC-22 in supermarkets, however, because of their high GWP, a number of other options are now being introduced. Indirect systems are the most effective option for emissions reductions in new centralised systems for supermarkets. In two stage systems in Europe, R-744 is used at the low-temperature level and HFC-134a, R-744 and HCs at the medium temperature level.
- In industrial refrigeration, R-717 (ammonia) and HCFC-22 are still the most common refrigerants; R-744 is gaining in low-temperature, cascaded systems where it primarily replaces R-717 (ammonia), though the market volume is small.
- In air-to-air air conditioning, HFC blends, primarily R-410A, but to a limited degree also R-407C, are still the dominant near-term replacements for HCFC-22 in air-cooled systems. HC-290 is also being used to replace HCFC-22 in low charge split system, window and portable air conditioners in some countries. Most Article 5 countries are continuing to utilise HCFC-22 as the predominant refrigerant in air conditioning applications.
- Up to now, car manufacturers and suppliers have evaluated several refrigerant options for new car (and truck) air conditioning systems including R-744, HFC-152a and HFC-1234yf, all with GWPs below the EU threshold of 150. These options can achieve fuel efficiency comparable to the existing HFC-134a systems with appropriate hardware and control development. The use of hydrocarbons or blends of hydrocarbons has also been considered but so far has not received support from vehicle manufacturers due to safety concerns. The eventual decision which refrigerant to select for vehicle air conditioning will be made based on the GWPs of the above three options along with additional considerations including regulatory approval, costs, system reliability, safety, heat pump capability and servicing.

Abstract Executive Summary

Current status

The required global phase-out of HCFCs, and the need to manage the lifetime operation of CFC- and also HCFC-based equipment, coupled with concerns to reduce global warming, drive transition from ozone depleting substance (ODS) refrigerants. The technical options are universal, but local laws, regulations, standards, economics, competitive situations and other factors influence regional and local choices. The primary current solutions are summarised below.

Refrigerants: More than 60 new refrigerants, many of them blends, were introduced for use either in new equipment or as service fluids (to maintain or convert existing equipment) since the 2006 assessment report. The primary focus for examination of new refrigerants is on unsaturated hydrofluorocarbons and unsaturated hydrochlorofluorocarbons. Additional refrigerants are still being developed to enable completion of scheduled phase-outs of ODSs. Significant focus is on alternatives, including blend components, offering lower global warming potentials (GWPs) to address climate change, forcing more attention than in the past on flammable or low-flammability candidates. Research continues to increase and improve the physical, safety, and environmental data for refrigerants, to enable screening, and to optimise equipment performance.

Domestic refrigeration: The conversion of new equipment production to the use of non-ODS refrigerants is essentially complete. More than one-third of newly produced units globally now use the refrigerant HC-600a; the balance uses HFC-134a. CFC emissions from the 150,000 tonnes domestic refrigerant bank are dominated by end-of-life disposal due to the high equipment reliability. Approximately 70% of the current, residual CFCs reside in Article 5 countries.

Commercial refrigeration: Hydrocarbons (HCs) and R-744 (CO_2) are gaining market shares for stand-alone equipment in Europe and in Japan; they are replacing HFC-134a, which is the dominant choice in most non-Article 5 and Article 5 countries. For condensing units and supermarket systems, the largest refrigerant bank consists of HCFC-22, which represents about 60% of the global commercial refrigerant bank. In developed countries, the replacement of HCFC-22 in supermarkets is dominated by R-404A and R-507A, however, a number of other options are used. In Europe, R-744 is used at the low-temperature level and HFC-134a, R-744 and HCs at the medium temperature level as alternatives to R-404A and R-507A because of their high GWP.

Industrial refrigeration: R-717 and HCFC-22 are the most common refrigerants for new equipment; cost considerations have driven small new systems to HFC use. R-744 is gaining in low-temperature, cascaded systems where it primarily replaces R-717 (ammonia), though the market volume is small for such systems. The ODS refrigerant bank consists of 20,000 tonnes of CFCs and 125,000 tonnes of HCFCs and HFCs. Annual ODS emission rates are in the range of 10-25% of the total banked refrigerant charge. R-717 remains the primary refrigerant in large industrial systems, especially those for food and beverage processing and storage.

Transport refrigeration: HCFC-22 has a low share in intermodal containers and road equipment, a high share in railcars (declining market) and a very high share in marine vessels. Today, virtually all new systems utilise HFC refrigerants (R-404A and HFC-134a). Non-fluorinated refrigerants have been commercialised to a small extent aboard marine vessels (R-717, R-744), and tested in marine containers, trailers (R-744) and trucks (HC-290). The refrigerant banks are estimated at 2,700 tonnes of CFCs and 27,200 tonnes of HCFC-22. The annual leak rate is in the range of 20-40%, depending on the specific application.

Air-to-air conditioners and heat pumps: HFC blends, primarily R-410A, but to a limited degree also R-407C, are still the dominant near-term replacements for HCFC-22 in air-cooled systems. HC-290 is also being used to replace HCFC-22 in low charge split system, window and portable air conditioners

in some countries. Most Article 5 countries are continuing to utilise HCFC-22 as the predominant refrigerant in air conditioning applications. The refrigerant bank for unitary air conditioners is in excess of 1 million tonnes of HCFC-22.

Water-heating heat pumps: Air-to-water heat pumps have experienced significant growth in Japan, Australia, China, and Europe during the last five years, especially owing to the government incentives in Europe and Japan, and in the USA in prior years. HCFC-22 is currently mainly used in Article 5 countries. The HFC blends R-410A and R407C are currently used in European 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, again influenced by significant subsidies. HC-290 is being applied but its use in Europe has decreased due to the introduction of the Pressure Equipment Directive. R-717 is mainly used for large capacity heat pump systems.

Chillers: HCFC-22 has been phased out in new equipment in the developed countries, but is still used in Article 5 countries. Both HCFC-123 and HFC-134a are used in centrifugal chillers. HFC-134a and R-410A are the most common options in smaller systems with scroll and screw compressors; limited R-407C usage is dropping. The application of HCs and R-717 in chillers is less common and extremely rare as a fraction of the total in large chillers.

Vehicle air conditioning: Today all new AC equipped passenger cars world-wide use HFC-134a; the transition from CFC-12 is complete for new systems, but not in old cars still in use especially in Article 5 countries. About one fifth of the total global refrigerant emissions are from Mobile Air Conditioning systems (about 60 percent if only HFC refrigerant emissions are considered); this includes the emissions in production, use, servicing, and end-of-life. Up to now, car manufacturers and suppliers have evaluated several refrigerant options for new car (and truck) air conditioning systems including R-744, HFC-152a and HFC-1234yf. These three options have GWPs below the EU threshold of 150 and can achieve fuel efficiency comparable to the existing HFC-134a systems with appropriate hardware and control development. The use of hydrocarbons or blends of hydrocarbons has also been considered but so far has not received support from vehicle manufacturers due to safety concerns. 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 ongoing.

What is left to be achieved

More than 100 refrigerants, including blends, are marketed at present, though approximately 20 consitute the overwhelming majority on a global basis and even that quantity is expected to fall as users converge on preferred options over time. Refrigerant manufacturers are in process of developing new candidates while equipment manufacturers are testing, selecting, and qualifying new refrigerants as well as associated lubricants and other materials. The technological options for air conditioning and refrigeration are expected to evolve over the next several years as designers continue to replace HCFC-22 with non-ODS alternatives and focus on developing lower GWP alternatives for R-410A and R-407C. There are several low and medium GWP alternatives being considered as replacements for HCFC-22. These include lower GWP HFC refrigerants (HFC-32, HFC-152a, HFC-161, HFC-1234yf and other unsaturated fluorochemicals, as well as blends of them), HC-290 and R-744. HC-290 and some of the HFC refrigerants are flammable and will need to be applied in accordance with an appropriate safety standard such as IEC-60335-2-40, which establishes maximum charge levels and ventilation requirements.

Several commercial chains have made good progress on the containment of refrigerant in supermarket systems. Indirect systems are the most effective option for emissions reductions and, in Europe, are gaining market share in new centralised systems for supermarkets. Technical development of alternatives in industrial refrigeration is expected to emphasise R-717 and R-744 in the near future. A significant amount of research, development and testing will be required before unsaturated HFCs can be deployed in large industrial systems, and even then their high refrigerant price will be an impediment to adoption. In heat pumps for water heating, further development of the lower GWP options is expected. In transport refrigeration, a rapid phase-out of remaining HCFCs due to the relatively short life span of intermodal containers, railcars and road vehicles (10-15 years) and marine vessels (< 25 years) is expected. Depending on the CO2 emissions associated with the electricity production and the energy efficiency of the systems, there is a large potential to reduce CO_2 emissions generated by fossil fuel operated heating systems by replacing them with heat pumps. The decision which refrigerant will be eventually selected for vehicle air conditioning will be made based on additional considerations along with the Global Warming Potential of the current alternative options (R-744, HFC-152a, and HFC-1234yf); these include regulatory approval, costs, system reliability, safety, heat pump capability and servicing.

World-wide, a significant amount of installed refrigeration equipment still uses CFCs and HCFCs. As a consequence, service demand for CFCs and HCFCs will continue. Refrigerant demand for service needs can be minimised by preventive service, containment, recovery, and recycling. Management of the CFC and HCFC banks in developing countries is an important issue. A critical step to address the refrigerant conservation topics above is thorough training of installers and service technicians, together with certification and regulation. Countries where programs have been successful have had comprehensive regulations requiring recovery and recycling, or destruction of refrigerant.

The way forward

The overarching climate change issue as well as changing refrigerant options for refrigeration and air conditioning will continue to advance innovations in this type of equipment. Many of the lower GWP refrigerant options are flammable, which increases the need to advance charge reduction technologies. HFCs and non-fluorochemical options are increasingly used in most sectors, with emphasis on optimising system efficiency (COP) and reducing emissions of high-GWP refrigerants. A high degree of containment applies to all future refrigerant applications, either for decreasing climate impact or for safety reasons. The competitive market is likely to result in refrigerant options for all common applications and either specialty products or equipment adaptation to accommodate new refrigerants for all applications, but the initial indications are that reduced efficiency is likely in several key uses. It is worth noting that manufacturing for refrigeration, air-conditioning, and heat pump equipment for export is increasing and is expected to increase further in Article 5 countries.

In domestic refrigeration, and to a lesser extent in commercial stand-alone equipment, an emerging trend is conversion from HFC-134a to HC-600a. Non-Article 5 countries completed the conversion from ODS refrigerants in domestic refrigeration approximately 15 years ago; older equipment now approaches the equipment useful lifetime; this results in non-Article 5 countries having a vanishing ODS refrigerant demand. The service demand for ODS refrigerants for domestic refrigeration in Article 5 countries is expected to remain strong for more than 10 years as a result of their later conversion to non-ODS refrigerants. In commercial stand-alone equipment in Article 5 countries, the use of HCs is expected to increase. For two-temperature centralised systems, R-744 is an option for the lower temperature level; in the near future, there will be the choice for the medium-temperature level for new low GWP HFCs on the one hand and R-744 or HCs on the other. In industrial refrigeration, there are substantial banks of CFCs in Article 5 countries and HCFCs in both non-Article 5 and Article 5 countries that need addressing. Article 5 countries moving away from HCFCs (HCFC-22) might transfer to saturated HFCs, unsaturated HFCs if proven for use in industrial systems, to R-717 and R-744, or to other not-in-kind solutions. In transport refrigeration, HFCs will replace HCFCs and become a dominant refrigerant on passenger vessels and on small ships of all categories. The industry is working towards the use of non-fluorinated refrigerants in marine containers, trailers (R-744) and trucks (R-290); both are currently in the development and testing stage. In air-to-air air conditioning and heat pumps, HFCs, HFC blends and HC-290 are the most likely near-term refrigerants to replace HCFC-22 in most air conditioning applications. Contrary to non-Article 5 countries, the demand for service refrigerants in most Article 5 countries will consist of HCFC-22 and HFC-based service blends; this tendency is driven by long equipment life and is also due to the costs of the field conversion to alternative refrigerants. In heat pumps for water heating, HFC-32 or unsaturated HFCs such as HFC-1234yf or blends with this refrigerant will be studied for future use by taking into account the performance, costs and the necessary safety regulations in relation to their mild flammability. The front running candidate among global car manufacturers for future vehicle air conditioning systems seems to be HFC-1234yf. One manufacturer has announced the intention to introduce this refrigerant in car serial production in 2013. OEMs indicate that they will design HFC-1234yf MAC systems in such a way that these systems can safely be used with HFC-134a refrigerant as well.

Executive Summaries of All Chapters

Chapter 2: Refrigerants

More than 60 new refrigerants were introduced for use either in new equipment or as service fluids (to maintain or convert existing equipment) since the 2006 assessment report. Significant focus is on alternatives, including blend components, offering lower global warming potentials (GWPs) to address climate change. That pursuit forces more attention than in the past on flammable or low-flammability candidates. Most of the new refrigerants are blends containing hydrofluorocarbons (HFCs) or in some cases blends of HFCs and hydrocarbons (HCs), the latter typically added to achieve miscibility with compressor lubricants to facilitate lubricant return to compressors.

Additional refrigerants including blend components still are being developed to enable completion of scheduled phase-outs of ozone-depleting substances (ODSs). They include unsaturated fluorochemicals with primary focus on unsaturated HFCs and hydrochlorofluorocarbons (HCFCs), also identified as hydrofluoro-olefin (HFO) and hydrochlorofluoro-olefin (HCFO) compounds. Considerable effort continues for examination of broader use of ammonia, carbon dioxide, and HCs. Research continues to increase and improve the physical, safety, and environmental data for refrigerants, to enable screening, and to optimise equipment performance.

The report updates and expands summary data for assessment of the new refrigerants as well as comparison to refrigerants already retired or being replaced as ODSs or for other environmental, performance, or safety reasons. The environmental data included are consistent with the 2010 WMO Scientific Assessment supplemented with additional data, to fill voids, from other consensus assessments and published studies.

The new assessment updates the tabular data summaries from prior assessments. The revised data reflect consensus assessments and published scientific and engineering literature where possible. The summaries address refrigerant designations, chemical formulae, normal boiling point (NBP), critical temperature (T_c), occupational exposure limits, lower flammability limit (LFL), safety classification, atmospheric lifetime (t_{atm}), ozone depletion potential (ODP), global warming potential (GWP), and control status. The updated chapter also summarises the ODP and GWP values prescribed for regulatory reporting.

The status of data for the thermophysical properties of refrigerants, which include both thermodynamic properties (such as density, pressure, enthalpy, entropy, and heat capacity) and transport properties (such as viscosity and thermal conductivity), is generally good for the most common and alternative refrigerants. Data gaps exist, however, for the thermodynamic and transport properties of blends and less-common fluids as well as for the transport properties of many fluids (but especially so for blends and for some of the new unsaturated fluorochemicals and blends containing them). The data situation for the less-common fluids is more variable; there is a need to collect and evaluate the data for such candidates. Significant research still is needed, but is not expected to retard scheduled ODS phase-outs.

A major uncertainty for all of the refrigerants is the influence of lubricants on properties. The working fluid in most systems is actually a mixture of the refrigerant and the lubricant carried over from the compressor(s). Research on refrigerant-lubricant mixtures is continuing. The need for further studies is driven by the introduction of new refrigerants, by the great variety of lubricants in use and being introduced, and by the often highly proprietary nature of the chemical structures of the lubricant and/or additives.

This chapter summarises data for refrigerants and specifically those addressed in subsequent sections of this assessment report. It discusses thermophysical (both thermodynamic and transport) properties as well as heat transfer, compatibility, and safety data.

This chapter does not address the suitability, advantages, and drawbacks of individual refrigerants or refrigerant groups for specific applications; such discussion is addressed for specific applications where relevant in subsequent chapters.

The updated chapter reviews the status heat transfer and compatibility data for refrigerants. It recommends further research of:

- test data for shell-side boiling and condensation of zeotropic mixtures
- local heat transfer data determined at specific values of vapour quality
- microchannel heat exchanger refrigerant-side heat transfer data including flow distribution effects
- effects of lubricants on heat transfer, especially for ammonia, carbon dioxide, hydrocarbons, unsaturated HCFCs, and unsaturated HFCs
- more accurate evaporation and condensation data for hydrocarbons for both plain tube and enhanced tubes
- inside-tube condensation heat transfer data for carbon dioxide at low temperatures such as –20 °C
- heat transfer correlations for carbon dioxide supercritical heat rejection and two-phase evaporation

Chapter 3: Domestic Refrigeration

Conversion of new domestic refrigerator production to non-ODS refrigerants is essentially complete. Broad-based refrigerant alternatives continue to be HC-600a and HFC-134a. In 2008, 36% of production units used HC-600a or a binary blend of HC-600a and HC-290; 63% used HFC-134a. The remaining 1% used regionally available refrigerants, such as HFC-152a. Second generation non-ODS refrigerant conversion from HFC-134a to HC-600a is complete in Japan and has begun in the United States and other countries. Significant extension of this second generation conversion is expected over the next decade. By 2020 it is estimated that three-fourths of refrigerant demand for new refrigerator production will be for HC-600a and one-fourth will be for HC-134a. No new technologies have surfaced which are cost and efficiency competitive with current vapour-compression technology.

Service conversion to non-ODS refrigerants has significantly lagged original equipment conversion. The distributed, individual-proprietor character of the service industry resists co-ordinated refrigerant management efforts. Field service procedures typically use originally specified refrigerants. Non-Article 5 countries completed new production conversion from ODS refrigerants approximately 15 years ago. This time span is approaching the useful equipment lifetime so service of ODS refrigerant containing products is transitioning to a sunset issue in these countries. Service demand for ODS refrigerants in Article 5 countries is expected to remain strong for more than ten years as a result of their later conversion to non-ODS refrigerants. Unless there is governmental intervention, service demand for CFC-12 refrigerant is expected to continue.

Enhanced product energy efficiency provides benefit to reduced global warming during the use phase of the refrigerator life cycle. Existing state-of-the-art models contain multiple, mature efficiency improvement options. Extension of these to all global products would yield significant benefits, but realisation will be constrained by capital funds availability.

In 2006 the global domestic refrigerant bank was estimated to be 153,000 tonnes consisting of 40% CFC-12, 54% HFC-134a and 6% HC-600a. The bank is equally divided between non-Article 5 and Article 5 countries. An estimated 71% of residual CFCs reside in Article 5 countries. Annual emissions from this bank were estimated to be 6.8%. The majority of domestic refrigerators never require sealed system service. Consequently, emissions are dominated by end-of-life product disposition; inferring legacy product emission management may be the largest opportunity for emission avoidance.

Chapter 4: Commercial Refrigeration

Commercial refrigeration comprises three different families of systems: centralised systems installed in supermarkets, condensing units installed mainly in small shops and stand-alone units installed in all types of shops. The refrigerant choices depend on the levels of conservation temperatures and the type of systems.

The number of supermarkets world-wide is estimated to 280,000 in 2006 covering a wide span of sales areas varying from 400 m2 to 20,000 m2. The populations, in 2006, of vending machines and other stand-alone equipment are evaluated to 20.5 and 32 million units, respectively, and condensing units are estimated to 34 million units. In 2006, the refrigerant bank was estimated at 340,000 tonnes and was distributed as follows: 46% in centralised systems, 47% in condensing units, and 7% in stand-alone equipment. The estimated sharing of refrigerant per type is about 15% CFCs which are still in use in Article 5 countries, 62% HCFCs the dominant refrigerant bank and still for many years, and 23% HFCs which have been introduced in new equipment in Europe and Japan as of 2000.

Stand-alone Equipment: HFC-134a fulfils most technical constraints in terms of reliability and energy performance for stand-alone equipment. When GWP of HFC-134a is considered prohibitive in relation to HFC emissions (country regulation or company policy), hydrocarbon refrigerants (isobutane and propane, i.e. HC-600a and HC-290) or CO_2 (R-744) are the current alternative solutions, presenting in most of the cases the same technical reliability and energy performance as HFC-134a. In the near future, unsaturated HFCs such as HFC-1234yf could be considered as an adapted solution, since the retrofit from HFC-134a to this new refrigerant is expected being rather simple, even if long term reliability has to be assessed. Energy efficiency standards are being issued or revisited in order to lower energy consumption of various types of stand-alone equipment.

Condensing Units: Their cooling capacities vary from 5 to 20 kW mostly at medium temperature. The refrigerant charge varies from 1 to 5 kg for HCFCs or HFCs and also HCs. HCFC-22 is still the most used refrigerant in the U.S. and in all Article 5 countries. For new systems, R-404A is the leading choice for cost reasons; the condensing units using the refrigerant R-404A are cheaper compared to HFC-134a units of the same cooling capacity because of smaller compressor. Nevertheless in hot climate and for medium temperature applications, HFC-134a is used due to its better energy performances at high ambient temperatures.

Supermarket systems: The size of centralised systems can vary from refrigerating capacities of about 20 kW to more than 1 MW related to the size of the supermarket. Refrigerant charges range from 40 up to 1500 kg per installation. The dominant refrigerant used in centralised systems is still HCFC-22. In Europe, new systems have been mainly charged with R-404A, but HFC-134a, ammonia (R-717), HCs and R-744 have been tested in many stores. R-744 is now considered off the shelf solution by the two major European manufacturers. Several designs have been experimented in hundreds of stores: distributed systems, indirect systems, cascade systems. Those designs have been developed in order to reduce the refrigerant charge to use more easily flammable or toxic refrigerants, or to limit the charge of high GWP HFCs. At the low temperature level the use of R-744 appears as an interesting option in terms of GWP, energy efficiency and even costs especially when HFCs are highly taxed. At the medium level temperature, the search for the best option is still ongoing. In the near term, servicing of current HCFC-22 may pose a problem due to possible shortage of this refrigerant. Several HFC blends are proposed to retrofit HCFC-22 installations with or without oil change, but those retrofit blends have not gained until now a significant momentum.

Chapter 5: Industrial Systems

Industrial systems are characterised primarily by the size of the equipment and the temperature range covered by the sector. This includes industrial cooling, industrial heat pumps and industrial air-conditioning. Industrial systems have special design requirements, including the need for uninterrupted service, which are not typically provided by traditional HVAC practices. Rankine cycle electrical generation systems using relevant fluids are also considered in the industrial systems chapter.

R-717 is the most common refrigerant in industrial systems, although with significant regional variations around the world. Where R-717 is not acceptable for toxicity reasons, R-744 has been used, either in cascade with a smaller R-717 plant, in cascade with a fluorocarbon or rejecting heat direct to atmosphere in a high pressure ("transcritical") system. In some cases, for example freezers or IT equipment cooling, R-744 offers additional advantages in performance or efficiency which merit selection ahead of any other refrigerant without consideration of toxicity or environment.

There is also a significant bank of HCFC refrigerant in industrial systems, particularly HCFC-22. Individual system charge can be high – in some cases several tonnes of refrigerant. These systems tend to have longer life than commercial equipment, often lasting over 20 years, but leakage rates can be high, particularly in older plants. A "drop-in" blend for replacing HCFC-22 in flooded industrial systems has not been developed; the common replacement blends used in commercial refrigeration such as R-407A or R-422D are difficult or impossible to use in large industrial systems. The cost of these blends is also a significant barrier to their use.

HFCs have not been widely used in large industrial systems. Where they have been adopted it is generally in low charge systems in order to reduce the financial consequences of refrigerant loss. It is very unlikely that unsaturated HFC refrigerants, whether single compounds or blends, will be adopted for use in industrial systems because in addition to cost considerations the risk of refrigerant decomposition due to the presence of contaminants is too great. HFC-245fa and HFC-134a have also been used in power generation units, utilising the Rankine cycle, although these systems are not yet widely available on the market.

Users of HCFCs in smaller industrial systems are now faced with the choice of whether to switch to HFCs and face a possible phase-down, or to change to R-717 or R-744 and deal with the change in operating practices that those refrigerants would require.

Chapter 6: Transport Refrigeration

Transport refrigeration includes transport of chilled or frozen products by means of road vehicles, railcars, intermodal containers, and small insulated containers (less than 2 m^3) and boxes. It also includes use of refrigeration and air conditioning on merchant, naval and fishing vessels above 100 gross tonnes (GT) (about over 24 m in length).

Transport refrigeration is a niche market in terms of refrigerant banks compared to other sectors. There are about 4,000,000 road transport refrigeration units, and about 950,000 marine container units in operation today, to mention the largest segments in terms of fleet size. Most equipment has a refrigerant charge below 6 kg. Although refrigerant charge can reach several tons aboard large vessels, their fleet is relatively small. There are approx. 150,000 marine vessels above 100 GT in the world fleet; thereof small and medium size vessels have the largest share.

The equipment lifetime is usually between 10 and 15 years for intermodal containers, railcars and road vehicles, and 20 to 25 years for equipment aboard marine vessels.

The vapour compression cycle is the technology used predominantly in transport refrigeration equipment. CFC and HCFC refrigerants can be found in older equipment. HCFC-22 has a low share in intermodal containers and road equipment, but a high share in railcars (declining market) and a very high share in marine vessels, where it remains to be the dominant refrigerant. The CFC and HCFC banks have been decreasing. Retrofit options to R-502 include R-408A, R-402A and R-404A.

Virtually all new systems utilise HFC refrigerants (HFC-134a, R-404A). Non-fluorinated refrigerants have been commercialised to a small extent aboard marine vessels (R-717, R-744), and tested in marine containers, trailers (R-744) and trucks (R-290). A wider application of these refrigerants in practice has not been possible so far because of various technical constraints. There is no practical experience with HFC-1234yf and other low-GWP candidate fluids in transport refrigeration.

Although hydrocarbons are technically feasible and may even outperform HFC systems, flammability makes people concerned about their use. Where they do not exist, standards need to be developed to address the safety concerns.

Carbon dioxide (R-744) is one of a few promising solutions in transport refrigeration. While direct emissions of R-744 are negligible, indirect emissions of R-744 may be comparable to HFCs depending on the climate where the vehicle is operated. Aboard marine vessels, because operation under high ambient temperatures is commonly required, R-774 use has been limited to low temperature stages of cascade or indirect system applications.

Due to safety concerns, use of ammonia (R-717) has been limited to indirect and cascade systems on larger ships which do not carry passengers but professional crew only. HFC refrigerants will continue to be used on passenger vessels, and on small ships of all categories. Ammonia has not been used in road vehicle and container transport in vapour compression cycles.

The transport industry is working to reduce the overall CO_2 emissions. The refrigerant type can influence both direct and indirect equivalent CO_2 emission of a vehicle. Refrigerant charge reduction, refrigerant leakage rate minimisation (for example use of hermetic/semi-hermetic compressors instead of open drive), and the use of low-GWP refrigerants influence the direct contribution. Design changes that would improve the energy efficiency can reduce the indirect contribution.

Transition of power supply systems from traditional diesel engines to alternative propulsion systems (hybrid, electric, etc.) will influence refrigerantion system change and the choice of low-GWP refrigerants in the future.

As in other refrigeration sectors, research and development of other not-in-kind systems, such as magnetic or acoustic refrigeration, remains in the laboratory prototype stage. Absorption and adsorption systems with water are under development too.

Chapter 7: 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 from 2.0 kW to 420 kW comprise a significant segment of the air conditioning market (the majority are less than 35kW). Nearly all air conditioners and heat pumps manufactured prior to 2000 used HCFC-22 as their working fluid. The installed base of units in 2008 represented an estimated HCFC-22 bank exceeding one million metric-tonnes. Approximately 85% of the installed population uses HCFC-22. In 2008, HFC demand globally represented approximately 32% of the total refrigerant demand for these categories of products. Most Article 5 countries are continuing to utilise HCFC-22 as the predominant refrigerant in air conditioning applications.

Options for new Equipment

HFC refrigerant blends R-410A and R-407C are the dominant alternatives being used to replace HCFC-22 in air-conditioners. HC-290 is also being used to replace HCFC-22 in products having low refrigerant charges.

Air conditioners using R-410A and R-407C are widely available in most non-Article 5 countries. Also, equipment using R-410A and R-407C is being manufactured in some Article 5 countries; especially in China where a large export market has created demand for these products. However, these units are typically not sold in the domestic market because of their higher cost.

There are several low and medium GWP alternatives being considered as replacements for HCFC-22 and the high GWP HFCs (R-410A and R-407C). These refrigerants include lower GWP HFC refrigerants, HC-290 and R-744. HC-290 and some of the HFC refrigerants are flammable and will need to be applied in accordance with an appropriate safety standard such as IEC-60335-2-40, which establishes maximum charge levels and ventilation requirements.

A number of moderate and low GWP HFC refrigerants are being considered for use in air conditioners. These include HFC-32, HFC-152a, HFC-161, HFC-1234yf and blends of HFC-1234yf with other refrigerants:

- HFC-32 is a class A2L flammable HFC having a GWP of 675, which is approximately 30% that of R-410A. R-410A systems can be redesigned for HFC-32 with minor modifications. However, because of its A2L flammability rating it will need to be applied using a safety standard such as IEC-60335-2-40.
- HFC-152a is an A3 flammable low GWP HFC having thermodynamic characteristics similar to HFC-134a. While it has been evaluated as an alternative to HCFC-22, it is unlikely to be commercialised in unitary air conditioning applications because its low density and flammability result in significantly increased system costs.
- HFC-161 is a flammable low GWP refrigerant, which is being evaluated as a low GWP alternative to HCFC-22. Like all flammable refrigerants, it would need to be applied using appropriate safety standards.
- Pure HFC-1234yf is not likely to be used as a replacement for HCFC-22 in air conditioners because of its low volumetric capacity. However, HFC-1234yf can be blended with other non-ODP refrigerants to arrive at thermodynamic properties similar to either HCFC-22 or R-410A. Blends of this type are under development, but are not commercially available.

Hydrocarbon refrigerants are also low GWP alternatives to HCFCs and HFCs for low charge applications. The most frequently used hydrocarbon refrigerant in air conditioning applications is HC-290. The high flammability of HC-290 limits its use to lower charge applications. All flammable refrigerants need to be applied using an applicable safety standard such as IEC-60335-2-40, which addresses the design requirements and charge limits for flammable refrigerants. Several manufacturers in China and India are now introducing low charge HC-290 split air conditioners.

R-744, CO_2, offers a number of desirable properties as a refrigerant. However, R-744 has a low critical point 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; particularly in high ambient climates. However, a number of cycle enhancements and component additions can be made to improve the efficiency of R-744 systems. While the addition of efficiency enhancing components can improve the efficiency of R-744 systems, they also substantially increase the system cost. In order for R-744 systems to become commercially viable, cost effective mitigation of the efficiency issue will be required.

High Ambient Considerations

In the near term, regions with hot climates should be able to rely on the refrigerants and technologies that are currently commercially available to replace HCFC-22 (R-407C, R-410A and HC-290). However, when replacing HCFC-22 products with those using R-410A or R-407C the application engineer may need to take special consideration of the reduced capacity at the design ambient temperature when sizing the equipment for the design cooling load. When replacing HCFC-22 in low charge applications (small split, window and portable room air conditioners), the system designer may want to consider the use of HC-290. In the longer-term products using HFC-32, new low and medium GWP HFC blends and HC-290 are the preferable options for high ambient air conditioning applications. R-744 is not a preferred option for high ambient air conditioning applications because its very low critical temperature results in significant performance degradation during high ambient operation.

Chapter 8: Water heating heat pumps

Heat pumps are classified by heat source (air, water, or ground) and heat sink (air, water), resulting in designations such as "air to water" (air source, water sink) heat pumps. This chapter covers only systems where water is the sink. The products for industrial process heating are covered in chapter 5 "Industrial systems". Air-to-air heat pumps are covered in chapter 7 (Air-to-air air conditioners and heat pumps).

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

Space heating heat pumps heat water for distribution to air handling units, radiators, or under-floor panels. The required water temperature depends on the type of emitter, low temperature application ranging from 25 to 35°C for under floor heating, for moderate temperature application such as air handling units around 45 °C, for high temperature application such as radiant heating 55 to 60°C and for very high temperature application as high as 65 to 80°C such as for the fossil fuel boiler replacement market. The required warm water temperature affects the selection of the refrigerant. Heat pump systems are more efficient at lower sink temperatures, but each product must fulfil the required operating temperature.

Air-to-water heat pumps have experienced significant growth in Japan, Europe, China, and Australia during the last five years.

Efficient heat pumps can reduce global warming impact compared with fossil fuel burning systems significantly. 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 year by year. Also the efficiency levels of the heat pumps are improving year by year. However, heat pumps tend to be higher in cost than fossil fuel systems because they employ complicated refrigerant circuits, larger heat exchangers and other special features. Government support programmes in Europe and Japan to promote heat pump systems have resulted in a rapid growth of heat pump system sales in recent years. More than 1 million air-to-water heat pumps were sold world-wide in 2008. Predictions of sales show very large growths in USA, Japan, China and Europe.

Current refrigerant options for new heat pumps

HFC-134a and HFC blends R-407C and R-410A are currently used for new water heating and space heating heat pumps to replace HCFC-22, R-407C with limited product redesign and R-410A for completely redesigned products.

HC-290 has properties similar to those of HCFC-22 apart from flammability. Until 2004 almost half of the heat pumps sold in the EU used HC-290. Use in Europe has declined due to introduction of Pressure Equipment Directive.

Development of R-744 heat pumps started around 1990. R-744 heat pump water heaters were introduced to the market in Japan in 2001, with heat pumps for heating of bath or sanitary water as the main application. The market for heat pump water heaters in Japan is steadily growing based on government and utility incentives.

Although the current market for space heating heat pumps for commercial buildings with combined radiator and air heating systems is limited, R-744 is considered to be a promising refrigerant.
R-717 is a non-ODS refrigerant and has a very low GWP, but it has higher toxicity and lower flammability characteristics. R-717 is used mainly for large capacity systems.

Future Refrigerant Options for New heat pumps

HFC-32 has a lower GWP of one third of R-410A. Heat pumps with HFC-32 can achieve lower charge than heat pumps with R-410A. HFC-32 has a low flammability with a low burning velocity. HFC-1234yf is similar in thermophysical properties to HFC-134a. 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. HFC-1234yf has low flammability with a low burning velocity. Due to the GWP value it has high potential in applications in systems that currently use HFC-134a. 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 in heat pump systems.
Future refrigerants options for new heat pumps include current options R-410A, HFC-134a, HC-290, HC 600a, R-744, and R-717 as well as HFC-32 and new refrigerants.

Since the numbers of heat pumps covered by this chapter still are limited, the refrigerant bank is relatively small. Accordingly, the refrigerant emissions are low compared to other products. On the other hand, heat pumps will increase in quantity leading to higher net refrigerant requirements and emissions in the future. However, it is important to emphasise that there is a large potential to reduce CO2 emission generated by fossil fuel combustion systems by replacing them with heat pump systems.

Chapter 9: Chillers

Chillers predominantly are used for comfort air conditioning in commercial buildings and building complexes. They are coupled with chilled water distribution and air handling/air distribution systems. Chillers also are used for cooling in commercial and industrial facilities such as data processing and communications centers, electronics fabrication, and molding.

Air-cooled chillers in capacities up to 1800 kW represent approximately 80 % of the annual unit production in chillers using positive displacement compressors (reciprocating piston, scroll, and screw). HFC-134a and R-410A are the most common refrigerants with the phase-out of HCFC-22. R-407C has been used as a transition refrigerant. Some chillers are available with R-717 or hydrocarbon refrigerants – primarily HC-290, HC-600a, or HC-1270. Such chillers are manufactured in small quantities compared to HFC-134a and R-410A chillers of similar capacities and require attention to flammability, and for R-717 also toxicity concerns, as reflected in safety codes and regulations. Chillers employing R-744 as the refrigerant are being marketed.

For water-cooled chillers, both positive displacement compressors and centrifugal compressors are used. Positive displacement water-cooled chillers employ the same refrigerants as the air-cooled versions. Centrifugal chillers are dominant above 2 MW. Centrifugal chillers are provided with HCFC-123 or HFC-134a refrigerants though extremely limited use is made of HFC-245fa. HCFC-123 offers an efficient, very-low GWP option for centrifugal chillers. Under terms of the Montreal Protocol, use of HCFC-123 in new equipment will end in most developed countries by 2020 and by 2030 in Article 5 countries.

Existing chillers employing CFC refrigerants are being replaced slowly by new chillers using HCFC-123 or HFC-134a. Today's new chillers use 25-50% less electricity than the CFC chillers produced decades ago, so the savings in energy costs often justify replacement of ageing CFC chillers. R-717 is not suitable for use in centrifugal chillers as its use would require four or more stages or, in very large capacities, a switch to axial compressor designs.

A continuing trend in chiller development is to improve both full-load and seasonal energy efficiency to address both energy-related global warming impacts and operating costs. A number of methods are used to achieve higher seasonal efficiencies. These include multistage compression with interstage economisers, use of multiple compressors to accommodate part-load conditions, continuous unloading capabilities for screw compressors, enhanced electronic controls, variable-speed compressor drives, and optimal sequencing of multiple chillers to maximise overall efficiency.

Refrigerants suggested as alternatives to ODS or high-GWP refrigerants in chillers include R-717, hydrocarbons, R-744, R-718, HFC-32, and new low-GWP refrigerants such as HFC-1234yf. Chillers using R-718 as refrigerant carry a cost premium over conventional systems because of their larger physical size and the complexity of their compressor technology, often entailing axial compressor designs operating under high vacuum. HFC-1234yf and other low- or ultra-low GWP refrigerants are too new to allow assessment of their suitability for use in chillers at this time, though that is likely to change in subsequent assessments.

Absorption chillers using working pairs ammonia-water (primarily in small capacities) or water-lithium bromide (generally in large capacities) are an alternative to chillers employing the vapour-compression cycle. They are particularly suitable for applications where surplus heat can be recovered. Other not-in-kind technologies in the research stage, such as thermoacoustic or magnetocaloric technologies, still are not ready for commercialisation and may not be found suitable or competitive.

Of particular note for both ozone depletion and global climate change, chillers as a group incur very low release rates for refrigerants. The environmental impact of chillers is dominated by the energy-related global warming associated with their energy consumption over their operating life (typically 20 years and sometimes longer than 40 years). Refrigerant emissions, with their direct global warming contributions, are a small fraction of the total global warming impact of chillers except for regions with very low carbon intensity for power generation.

Chapter 10: Vehicle air conditioning

Today all new passenger cars world-wide sold with air conditioning systems are using HFC-134a and the transition from CFC-12 is complete. About one fifth of the total global refrigerant emissions are from MACs (about 60 percent if only HFC refrigerant emissions are considered) including the emissions in production, use, servicing, and end-of-life. In the USA, 19% of the fleet of passenger vehicles is still using CFC-12 refrigerant based on recent survey results. The European Union has in place legislation for cars and light trucks banning the use of refrigerants with GWP>150 [e.g.; HFC-134a] in new-type vehicles from 2011 and all new vehicles from 2017. There are limited replacement refrigerants with a global warming potential (GWP) less than 150. Other countries will probably follow the regulatory direction of the EU or provide incentives to reduce the usage of HFC-134a in vehicles.

For MAC systems, the use of hydrocarbons or blends of hydrocarbons as a refrigerant has been investigated but has so far not received support from vehicle manufacturers as a possible alternative technology due to safety concerns. In Australia and the North America, hydrocarbon refrigerants have been introduced as drop-in refrigerants to replace CFC-12 (which is illegal in the USA and in some Australian states). These same refrigerants are used to a lesser extent for a replacement of HFC-134a.

Up to now, car manufacturers and suppliers have evaluated three refrigerant options for new car and truck air conditioning systems, R-744, HFC-152a and HFC-1234yf. All three have GWPs below the EU threshold of 150 and can achieve fuel efficiency comparable to existing HFC-134a systems. The CO2 equivalent impact of direct emissions from the refrigerant over the vehicle lifetime is much less than the impact related to the energy required to operate the system. The energy required to operate the MACs results in increased CO2 vehicle tail pipe emissions. Therefore, MAC systems designed to provide efficient cooling performance have become the major environmental goal. With the usage of appropriate controls and components, all three refrigerant options have been demonstrated to be comparable to HFC-134a with respect to cooling performance and total CO2 equivalents of MAC systems.

Hence, the global warming impact is almost identical for all three refrigerant options when considered on a global basis. 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, such as regulatory approval, cost, system reliability, safety, heat pump capability, suitability for hybrid electric vehicles, and servicing.

The emerging global car manufacturers' refrigerant choice for future car air conditioning systems seems to be HFC-1234yf and one manufacturer has announced the intention to introduce this refrigerant in car serial production in 2013. Currently, hurdles exist (miscibility with oil, stability problems in the presence of small amounts of water and air in the air conditioning system, mixing with HFC-134a, additional costs) that will require resolution prior to the commercial implementation of HFC-1234yf as refrigerant for car air conditioning. OEM's indicate that they will design HFC-1234yf MAC systems in such a way that these systems can safely be used with the refrigerant HFC-134a as well. This will affect the world-wide transition from HFC-134a to HFC-1234yf for MAC systems.

The development status of other refrigeration technologies, like sorption or thermoelectric systems, are still far away from serial production and presently show very poor price competitiveness and poor system performance and efficiency.

The rapid evolution of hybrid electric vehicles and electric vehicles with electrically driven compressors introduces new challenges for any new alternative refrigerant.
At present, no regulation exists that controls 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 will influence the choice of refrigerant for air conditioning systems in buses and trains.

World-wide, an approximate 50% of the bus and train fleet is still equipped with HCFC-22 systems. The rest use mostly HFC-134a or R-407C systems. Most new bus or train air conditioning systems are equipped with the refrigerants HFC-134a or R-407C. The only reported low GWP refrigerant activities are on-going fleet tests of R-744 systems in buses.

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 stratospheric 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, a large number of Western European countries, Egypt, Ghana, Kenya, Mexico, Panama, Senegal, Togo and Venezuela, as well as the European Community as a regional organisation, 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 represented over 90 percent of the 1991 world production of CFCs and halons. At present all countries in the world have ratified the Vienna Convention and the Montreal Protocol, so its Decisions are truly global.

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 an assessment should be carried out in the year 1989.

In June 1990, the Parties to the Montreal Protocol met in London, considered the data from the 1989 Assessment Reports, and agreed to Protocol adjustments requiring more stringent controls on the CFCs and halons as specified in the original agreement. They also agreed to amendments placing controls on other ozone depleting substances, including carbon tetrachloride and 1,1,1-trichloroethane. In London, a new assessment was again decided, which was carried out in 1991 for consideration in 1992. The London Amendment acknowledged the need for financial and technical assistance of the developing countries, and established a (Interim) Multilateral Fund.

At their 4th Meeting in Copenhagen, Denmark, the Parties considered the Assessment Reports and took decisions that again advanced the phase-out schedules in non-Article 5 countries for most ozone depleting substances, including methyl bromide. They continued the financial mechanism and decided a new assessment to be carried out in 1994 (Decision IV/13), for decisions by the Parties at their 1995 Meeting.

At the 7th Meeting in Vienna (November 1995) the Parties considered the Assessment Reports and focused on the progress made in phasing out ozone depleting chemicals. A reduction in the maximum permissible annual consumption of HCFCs (the “cap”) for the developed countries was decided (2.8% instead of 3.1%, as decided in Copenhagen). A control schedule for the HCFC consumption for the Article 5 countries was agreed upon (in fact, this consisted of a freeze in consumption by the year 2016 and a phase-out by the year 2040). Article 5 countries also agreed to freeze their methyl bromide consumption by the year 2005. The Parties, in Decision VII/34, requested a new assessment to be carried out by the Assessment Panels in the year 1998.

Updated and more detailed Terms of Reference for the Technology and Economic Assessment Panel and its Technical Options Committees (compared to the original 1989 ones) were decided and were given in the 1996 Report of the Technology and Economic Assessment Panel (these TOR were again considered in the light of disclosure of interest and conflict of interest at the 18th Meeting of the Parties (2006) in New Delhi, where a separate Decision on these topics was taken).

The 15th Meeting of the Parties, held in Nairobi in November 2003, considered the 2002 Assessment Reports, next to a number of other issues, including destruction technologies, process agent uses and the handling and destruction of foams at end-of-life. Parties decided to request the Assessment Panels to update their 2002 reports in 2006 and submit them to the Secretariat by 31 December 2006 for consideration by the Open-ended Working Group and by the Nineteenth Meeting of the Parties in 2007 (MOP-19, to be held in Montreal, September 2007). In the relevant Decision (XV/53), the Parties also requested the TEAP to consider, among other matters, five specific issues, including "(c) Technically and economically feasible choices for the elimination of ozone-depleting substances by the use of alternatives that have superior environmental performance with regard to climate change, human health and sustainability;" and "(e) Accounting of the production and use of ozone-depleting substances and of ozone-depleting substances in inventory or contained in products".

The 19th Meeting of the Parties, held in Montreal in September 2007 (on the occasion of the twentieth Anniversary of the Protocol) reached agreement to adjust the Montreal Protocol's HCFC phase-out schedule to accelerate the phase-out of production and consumption of HCFCs. This decision will result in significant reduction of ozone depletion and well as of global warming or global climate forcing. This meeting also considered all 2006 Assessment Reports, next to a large number of other issues. Parties decided to request the Assessment Panels to update their 2006 reports in 2010 and submit them to the Secretariat by 31 December 2010 for consideration by the Open-ended Working Group and by the Twenty-Third Meeting of the Parties in 2011 (MOP-23). In the relevant Decision (XIX/20), the Parties also requested the TEAP (and its TOCs) in paragraph 6 to consider

(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 2010 TEAP Assessment Report -together with the 2010 TOC Assessment Reports- forms the direct response to the above-mentioned decision.

In the important Decision XIX/6 on the HCFC phase-out for developing countries, taken at MOP-19 in Montreal in September 2007, subparagraphs mention:

"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;

To agree that the Executive Committee, when developing and applying funding criteria for projects and programmes, and taking into account para 6, give priority to cost-effective projects and programmes which focus on, inter alia:

1. *Phasing-out first those HCFCs with higher ozone-depleting potential, taking into account national circumstances;*
2. *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; etc."*

In Decision XX/8 on substitutes for HCFCs and HFCs, taken at MOP-20 in Doha, it is mentioned that more information on the HCFC and HFC substitution process is needed:

"Recognizing that decision XIX/6 encourages Parties to promote the selection of alternatives to hydrochlorofluorocarbons to minimize environmental impacts, in particular impacts on climate,

Recognizing also that there is scope for coordination between the Montreal Protocol and the United Nations Framework Convention on Climate Change and its Kyoto Protocol for reducing emissions and minimizing environmental impacts from hydrofluorocarbons, and that Montreal Protocol Parties and associated bodies have considerable expertise in these areas which they could share,

Recognizing further that there is a need for more information on the environmental implications of possible transitions from ozone-depleting substances to high-global warming potential chemicals, in particular hydrofluorocarbons,

1. *To request the Technology and Economic Assessment Panel to update the data contained within the Panel's 2005 Supplement to the IPCC/TEAP Special Report[1] and to report on the status of alternatives to hydrochlorofluorocarbons and hydrofluorocarbons, including a description of the various use patterns, costs, and potential market penetration of alternatives no later than 15 May 2009;*

2. *To request the Ozone Secretariat to prepare a report that compiles current control measures, limits and information reporting requirements for compounds that are alternatives to ozone-depleting substances and that are addressed under international agreements relevant to climate change; etc.*

In Decision XXI/9 on substitutes for HCFCs and HFCs, taken at MOP-21 at Port Ghalib in Egypt, it is again mentioned that more information on the HCFC and HFC substitution process is needed:

"Recalling that decision XIX/6 requests the Parties to accelerate the phase-out of production and consumption of hydrochlorofluorocarbons (HCFCs);

Mindful of the need to safeguard the climate change benefits associated with phase-out of HCFCs;

Aware of the increasing availability of low-Global Warming Potential (GWP) alternatives to HCFCs, in particular in the refrigeration, air-conditioning and foam sectors;

Aware also of the need to appropriately ensure the safe implementation and use of low-GWP technologies and products;

Recalling para 9 and 11 (b) of decision XIX/6;

1. To request the Technology and Economic Assessment Panel (TEAP), in its May 2010 Progress Report and subsequently in its 2010 full assessment, to provide the latest technical and economic assessment of available and emerging alternatives and substitutes to HCFCs; and the Scientific Assessment Panel (SAP) in its 2010 assessment to assess, using a comprehensive methodology, the impact of alternatives to HCFCs on the environment, including on the climate; and both the SAP and the TEAP to integrate the findings in their assessments into a synthesis report;

2. To request the Technology and Economic Assessment Panel in its 2010 progress report:

(a) To list all sub-sectors using HCFCs, with concrete examples of technologies where low-GWP alternatives are used, indicating what substances are used, conditions of application, their costs, relative energy efficiency of the applications and, to the extent possible, available markets and percentage share in those markets and collecting concrete information from various sources including information voluntarily provided by Parties and industries. To further ask TEAP to compare these alternatives with other existing technologies, in particular, high-GWP technologies that are in use in the same sectors;

(b) To identify and characterize the implemented measures for ensuring safe application of low-GWP alternative technologies and products as well as barriers to their phase-in, in the different sub-sectors, collecting concrete information from various sources including information voluntarily provided by Parties and industries;

(c) To provide a categorization and reorganization of the information previously provided in accordance with decision XX/8 as appropriate, updated to the extent practical, to inform the Parties of the uses for which low- or no-GWP and/or other suitable technologies are or will soon be commercialized, including to the extent possible the predicted amount of high-GWP alternatives to ozone-depleting substances uses that can potentially be replaced;

3. To request the Ozone Secretariat to provide the UNFCCC Secretariat with the report of the workshop on high global-warming-potential alternatives for ozone-depleting substances;

4. To encourage Parties to promote policies and measures aimed at avoiding the selection of high-GWP alternatives to HCFCs and other ozone-depleting substances in those applications where other market-available, proven and sustainable alternatives exist that minimise impacts on the environment, including on climate, as well as meeting other health, safety and economic considerations in accordance with decision XIX/6;

5. To encourage Parties to promote the further development and availability of low-GWP alternatives to HCFCs and other ozone-depleting substances that minimise environmental impacts particularly for those specific applications where such alternatives are not presently available and applicable;

6. To request the Executive Committee as a matter of urgency to expedite the finalisation of its guidelines on HCFCs in accordance with Decision XIX/6;

7. To request the Executive Committee, when developing and applying funding criteria for projects and programmes regarding in particular the phase-out of HCFCs:

(a) to take into consideration paragraph 11 of decision XIX/6;

(b) to consider providing additional funding and/or incentives for additional climate benefits where appropriate;

(c) to take into account, when considering the cost-effectiveness of projects and programmes, the need for climate benefits; and

(d) to consider in accordance with decision XIX/6, further demonstrating the effectiveness of low-GWP alternatives to HCFCs, including in Air Conditioning and refrigeration sectors in high ambient temperature areas in Article 5 countries and to consider demonstration and pilot projects in Air conditioning and refrigeration sectors which apply environmentally sound alternatives to HCFCs;

8. To encourage Parties to consider reviewing and amending as appropriate, policies and standards which constitute barriers to or limit the use and application of products with low- or zero-GWP alternatives to ozone-depleting substances, particularly when phasing out HCFCs.

The decisions as given above are based upon the perception that more actions are needed for the protection of the ozone layer, however, the emphasis in all relevant paragraphs is on the climate aspect of high-GWP ozone depleting substances, the high or possibly low-GWP replacements and their climate impact. In particular the above Decision XXI/9 mentions numerous times the development, availability, implementation and use of low-GWP alternatives to HCFCs, as well as a comparison with high-GWP alternatives.

How the RTOC has been involved in the work of the Task Forces that addressed the requests by Parties in Decisions XX/8 and XXI/9 is given in section 1.2.

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 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.

The Parties in Copenhagen took a number of decisions, which concern the work of the Technology and Economic Assessment Panel and its Committees. A decision (IV/13) on "Progress" requested the TEAP and its TOCs to annually report on progress in the development of technology and chemical substitutes. This decision was re-evaluated and restated in the meeting in Vienna, in 1995 (VII/34). As a result, progress reports have been conceived annually by the TEAP and its Committees; they were submitted to the Parties in the years 1996-2006 as part of the annual report of the TEAP (next to the progress reports, the annual reports deal with a large variety of issues on the basis of which Parties have taken certain decisions in the 1996-2006 period).

In Vienna, the Parties also requested "to offer the assistance of the Scientific, Environmental Effects and Technology and Economic Assessment Panels to the SBSTA, the Subsidiary Body on Science and Technology under the United Nations Framework Convention on Climate Change (UNFCCC), as necessary" (VII/34). The SBSTA encouraged the Secretariat to continue its close collaboration with other relevant bodies such as the Technology and Economic Assessment Panel of the Montreal Protocol on Substances that Deplete the Ozone Layer, on technical and methodological issues." In order to assess the status of the use of fluorochemicals, the IPCC and the TEAP organised a workshop in Petten, the Netherlands, in mid-1999. Output from this workshop was reported to the SBSTA in October 1999, before the UNFCCC Fifth Conference of the Parties (COP-5). Output was also used in the drafting of a TEAP report on HFCs and PFCs, which became available in October 1999. A new decision on a study on the status of HFCs and alternatives to HFCs and PFCs, to be performed in 2003-2004, was decided by the Parties to the UNFCCC in Delhi (COP-8) in 2002 and by the Parties to the Montreal Protocol in 2002 (MOP-14, Rome, Mirror Decision XIV/10). It asked for a joint undertaking by the Intergovernmental Panel on Climate Change (IPCC) and TEAP in order to prepare a Special Report on "Safeguarding the climate system and protecting the ozone layer; issues related to hydrofluorocarbons and perfluorocarbons". A Steering Committee, consisting of six members (three IPCC Working Group co-chairs and the three TEAP co-chairs) has directed the Special Report study. The report (as well as a Technical Summary and a Summary for Policy Makers) has been adopted by governments in a Meeting in Addis Ababa, April 2005, and was published mid-2005. This Report has been the basis for many discussions that took place at the various Meetings of the Parties to the Montreal Protocol and the Kyoto Protocol. A Supplement Report to the Special Report was published in 2006 and contained a large amount of information on the size of banks and emissions in the different sectors, where refrigeration and air conditioning is actually the most important contributing sector.

At the MOP-19 in Montreal an important Decision, Decision XIX/6 (as described in section 1.1), 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.

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 (see above), 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 (see above), 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 -having a large number of RTOC members-, 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. The information collected for this XXI/9 report has also been used in the preparation of the 2010 TOC Assessment Reports, including that of the RTOC.

The 2010 Technical and Economic Assessment study has been carried out by the Technology and Economic Assessment Panel and its six Technical Options Committees. The six Committees consisted of more than 140 experts from a large number of countries (for a list, see the annex to the Technology and Economic Assessment Panel Report 2010).

The 2010 Technical Options Committees consisted of several members of the 1998, 2002, and 2006 Committees and additional new experts, to provide the widest possible international participation in the review. Much attention was again paid to adequate participation by technical experts from Article 5 and CEIT countries, dependent upon budgetary constraints. The Technical Options Committee reports 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") also forms part of the UNEP review pursuant to Article 6 of the Montreal Protocol.

It is part of the 2010 assessment work of the Technology and Economic Assessment Panel (requested by the Parties in Montreal (XIX/20)). The information collected (particularly in the form of the the Executive Summaries) will also be part of the Technology and Economic Assessment Report 2010, as well as the overall 2010 Synthesis Report composed by the three Assessment Panel co-chairs, the beginning of 2011.

The 2010 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 refrigerant conservation. The structure of the 2010 report was chosen similar to the structure of the 2006 RTOC Assessment Report.

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

Austria	France	Netherlands
Belgium	Georgia	Norway
Brazil	Germany	Sweden
China	India	United Kingdom
Czech Republic	Jamaica	United States
Denmark	Japan	

Each of the chapters was developed by 2-6 experts in the specific sector, and each chapter was chaired by a Chapter Lead Author - who did the larger part of the drafting and the co-ordination. The 2010 RTOC included 29 representatives from Asian, European, 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 (actually, only in a few chapters, e.g. chapters 2 and 9).

Affiliations of the members are listed in Table 1-2 (29 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 September 2008, preliminary draft March 2009, draft September 2009, peer review draft August 2010 and final report December 2010). A preliminary committee meeting was held in Copenhagen (back to back with an IIR meeting), September 2008. Drafting and reviewing meetings were held in Canada (Montreal), March 2009, Brazil (Sao Paulo), September 2009, Czech Republic (Prague), August 2010, and China (Hangzhou), December 2010.

The report has been peer reviewed by a number of institutions and associations, each of them reviewing the different chapters sections in a co-ordinated effort in a tight timeframe, i.e., between the end of October and the end of November 2010 (see Table 1-3 for the peer review organisations involved).

Peer review comments were collected and sorted out, and subsequently sent to all CLAs. They studied all peer review comments and made suggestions how to deal with the comments before the RTOC Meeting in December 2010.

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

Braunschweig University	Germany
Calm, James M., Engineering Consultant	U.S.A.
Carrier Corporation	U.S.A.
Daikin Europe	Belgium
Danish Technological Institute	Denmark
Devotta, Sukumar, Independent Consultant	India
Paris Mines Tech, Ecole des Mines	France
FK Consultancy	U.S.A.
General Electric, Consumer Industrial, Retired	U.S.A.
heat AG / UHTC	Austria/Germany
Hill (Consultant)	U.S.A.
IEA Heat Pump Center	Sweden
Indian Institute of Technology Delhi	India
Ingersoll Rand	Czech Republic
Johnson Controls	Denmark
Johnson Controls	USA
Karlsruhe University of Applied Sciences	Germany
Maua Institute of Technology	Brazil
National Refrigeration Association, representative	Georgia
Nelson, private person	Jamaica
Panasonic Corporation	Japan
Re/genT b.v.	Netherlands
Re-phridge Consultancy	United Kingdom
SINTEF Energy Research, Trondheim	Norway
Star Refrigeration	United Kingdom
Technical University Eindhoven	Netherlands
The Trane Company	U.S.A.
U.S. Environmental Protection Agency	U.S.A
HAPI Consultancy, Joinville	Brazil
Zhejiang University, Hangzhou	China

The RTOC worked in chapter groups to address all peer review comments during the RTOC meeting in Hangzhou, China, December 2010. CLAs took note of how the groups decided to deal with the comments and whether or not to modify or amend the text; all suggestions were archived per chapter. CLAs then submitted the final chapters to the co-chairs.

The final report was put together including Key Messages and an Abstract Executive Summary upfront, as well as Executive Summaries for all chapters (except chapter 11). UNEP's Ozone Secretariat assisted in final formatting and heading style insertions. The report was then once more circulated to all RTOC members for a final check.

The RTOC greatly acknowledges the voluntary involvement from the peer reviewers and the peer review institutions.

Table 1-3: Institutions and organisations involved in the peer review of the 2010 RTOC report

ACEA	European Automobile Manufacturers' Association
AHRI	American Heating and Refrigeration Institute
AIRAH	Australian Institute of Refrigeration, Air conditioning and Heating
ARAP	Alliance for Responsible Atmospheric Policy
CRAA	Chinese Refrigeration and Air Conditioning Association
CRT	CRT Cambridge
DKV	German Refrigeration Association
EIA	Environmental Investigation Agency
EHPA	European Heat Pump Association
EPEE	European Partnership for Energy and Environment
Greenpeace	Greenpeace International
IIAR	International Institute for Ammonia Refrigeration
IIR	International Institute for Refrigeration
IOR	Institute of Refrigeration UK
JAMA	Japanese Automotive Manufacturer Association
JRAIA	Japanese Refrigeration and Air Conditioning Industry Association
SAE	Society of Automotive Engineers
SAIRAC	South African Institute for Refrigeration and Air Conditioning
Shecco	Shecco Brussels
Transfrigoroute	Transfrigoroute International
Transicold	Carrier Transicold

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 a simple, economic, efficient and reliable way for refrigeration (this includes cycles using ammonia, carbon dioxide, fluorochemicals and hydrocarbons as refrigerants).

The process of selecting a refrigerant for the vapour compression cycle is rather complex (not taking into account economic and costs aspects), 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 fifteen years in the developed countries, and the CFC phase-out in the developing countries has been completed by 2010. 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 (HFCs, unsaturated HFCs (HFOs));
- water (R-718).

None of the above mentioned refrigerants is perfect; all have both advantages and disadvantages that should be considered by governments, equipment manufacturers and equipment users. For instance, ammonia, carbon dioxide and hydrocarbons have negligible or low Global Warming Potentials (GWP), most HFCs have a relatively high GWP (this is not valid for the unsaturated HFCs (HFOs), which have a low GWP), ammonia is more toxic than the other options, and ammonia and hydrocarbons are flammable to certain extents. Appropriate equipment design, maintenance and use can address these concerns, though sometimes at the cost of greater capital investment or lower energy efficiency.

The five refrigerant options above are in different stages of development or commercialisation. High GWP HFCs are widely applied in many sectors, 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 installations have been extensively tested on the market. Currently CO_2 is gaining a substantial part of the supermarket refrigeration equipment market in certain regions. 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 2010 RTOC Assessment report.

The Framework Convention on Climate Change via its Kyoto Protocol as adopted in 1997 considers six important global warming gases in one basket (CO_2, CH_4, N_2O, and the industrial gases HFCs, PFCs and SF_6) using their respective Global Warming Potentials (GWP). The control process is based upon the control of equivalent global warming emissions via reductions. Of course, under the Kyoto Protocol, any national government is free to prioritise emission reductions, which in principle could also be done via a phase-out of HFC chemicals at a certain stage. On the contrary, it could also involve a certain growth in certain sectors in certain countries (e.g., the HFCs) which would have to be balanced by larger than average reductions in other greenhouse gas emissions. Although CFC and HCFC are not in the basket of Kyoto protocol, these are also significant warming impact gases. HFCs have similar GWP values than HCFCs but the GWPs of the CFCs are much higher. Insofar, the Montreal Protocol has been quite effective in reducing warming impacts during the CFC phase-out period.

In the Special Report (IPCC TEAP, 2005) and its Supplement Report, as mentioned before, two scenarios were developed for the projections of the demand, banks and emissions of CFCs, HCFCs, HFCs and some PFCs (where these are used as replacements for ozone-depleting substances). Annually, the demand is defined as the amount of chemical required for use in a certain year, banks are equal to the different inventories of products, and the emissions are defined as the amount of chemical that is emitted during manufacturing, plus the amount emitted during the lifetime of the product (leakage from banks), plus the amount of chemical emitted at disposal. The activities underlying emissions of fluorocarbons are expected to expand significantly. These activities (such as the requirements for refrigeration, air conditioning and insulation) will involve a number of technologies. In non-Article 5 countries, the use and emissions of CFCs and HCFCs will decline and stop as all obsolete equipment is retired. In Article 5 countries, ozone-depleting substances (particularly HCFCs) may be used for another one to two decades; a virtual phase-out has been decided for 2030 (Decision XIX/6).

Current emission profiles are largely determined by historic use patterns, resulting in a still relatively high contribution (at present) from CFCs and HCFCs banked in equipment and foams. The largest bank of ODS (CFCs) is in foam products, which are located in the non-Article 5 countries. This will remain the case for the next few decades (see also the TEAP report on destruction and waste streams from the different sectors, by the Decision XX/7 Task Force). Banks of halons are also important, and are roughly split equally between non-Article 5 and Article 5 countries. The size of this bank is expected to decrease. It should be noted, that recovery efforts and the associated costs may vary widely, to the extent that certain, large amounts of ODS in banks are virtually unrecoverable, although still existing. However, the option for destruction still remains open. For example, refrigerants are generally considered to be easily recoverable but recovery of foam blowing agents can be more complicated (see again the report by the Decision XX/7 Task Force).

In general, emissions, i.e., bank-turnover varies significantly from application to application: from months (e.g. solvents), several years (refrigeration applications) to over half a century (foam insulation). The banks stored in equipment and foams may leak during the use phase of the products they are part of, and at the end of the product life-cycle (in case they are not recovered or destroyed).

1.4.3 Set up of the 2010 TOC Refrigeration, A/C and Heat Pumps Assessment Report

The report has Key Messages and an Abstract Executive Summary (e.g. for policy makers), both of which were extracted from the Executive Summaries for all chapters, which are presented in the beginning of the report. Where the Executive Summaries were agreed by the separate chapters, the Key Messages and the Abstract Executive Summary were circulated numerous times to all CLAs and finally amongst Committee members until full agreement was reached.

This chapter 1 gives a general introduction, and describes the process how the RTOC report was put together by the members. 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-to-air air conditioning and heat pumps for water heating. 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; it evaluates the potential the options unsaturated HFCs (HFOs), carbon dioxide, hydrocarbons and other options will have. Chapter 11 deals with refrigerant conservation in the broadest sense; via adequate practices one can reduce the emission of (ozone depleting and global warming) refrigerants to the atmosphere (recover and recycle, containment).

The names and contact details of all RTOC members (CLAs and Co-authors) as well as the names of all Contributors from outside the RTOC are all given in Annex 1.

In the last RTOC meeting in December 2010, the RTOC members also agreed to attach to the report an Extract of a 2009 report on demand, banks and emissions done by ADEME/ ARMINES (Denis Clodic, CLA Chapter 4 responsible). This report has been attached as Annex 2 for information purposes only, in order to expand on the banks and emissions information available in the separate chapters. This report in Annex 2 has no direct link to the separate chapters and has not been reviewed by the RTOC as a committee. It is therefore preceded by a disclaimer outlining this.

Chapter 2

Refrigerants

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2 Refrigerants

More than 60 new refrigerants were commercialised for use either in new equipment or as service fluids (to maintain or convert existing equipment) since the 2006 assessment report. Of them, 21 obtained standardised designations and safety classifications while the remainder are marketed with only proprietary identifiers (without public disclosure of compositions or without application for standardised designations). Most of the new refrigerants are blends containing hydrofluorocarbons (HFCs) or, in some cases, blends of HFCs and hydrocarbons (HCs). Additional refrigerants, including blend components, still are being developed to enable completion of scheduled phase-outs of ozone-depleting substances (ODSs). Significant focus is on alternatives, including blend components, offering lower global warming potentials (GWPs) to address climate change. That pursuit forces more attention than in the past on flammable – primarily low-flammability – candidates. Considerable effort continues for examination of broader use of ammonia (NH_3, R-717), carbon dioxide (CO_2, R-744), and HCs as well as of blends of them or them with low-GWP HFCs. Additional research seeks to increase and improve the physical, safety, and environmental data for refrigerants, to enable screening, and to optimise equipment performance.

Despite the number of new introductions, approximately 20 older and new refrigerants, some of them blends, constitute the majority of usage on a global basis. Even this number is likely to decline to approximately 10 or 12 as older equipment using ODSs or high-GWP options is retired, along with need for service fluids for them, and as manufacturers converge on preferred refrigerants for the future.

2.1 Introduction

This chapter discusses and provides tabular summaries for identifiers as well as physical, safety, and environmental data for refrigerants. It addresses the status of thermophysical (both thermodynamic and transport) property data and of ongoing examination of heat transfer and compatibility. This chapter does not address the suitability, advantages, and drawbacks of individual refrigerants or refrigerant groups for specific applications; such discussion is addressed for specific applications where relevant in subsequent chapters.

2.1.1 Refrigerant Progression

The historic progression of refrigerants encompasses four generations based on defining selection criteria /Cal08/:

- 1830s-1930s – <u>whatever worked</u>: primarily familiar solvents and other volatile fluids including ethers, R-717, R-744, sulfur 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."
- 1931-1990s – <u>safety and durability</u>: primarily chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), ammonia, and water.
- 1990-2010s – <u>stratospheric ozone protection</u>: primarily HCFCs (for transition use), HFCs, ammonia, water, hydrocarbons, and carbon dioxide.
- 2010-? – <u>global warming mitigation</u>: still in determination, but likely to include refrigerants with very low or no ozone depletion potential (ODP), low global warming potential (GWP), and high efficiency; likely to include, at least initially, unsaturated hydrofluorocarbons (hydrofluoro-olefins, HFOs discussed below), ammonia, carbon dioxide, hydrocarbons, and water.

GWP demarcation for acceptability is defined, at least initially, as having a GWP relative to CO_2 for 100 yr integration of 150 or less, predicated on European regulations for mobile air conditioning (see chapter 10). A proposed further classification scheme distinguishes between *very low* (or *ultra-low*) with GWP < ~30, *very low* with GWP < ~100, *low* with GWP < ~300, *moderate* with GWP < ~1000, *high* with GWP < ~3,000, *very high* with GWP < ~10,000, and *ultra-high* with GWP > ~10,000 /UNEP10/.

2.1.2 Unsaturated Hydrofluorochemicals

Facing regulatory pressures to eliminate refrigerants with high GWPs, and at least for automobile systems GWPs exceeding 150, the major refrigerant manufacturers have aggressively 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. The double carbon-carbon bond(s) make(s) the compounds more reactive. That leads to rapid decomposition in the lower atmosphere, because such fluoro-alkenes are less stable in presence of the oxidative reactants there. Some also are subject to photolytic decomposition. 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 fluorination, in part as a trade-off between flammability with low fluorine content and typically increasing GWP and cost with higher fluorine content. Chemical producers are pursuing alternatives for the most widely used low-, medium-, and high-pressure refrigerants. Among the unsaturated HFCs, various HFC-1225 isomers previously pursued seem abandoned predicated on toxicity findings. HFC-1234yf (CH_2=$CFCF_3$) in particular is being widely considered both as a single-compound refrigerant and as a blend component. Manufacturer announcements also indicate pursuit of HFC-1234ze(E) (CHF=$CHCF_3$), HFC-1243zf (CH_2=$CHCF_3$), and other HFC-1234 and HFC-1243 isomers and enantiomers. Some manufacturers also are pursuing unsaturated HCFCs (also identified as hydrochlorofluoro-alkene or hydrochlorofluoro-olefins, HCFOs), notably HCFC-1233 isomers, to obtain similar benefits with reduced or avoided flammability, but they introduce a trade-off concern with ODP albeit extremely low.
While complete data are not yet available, or publicly available due to the proprietary nature of development, the limited information already in the public domain suggests that some unsaturated hydrofluorochemicals will be technically and commercially viable.

Opponents of unsaturated fluorochemicals argue, often vehemently, that they pose additional environmental or safety hazards not justified with existence of available “natural refrigerant” alternatives. The extent of long-term acceptability of unsaturated HFCs (HFOs) or more broadly unsaturated hydrohalochemicals is uncertain, though a number of initial studies indicate manageable environmental impacts /Leu10, Kaj10, Pap09/.

The relatively recent commercial pursuit of unsaturated fluorochemicals, as well as blends of them or containing them, has catalyzed a number favourable claims but also counterclaims. More information is likely to emerge in the next assessment cycle. For now, the various application chapters that follow address consideration of specific unsaturated fluorochemicals as appropriate. Further information is likely to emerge in the next assessment cycle.

2.2 Data Summary

Table 2-1 provides summary data for refrigerants – both single-compound and blend – addressed in this report as well as those used historically, under consideration as candidates for future use, and undergoing renewed interest (historical and now candidates for broader application). The table excludes proprietary blends for which the composition (components) and/or formulation (their proportions) have not been disclosed.

The table has been updated from prior assessments to reflect current data from consensus assessments and published scientific and engineering literature where possible. The summary table also adds two new single-compound refrigerants and 21 new blends introduced since the 2006 assessment report /UNEP06/.

The data in this table were extracted from more extensive summaries by Calm and Hourahan /Cal07, Cal11/, the *Refrigerant Database* /Cal10/, and informatory appendices to ASHRAE Standard 34-2010 /ASH10a/ and addenda thereto /ASH10b/. Those references provide further information on the refrigerants included and address additional refrigerants. Some of the data have been updated with further revisions (later editions) of the cited sources, notably including REFPROP 9.0 /Lem10/ for thermophysical properties, though in some cases with updated fluid and mixture models for planned inclusion in future revisions. The database also identifies the sources for the data presented in the table as well as, for some refrigerants, additional data where conflicting values were reported by different investigators. The data and their limitations should be verified in the referenced source documents, particularly where use of the data would risk loss to life or property. REFPROP can be used to calculate additional properties for many of the refrigerants and additional blends.

Table 2-1: Physical, Safety, and Environmental Data for Historical, Current, and Candidate Refrigerants

refrigerant number	chemical formula - common name	physical data: molec- ular mass	NBP (°C)	Tc (°C)	safety data: OEL (PPM)	LFL (%)	Std 34 safety group	environmental data: atmos- pheric life (yr)	ODP	GWP 100 yr	st at us
CFC-11	CCl3F	137.37	23.7	198.0	C1000	none	A1	45	1.000	4750	M
CFC-12	CCl2F2	120.91	-29.8	112.0	1000	none	A1	100	0.820	10900	M
BCFC-12B1	CBrClF2 - halon 1211	165.36	-4.0	154.0		none		16	7.900	1890	M
CFC-13	CClF3	104.46	-81.5	28.9	1000	none	A1	640	1.000	14400	M
BFC-13B1	CBrF3 - halon 1301	148.91	-58.7	67.1	1000	none	A1	65	15.900	7140	M
FC-14	CF4 - carbon tetrafluoride	88.00	-128.0	-45.6	1000	none	A1	50000	0.000	7390	K
HCFC-22	CHClF2	86.47	-40.8	96.1	1000	none	A1	11.9	0.040	1790	M
HFC-23	CHF3 - fluoroform	70.01	-82.0	26.1	1000	none	A1	222	0.000	14200	K
HFC-32	CH2F2 - methylene fluoride	52.02	-51.7	78.1	1000	14.4	A2L r	5.2	0.000	716	K
CFC-113	CCl2FCClF2	187.38	47.6	214.1	1000	none	A1	85	0.850	6130	M
CFC-114	CClF2CClF2	170.92	3.6	145.7	1000	none	A1	190	0.580	9180	M
CFC-115	CClF2CF3	154.47	-39.2	80.0	1000	none	A1	1020	0.570	7230	M
FC-116	CF3CF3 - perfluoroethane	138.01	-78.1	19.9	1000	none	A1	10000	0.000	12200	K
HCFC-123	CHCl2CF3	152.93	27.8	183.7	50	none	B1	1.3	0.010	77	M
HCFC-124	CHClFCF3	136.48	-12.0	122.3	1000	none	A1	5.9	0.020	619	M
HFC-125	CHF2CF3	120.02	-48.1	66.0	1000	none	A1	28.2	0.000	3420	K
HFC-134a	CH2FCF3	102.03	-26.1	101.1	1000	none	A1	13.4	0.000	1370	K
HCFC-142b	CH3CClF2	100.50	-9.1	137.1	1000	8.0	A2	17.2	0.060	2220	M
HFC-143a	CH3CF3	84.04	-47.2	72.7	1000	8.2	A2L r	47.1	0.000	4180	K
HFC-152a	CH3CHF2	66.05	-24.0	113.3	1000	4.8	A2	1.5	0.000	133	K
HFC-161	CH3CH2F - ethyl fluoride	48.06	-37.6	102.2		3.8		0.18	0.000	12	K
HC-170	CH3CH3 - ethane	30.07	-88.6	32.2	1000	3.1	A3	0.21	0.000	~20	
HE-E170	CH3OCH3 - DME	46.07	-24.8	127.2	1000	3.4	A3	0.015	0.000		
FC-218	CF3CF2CF3 - perfluoropropane	188.02	-36.8	71.9	1000	none	A1	2600	0.000	8830	K
HFC-227ea	CF3CHFCF3	170.03	-16.3	101.8	1000	none	A1	38.9	0.000	3580	K
HFC-236fa	CF3CH2CF3	152.04	-1.4	124.9	1000	none	A1	242	0.000	9820	K
HFC-245fa	CHF2CH2CF3	134.05	15.1	154.0	300	none	B1	7.7	0.000	1050	K
HC-290	CH3CH2CH3 - propane	44.10	-42.1	96.7	1000	2.1	A3	0.041	0.000	~20	
R-400(50/50)	R-12/114 (50.0/50.0)	141.63	-20.8	129.1	1000	none	A1		0.700	10000	M
R-400(60/40)	R-12/114 (60.0/40.0)	136.94	-23.2	125.6	1000	none	A1		0.724	10000	M
R-401A	R-22/152a/124 (53.0/13.0/34.0)	94.44	-32.9	107.3	1000	none	A1		0.028	1200	M
R-401B	R-22/152a/124 (61.0/11.0/28.0)	92.84	-34.5	105.6	1000	none	A1		0.030	1300	M
R-401C	R-22/152a/124 (33.0/15.0/52.0)	101.03	-28.3	111.7	1000	none	A1		0.024	930	M
R-402A	R-125/290/22 (60.0/2.0/38.0)	101.55	-48.9	75.8	1000	none	A1		0.015	2700	M
R-402B	R-125/290/22 (38.0/2.0/60.0)	94.71	-47.0	82.9	1000	none	A1		0.024	2400	M

Table 2-1: Physical, Safety, and Environmental Data for Historical, Current, and Candidate Refrigerants (continued)

		physical data			safety data			environmental data			
refrigerant number	chemical formula - common name	molec-ular mass	NBP (°C)	Tc (°C)	OEL (PPM)	LFL (%)	Std 34 safety group	atmos-pheric life (yr)	ODP	GWP 100 yr	st at us
R-403A	R-290/22/218 (5.0/75.0/20.0)	91.99	-47.7	87.0	1000	wff	A2		0.030	3100	M
R-403B	R-290/22/218 (5.0/56.0/39.0)	103.26	-49.2	79.6	1000	none	A1		0.022	4400	M
R-404A	R-125/143a/134a (44.0/52.0/4.0)	97.60	-46.2	72.0	1000	none	A1		0.000	3700	K
R-405A	R-22/152a/142b/C318 (45.0/7.0/5.5/42.5)	111.91	-32.6	106.1	1000	none	d		0.021	5300	M
R-406A	R-22/600a/142b (55.0/4.0/41.0)	89.86	-32.5	116.9	1000	8.2	A2		0.047	1900	M
R-407A	R-32/125/134a (20.0/40.0/40.0)	90.11	-45.0	82.3	1000	none	A1		0.000	2100	K
R-407B	R-32/125/134a (10.0/70.0/20.0)	102.94	-46.5	75.0	1000	none	A1		0.000	2700	K
R-407C	R-32/125/134a (23.0/25.0/52.0)	86.20	-43.6	86.0	1000	none	A1		0.000	1700	K
R-407D	R-32/125/134a (15.0/15.0/70.0)	90.96	-39.2	91.4	1000	none	A1		0.000	1600	K
R-407E	R-32/125/134a (25.0/15.0/60.0)	83.78	-42.7	88.5	1000	none	A1		0.000	1500	K
R-408A	R-125/143a/22 (7.0/46.0/47.0)	87.01	-44.6	83.1	1000	none	A1		0.019	3000	M
R-409A	R-22/124/142b (60.0/25.0/15.0)	97.43	-34.4	109.3	1000	none	A1		0.038	1600	M
R-409B	R-22/124/142b (65.0/25.0/10.0)	96.67	-35.6	106.9	1000	none	A1		0.037	1500	M
R-410A	R-32/125 (50.0/50.0)	72.58	-51.4	71.4	1000	none	A1		0.000	2100	K
R-410B	R-32/125 (45.0/55.0)	75.57	-51.3	70.8		none	A1		0.000	2200	K
R-411A	R-1270/22/152a (1.5/87.5/11.0)	82.36	-39.5	99.1	990	5.5	A2		0.035	1600	M
R-411B	R-1270/22/152a (3.0/94.0/3.0)	83.07	-41.6	95.9	980	7.0	A2		0.038	1700	M
R-412A	R-22/218/142b (70.0/5.0/25.0)	92.17	-38.0	107.2	1000	8.7	A2		0.043	2200	M
R-413A	R-218/134a/600a (9.0/88.0/3.0)	103.95	-33.4	96.6	1000	8.8	A2		0.000	2000	K
R-414A	R-22/124/600a/142b (51.0/28.5/4.0/16.5)	96.93	-33.0	112.7	1000	none	A1		0.036	1500	K
R-414B	R-22/124/600a/142b (50.0/39.0/1.5/9.5)	101.59	-32.9	111.0	1000	none	A1		0.034	1300	M
R-415A	R-22/152a (82.0/18.0)	81.91	-37.2	102.0	1000	5.6	A2		0.033	1500	M
R-415B	R-22/152a (25.0/75.0)	70.19	-26.9	111.4	1000	wff	A2		0.010	550	M
R-416A	R-134a/124/600 (59.0/39.5/1.5)	111.92	-23.9	107.1	1000	none	A1		0.008	1100	M
R-417A	R-125/134a/600 (46.6/50.0/3.4)	106.75	-39.1	87.1	1000	none	A1		0.000	2300	K
R-417B	R-125/134a/600 (79.0/18.3/2.7)	113.12	-44.9	75.2	1000	none	A1		0.000	3000	K
R-418A	R-290/22/152a (1.5/96.0/2.5)	84.60	-41.7	96.2	1000	8.9	A2		0.038	1700	M
R-419A	R-125/134a/E170 (77.0/19.0/4.0)	109.34	-42.6	82.1	1000	wff	A2		0.000	2900	K
R-420A	R-134a/142b (88.0/12.0)	101.84	-24.9	104.8	1000	none	A1		0.007	1500	M
R-421A	R-125/134a (58.0/42.0)	111.75	-40.7	82.8	1000	none	A1		0.000	2600	K
R-421B	R-125/134a (85.0/15.0)	116.93	-45.6	72.4	1000	none	A1		0.000	3100	K
R-422A	R-125/134a/600a (85.1/11.5/3.4)	113.60	-46.5	71.7	1000	none	A1		0.000	3100	K
R-422B	R-125/134a/600a (55.0/42.0/3.0)	108.52	-41.3	83.2	1000	none	A1		0.000	2500	K
R-422C	R-125/134a/600a (82.0/15.0/3.0)	113.40	-45.9	73.1	1000	none	A1		0.000	3000	K
R-422D	R-125/134a/600a (65.1/31.5/3.4)	109.93	-43.2	79.6	1000	none	A1		0.000	2700	K

Table 2-1: Physical, Safety, and Environmental Data for Historical, Current, and Candidate Refrigerants (continued)

		physical data			safety data			environmental data			
refrigerant number	chemical formula - common name	molec-ular mass	NBP (°C)	Tc (°C)	OEL (PPM)	LFL (%)	Std 34 safety group	atmos-pheric life (yr)	ODP	GWP 100 yr	st at us
R-423A	R-134a/227ea (52.5/47.5)	125.96	-24.2	99.1	1000	none	A1		0.000	2400	K
R-424A	R-125/134a/600a/600/601a (50.5/47.0/0.9/1.0/0.6)	108.41	-39.7	85.9	970	none	A1		0.000	2400	K
R-425A	R-32/134a/227ea (18.5/69.5/12.0)	90.31	-38.2	93.9	1000	none	A1		0.000	1500	K
R-426A	R-125/134a/600/601a (5.1/93.0/1.3/0.6)	101.56	-28.4	99.8	990	none	A1		0.000	1400	K
R-427A	R-32/125/143a/134a (15.0/25.0/10.0/50.0)	90.44	-43.0	85.3	1000	none	A1		0.000	2100	K
R-428A	R-125/143a/290/600a (77.5/20.0/0.6/1.9)	107.53	-48.3	69.0	1000	none	A1		0.000	3500	K
R-429A	R-E170/152a/600a (60.0/10.0/30.0)	50.76	-25.5	123.5	1000	2.9	A3		0.000	20	K
R-430A	R-152a/600a (76.0/24.0)	63.96	-27.6	107.0	1000		A3		0.000	110	K
R-431A	R-290/152a (71.0/29.0)	48.80	-43.2	100.3	1000	2.2	A3		0.000	53	K
R-432A	R-1270/E170 (80.0/20.0)	42.82	-46.6	97.3	710	2.2	A3		0.000	16	
R-433A	R-1270/290 (30.0/70.0)	43.47	-44.4	94.4	880	2.0	A3		0.000	~20	
R-433B	R-1270/290 (5.0/95.0)	43.99	-42.5	96.3	950	1.8	A3		0.000	~20	
R-433C	R-1270/290 (25.0/75.0)	43.57	-44.1	94.8	790	1.8	A3		0.000	~20	
R-434A	R-125/143a/134a/600a (63.2/18.0/16.0/2.8)	105.74	-45.0	75.5	1000	none	A1		0.000	3100	K
R-435A	R-E170/152a (80.0/20.0)	49.04	-26.1	125.2	1000	3.5	A3		0.000	27	K
R-436A	R-290/600a (56.0/44.0)	49.33	-34.3	115.9	1000	1.7	A3		0.000	~20	
R-436B	R-290/600a (52.0/48.0)	49.87	-33.4	117.4	1000	1.7	A3		0.000	~20	
R-437A	R-125/134a/600/601 (19.5/78.5/1.4/0.6)	103.71	-32.9	96.3	990	none	A1		0.000	1700	K
R-438A	R-32/125/134a/600/601a (8.5/45.0/44.2/1.7/0.6)	99.10	-42.3	85.3	990	6.2	A1		0.000	2200	K
R-439A	R-32/125/600a (50.0/47.0/3.0)	71.21	-52.0	72.0	1000	10.4	A2 r		0.000	2000	K
R-440A	R-290/134a/152a (0.6/1.6/97.8)	66.23	-25.4	112.9	1000	4.8	A2 r		0.000	150	K
R-441A	R-170/290/600a/600 (3.1/54.8/6.0/36.1)	46.81	-41.5	117.3	1000	1.7	A3 r		0.000	~20	
R-500	R-12/152a (73.8/26.2)	99.30	-33.6	102.1	1000	none	A1		0.605	8100	M
R-502	R-22/115 (48.8/51.2)	111.63	-45.3	81.5	1000	none	A1		0.311	4600	M
R-503	R-23/13 (40.1/59.9)	87.25	-87.8	18.4	1000	none			0.000	14000	M
R-507A	R-125/143a (50.0/50.0)	98.86	-46.7	70.6	1000	none	A1		0.000	3800	K
R-508A	R-23/116 (39.0/61.0)	100.10	-87.6	10.2	1000	none	A1		0.000	13000	K
R-508B	R-23/116 (46.0/54.0)	95.39	-87.6	11.2	1000	none	A1		0.000	13000	K
R-509A	R-22/218 (44.0/56.0)	123.96	-49.7	68.4	1000	none	A1		0.018	5700	M
R-510A	R-E170/600a (88.0/12.0)	47.24	-25.2	127.9	1000	3.0	A3		0.000	3	K
R-600	CH3CH2CH2CH3 - butane	58.12	-0.5	152.0	1000	2.0	A3	0.018	0.000	~20	
R-600a	CH(CH3)2CH3 - isobutane	58.12	-11.7	134.7	1000	1.6	A3	0.016	0.000	~20	
R-601	CH3CH2CH2CH2CH3 - pentane	72.15	36.1	196.6	600	1.2	A3	0.009	0.000	~20	
R-601a	(CH3)2CHCH2CH3 - isopentane	72.15	27.8	187.2	600	1.3	A3	0.009	0.000	~20	
R-610	CH3CH2OCH2CH3 - ethyl ether	74.12	34.6	214.0	400	1.9			0.000		

Table 2-1: Physical, Safety, and Environmental Data for Historical, Current, and Candidate Refrigerants (continued)

		physical data			safety data			environmental data			
refrigerant number	chemical formula - common name	molecular mass	NBP (°C)	Tc (°C)	OEL (PPM)	LFL (%)	Std 34 safety group	atmospheric life (yr)	ODP	GWP 100 yr	status
R-611	HCOOCH3 - methyl formate	60.05	31.7	214.0	100	4.5	B2	0.197	0.000		
R-630	CH3(NH2) - methylamine	31.06	-6.7	156.9	5	4.9					
R-631	CH3CH2(NH2) - ethylamine	45.08	16.6	183.0	5	3.5					
R-704	He - helium	4.00	-268.9	-268.0		none	A1		0.000		
R-702	H2 - normal hydrogen	2.02	-252.8	-240.0		4.0	A3		0.000		
R-717	NH3 - ammonia	17.03	-33.3	132.3	25	16.7	B2L r	<0.02	0.000	<1	
R-718	H2O - water	18.02	100.0	373.9		none	A1		0.000	<1	
R-729	air - 78% N2, 21% O2, 1% Ar, +	28.97	-194.2	-140.3		none			0.000	0	
R-744	CO2 - carbon dioxide	44.01		31.0	5000	none	A1	>50	0.000	1	
R-764	SO2 - sulfur dioxide	64.06	-10.0	157.5	2	none	B1		0.000		
HC-1150	CH2=CH2 - ethylene	28.05	-103.8	9.2	200	3.1	A3	0.004	0.000	<20	
HFC-1234yf	CH2=CFCF3	114.04	-29.5	94.7	500r	6.2	A2L r	0.029	0.000	<4.4	K
HFC-1234ze(E)	CHF=CHCF3	114.04	-19.0	109.4	1000	7.6		0.045	0.000	6	K
HC-1270	CH3CH=CH2 - propylene	42.08	-47.6	91.1	500	2.7	A3	0.001	0.000	<20	

NBP = normal boiling point temperature; Tc = critical temperature; OEL = Occupational Exposure Limit (8 hr time-weighted average unless preceded by C for ceiling limit); LFL = lower flammability limit (% volume in air), "wff" signifies that the worst case of fractionation is flammable; ODP = ozone depletion potential; GWP = global warming potential; status code of "K" or "M" indicates control by the Kyoto or Montreal Protocol

Suffixes to safety classifications indicate changes that are not final yet ("d" for deletion or "r" for revision or addition) or classifications assigned as provisional ("p"); "d" alone indicates that a prior classification was deleted (withdrawn).

Data sources are identified in the Refrigerant Database; verify data and limitations in these sources before use.

The data presented, from left to right in the table are:

- refrigerant number, if assigned, in accordance with American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 34 /ASH10a, ASH10b/: A revision to an international standard is in preparation, but not yet final, as the primary document for designation and safety criteria /ISO05b, ISO08/, but the proposed designation systems are essentially consistent.
- chemical formula, in accordance with the International Union of Pure and Applied Chemistry (IUPAC) convention /IUP79/ or, for blends, the blend composition in accordance with ASHRAE Standard 34 /ASH10a, ASH10b/
- molecular mass calculated /Cal11/ based on the updated IUPAC atomic weights /Wie09/
- normal boiling point (NBP) or, for blends, the bubble point temperature at 101.325 kPa based on REFPROP 9.0 /Lem10/ when included
- critical temperature (T_c) in °C or, for blends, the calculated pseudo-critical temperature based on REFPROP 9.0 /Lem10/ when included
- Occupational Exposure Limit (OEL) such as the Threshold Limit Value (TLV) in ppm v/v assigned by the American Conference of Governmental Industrial Hygienists (ACGIH), Workplace Environmental Exposure Level (WEEL) by the American Industrial Hygiene Association (AIHA), or a consistent occupational exposure limit on a time-weighted average (TWA) basis for an 8 to 10 hr day and 40 hr work week
- lower flammability limit (LFL) in % concentration ambient air: Where evident, the tabulated values are those determined in accordance with ASHRAE Standard 34 /ASH10a, ASH10b/.
- safety classification, if assigned, in accordance with ASHRAE Standard 34 /ASH10a, ASH10b/: The leading letters A and B signify "lower" and "higher" toxicity, respectively, based on occupational exposure limits. The numbers 1, 2, and 3 indicate "no flame propagation," "lower flammability," and "higher flammability," respectively, at specified test conditions predicated on both LFL and heat of combustion. wff signifies that the worst case of formulation and the worst case of fractionation for flammability, respectively, both as defined in /ASH10a/, is flammable in either the vapour or liquid phase. A recent modification to ASHRAE 34, also proposed for International Organization for Standardization (ISO) 817 /ISO08/, subdivides group 2 based on the burning velocity, with 2L implying those more difficult to ignite /ASH10a/. Some of the classifications are followed or replaced by lower case letters that indicate:
  - d a prior classification was deleted and the refrigerant no longer has a safety classification
  - p a classification assigned on a provisional basis
  - r a recommended revision or addition as shown, but pending final approval and/or publication
- atmospheric lifetime (τ_{atm}) in years: Note that τ_{atm} normally is not indicated for blends since it is ambiguous whether the lifetime pertains to the blend as formulated, a modified formulation as some components decompose more rapidly than others, or the most enduring component.
- ozone depletion potential (ODP) relative to CFC-11: ODPs indicate the relative ability of refrigerants (and other chemicals) to destroy stratospheric ozone. The values included reflect the latest scientific consensus data as adopted in the *Scientific Assessment* /WMO10/. Additional, consistent ODP data are included as available from references Cal10 and Cal11 for refrigerants for which consensus ODPs were not adopted. The ODPs indicated for blends are calculated mass-weighted averages /Cal10, Cal11/ based on the latest accepted IUPAC atomic weights /Wie09/ for the components.
- global warming potential (GWP) relative to CO_2 for 100 year integration based on the values reported in the IPCC *Fourth Assessment Report* /IPCC07/ and the

Scientific Assessment /WMO10/. The values shown are direct GWPs; indirect and net GWPs are discussed in references IPCC07 and WMO10. Additional, consistent GWP data are similarly included as available from references Cal10 and Cal11 for refrigerants for which consensus GWPs were not adopted. The GWPs indicated for blends are calculated mass-weighted averages /Cal10, Cal11/ based on the latest accepted IUPAC atomic weights /Wie09/ for the components. The GWP values shown as "~20" or "<20" in Table 2-1 for hydrocarbons reflect uncertainty in calculation, for which there is no scientific consensus at this time. The approximations shown lie in the ranges of uncertainty.

- status: Refrigerants restricted (production limitations, phaseout, or measures to reduce releases) for environmental reasons are noted as follows:

  M controlled (or for blends one or more components is controlled) under the Montreal Protocol

  K controlled (or for blends one or more components is controlled) under the Kyoto Protocol

2.2.1 Ozone Depletion Potentials

The ODPs indicated in the Table 2-1 are *semi-empirical* values except for HCFC-123, for which a model-derived value was adopted in scientific assessments due to its short atmospheric lifetime /WMO10/. Semi-empirical ODPs are calculated values that incorporate adjustments for observed atmospheric measurements. This approach is conceptually more accurate than other measures, but the data needed are difficult to measure precisely and it is still evolving with further and improved measurements and understanding. There are other ODP indices, among them *modelled, time-dependent*, and *regulatory* variants /Cal07, Cal11/. Modelled data are determined by large models that calculate impacts based on decomposition paths and rates as well as atmospheric conditions including the influences of additional ozone depleting substances. Time-dependent ODPs use chemicals other than CFC-11 as the reference to emphasise impacts for other, typically shorter, timeframes. Normalising values to short-lived compounds accentuates near-term impacts, but discounts long-term effects. Time-dependent ODPs are not cited often, particularly since the release of ozone-depleting substances already has peaked and recovery of the stratospheric ozone layer is underway. Regulatory ODPs generally are old data used to set phase-out steps, determine compliance with the Montreal Protocol, and allocate production quotas in national regulations. Because of the political and competitive complexities in changing consumption targets and production allocations, these values commonly are left unchanged even when newer scientific findings improve the quantification precision. The ODP values listed in the annexes to the Montreal Protocol, for example, have not been updated since 1987 for chlorofluorocarbons (CFCs) and 1992 for hydrochlorofluorocarbons (HCFCs). A note in the Protocol indicates that the values "are estimates based on existing knowledge and will be reviewed and revised periodically," but that has not happened yet /UNEP09/.

2.2.2 ODP and GWP Data for Regulatory and Reporting Purposes

The ODP and GWP data presented in Table 2-1 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 2-2 compares the latest consensus ODP data /WMO10/ to the "regulatory" ODPs used in the Montreal Protocol /UNEP09/. Table 2-3 similarly contrasts the latest consensus GWPs, for 100 yr integration, with those used for reporting and emission reductions under the Kyoto Protocol (from /IPCC95/).

Table 2-2: Scientific and Regulatory ODPs for BFC, CFC, and HCFC Refrigerants

	ODP	
refrigerant	scientific [a]	regulatory
11	1.0	1.0
12	0.82	1.0
12B1	7.9	3.0
13		1.0
13B1	15.9	10.0
21		0.04
22	0.04	0.055
113	0.85	0.8
114	0.58	1.0
115	0.57	0.6
123	0.01	0.02
124	0.02	0.022
142b	0.06	0.065

[a] ODPs indicated are as adopted in reference /WMO10/. They are semi-empirical except for HCFC-123, which is a modelled value (0.0098) based on its short atmospheric lifetime.

Table 2-3: Current Consensus and Reporting GWPs for 100 yr Integration for HFC and PFC Refrigerants

	GWP	
refrigerant	/WMO10/	reporting
14	7,390	6,500
23	14,200	11,700
32	716	650
116	12,200	9,200
125	3,420	2,800
134a	1,370	1,300
143a	4,180	3,800
152a	133	140
218	8,830	7,000
227ea	3,580	2,900
236fa	9,820	6,300
C318	10,300	8,700
744	1	1

2.3 Status and Research Needs for Data

2.3.1 Thermophysical Properties

The status of data for the thermophysical properties of refrigerants, which include both thermodynamic properties (such as density, pressure, enthalpy, entropy, and heat capacity) and transport properties (such as viscosity, thermal conductivity, and surface tension), is generally good. The data are sufficient to permit evaluation and testing of virtually all candidate refrigerants, with notable exception for the newer unsaturated hydrofluorochemicals (see §2.1.2 above). Data gaps do exist, however, for the thermodynamic and transport properties of blends and less-common fluids.

The thermodynamic data and models for the most-common HFCs (HFC-32, HFC-125, and HFC-134a) and HFC blends (R-404A, R-407C, R-410A, and R-507A) are generally excellent. The data often are limited for new blends. The transport data for these fluids are good for the single-compound refrigerants, but additional data and improved models are needed for the HFC and some HC blends. The thermodynamic data for HC-290 (propane), HC-600 (n-butane), and HC-600a (isobutane) are generally very good. The data for R-717 (ammonia) are not as good as commonly assumed; much of the data are old and sometimes inconsistent and/or limited in coverage. The property data for R-744 (carbon dioxide) are excellent.

An international standard provides thermodynamic properties of ten single-compound refrigerants and four blends /ISO05a/. The U.S. National Institute of Standards and Technology (NIST) REFPROP database /Lem10/ implements and provides references to published models for the thermodynamic and transport properties of all of the most common refrigerants and blends. It calculates properties over wide ranges of temperature, pressure, and composition, and it is compliant with the ISO standard /ISO05a/.

The data situation for the less-common fluids is more variable. There is interest in the ethers and particularly the hydrofluoroethers (HFEs) /Biv97, Sek00/. The available data for them are often scattered among obscure sources. There is a need to collect and evaluate the data for such candidates.

Properties are beginning to emerge for unsaturated HFCs /for example Bro09a, Bro09b, Din10, Gre09, Hig10, Kay10, McL10, Ric10, Tan09 and Tan10/ and further studies are underway. Two such refrigerants were added to REFPROP 9.0 in 2010 /Lem10/.

A major uncertainty for all of the refrigerants is the influence of lubricants on heat transfer and other properties. The working fluid in most systems is actually a mixture of the refrigerant and the lubricant carried over from the compressor(s). Research on the refrigerant-lubricant mixtures is underway. It is complicated by the great variety of lubricants in use and by the often highly proprietary nature of the chemical structure or compositions of the lubricant and/or additives. In addition to impacting properties themselves (and especially viscosity and heat transfer), lubricant selections, properties, and degradation have substantial impacts on equipment wear that in-turn alters performance from predictions based on refrigerant properties.

2.3.2 Heat Transfer and Compatibility Data

Refrigerant heat transfer technology has been extensively studied and documented by researchers in many countries. Two reports by Thome /Tho98a and Tho98b/ provide comprehensive reviews of evaporating and condensing heat transfer for many refrigerants including fluorochemicals, hydrocarbons, ammonia, and carbon dioxide. The reports cover in-tube and shell-side boiling and condensing of single-compound refrigerants, azeotropic and zeotropic blends, and refrigerant-lubricant mixtures. They address plain tubes, internally finned tubes with conventional and cross-grooved fins, and both conventional low-fin and enhanced externally-finned tubes plus falling-film evaporation. Other reviews for refrigerant heat transfer technology include Ohadi et al. /Oha96/ for ammonia, Pais and Webb /Pai91/ for pool boiling on enhanced surfaces, Cavallini et al. /Cav95/ for condensation models of refrigerants inside smooth and enhanced tubes, Darabi et al. /Dar95/ for flow boiling correlations in smooth and augmented tubes, Singh et al. /Sin95/ on electrohydrodynamic enhancement of heat transfer, and a series of articles on heat transfer of carbon dioxide, ammonia, and hydrocarbons /IIR97/.

Many types of refrigeration and air-conditioning systems are operating with fluorochemical, hydrocarbon, ammonia, and carbon dioxide refrigerants, suggesting reasonably adequate refrigerant heat transfer data. The best heat transfer data availability are for fluorocarbon (now mainly HFCs) and ammonia refrigerants. From the above-mentioned reports, plus input from other researchers, the following research needs were determined:

- further test data for shell-side boiling and condensation of zeotropic mixtures
- local heat transfer data determined at specific values of vapour quality
- microchannel heat exchanger refrigerant-side heat transfer data including flow distribution effects
- effects of lubricants on heat transfer, especially for ammonia, carbon dioxide, hydrocarbons, unsaturated HCFCs, and unsaturated HFCs
- accurate plain tube and microfin tube evaporation and condensation data for hydrocarbons
- inside-tube condensation heat transfer data for carbon dioxide at low temperatures such as –20 °C
- heat transfer correlations for carbon dioxide supercritical heat rejection and two-phase evaporation

Materials compatibility data are available from many sources, among them manufacturers' literature (refrigerant, plastics, and elastomer manufacturers), materials chemical resistance publications, and a series of studies performed for the Materials Compatibility and Lubricants Research (MCLR) Program of the Air-Conditioning and Refrigeration Technology Institute (ARTI). The MCLR reports addressed compatibility of refrigerants and lubricants with metals, hermetic motor materials, elastomers, engineering plastics, desiccants, and lubricant additives /Cav93, Cav97, Doe93, Doe96, Fie95, Ham94, and Hut92/. The MCLR studies focused primarily on fluorochemical replacements for CFCs via sealed-tube and other laboratory tests. In general, HFCs were found to be less reactive than HCFCs such as HCFC-22 or HCFC-123. As a result, most materials accepted as compatible with HCFCs also were deemed compatible with HFCs. A statistical study of compressors identified air as the most aggressive contaminant, forming oxidised lubricant products, based on tests for non-ideal contaminant conditions (with added water, air, and organic acids) /Cav00/. Additionally, water and acid development with air affected overall mechanical performance /Cav00/. The study suggests that further compatibility studies may be needed for non-ideal conditions.

While actual data are as yet very limited, unsaturated halochemicals (for example unsaturated HFCs – HFOs) may be less thermally stable at compressor operating temperatures. Limited studies report favourable stability in anhydrous, air free, sealed tube tests /Lec09/, but decomposition or corrosion effects – particularly in the presence of common contaminant levels in actual systems – need further study.

A major source of materials compatibility data for carbon dioxide, ammonia, and hydrocarbons are three chemical resistance guides by Pruett covering metals, elastomeric compounds, and engineering plastics /Pru83, Pru94, and Pru95/. Since plastics and elastomers contain many types of additives (most of them proprietary), specific materials should be tested to ensure compatibility.

Ammonia is incompatible with most types of electrical wiring insulation. Metals inside ammonia systems normally are limited to stainless and carbon steel, but two publications from Germany /Kna97 and Lip97/ report good compatibility of ammonia with copper and copper alloys in systems with careful moisture control, as water intrusion can result in severe copper corrosion. Aluminium is compatible with pure (dry) ammonia, but it is sensitive to corrosion in water circuits due to the presence of chlorides. Aqueous solutions of ammonia cause corrosion that puts aluminium components at risk, but coatings may offer corrosion prevention /Eur00/. Further study is needed to determine the precise levels of moisture of concern with consideration of the dissimilar levels of hygroscopicity of different lubricants.

A materials issue with carbon dioxide is explosive decompression with elastomers, especially in systems with pressure cycling. Carbon dioxide is very soluble in many types of elastomers, and if it cannot diffuse out of the elastomer quickly enough, bubbles of gas may grow and cause rupture of the elastomer shapes, such as o-ring seals. Explosive decompression can be minimised by selecting elastomers with appropriate mechanical properties and tear strength, a low carbon dioxide solubility coefficient, and a high carbon dioxide diffusion coefficient /Har99/.

Sealed tube tests containing HC-290 (propane) and HC-600a (isobutane) with various oils, materials, and air show negligible degradation /San96/. In further sealed tube tests, a variety of elastomers were tested with an R-290/600a blend or HC-601 (n-pentane) with a mineral or polyolester (POE) oil; Buna N, hydrogenated nitrile butadiene rubber (HNBR), Viton, and neoprene performed well while natural, silicon, and ethylene propylene diene terpolymer (EPDM) rubbers were less suitable /Col00/. Impurities at the level of 3% in HC-290 were found to not affect performance within measurement uncertainties, provided that the levels of sulfur, water, and unsaturated hydrocarbons were strictly limited /Kru97/.

2.3.3 Safety Data

The primary hazards from refrigerant handling and use arise from pressure explosions, toxicity, flammability, and air displacement, the last of which may lead to oxygen deprivation and asphyxiation /Cal94/.

Pressure data are generally well characterised as necessary for component and system design. Safety standards such as American National Standards Institute / American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ANSI/ASHRAE) 15, *Safety Standard for Refrigeration Systems* /ASH10c/, which is the basis of many national and international standards and regulations, provide guidance on vessel requirements, pressure relief devices, and testing.

Toxicity concerns arise from both accidental releases and occupational handling, for example to install, service, and remove equipment /Cal94 and Cal96/. The data are divided into acute (short-term, single exposure) and chronic (long-term, possibly repeated exposure). Key acute effects include lethality, cardiac sensitisation, central nervous system (CNS) or anesthetic effects, and others that may impair the ability to escape or cause permanent injury. Most of these effects arise from inhalation rather than contact or ingestion, since a desirable attribute of refrigerants is that they be volatile compounds and, as a result, either are vapours at typical conditions or vaporise quickly in contact with body temperatures. Accordingly, it is hard to have extended contact or to ingest sufficient quantities before inhalation effects come into play. Exceptions are refrigerants that irritate or corrode the skin.

Safety data and resulting recommendations for refrigerant concentration limits and occupational exposure limits generally are available for fluorochemical refrigerants /Cal00, Cal07, and Cal10/. The data typically are developed, primarily through animal testing, by manufacturers in the course of qualifying new candidates. A collaborative effort among manufacturers, the Programme for Alternative Fluorocarbon Toxicity Testing (PAFT), developed extensive data for new fluorochemical replacements for CFCs /PAF95 and PAF96/.

Data are less readily available for hydrocarbons and generally are sparse for exposures above fire hazard concentrations, though toxic effects from hydrocarbons generally are not manifest below them /Kir76/. The risks inherent to testing flammable mixtures and historical presumption that application exposures will be kept below the LFL both mitigate against testing higher concentrations.

Extensive data are available for ammonia /Cle90 and Syr90/ and carbon dioxide /NIO76/, though much of it predates currently accepted toxicity test criteria and results in conflicts from early tests with primitive laboratory methods and contaminated samples.

Further data are needed for fluoroether and hydrofluoroether candidates /Biv97 and Sek00/ and for unsaturated fluorochemicals.

Flammability data generally are available /Ric92, Cal07, ASH10a/, though data dispersion from different test methods and laboratories leads to a degree of uncertainty in some cases.

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Chapter 3

Domestic Refrigeration

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3 Domestic Refrigeration

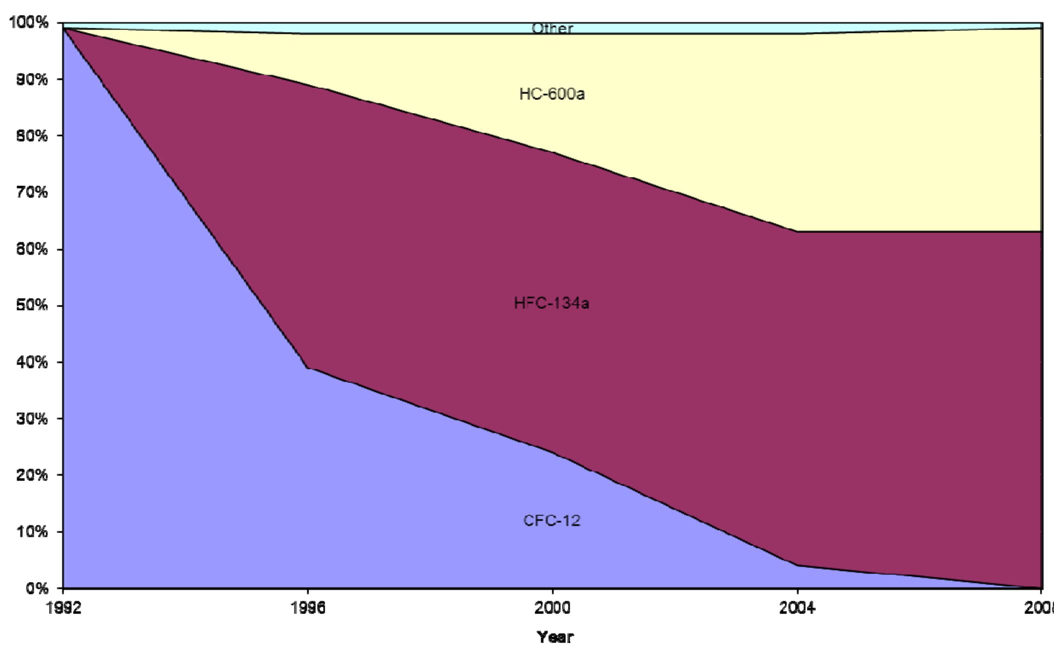
3.1 Introduction

Approximately 100 million domestic refrigerators and freezers are produced annually. Most of these are used for food storage in dwellings. Beverage dispensing machines represent a small fraction of these total units. Typical storage volumes range from 20 to 850 liters/unit. 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 watt induction motor and containing 50 to 250 grams of refrigerant. Niche market products in some cases employ alternative technologies to vapour-compression refrigeration. The age distribution of the global installed products is extremely broad /Wes97/ with median age estimates ranging from 9 to 19 years at retirement . Long product life and high volume annual production combine for an estimated 1500 to 1800 million unit global installed inventory.

3.2 Options for New Equipment

HFC-134a or HC-600a (isobutane) continue to be the options for domestic refrigeration new production. No new alternatives have matured to become energy-efficient, cost-competitive opportunities for these products. New, or original equipment manufacturing production conversion from use of ODS alternatives was essentially completed by 2008. The conversion trend and refrigerant selection is shown graphically in Figure 3-1. HC-290 usage in blends with HC-600a has been included with HC-600s usage in this Figure and data has <u>not</u> been normalised to be independent of production volumes. Refrigerant conversion to HC-600a is expected to continue, driven by conversion from HFC-134a usage. This is discussed below in section 3.2.1.1.

Fig. 3-1: OEM Refrigerant Conversion Trend



Field service conversion to non-ODS alternatives continues to lag new product conversion. This is a consequence of long product life and the absence of drop-in substitutes for the refrigerants used in the pre-conversion production units still in service.

Future product configurations will incorporate evolutionary energy efficiency improvements. These will directly influence energy-related emissions. Design approaches for environmentally responsible product disposal or recycling at end-of-life retirement is also a topic of accelerating interest.

3.2.1 Refrigerant Options

As stated above, HFC-134a and HC-600a continue to be the options for domestic refrigeration new production. Throughout this chapter, HC-600a discussions include both HC-600a and binary blends of HC-600a and HC-290. In situations where capital resources are constrained, the use of binary hydrocarbon blends allow matching the volumetric capacity of previously used CFC-12 to avoid investments required to modify compressor manufacturing tools. These blends result in a small reduction in thermodynamic efficiency versus pure HC-600a and could migrate to use of pure HC-600a as capital funds become available. Two industry dynamics are of interest: (1) second-generation non-ODS refrigerant usage shift from HFC-134a to HC-600a, and (2) preliminary suggestions of low GWP unsaturated fluorocarbons to displace HFC-134a usage. Binary hydrocarbon blends can also be used when converting from HFC-134a to hydrocarbon refrigerants to match the volumetric capacity of currently used compressors and avoid manufacturing investment.

3.2.1.1 Non-ODS Refrigerant Usage Conversion from HFC-134a to HC-600a

European production of American style refrigerators began conversion from HFC-134a to HC-600a in the early 2000's. Initial conversions of new production automatic defrost refrigerators in Japan from HFC-134a to HC-600a were discussed in the 2006 report of this committee /UNEP06/ It is estimated that this conversion, motivated by global warming considerations, has progressed to include the majority of new refrigerator production in Japan.

Recently a major U.S. manufacturer announced its intent to introduce auto-defrost refrigerators using HC-600a refrigerant to the U.S. market. This introduction represents a significant departure from current North American practices for domestic refrigeration. U.S. codes and standards interpretations and modifications required for broad use of HC-600a refrigerant are currently in process. Commercial introduction occurred during 2010. Concurrently, the number of HC-based refrigerator models offered by manufacturers based in countries such as Brazil is rising as well.

The trend of conversion to hydrocarbon refrigerants will continue in the opinion of the authors. Excluding any influence from government regulatory intervention, a ten-year-horizon estimate is that 75% of new refrigerator production will use HC-600a and 25% will use HFC-134a by 2020 /UNEP10/. This estimate is based on the assumptions:

- All current HC-600a applications will continue.
- 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 binary hydrocarbon blend having matched volumetric capacity to HFC-134a.
- 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 a binary hydrocarbon blend.

- Conversions will be influenced by regional market or climate change policy choices. Government regulatory influence was not considered.
- Substitution will be on an equal-molar basis, i.e. 100 grams of HFC-134a will be replaced by 57 grams of HC-600a.

Technology to accomplish conversions is readily available. 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 introduced by modified electrical components, increased use of reduced voltage to avoid electrical arcing and any specified redundant safety devices. Cost pressures will be more significant on model offerings with lower profit margins subject to erosion. These will typically be less-featured, lower-end models.

Conversion of currently installed refrigerators to refrigerants with different characteristics can be problematic. Conversion is not recommended without the oversight and endorsement of the original manufacturer.

3.2.1.2 Consideration of Low-GWP Unsaturated Fluorocarbon Refrigerants

Chemical manufacturers developed low atmospheric life unsaturated HFC compounds to replace HFC-134a in automotive air conditioning applications. These unsaturated fluorocarbons are developmental products and evaluation of their use in stationary applications has begun but is not being pursued with high priority. A preliminary, theoretical assessment is that HFC-1234yf has the potential for comparable efficiency to HFC-134a in domestic refrigerators. Numerous application criteria have not yet been addressed: thermal stability, hermetic system chemical compatibilities, process fluid compatibilities, contamination sensitivities, etc. Long-term reliability expectations for domestic refrigeration use are significantly more demanding than automotive applications. Much new information is required before this refrigerant can be established as a viable alternative candidate. However, the low GWP and reduced flammability versus HC-600a justify continued attention.

3.2.2 Not-In-Kind Alternative Technologies

Alternative refrigeration technologies continue to be pursued for applications with unique drivers such as very low noise, portability or no access to electrical energy distribution network. Technologies of interest include Stirling cycle, absorption and adsorption cycles, thermoelectric, magnetic and trans-critical CO_2. 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 refrigeration equipment. 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. Equipment for trans-critical CO_2 use of Stirling cycle technology is developed and available for limited quantity usage in applications such as packaged beverage vending machines. This technology is not considered a logical candidate for domestic refrigeration because of very small compressor swept volume requirements, reduced thermal efficiency and higher system cost versus current practice /Bee08/. Magnetic refrigeration is considered a conceptual development topic and is premature for consideration as a viable alternative. 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.

3.2.3 Product Energy Efficiency Improvement Technologies

The energy efficiency of domestic refrigeration products is a topic of accelerating consumer and regulatory interest. Relative energy efficiency provides direct linkage to relative energy-related global warming of refrigeration technology options via power consumed during the product useful life. A more extended discussion of efficiency improvement options was included in the 2002 report of this committee /UNE02/. Additional comments are contained in reports under the Eco-Design Directive studies /Eco06/. These studies provided capability background used for updating European minimum energy efficiency standards /EU09/.

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. Various energy test procedures have the intent to predict consumer energy consumption. Though standardisation activities aiming at a universal test protocol are in progress /IEC59M/, currently 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. Similarly, retooling compressor manufacturing facilities would allow recovery of the minor efficiency penalties incurred with the use of HC-600a/HC290 blends versus pure 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. The premium-cost of these options currently restrict their application to high-end models and constrain their proliferation for general use.

- 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.
- 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 initiatives reduce energy service provider peak load demands. Early embodiments created intermittent loss of product function and resulted in consumer dissatisfaction. More recent developments provide utility-triggered feature constraint or capacity reduction of the product.

3.3 Options for Existing Equipment

Service conversion to non-ODS refrigerants has significantly lagged original equipment conversion. The distributed, individual proprietor character of the service industry resists 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. Their acceptance has been good in regions with mandatory service regulations promoting their use. Blend selection appears to be more related to provider distribution strength than technical performance. The interested reader is referred to the 1998 report of this committee for an extended discussion of field repair and conversion options /UNEP98/. Chapter 2 in this current report contains an updated listing of refrigerant blend options.

Non Article 5 countries completed conversions of new equipment production to non-ODS substances approximately 15 years ago. The final production ODS-containing products are now approaching the end of their life cycle, transitioning this to a sunset issue in these countries. In Article 5 countries, service demand for ODS refrigerants is expected to remain strong for more than ten-years as a result of their later conversion to non-ODS refrigerants. Limited capital resources also favour rebuilding service options in Article 5 countries versus replacement by new equipment. This further delays installation of new production units employing non-ODS refrigerants. Rebuilding has the accompanying consequence of voiding the opportunity to significantly improve product energy efficiency and reduce stress on the power distribution grid. Unless there is governmental intervention, service refrigerant demand for CFC-12 is expected to continue for legacy products.

3.3.1 Drop-In Conversion of In-Service Products

Drop-in conversion of existing in-service units to alternative refrigerants has been limited. Consumer safety consideration requires that any potential for 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 very 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 by some spokesmen, 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 -- thermostats, convective fans, radiant defrost heaters, lights, icemakers, etc. – providing an elevated 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 Conservation and Containment Concerns

Domestic refrigerators typically contain 50 to 250 grams of refrigerant. 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. Mandatory end-of-life refrigerant handling regulations have existed in many countries for several years. Chapter 11 of this report addresses this and related conservation approaches.

3.5 Current Refrigerant Use

Domestic refrigeration annual refrigerant demand data are not reported but can be estimated using reasonable assumptions. Data required are historic annual unit production quantities, original equipment specified refrigerant and charge quantity information. Annual refrigerant demand for new equipment production has been calculated using this information and is summarised in Table 3-1. Field service refrigerant demand estimates are significantly less certain and have not been included for that reason.

3.5.1 New Equipment Production

The conversion of domestic refrigeration original equipment manufacture to non-ODS refrigerants is summarised in Table 3-1. Transition to non-ODS refrigerants in original equipment manufacture is essentially complete. Sixty-three percent of current production uses HFC-134a refrigerant, 36% uses either HC-600a or an HC-600a/HC-290 blend and 1% uses other refrigerants, primarily HCFC-22 or HFC-152a.

Table 3-1 Estimated 1992 to 2008 Production of Domestic Refrigerators and Freezers by Refrigerant Type

Global Region	Year	New Unit Production, Units					New Unit Refrigerant Use, Tonnes				
		CFC12	HFC134a	HC600a[1]	Other[2]	Total	CFC12	HFC134a	HC600a[1]	Other[2]	TOTAL
Weatern Europe	1992	16.3				16.3	2280				2280
	1996		11.2	6.1		17.3		1220	410		1630
	2000		8.2	11.3		19.5		890	760		1650
	2004		3.5	16.4		19.9		380	1080		1480
	2008		3.6	19.2		22.8		390	1260		1650
Eastern Europe	1992	7.5				7.5	1500				1500
	1996	2.8	3.2			6.0	320	370			690
	2000	0.7	2.1	0.3	0.1	3.2	140	260	30	20	450
	2004		1.7	2.6		4.3		210	210		420
	2008		3.3	5.0		8.3		410	400		810
North America	1992	11.6				11.6	1750				1750
	1996		12.5			12.5		2290			2290
	2000		13.6			13.6		2420			2420
	2004		17.1			17.1		3150			3150
	2008		16.1			16.1		2970			2970
Central & South America	1992	4.0				4.0	600				600
	1996	8.2				8.2	1280				1280
	2000	1.4	6.1			7.5	230	1360			1590
	2004		8.4			8.4		1850			1850
	2008		12.6			12.6		2640	140		2780
Asia & Oceania	1992	18.7			0.5	19.2	3160			80	3240
	1996	14.0	9.5	0.2	1.6	25.1	2270	1520	20	200	4010
	2000	9.7	9.2	4.4	1.2	24.5	1570	1470	440	150	3630
	2004	2.2	15.7	8.3	1.5	27.7	360	2530	830	190	3910
	2008		25.9	12.9	1.5	40.3		4170	1290	190	5650
Africa & Mid-East	1992	5.2				5.2	840				840
	1996	3.4	0.7			4.1	590	120			710
	2000	2.8	0.9			3.7	490	150			640
	2004	0.8	3.8			4.6	140	640			780
	2008		4.3			4.3		880			880
World Totals	1992	63.3			0.5	63.8	10130			80	10210
	1996	28.4	37.1	6.3	1.6	73.4	4460	5520	430	200	10610
	2000	14.6	40.1	16.0	1.3	72.0	2450	6550	1230	170	10400
	2004	3.0	50.2	27.3	1.5	82.0	500	8760	2120	190	11570
	2008		65.8	37.1	1.5	104.4		11460	3090	190	14740

Footnotes: [1] Includes HC-600a + HC-290 blends [2] HCFC-22 and HFC-152a

3.5.2 Field Service

Data are not available to reasonably predict global refrigerant demand for field service. First order estimates with assumed service rates from industry service sources suggest 3 to 5 kilotonnes total annual demand. Approximately one-half of this demand is estimated to be ODS refrigerant to service legacy products in the field. The remaining demand is expected to be for non-ODS refrigerants used to service products manufactured following new equipment production conversions. New product refrigerant service demand will be proportional to the various new product refrigerant demands.

As mentioned above, transition from ODS refrigerants in non-Article 5 countries was completed over 15 years ago. ODS service refrigerant demand in these countries is significantly reduced since the elapsed time following the conversion is comparable to the typical product life span. The limited residual ODS refrigerant service demand is served with recovered and recycled original charge refrigerant. Service blends are used where adequate recycled ODS refrigerant supply is not available or regulations preclude the use of ODS. The remaining majority of service demand is for non-ODS refrigerants to service products produced after the transition from ODS refrigerants. This demand is served with newly manufactured refrigerant.

Conversion of new equipment production to non-ODS refrigerants in Article 5 countries occurred over a span of two to fifteen years ago. This later conversion extends the service transition issue in these countries. Service refrigerant demand is expected to continue to be for originally specified refrigerants: CFC-12 for legacy product and either HFC-134a or HC-600a and HC-290 for new production. CFC-12 demand for product service will continue to be strong for another decade and then diminish over the subsequent decade. ODS refrigerants will continue to be used while they are available and economic. The dispersed and uncoordinated nature of the service industry limits opportunities to develop an effective recovery and recycling supply stream. Mandatory service regulations could promote use of drop-in replacement refrigerants and reduce emissions of ODS refrigerants.

3.5.3 Future Refrigerant Demand Implications

Refrigerant demand for domestic refrigeration use is expected to continue to grow slowly, driven by product saturation increase in Article 5 countries and the growing number of global dwelling units. Two factors are anticipated to alter refrigerant selection and influence relative demands plus there is always the remote possibility for new developments to modify demand in a discontinuous manner.

Second generation non-ODS refrigerant migration 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 was recently introduced on a limited basis in 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 premium cost results from design changes to allow the use of flammable refrigerants in automatic defrost refrigerators. This suggests that voluntary migration across all product lines is not likely in countries with high litigation frequency.

Second generation conversion from HC-600a/HC-290 blends to pure HC-600a could result from desires for improved product energy efficiency. No new technology would be required. Efficiency differences are small and controversial. Economic or energy efficiency drivers alone may not be sufficient to justify this conversion. Charging method simplification and compressor component standardisation for hydrocarbon usage are added benefit opportunities.

The integrated implications of historic refrigerant demand are summarised in the refrigerant bank discussion in the Annex of this report /Pal03, Clo06, CEP09/. The 2006 update of these data continue to demonstrate domestic refrigeration bank growth. The data indicate an 11% typical 3-year growth rate for the bank in Article 5 countries and a 3% typical 3-year growth rate in non-Article 5 countries. The aggregate domestic refrigerant bank in 2006 was estimated to be 153,000 tonnes: 40% CFC-12, 54% HFC-134a and 6% HC-600a. Approximately 53%of the bank resides in Article 5 countries and 47% resides in non-Article 5 countries. The composition of the bank reflects growth of HFC and HC refrigerants and decline of CFC refrigerants, consistent with substitution of non-ODS refrigerants for CFCs. An estimated 71% of residual CFCs in the bank reside in Article 5 countries.

3.5.4 Future Refrigerant Emission Implications

The 2006 aggregate domestic refrigeration emissions, including end of life emissions, were estimated to be 9619 tonnes, or 6.8% of the total domestic refrigerant bank. Emissions were 77% CFC-12, 21% HFC-134a and 2% HC-600a. Since transition from use of CFC-12 in new production is complete, nearly all of the CFC emissions originate from the existing bank of legacy refrigerators. Geographic distribution of these emissions will be biased toward Article 5 countries since they hold the majority of the bank /CEP09/, have higher equipment repair rates /UNEP98/ and longer product lifetimes /CEP09/.

The emissions trend to non-ODS alternatives from the refrigerant bank is heavily damped. This sluggish response results from the 1500 to 1800 million unit installed base and long product life. Refrigerant systems are hermetically sealed during manufacture; and the majority of these units never require sealed system service. This intrinsic reliability results in emissions being dominated by end-of-life disposition. This suggests management of CFC-12 potential emissions from legacy refrigerators may be the largest domestic refrigeration opportunity for emission avoidance.

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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 retail environments. The refrigerating capacities of equipment vary from some hundred Watts to 1.5 MW. Refrigerant choices are depending on the two main levels of temperatures necessary for the conservation of fresh food and beverages on one hand, and frozen food on the other hand. The more compact the equipment, the better the refrigerant containment. Centralised systems used in large supermarkets are the most emissive due to the large number of joints, expansion valves, and the possible failures due to oil return, corrosion, and vibrations. HCFC-22 represents still the largest refrigerant bank in commercial refrigeration and is used at all temperature levels. . Research and field tests have been carried out aiming at defining new technical options in order to use refrigerants with zero ODP and low GWP, to keep at least the same energy efficiency for the new systems, to improve their leak tightness, and to lower the refrigerant charges.

4.2 Application

4.2.1 Equipment and Systems

Commercial refrigeration is composed of three main categories of equipment: stand-alone equipment, condensing units, and supermarket systems.

Stand-alone equipment consists of systems where all refrigeration components are integrated and, for the smallest types, the refrigeration circuit is entirely brazed or welded. Stand-alone equipment, including freezers, vending machines, and beverage coolers, are extensively used in many Article 5 countries.

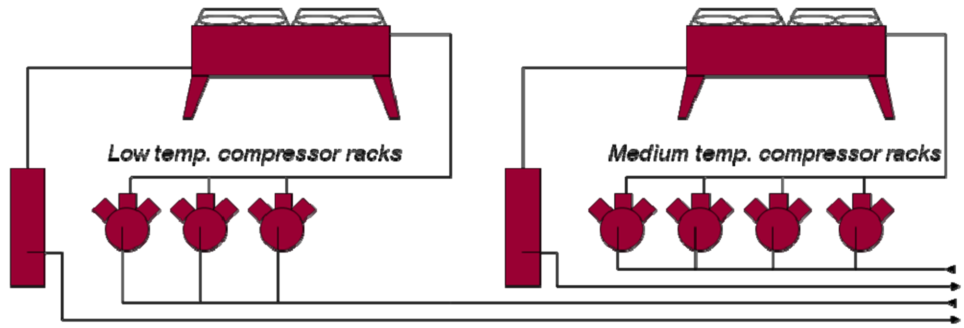
For developing countries, domestic refrigerating equipment, refrigerators and freezers can be found in small shops and are used for commercial purposes. Stand-alone equipment emits its refrigerant charge mainly at end of life when decommissioning, if no stringent recovery policy is in place and enforced.

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 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 small supermarkets, one can find a large number of condensing units (typically up to 20) installed side-by-side in a small machinery room. In most of the A5 countries, the use of systems employing condensing units is very extensive. Annual emission rates are estimated between 7 and 12%.

Centralised systems are the preferred option in supermarkets. They operate with racks of compressors installed in a machinery room (see figure 4-1). A number of possible designs exist. Two main design options are used: direct and indirect systems.

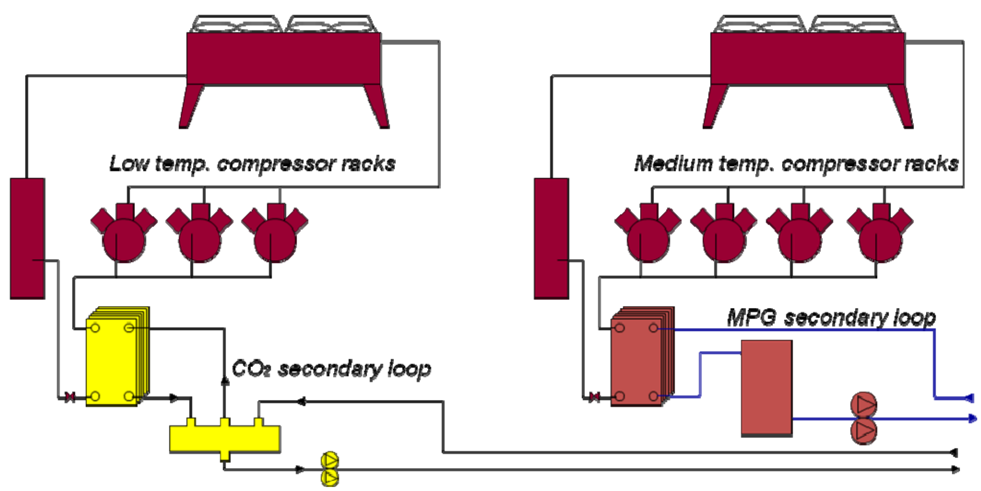
Direct systems are the most widespread. The refrigerant circulates from the machinery room to the sales area, where it evaporates in display-case heat exchangers, and then returns in vapour phase to the suction headers of the compressor racks. The supermarket cold rooms are cooled similarly.

Figure 4-1: Multiple compressor racks in machinery rooms for medium and low temperature display-cases / Clo08/



In the machinery room, racks of multiple compressors are installed with common suction and discharge lines, and each rack is usually associated with an air-cooled condenser. 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 led to large losses when ruptures occur. Some commercial companies have studied /Ets07/ and taken measures in order to limit refrigerant leaks; their report show how they reduce emissions from 25% annual emission level to about 12%. So the 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 non-Article 5 situation. The emission rates for most of the Article 5 countries are much higher.

Figure 4-2: Indirect system with MPG (Mono-propylene-glycol) at the medium temperature level and R-744 at the low temperature level / Clo08/



Indirect systems (see Figure 4-2) 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 comes back to the primary heat exchanger. HTFs have received much interest in recent years because indirect systems allow for a lower primary refrigerant charge and facilitate the use of flammable or toxic refrigerants when isolated from the sales area /Rhi09/. Other designs including the so-called distributed systems and hybrid systems have been developed (see section 4.5.3).

4.2.2 Data on Outlets and stand-alone equipment

Commercial refrigeration encompasses equipment installed in hotels, bars, restaurants, gas stations, train platforms, speciality shops (butchers, fishmongers, deli shops...), convenience stores and supermarkets. The sizes of the stores depend on opening hours, social habits, road infrastructure, and type of habitat. In 2006, the number of supermarkets world-wide is estimated at 280,000 covering a wide span of sales areas varying from 400 m^2 to 20,000 m^2 (among them 10,000 very large supermarkets with food sales areas varying between 2,000 and 5,000 m^2).

> *Note: Available data are coming from marketing studies where the type of outlets is defined in different ways depending on the study. The data imply uncertainties on the level of refrigerating equipment especially in fast developing countries.*

World-wide in 2006, the number of mini-markets is estimated at 4 million where condensing units are mostly used. Condensing units are also used in many other stores; their number is estimated at 34 million units.

The number of food retail stores is estimated at 9.8 million where stand-alone equipment and even domestic refrigerators and freezers are found. In 2006, the population of vending machines and other stand-alone equipment is evaluated at 20.5 and 32 million units, respectively.

Based on those data, the refrigerant bank in 2006 was estimated at 340,000 MT and was distributed as follows:

- 46% in centralised systems;
- 47% in condensing units, and
- 7% in stand-alone equipment.

The estimated sharing of refrigerants per type is about 15% CFCs, which are still in use in Article 5 countries, 62% HCFCs the dominant refrigerant bank and still for many years, and 23% HFCs that have been introduced in new equipment in Europe and Japan as of 2000 .

Note: In 2006, HCs mainly introduced in standalone equipment are not visible in terms of refrigerant bank.

4.3 Options for New Equipment

Complementary to information on refrigerant choices, issues on energy conservation and energy efficiency will be briefly addressed in order to underline possible advantages and drawbacks of refrigerant choices on energy efficiency.

4.3.1 Stand-Alone Equipment

The main families of stand-alone equipment are vending machines, ice makers, ice cream freezers, water fountains, and plug-in display cases.

Part of stand-alone equipment such as wine-coolers, professional kitchen refrigerators and freezers, and hotel mini-bars, is based on the same technology as domestic refrigerators and freezers. Consequently the technical options of these series of equipment are analysed in Chapter 3, and similar trend of replacement of HFC-134a by hydrocarbons (HC-) is observed but for standalone equipment HC-290 is the refrigerant of choice rather than HC-600a.

Other types of stand-alone equipment have a specific design: water coolers, ice makers, vending machines, and display cases, and are covering also several levels of temperatures.

For food and beverages kept at temperatures ranging from +1 °C up to 10 °C, HFC-134a is the dominant refrigerant, replaced by HC-600a and HC-290 in some families of equipment where generally the refrigerant charge is small lower than 150 g for most manufacturers even if some European brands commercialise equipment with Hydrocarbon charge up to 1 kg and even 2.5 kg depending on national regulation. For other companies R-744 is the preferred refrigerant choice.

Ice Cream freezers

For ice cream freezers, R-404A as well as HFC-134a has been the standard design since 1995; the switch from HFC refrigerant to propane (HC-290) is steady. The lifetime of the equipment is about 10 years, The estimated installed base using HC is of 500,000.

Water Fountains

Water fountains for both bottled water and tap water are installed in office buildings, supermarkets, etc. They are installed with a small compressor refrigeration system and so far HFC-134a is the most used refrigerant. Typical HFC-134a charge is about 40 g. Some companies are now introducing HC-600a with refrigerant charge as low as 20 g and the market share of those HC systems is growing. 25% of the installed base in 2010 is estimated to be using HC-600a taking into account a life time of 10 years and knowing the current policies of the large global companies.

Ice Machines

A large number of ice machines are installed in restaurants, bars, and hotels. Several sizes are available and refrigeration capacities vary from 1 to 10 kW, with refrigerant charge varying accordingly from some hundred grams to 1 kg. Company policies as well as country regulations will lead to different refrigerant choices: HFC-134a, hydrocarbons and possibly R-744. So far, HFC-134a is globally the dominant choice.

Vending Machines

The cooling capacity of vending machines is about 600 W for rapid cooling of cans. HFC-134a is the standard refrigerant in vending machines. One global company has chosen R-744 as a refrigerant. This new R-744 system is installed inside a plug-in/pull-out cassette and its energy efficiency, as measured, is as good as the reference HFC systems up to 32°C ambient temperature. One global company has taken the commitment that all new equipment will be HFC free as of 2015. Several others are following the same path. R600a appliances have also been developed, but its application is limited to certain styles of construction.R-744 and HC vending machines are taking a significant market share in Japan. One OEM has developed a not-in-kind Stirling refrigeration prototype for vending machines. The energy efficiency of this new system was better than the reference vapour compression base line, but the cost was considered too high by customer companies and so this system did not reach the market.

Glass-Door Coolers

Glass-door bottle coolers can be found in supermarkets, convenience stores, gas stations etc. The most common type is the one-door 400-litre-type. Glass-door coolers are often installed by a soft drink company.

Currently, HFC-134a is the standard choice. Since 2000, several thousand units have been installed in Europe using mostly HC-600a and, for some brand names, HC-290. Some global companies have rather chosen R-744 systems for their bottle coolers.

Plug-in Display Cabinets

The use of plug-in display cabinets is increasing in small and medium size supermarkets. This choice is made because plug-in cabinets are cheaper and more flexible than remote display cabinets connected to a centralised system. In warm climate countries and in general during the hot season, the heat released by the condenser of each and every plug-in cabinet in the sales area has to be removed by an air-conditioning system, which has to be designed with a significant larger cooling capacity. On the other hand, in colder climates such as Northern Europe, the heat rejected by the condenser and compressor is useful in heating the store and can be regarded as heat recovery in the cold season. So far, R-404A refrigerant is the standard choice, and the charge per unit varies from 220 g up to 3 kg. Especially in Germany, UK and the Northern European countries plug-in display cabinets running on HC-290 are gaining market share. Several German supermarket chains only purchase HC plug in cabinets /Rhi09/.

There has been conversion of production facilities from HCFC and HFC to HC for stand-alone commercial refrigeration equipment in Article 5 countries for the domestic market /GTZ09i/.

In many Article 5 countries, even in large supermarkets, plug-in cabinets are preferred to remote cabinets connected to a centralised system. The evident drawback is that plug-in cabinets are releasing all heat inside the sales area and either the AC system has to be designed in order to absorb this additional heat load or the temperature inside the supermarket can reach very high values (above 30 °C and sometimes above 40 °C) leading to a poor capability of plug-in cabinets to keep the products at the right temperature. Moreover, the overall energy efficiency of supermarkets using plug-in cabinets is low due to the fact that the energy efficiency of small motor-compressors is lower than medium and large size compressors.

For all stand-alone equipment, energy conservation standards can be and are being issued or revisited because laboratory tests can be performed in order to assess refrigerating capacities and electric input power, and so establishing equipment energy efficiency. The base line energy consumption can be established, engineering analyses can be performed, and improvements can be targeted. Regulations as well as electricity costs are the drivers for significant improvements of energy efficiency, the market being driven by initial costs so far.

It is estimated that all refrigerants banked in stand-alone equipment represent an amount of about 38,000 tonnes, emission levels during the lifetime is estimated from 1 to 5 % depending on servicing quality, corrosion and day to day handling of goods . Due to the compact refrigeration circuit, leaks at the beginning of the life cycle of the equipment are well handled; the number of joints being minimal or even nil (all brazed or welded circuit). The critical issues are related to corrosion, equipment day-to-day handling, and aggressive cleaning leading to possible circuit ruptures. Emissions occur essentially at end of life decommissioning.

In summary, HFC-134a fulfils the technical constraints in terms of reliability and energy performance for stand-alone equipment. In many developed countries GWP of HFC-134a is more and more considered as prohibitive in relation to refrigerant emissions, so HC refrigerants and R-744 are gaining significant market shares in Europe and Japan. In the near future, unsaturated HFC such as HFC-1234yf could be considered as an option, the retrofit from HFC-134a to this new refrigerant expected as being rather simple even if long-term reliability has to be assessed /See 10/.

4.3.2 Condensing Unit Systems

Condensing units are found in many convenience stores and food specialist stores for cooling a small cold room and one or several display cases. The technology can be considered as a mass production one with usually hermetic compressors, sometimes semi-hermetic ones. Condensing unit is a well spread option in Article 5 countries. Even in supermarkets, especially in some Article 5 countries, several racks of condensing units are installed side-by-side in small machinery rooms. Condensing units are less energy efficient, compared to a well-designed small-centralised system but condensing units are chosen for initial cost reasons, easiness of installation, and are found ready to install.

The cooling capacity varies from 1 to 20 kW mostly at medium temperature and the refrigerant charge varies from 1 to 5 kg for HCFCs or HFCs. HCFC-22 is still the most used refrigerant in the U.S. and in all Article 5 countries. New equipment can use HFC-134a, HCFC-22, R-404A, R-407C, R-507, R-410A other HFC and HCFC blends, HC refrigerants and R-744. HFC-134a, HCFC-22 and R-404A are the dominant refrigerants. In Europe, due to the E.U. regulation, a shift from HCFC-22 to R-404A or sometimes R-507A has occurred as of 2000. R-404A is the leading choice also for cost reasons; the condensing units using this refrigerant are cheaper compared to HFC-134a units of the same cooling capacity because of smaller compressor. Nevertheless in hot climate and for medium temperature applications, HFC-134a is used due to its better energy performances at high ambient temperatures compared to R-404A.

Condensing units are always designed as direct expansion systems, and so their environmental impacts are related to refrigerant choice and energy efficiency.

What is described for stand-alone equipment is also verified for condensing units when the units are replacing larger compressors. As stated previously, this non-efficient solution in terms of energy consumption is chosen due to investment cost reasons and to the availability of condensing units everywhere in the world. Moreover, these condensing units are also produced in large series in Article 5 countries avoiding the import of large size compressors.

4.3.3 Supermarket Systems

Centralised systems

For large supermarkets, the dominant design is the so-called centralised system where all the compressor racks are installed in a single machinery room. This concept has led to the installation of up to several kilometres of piping, containing refrigerant in liquid phase from the machinery room to the sales area and refrigerant in vapour phase back from the sales area to the machinery room. The size of centralised systems can vary from refrigerating capacities of about 20 kW to more than 1 MW related to the size of the supermarket.

The refrigerating capacities are generated by independent racks of compressors at two main levels of evaporating temperatures -40 / -35°C for frozen food (and ice-creams) and -15 / -10°C for fresh food (dairy, meat etc.). Low-temperature racks represent about 10 to 30% of the refrigerating capacities and so the medium-temperature racks represent 70 to 90% of the total refrigerating capacities. In terms of energy consumption, the low-temperature racks consume 20 to 35% of the total energy consumption due to lower energy efficiency related to the level of temperature. The refrigerant charges are related to the refrigerating capacity and store layout. For large supermarkets (food sales area larger than 3,000 m^2) with current direct expansion centralised systems, the refrigerant charge varies from 800 kg to 2 tonnes.

Heat recovery for heating the store typically requires a 4-way valve on each condensing circuit and also dedicated heat exchangers in order to recover the condensation capacity during the heating season; this energy is usually released to the environment by the air cooled condensers. This possible design is popular in cold regions in the USA and in some European countries, . The circuit is more complicated, the refrigerant charge is higher by at least 20%. This technical option has to be studied in terms of return on investment, level of refrigerant emissions and servicing. For moderate and hot climates this option is not selected due to the added complexity and the low heating needs that hamper the return on investment. Other simpler designs are found in Europe, especially in the northern countries where domestic hot water is produced by de-superheating the refrigerant before entering the condenser. A new system design mostly introduced in small supermarkets integrates the cooling / heating system of the shop with the refrigeration system, making an interesting example of a holistic approach for energy management.

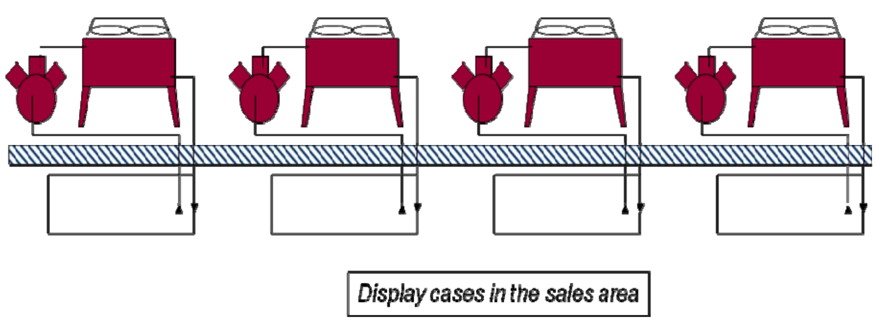
In order to simplify servicing in the current centralised design, most of the commercial companies, except in Japan, has chosen to use the same refrigerant at the two levels of temperatures. This choice is arguable because as an example HFC-134a or R-407C and R-717 are more efficient as refrigerants at the medium-temperature level compared to R-404A and on the contrary R-404A or R-744 are the most efficient refrigerants at the low-temperature level. As always the design of the system defines the effective energy efficiency and so efficient design can be found even with a less efficient refrigerant. Nevertheless, in terms of choice of refrigerant, one can keep in mind that refrigerants could be different for the medium-temperature level and for the low-temperature level giving a larger number of technical options when environmental impacts of refrigerants have to be limited.

One of the major consequences of making separate choices for refrigerants dedicated to the low-temperature and to the medium-temperature is that R-744 can be the preferred choice at the low-temperature level in a cascade design and the choice for the medium-temperature level is under evaluation in developed countries depending on global warming, costs, and easiness of use. In parallel to refrigerant evaluation, technical options have been developing since nearly 15 years in order to lower the refrigerant charge by the development of indirect systems and distributed systems.

Distributed Systems

This technical alternative has been studied and realised as of 2000. The concept is to install the compressors close to the display cases either inside or very close to the sales area.

Figure 4-3: Distributed system where a single package refrigerating system provides refrigeration to a series of display cases / Clo08/



This design is more practical for the typical US layout of supermarkets where most of the medium-temperature display cases are installed near by the walls and not in aisles, as it is usual in Europe. The reference design of distributed system integrates water condensers in a soundproof box with the compressor(s). The water, used as a coolant in the condensers, is cooled usually by roof-mounted dry coolers. The refrigerant charge can be reduced by more than 50% and up to 75%. While at the same time leakage rates are reduced due to fewer joints.

The energy efficiency of such a system has to be carefully analysed. Energy gains can be made due to the huge reduction of piping length and thereby reduced pressure losses, but the compressors are smaller and so their energy efficiencies are usually lower. Moreover, an additional difference of temperature is created when using water-cooled condensers that are releasing their heat in air-dry coolers. The complexity of the comparison between the baseline (centralised system) and the new distributed system is enhanced when changing the refrigerant (HFCs, HCs, or R-744 compared to R-22); so a wide variation of performances can be found in the technical literature. Distributed systems are still not a widespread option and are mainly installed in new US supermarkets with HFC refrigerants.

It has to be noted that indirect-distributed systems have been developed in UK. The system uses hydrocarbon as a refrigerant and a heat transfer fluid for transferring heat from the display cases to the evaporator.

Indirect Systems

Indirect systems represent a small market share of new installations and they replace direct expansion centralised systems in supermarkets. This option has been developed in Europe as of 1995 and has expanded initially slowly. It has to be noticed that several US commercial chains have decided since 2006 to install indirect systems. The driver to change from usual direct expansion systems is the significant reduction of refrigerant charges (50 to 85 %) and a much better refrigerant containment.

Depending on the country, R-404A or R-507, sometimes R-717, HCs (HC-290 or HC-1270), and R-744 are used as primary refrigerants in the refrigerating system entirely installed in the machinery room. Due to high latent heat of vaporisation and low liquid density, the ammonia (R-717) charge can be 10% of the usual HFC refrigerant charge. Such systems can be installed in special machinery rooms with safety features allowing high ventilation rates in case of significant leaks.

The same applies to HC refrigerants with charge typically 10% of the direct system HFC reference charge. For safety reasons, the refrigerant circuits are separated in several independent ones, limiting the refrigerant charge of each system /IPCC05/.

Many indirect systems have been designed, still using R-404A as primary refrigerant in the machinery room, the reduction of the charge yields to significant reduction of the environmental impact.

Well-designed indirect systems can be as efficient as well-designed direct systems due to better heat exchange in the air coils, but heat transfer fluids (HTF) such as mono-propylene-glycol (MPG) used in indirect systems need special attention, especially at low temperatures where pumping power may be excessive. Alternative HTFs exist which have lower viscosity at low temperatures. Nonetheless, indirect systems are nowadays mainly built for the Medium Temperature range. Also the pumps have to be carefully chosen in order to avoid significant additional energy consumption.

For indirect systems, R-744 as HTF is mainly used in low-temperature display cases and cold rooms. R-744 is partially evaporated in the display-case evaporators, returns in two-phase flow to the primary evaporator in the machinery room, where R-744 is fully condensed or “liquefied”, and then pumped back to the display cases. Such design is energy efficient because there is no superheat zone at the exit of each evaporator. The only threat for indirect systems using R-744 is the possible release of the entire R-744 charge related to a lack of cooling due to an incident on the refrigerating system. The R-744 pressure increases progressively with the lack of cooling and is related to the temperature in the circuit. If the safety valve is set around 3 MPa (which is usual), the opening of the safety valve will occur when the temperature of the coldest part of the system is about – 5 °C leading to a release of R-744.

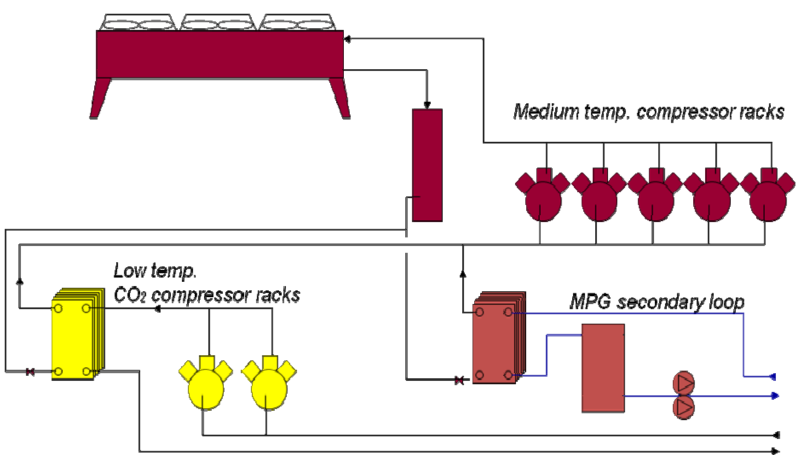
More generally, indirect systems are linking all cooling elements one to the others, which in case of a significant failure leads to the complete loss of refrigeration and the possible loss of food. The current multiple-rack centralised system offers the possibility of limiting the incident on a single rack, the other ones being capable to provide the complementary cooling during the repair. Special charge limitation rules have led to a similar design for indirect systems in Sweden. Namely racks of individual refrigeration systems, all cooling the same indirect loop. Up to 20 such racks are installed in large Swedish supermarkets. One German discount chain has announced that they will only purchase indirect hydrocarbon systems for their new supermarkets.

A drawback of indirect systems is related to the necessary insulation of all piping in order to avoid humidity condensation and icing. Valves and pumps can present difficulties for efficient insulation and may become ice blocks with water dripping continuously around the ice blocks; moreover, for liquid HTF used at the medium-temperature level, quantities are enormous representing several metric tonnes, and possible leaks of HTF are difficult to diagnose especially in the display cases. All those lessons learnt from the existing indirect systems are to be tackled by improved designs.

Hybrid and Cascading Systems

Hybridisation between direct and indirect systems can be found in the current technical offerings (one example is shown in figure 4-4) with a limited additional cost if any.

Figure 4-4: Hybrid system comprising a R-744 cascade at the low temperature level and a secondary system at the medium temperature level / Clo08/



R-744 is no more a HTF but a refrigerant used in a cascade system. The overall design consists in a low-temperature compressor rack with R-744 compressors working between an evaporating pressure of 1.2 MPa (evaporating temperature around –35°C) and a condensing pressure of 2.5 MPa (condensing temperature at –12°C) possibly 3 MPa (condensing temperature at –5.5 °C), and so keeping the tubing and the components under the 2.5 or 3 MPa pressure threshold, which are the thresholds of current technologies. The consequence is that the costs are kept similar between R-744 and HFC systems. For larger stores (above 2500 m^2 sales area) the use of R-744 in cascade system is even more cost effective due to smaller pipe dimensions.

In a hybrid system, the condensation of the R-744 low-temperature stage is made by either exchanging heat with the heat transfer fluid used at the medium-temperature stage or by the evaporation of the medium temperature refrigerant in an evaporator – condenser as shown in figure 4-4, so that the heat of the R-744 system is delivered at the medium-temperature stage and then released outdoor by the medium-temperature vapour compression system. This concept has been installed in very large supermarkets and is claimed to meet the same initial costs as R-404A direct systems, because the R-404A charge is reduced from 1.5 tonne to less than 250 kg. This design is in competition with full cascading systems presented in the following section.

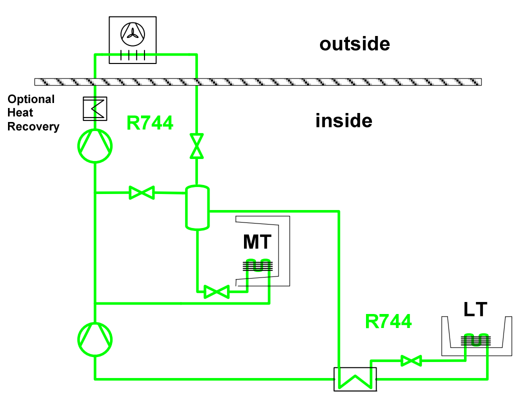
Such systems are starting to be used in some Article 5 countries, for example see /GTZ09ii/.

Another variation is the use of a high temperature HTF circuit which is fed to water-cooled condensing units positioned within medium and low temperature display cases and next to cold stores. This enables the minimisation of refrigerant charge within the retail area (figure 4-5), thereby allowing the use of HCs. At least one supermarket chain is now using this approach /ACR09/.

Two stage R-744 booster systems

The most up-to-date design of R-744 refrigeration system employs R-744 both for the low temperature and the medium temperature range. One common design is the one described in Fig 4-1, another is that the compressors for the low temperature stage are cascaded with those of the medium temperature stage, figure 4-5. This design is becoming popular in Central and Northern Europe where it exhibits lower energy consumption on a yearly basis compared to usual centralised systems. For high outdoor temperatures, R-744 is no longer condensed in the outdoor air cooled condenser due to R-744 low critical temperature of 32 °C. The energy efficiency can be lower than that of a comparable R404A system during this transcritical operation. This is the reason why such systems have only been installed in moderate climates. One German discount chain has announced that it will only purchase R-744 refrigeration systems from January 2010 on and various UK supermarkets have given similar such commitments /Kau07/.

Figure 4-5: All-R-744 centralised refrigeration system /Rhi09/.



Current Centralised systems

HCFC-22 is now being phased-out in new installations in all developed countries, Europe having begun as of 2000. HCFC-22 represents still the largest refrigerant bank in supermarkets and hypermarkets in the U.S., in Russia, and in almost all A5 countries. For new systems, the dominant choice is R-404A for all non-Article 5 countries except some Northern European countries. For example in Norway and Denmark, due to the high level of taxes on R-404A, nearly all new centralised systems (40 to 70 each year) are working with R-744 at the low and the medium level temperatures. In addition, Denmark has prohibited the use of HFC in systems with more than 10 kg refrigerant charge. Consequently many non-HFC systems are being built. In UK and Germany even without high taxes on high GWP refrigerants, R-404A is no longer the preferred choice.

In Japan, R-407C is the leading choice for medium-temperature applications, which is the dominant use of commercial refrigeration due to the large consumption of fresh and raw food. R-404A is used for all low-temperature applications.

In China HCFC-22 and HFC-134a, to a lesser extent, are the most used refrigerants with R-404A being used for HCFC-22 replacement in many low-temperature systems.

HCFC-22 is still a dominant option for all Article 5 countries because the cost of HCFC-22 technology is the cheapest and compressors are available on the global or local market.

Under hot climates, R-404A exhibits lower energy efficiency compared to HCFC-22 due to its lower critical temperature (72 °C) compared to HCFC-22 (86.5 °C).

Additional sub-cooling of R-404A is a cost and energy efficient strategy that can be performed by a small independent cooling system for cooling only the R-404A liquid phase leaving the condenser.

In moderate climates of Central and Northern Europe direct systems with R-744 as refrigerant in a trans-critical / sub-critical cycle depending on the ambient temperature, have been introduced in several countries for medium and large size supermarkets. The systems give a low GWP refrigerant solution with only one refrigerant for both low and medium-temperature refrigeration. About 300 systems have been installed in Europe during the past years. A complementary option is a cascade system where R-744 is the refrigerant of the low-temperature circuit; as shown previously for the hybrid system (Figure 4-4). This design is more efficient than a full R-744 cascade system in hot climates, and is being considered for application in some Article 5 countries. However, all-R-744 systems with slightly modified cycle design in order to increase efficiency at the highest ambient temperatures are now being field-tested.

In summary, for supermarkets with refrigerating capacities varying from less than 100 kW to at least 1 MW, several designs have been experimented in several hundreds of stores. The main specifications of commercial chains are to keep the design simple, easy to maintain and service, and capable to avoid the loss of food products when a failure occurs on the refrigerating systems. Those specifications have to be compatible with refrigerant charge reduction and choice of refrigerants with 0 ODP, lower GWP, and energy efficiency improvements.

4.5 Options for Existing Equipment

CFCs (CFC-12 and R-502) have been phased-out in new commercial refrigeration equipment in most Article 5 countries as of 2005; there is still a need for servicing commercial refrigerating systems running with those CFCs during the next years. So far, no shortage of recycled CFCs has been identified, confirming the same evaluation as noticed ten years before in developed countries. Intermediate HFC-blends such as R-413A are used for retrofit of CFC-12 medium-temperature systems, and R-417A or R-422B for retrofit of R-502; those retrofits have not taken a significant market share of refrigerant sales.

Retrofit of commercial refrigeration equipment raises a larger interest in Article 5 countries to save cost. In order to make reliable retrofit, a significant training of servicing technicians is necessary even if technical solutions are well established. For many servicing companies, the knowledge as well as the equipment is not always available. Retrofits require the change of lubricant and need more technical precautions. The availability of the new POE lubricants as well as the new filter dryers has to be verified. In Article 5 countries, for many servicing companies still a significant lack of adequate tooling is obvious: recovery equipment, connecting hoses, recovery cylinders, dry vacuum pump, and precise scale. All those tools and equipment are necessary to realise proper retrofit including the main steps: recovery, evacuation, oil flushing, change of oil, and careful charge of the new refrigerant, all those elements are part of training programs currently implemented in Article 5 countries.

For HCFCs, the status of use varies widely depending on regulations. In Europe, the use of virgin HCFC-22 for servicing purposes ceases as of 1st January 2010; only recycled HCFCs can be used until 1st January 2015.

In the US, HCFC-22 production and import cease as of 1st January 2010 for new refrigerating equipment; servicing is authorised until 2020, but HCFC quantities are limited. For developed countries several studies indicate the need of strong conversion programs of existing commercial refrigerating systems due to possible shortages of HCFC-22 for servicing. As it will be shown in the following paragraph, several options are proposed.

Stand-Alone Equipment and Condensing Units

Three known options are available depending on projected remaining lifetime and costs:

- Disposal of the old equipment and buy a new one using a non-ODS refrigerant,
- Repair and recharge with the same refrigerant, and
- Repair and recharge with a low-ODP or zero-ODP refrigerant.

Conversions of stand-alone equipment and condensing units moving from CFC-12 to HFC-134a are well established. The conversion from HCFC-22 to HFC blends is now ongoing in developed countries. It has to be underlined that for all brazed stand-alone equipment equipped with a capillary tube and having an all brazed refrigerating circuit, conversion is unlikely. The possible retrofit concerns mostly condensing units and involves several steps. Chemical manufacturers propose several HFC blends. The choice depends on the level of temperature and is the same for condensing units and large centralised systems.

The change from alkyl-benzene oil to POE lubricant is recommended, the adjustment of the superheat in case of thermostatic expansion valve, and the replacement of the filter dryer. These procedures have been well established since several years, but continuous training is still necessary in many Article 5 countries to ensure retrofit quality and so the remaining lifetime of the retrofitted equipment.

Supermarket Systems

In developed countries, supermarket equipment is partially or totally renewed every 7 to 10 years, depending on countries. In Article 5 countries, the lifetime is significantly longer, 15 years up to 25 years, so the retrofit options have a very significant impact in order to limit costs to avoid the change of the refrigerating system.

R-502 Retrofit

Due to lubricants issues, R-502 retrofits are mainly carried out with HCFC-22-based blends (R-408A or R-402B). Studies performed on energy consumption show that energy efficiency obtained with these blends is comparable with R-502. Neither major problems nor breakdowns have been recorded. It appears to be a straightforward and reliable option.

HCFC-22 Retrofit

New HFC blends such as R-422D and R427A, have been developed in order to make easy retrofit from HCFC-22 to those HFC blends. R-422D is presented as a blend where no oil change is necessary due to the 3.4% of HC-600a mixed with 65.1% of HFC-125 and 31.5% of HFCF-134a. Different tests have shown that depending on the circuit, a progressive change of the previous alky-benzene oil by POE leads to a better oil return to the compressor racks. R-427A is presented as refrigerant blend for HCFC-22 replacement with an initial change of oil. Retrofit has begun in Europe and in the U.S. but has not gained a significant momentum until now. Moreover, the price of HCFC-22 remained low until 2008 not indicating any immediate shortage; only in 2009 did HCFC-22 prices raise but not in all developed countries.

For energy efficiency, the change from R-22 to those retrofit blends indicates a loss in refrigerating capacities varying from 5 to 10% and a loss in energy efficiency in the same order of magnitude. For such large systems it may be unnecessary to adopt such alternative intermediate blends and instead directly apply R-407C, especially since it has a lower GWP compared to those two blends and that the oil change required for the use of this refrigerant is a better servicing practice.

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Chapter 5

Industrial Refrigeration

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5 Industrial systems

5.1 Introduction

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. Previous RTOC reports have concentrated on Industrial Refrigeration: cooling systems for production, storage or distribution of food, drink, chemicals, pharmaceuticals and other products. This report will extend the discussion on Industrial Heat Pumps: heating systems similar in scale and application to Industrial Refrigeration systems and will introduce a new sector called Industrial Air-Conditioning. This sector includes 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 /ASH09/. 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.

Industrial Refrigeration systems are characterised by heat extraction rates in the range 10kW to 10MW, 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 are used on 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. 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 in the United States in recent years where HCFC-22 has just been prohibited. 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. It is also noted that the prohibition of HCFC-22 in the USA from 1 January 2010 will cause a rapid shift to either R-717 or HFCs, but it is not clear which will be preferred.

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%	80%	10%
India/China	500	5%	90%	5%

For Article 5 countries still using HCFC-22 and looking to the future it is possible that a different pattern will emerge. Fear of the consequences of a possible "phase-down" of HFCs might result in a switch directly from HCFC-22 to R-717 for new systems. 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.

Industrial Heat Pump systems have heat delivery rates from 100kW to over 100MW, 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 ^{o}C to 80 ^{o}C, although if the recovered heat is to be used for steam raising then it needs to be at least 120 ^{o}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.

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.

An assessment of the relative importance of the traditional HCFC and HFC alternatives in the three main market segments of the industrial sector is shown in Table 5-3 /UNE10/. Where blends containing HCFCs are shown, for example in the case of R-403B, these are refrigerant formulations developed as substitutes for CFCs, in particular R-502. Blends shown as HFCs, for example R-404A, were developed as CFC replacements too, but have also been used in new build and retrofit applications as replacements for HCFCs.

Each of the three sub-sectors described in the table is broken down in a more detailed review in section 5.2 where sub-sub-sectors such as cold storage, leisure and process are identified and analysed.

Table 5-3: Assessment of alternatives in the Industrial Sector

	Sector using HCFCs	Industrial Systems											
		Industrial Refrigeration				Industrial Heatpumps				Industrial AC			
		% use in total				% use in total				% use in total			
1	**Which HCFCs used**												
		HCFC-22		blends(eg R-403B)		HCFC-22		blends(eg R-403B)		HCFC-22		blends(eg R-403B)	
2	**Percentage HCFCs** (in the total) used in the sector globally	banks	new build	banks	new build	banks	new build	banks	newbuild	banks	new build	banks	new build
		40%	10%	10%	0%	30%	0%	0%	0%	50%	0%	0%	0%
3	**Percentage high-GWP alternatives** (in the total) --such as HFCs-- used in the sector globally	HFC-134a		blends(eg R-404A)		HFC-134a		blends(eg R-404A)		HFC-134a		blends(eg R-404A)	
		5%	5%	15%	20%	60%	40%	0%	0%	10%	40%	15%	20%
4	**Which low-GWP alternative** is already used												
		R-717	R-744	HC		R-717	R-744	HC		R-717	R-744	HC	
5	**Relative cost comparison** of the product with the low-GWP alternative compared to the HCFC based product												
		+20%	+40%	+50%		0%	N/A	N/A		+50%	+100%	+50%	
6	**Energy efficiency comparison** of the product with the low-GWP alternative compared to the HCFC based product												
		+20%	0%	+10%		+10%	N/A	N/A		+20%	0%	+10%	
7	**Market penetration** of the low-GWP alternative in developed countries												
		80%	10%	2%		5%	N/A	N/A		30%	0%	10%	
8	**Market penetration** of the low-GWP alternative in developing countries												
		40%	0%	0%		0%	N/A	N/A		10%	0%	5%	
9	Comparison of the low-GWP alternative with the high-GWP option normally used (indicate which high-GWP option) **for energy efficiency**	R-404A	R-404A	R-404A		HFC-134a				HFC-134a			
		+30%	0%	+20%		+20%	N/A	N/A		+10%			
10	**Which low GWP alternatives** have not been commercialised yet, but may be commercialised in future												
		air cycle	water vapour compression			not applicable		not applicable		not applicable		not applicable	
11	**Indication of the time scale** for this anticipated commercialisation												
		unknown		unknown		not applicable		not applicable		not applicable		not applicable	

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) /Zyh03/. 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 /Les09/.

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 1000, whereas for HFC-236fa it is approximately 9300, 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 ($CF_3CF_2C(O)CF(CF_3)_2$, also known as C6F) has been used as an alternative. It has zero ODP and zero GWP but less favourable properties than HFC-245fa /Bra08/. Rankine cycles have also been produced using R-717 and ammonia-water mixtures as the working fluid, although strictly speaking these cannot be described as "Organic". 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.

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 ^{o}C, was common for small to medium sized applications and R-717 was used in larger systems. Industrial Air-Conditioning was less common at that time, and tended to use standard chillers with CFC refrigerant. 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 /Bro92/. 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. Other parts of the world followed similar patterns, 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. In Article 5 countries where R-717 was already used these systems were retained and extended, 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. This is not only expensive to install and maintain, it is also much less efficient in operation.

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 system integration to make better use of waste heat recovery.

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. The motivation seems to be primarily based on the fear of as-yet unknown future regulation rather than the immediate effect of the current rules, 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.

To date there has not been any significant discussion of sustainable manufacture of industrial systems. It is left to producers to minimise material content on cost grounds rather than for environmental reasons, however this can lead to acceptance of lower efficiency systems in some cases. For example the design temperature difference used for selection of air-cooled condensers is in the range 15 – 20 K, resulting in relatively cheap, small heat exchangers. It is possible to get improved efficiency by using larger heat exchangers but they use more raw material and are more expensive. There is no clear guidance on optimising this design decision, for example information on the embodied energy in the heat exchanger, or preferred source of materials. The use of recycled aluminium in heat exchangers is one example of sustainable manufacture. Design for minimising steel or copper content is another. In future it is expected that greater use of plastics and other synthetic materials will raise awareness of sustainable manufacture.

5.2 Applications (including size of market, current practice, regional variations)

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.

A technique developed in Japan offers the prospect of successful freezing of difficult products such as milk and soft fruit, using a magnetic field to condition the product during the freezing process /Suz05/. This may help to overcome the 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.

5.2.2 Cold Storage

Cold storage facilities usually operate at two temperature levels. Frozen produce must be stored below -18°C, and it is usual to maintain the store between -22°C and -26°C to provide a factor of safety in the event of major equipment failure. Some products require lower temperatures. 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 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 /Hut05/. Typical loads for these applications may be up to 2kW per m^2 in comparison to a typical office load of 40W 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.

5.2.4 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 (8100kW heating capacity) and Akershus hospital, Norway (8000kW heating capacity). These systems are custom-designed, using R-717 as the refrigerant /Ste08/.

Even larger systems are used for district heating systems, with many examples in Scandinavia. The smallest of these systems are about 5000kW. Most installations use HFC-

134a in centrifugal compressors, with some (up to 15000kW) using R-717. The largest is in Stockholm, with a total capacity of 180000kW (180MW) 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 /Bai06/.

5.2.5 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 1km long.

5.2.6 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.

5.3 Working Fluid Options for New Equipment

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^{o}C /IIR08/. 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^{o}C makes R-717 very suitable for high temperature heat pumps. It is at atmospheric pressure at -33^{o}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 /Nie00/.

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. There is currently no alternative to HFC-134a in this technology.

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 HFC143a; 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 probably 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.

Unsaturated: unsaturated hydrofluorocarbons such as HFC-1234yf and HFC-1243zf have not to date been used in industrial systems. The low global warming potential suggests that they may 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.

5.3.3 HCFC-22

Where its use is still permitted in new systems, particularly in article 5 countries, HCFC-22 is still common. It has not been supplanted by HFC blends because it is cheaper than any of the blends and usually offers better system efficiencies. Where HCFC-22 was widely used in smaller industrial and heavy commercial systems and has subsequently been superseded by R-404A, which has a significantly higher global warming potential.

5.3.4 Hydrocarbons

Hydrocarbons are not widely used in industrial refrigeration except where the additional safety measures required 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. HC-290 is generally similar to HCFC-22 and R-717 in terms of operating temperatures and pressures, and requires similarly sized compressors.

5.3.5 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°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 /Mad09/.

R-744 is particularly suitable for use in freezer systems because it is at positive pressure down to -56°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 /Pea09/. 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 /ASH10/.

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.

5.3.6 R-718 (Water)

In general R-718 is not suitable for most industrial applications because the triple point is very slightly above 0°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.

5.3.7 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 then 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. There is an increase however 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 vapour compression plant, but with some absorption cooling available to augment the cooling capacity when the generator is running.

5.4 Retrofit 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. Usually the compressors and 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 /New08/. 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 (propane or isobutane) where the system efficiency can be improved. In this case it is essential that suitable safety measures are ensured.

5.5 Overview of Refrigerant Consumption, Banks and Emissions

It is difficult to estimate the size of CFC, HCFC and HFC banks associated with the industrial sector because the technology is used in a very wide range of applications. A report published by ADEME in 2010 /ADE10/ provided estimates based upon published data from various food sectors as collated by the Food and Agricultural Organisation of the United Nations. This report indicated that the total demand for refrigerants in the industrial sector was about 50,000 tonnes, with HCFCs accounting for about one-half of this. The remainder of the demand was approximately 15,000 tonnes of ammonia, 5,000 tonnes of CFCs (principally in Article 5 countries) and 5,000 tonnes of HFCs, principally in Europe. The estimated size of the banks of refrigerant within existing equipment ranges from 3.5 times the demand to 7 times the demand.

The emissions figures for refrigerant type and region are also very difficult to estimate. They range, as a percentage of the bank for each region, from 4% to about 21%, with the exception of CFC emissions, which are estimated to be 27.7% of the total bank. This is presumably a result of the condition of the residual equipment still using CFCs, and suggests that there is a strong imperative to incentivise a switch to alternatives as quickly as possible, provided the old refrigerant is recovered and reprocessed.

A summary of the approximate figures for 2006 is given in tables 5-4 to 5-7.

Table 5-4: Refrigerant Demand in 2006

Demand (tonnes)	**USA**	**Europe**	**Total**
CFC	0	0	5,563
HCFC	1,446	1,290	25,372
HFC	1,087	2,405	4,707
R-717	3,845	2,930	15,667

Table 5-5: Refrigerant Banks in 2006

Banks (tonnes)	**USA**	**Europe**	**Total**
CFC	3	13	19,896
HCFC	12,681	15,819	93,985
HFC	7,681	17,498	30,735
R-717	26,401	20,533	105,923

Table 5-6: Refrigerant Emissions in 2006

Emissions (tonnes)	**USA**	**Europe**	**Total**
CFC	0	0	5,512
HCFC	1,106	1,390	20,229
HFC	628	1,261	2,521
R-717	1,226	800	9,408

Table 5-7: Refrigerant Emission as a percentage of the bank in 2006

Emissions (%)	**USA**	**Europe**	**Total**
CFC	-	-	27.7%
HCFC	8.7%	8.8%	21.5%
HFC	8.2%	7.2%	8.2%
R-717	4.6%	3.9%	8.9%

It is difficult to reconcile these figures with other published data, which suggests, for example that the R-717 refrigeration market is much larger than this. Given the characteristics of the substances it also seems unlikely that the percentage leakage rate of R-717, which has a characteristic pungent smell, would be higher than the leakage rate for odourless HFCs. Other studies report much higher leakage rates for HFCs, noting that poor workmanship during installation can result in higher leak rates during the first few months of operation until all problems have been resolved.

5.6 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.

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Chapter 6

Transport Refrigeration

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6 Transport Refrigeration

6.1 Introduction

Transport refrigeration includes transport of chilled or frozen products by means of road vehicles, railcars, intermodal containers, and small insulated containers (less than 2 m^3) and boxes. It also includes use of refrigeration and air conditioning on merchant, naval and fishing vessels above 100 gross tonnes (GT) (about over 24 m in length).

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 (more than 20 % of the European market for truck and trailers).

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.

6.2 Technical Progress

6.2.1 Merchant, Naval and Fishing Vessels

There are enormous differences between vessels in terms of category, tonnage, length etc. Some of the main markets are ferries, cruisers, container ships, reefers, trawlers, fish factory ships, submarine navy, surface navy, tankers, and bulk carriers.

The overall size of a ship is measured in terms of gross tonnage, which also forms the basis for manning regulations, safety rules, registration fees, etc. Unless stated otherwise, data presented in this report are limited to vessels above 100 gross tonnes (GT), or about over 24 m in length. 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.

A relationship between the vessel category, tonnage and use of refrigeration (refrigerant, charge) is difficult to establish mainly because of a limited access to registry statistics. Instead, although less accurate, our estimates of banks and emissions are based on a number of vessels and their refrigerant charge on average.

Merchant (or commercial) vessels include in principle cargo ships, passenger ships, and special-purpose ships. According to Equasis /Equ07/, the world merchant fleet amounted to 72,000 vessels with 780 million GT combined. 86 % were small and medium size ships below 25,000 GT. About 3,000 merchant vessels were above 60,000 GT. According to another source, the 2009 Review of Maritime Transport /Rev09/, the world merchant fleet is a little below 100,000 vessels.

Reefer ships are one category of merchant ships – used for transport of perishable commodities such as fresh or frozen food. At the end of 2008, the total reefer fleet stood at about 1,000 /IIR09/. There were 137 reefer ships in EU registers in 2009. This number was predicted to decrease to about 50 by 2020 /Tec09/. Instead, the share of goods transported by means of intermodal containers will continue to increase, hand in hand with the expansion of the fleet of container ships /Rev09/.

The fleet of naval ships is difficult to estimate. The US Navy /Nav10/, largest in the world, operated 290 ships in active service as of August 2010. The world fleet of naval ships is estimated to be less than 5,000.

There are about 4 million fishing vessels of various types in operation, of which one third are decked. The average size of decked vessels is about 20 GT (around 10-15 m). Those larger than 100 GT amounted to 50,000 units. China has approx. 50 % of these larger vessels /FAO10/. At the end of 2009, the EU Fleet Register listed some 3,700 fishing vessels greater than 100 GT /Tec09/.

Regulation of refrigeration systems in ships is typically a flag state right, which implies that the ship owner may change the flag state should any restrictions be imposed in the current flag state. On the other hand, if a ship arrives to a country where a group of refrigerants is not allowed, refrigerant availability can be an issue in case of a refrigerant loss.

In 2009, 93 % of the worlds merchant fleet in terms of deadweight tonnage, or dwt (= loaded ship displacement minus the lightship weight) registered under the flag of 35 countries and territories. The top registries (by dwt share) were Panama, Liberia, Marshall Islands, Hong Kong (China), Greece, Bahamas, Singapore and Malta, accounting for 65 % of the world's dwt /Rev09/.

More than two thirds of fishing vessels in operation in 2007 were registered in countries in which they were also built. The major registries for fishing vessels have been China, Japan, S. Korea, Peru, the Russian Federation, Poland, Spain, and USA /FAO07 and Ana99/.

Air pollutant emissions from ships are covered by Annex VI of the Marine Pollution Convention, MARPOL 73/78, of the International Maritime Organization /Mar10/. MARPOL Annex VI (reg 12) prohibits new installations containing ozone-depleting substances on all ships from May 19, 2005, but new installations containing HCFC refrigerants are permitted until January 1, 2020. As of 31 July 2010, there were 60 contracting states which represent 84 % of the world tonnage.

For developed countries, the Montreal Protocol has introduced a stricter regulation of HCFC fluids than MARPOL. For example, Regulation (EC) No 2037/2000 of the European Parliament prohibits the use of HCFC refrigerants in new equipment from 2002 onward;

HCFC will be allowed for maintenance of existing equipment only until 2015 and only with recycled HCFC from beginning of 2010.

HCFC-22 has been the dominant refrigerant used aboard ships (80 % of present fleet). It has been used universally for air conditioning systems, cooling and freezing of food for passengers and the crew, and in the holds and in the production on trawlers and factory vessels. HFC refrigerants have been replacing HCFC-22 in new-built ships following the phase out of ozone-depleting substances under the Montreal Protocol.

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 fields. HFC-23 is used for freezing at -60 °C and below (mainly fish). Natural refrigerants have been used in a relatively few vessels; primarily larger trawlers and reefers (see section 6.4). The current share of HFC refrigerants in the world's fleet is estimated at 10 %.

A typical refrigerant charge for vessels above 100 GT is between 100 and 500 kg for direct systems, and between 10 and 100 kg for indirect systems. The annual refrigerant leakage rate could be as high as 20 - 40 %.

There has been a trend to build fewer larger ships rather than a larger quantity of smaller ships in many categories – fish carriers /Stao07/, oil tankers, bulk carriers /Rev09/. One reason could be the recent increase in fuel prices.

6.2.2 Road Transport

The road refrigeration market comprises several vehicle segments: small trucks and vans with a cargo volume below roughly 19 m^3, large trucks with a volume between 20 and 59 m^3, and trailers and semi-trailers with a box volume up to more than 100 m^3. Small trucks and vans are used predominantly for distribution in urban and sub-urban areas, while long haul transport favours large trucks and trailers.

The total world fleet is estimated at 4,000,000 vehicles, of which about 30 % are trailers, 30 % are large trucks and 40 % are small trucks and vans. The portion may vary from region to region. It is predicted, for example, that the total fleet of temperature controlled trucks in China will reach 80,000 in 2010. There are estimated 100,000 refrigerated trucks in Japan and more than 100,000 in France. Each vehicle is typically equipped with a single refrigeration unit.

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, while the countries committed to the ATP Agreement /Agr10/ prefer the box temperatures of –20 ºC and 0 ºC at an ambient temperature of 30 ºC.

For 15 years multi-temperature equipments have been developed. They allow the same vehicle with only one refrigeration unit to carry products at different temperatures in 2 or 3 compartments. They represent more than 30 % of the European market for new equipment, and some 20 % of current fleet. 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 independant gas heating equipment.

Power supply management and power transmission management can give the largest differences in design of refrigeration units for trailers, large trucks and small trucks or vans. Small truck units are typically driven directly from the vehicle engine. Very small units (for vans) may be powered by a DC power from the battery and alternator of the vehicle. Large trucks and trailers are powered by an independent, usually diesel engine, which is integrated inside the unit. In order to eliminate exhaust emissions, most units also include an electrical motor that can drive the compressor from the electricity grid at stops. Power can be transmitted from the engine to the loads either mechanically or electrically. The mechanical solution relies on mechanical coupling between engine and an open drive compressor, while in the electric solution the engine drives a generator which powers a hermetic or semi-hermetic compressor and fan motors. The use of hermetic compressor significantly reduces refrigerant leaks, with obvious benefits.

The refrigerant charges are between several hundred grams and 10 kg, usually less than 6 kg for small and large trucks. Although small truck units have a lower capacity than large truck units, they include refrigerant hoses that connect the unit with the compressor mounted on the engine block. Trailer units may have a typical refrigerant charge around 7.5 kg. Refrigerants typically used are R-404A and HFC-134a, but also R-410A or R-407C.

There is an ongoing effort in the industry to reduce the greenhouse gas emissions. This is being realised through a number of complementary steps, including design changes that would improve the energy efficiency, reduction of the refrigerant charge and the refrigerant leakage rates, use of low-GWP refrigerants, and transition of power supply systems from traditional diesel engines to alternative propulsion systems (hybrid, electric, etc.).

6.2.3 Railcars

On a global scale, refrigerated railcars have become a very scarce type of vehicle used for transport of perishable and frozen product. There is a clear and definite trend to replace the refrigerated railcars with mobile boxes or intermodal refrigerated containers that can be, if railway is to be used, placed on a flat car. In some countries two containers can be transported on one railcar (one on the top of the other). Transport by rail is used mainly for long distances.

It is estimated that there are no more than 20,000 refrigerated railcars used globally (7,000 in the former Soviet Union, 2,000 in China, 7,000 in USA, 2,000 in the European Union and 2000 in the rest of the word). This is roughly one fifth of the global demand for new intermodal refrigerated containers in one year.

A factory in Eastern Germany since 1945 exported nearly 42,000 railcars to the former Soviet Union, and over 12,000 railcars to China and other states in Europe /Kue09/. Today, a company leading the Russian perishables transportation market operates 3,500 refrigerated railcars /Ref09/. In China, production of refrigerated railcars with water ice closed down in 1993, production of mechanically refrigerated railcars closed down in 2003, and the fleet is being gradually phased out. At present, there are about 2,000 cars with 4,000 refrigeration units in operation in Europe. A European network named Interfrigo reported just 285 refrigerated railcars in 2002 /Sch09/. In 1987, Interfrigo used to manage nearly 19,000 railcars of all types. A few railcars may still be operated by individual European railways. In USA it was estimated that the supply of refrigerated rail cars would decrease from about 19,000 in

1980 to about 5,000 by 1990 /Hil80/. According to /All00/, a major railway company managed 5,200 refrigerated railcars, constituting about 70 % of the entire US fleet in 2000.

All mechanically refrigerated railcars in service utilise the vapour compression cycle. In terms of design, the refrigeration systems are similar to those employed in road transport and intermodal containers. The refrigerants used were CFC, HCFC, and HFC for the newest systems. In China, CFC-12 is being replaced by HCFC-22 gradually since 2008. More than ten eutectic plate refrigerated railcars were manufactured in China, however, they did not proceed into serial production.

Not all railcars used for transport of perishable and frozen products are mechanically refrigerated. Many railcars have used water ice to maintain the temperature – they are dependent on ice banks along their routes. Many cars have been only insulated. None of these types have been considered in this section.

6.2.4 Intermodal Containers

The size of intermodal refrigerated containers has been standardised /ISO08/. The weight of the heaviest cargo limited the size of the first containers to about 6 m (20 ft). As most cargo is somewhat lighter, 12 m (40 ft) containers have been developed. 40 ft containers are today used to a greater extent than 20 ft containers. Containers differ also in height, but the difference in height is small compared to the length.

The volume of cargo transported is commonly expressed in terms of Twenty-foot Equivalent Units, or TEU. A 40 ft container equals roughly to 2 TEU, but is refrigerated by a single refrigeration system just like the 20 ft container. The difference in size makes it difficult to estimate the global fleet, because statistics usually describe the total TEU regardless of the container size.

Data of intermodal refrigerated containers is available only for those still being used in ocean traffic. It is not known how many refrigerated containers are still in use on landside applications after they were retired from ocean traffic.

In 2009, there were approximately 150,000 units of 20 ft containers and 800,000 units of 40ft containers in use. The total number of units in operation was thus 950,000 (or 1,750,000 TEU). At the beginning of 2009 /Rev09/, there were 4,638 fully cellular container ships, with a total capacity of 12 million TEU (all cargo, not only refrigerated). Up to 100,000 new refrigerated containers were built annually until the year 2007. This number has dropped as a consequence of the global economic recession in the years following 2007.

The vapour compression cycle has been the only technology used in intermodal refrigerated containers. First systems utilised CFC refrigerants and some HCFC refrigerants, but new systems today utilise only HFC-134a, or HFC blend R-404A (approx. 10-15 %). Four manufacturers dominate the global market.

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 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.

Approximately 60 % of new units are fitted with hermetic scroll compressors offering many advantages including reliability, leakproofness, low weight, small size and low noise. The current technology features reduced refrigerant charges and emissions. The typical refrigerant charge is between 3.8 kg to 5.3 kg per unit with an average of approximately 4.5 kg.

During the last years, there have been strong efforts to reduce the energy consumption of container units in order to reduce fuel consumption and carbon dioxide emissions. The controller reduces the amount of circulated air inside the container thus reducing fan power and consequently compressor power, too. For example, the fans are cycled between half and full speed instead of running continuously on full speed, or they are temporally switched off completely.

Porthole type containers (insulated containers ventilated by chilled air refrigerated centrally) are not in operation any more and no new porthole containers, nor porthole container ships, are built. The last ships that offered refrigeration capacities for porthole containers have been converted for the transport of containers equipped with an integral refrigeration unit.

China became the major producer of insulated marine containers (small productions are remaining in the world; for example in France, two manufacturers are building containers for military or NGO applications. There are three Chinese producers with a maximum annual production capacity of 230,000 TEU.

6.2.5 Small Containers and Boxes

The number of small containers may be equivalent to the number of other equipments in many European countries. On average, they transport a load of up to a few hundred kg. They are refrigerated mainly with solid carbon dioxide, but also with eutectic plates or small absorption or 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. Their use is increasing for direct distribution to the consumer of products bought online. Refrigeration by means of ice slurry in double walls of small containers and boxes is under development.

6.3 Refrigerant Options for Existing Equipment

All new intermodal containers, majority of road vehicles and railcars, and many new merchant and fishing vessels use equipment with HFC refrigerants. HCFC refrigerants have been used in systems aboard vessels, and in older road and rail equipment. To retrofit HCFC refrigerants, only some refrigerant options will find its application in transport due to necessary service infrastructure and commonality of the working fluids.

In road transport, R-408A, containing 47 % HCFC-22, is a retrofit solution for units that are currently using R-502. The retrofit to R-408A often improves system capacity and efficiency, while the compressor head pressure may slightly increase at high ambient environments. It is important that systems operating with R-502 and mineral oils may continue to use mineral oils provided the oil returns adequately to the compressor. If not, alkylbenzene or POE may be added (or used alone) to improve the miscibility and oil return. System components do not require changing when retrofitting.

R-402A, containing 38 % HCFC-22, was used as a retrofit substitute for R-502 in the mid-to-late '90's in the USA, and may be still used in some countries.

Rather than R-408A or R-402A, it may be more suitable for some operators to retrofit with R-404A. Although R-404A behaves much like R-502, several components incl. compressor may need to be replaced due to inferior lubricity of POE lubricant when compared to alkyl benzene, and marginally higher operating pressures of R-404A. Nevertheless, being an HFC blend, R-404A is a longer-term solution than R-408A.

Aboard ships, R-407C and R-404A have been used most often to retrofit HCFC-22 in existing systems. These refrigerants have lower energy efficiency, but efficiency did not seem to be a major concern for many ship owners several years ago. Sometimes, HFC-134a has been used to retrofit HCFC -22 at the expense of losing about 30 % of refrigerating capacity.

No natural refrigerant can be used to retrofit HCFC-22 without remodelling of the entire refrigeration system. Remodelling is often impossible due to existing layout and size of the refrigeration equipment.

6.4 Refrigerant Options for New Equipment

The vapour compression cycle will remain the dominant principle of refrigeration units in transport. HFC refrigerants will remain the preferred refrigerant options. Discussions about use of several new fluorinated refrigerants, such as HFC-1234yf, have recently taken place. These opportunities have not been considered in the present report – they have not been used commercially so far, and so no practical experience is available.

Non-fluorinated refrigerants have received great attention over the last decade, and in several cases operational samples have been tested and presented to the public. However, various technical, legal, financial, logistic, service and other constraints have yet prevented a wider application of these new technologies in practice. Most applications of non-fluorinated refrigerants can be found aboard marine vessels.

Hydrocarbons

Although hydrocarbons are technically feasible and may even outperform HFC systems, flammability makes people concerned about their use /Cor08/. Where they do not exist, standards need to be developed to address the safety concerns.

Effort is being made to reduce the refrigerant charge through indirect systems and compact heat exchangers, outdoor placing of the units, leakage sensors and alarms and forced ventilation /Pal08/. Indirect systems are often penalised with a lower overall efficiency (higher fuel consumption), a greater complexity (reliability and maintenance cost), higher weight (fuel consumption) and larger size (cargo space), if compared with direct expansions systems.

Equipment with charges of hydrocarbons greater than 1 kg is, in general, possible only if all the refrigerant containing parts are placed outdoors or in a special machinery room. Because these requirements cannot be met aboard marine vessels, HC refrigerants are not likely to be used there.

HCs are currently trialled in trucks and home delivery vans in Great Britain and Germany, suggesting that their use may grow.

Carbon dioxide

Carbon dioxide (CO_2, R-744) has the advantage that it is widely available world wide, but it must overcome several challenges before use in transport refrigeration is possible. Under high ambient temperature operation, sophisticated refrigeration cycles (two-stage cycles, work recovery devices, etc.) are necessary to match the system efficiency of equivalent HFC units. The cycle operation is almost always transcritical, which results in compressor discharge pressures up to 7 times higher than those in HFC systems. Therefore, entirely new parts, design approaches, test procedures, service training, etc. are needed to design, build and operate a transcritical R-744 system. The ability of using R-744 for heating in a heat pump cycle can be advantageous due to efficiency and capacity that is possible.

Aboard ships, R-744 has been used in the subcritical state, either as a refrigerant with own compressors (second stage in a cascade), or a secondary coolant being circulated by pumps. It features excellent thermodynamic properties. When used in the second stage, it can cover the temperature range between -10 and -50 °C. HFCs or ammonia is used in the first stage.

R-744 has a low temperature limit of about -54 °C and so it cannot be used, for example, on the Japanese market with requirements for fish freezing at -60 °C. Apart from that, R-744 in the subcritical state is suitable for ships, especially because it is not flammable and does not form aggressive or toxic products in contact with hot surfaces. It was reported /Tec09/ that R-744 systems used in the second stage for freezing of fish and in reefer ships were able to save up to 25 % energy consumption compared to single stage HCFC-22 systems.

No commercial solutions with transcritical CO_2 are sold today in transport refrigeration. At least one manufacturer claims to field test transcritical R-744 units for marine containers in their full operating range. A trailer featuring a transcritical R-744 unit was presented at a recent international trade fair. Therefore, it is possible that commercial solutions will be available within the next few years. Because compressors, heat exchangers and other parts have special requirements in terms of robustness, weight, corrosion resistance, etc., vigorous performance verification must be carried out in order to qualify these systems for commercialisation. In addition, the energy efficiency in the transcritical operation mode has to be improved for hot climate applications.

Ammonia

Toxicity and flammability makes ammonia (NH_3, R-717) a difficult option among alternate refrigerants for road vehicles, railcars and intermodal containers. The situation is different for marine vessels.

From 2001, NH_3 started to be used in large fishing vessels and in reefers in indirect and cascade systems. Meanwhile, classification bodies and authorities have widely ceased from their reservation towards NH_3, in particular if exclusively professional personnel is on board. As for new-built fishing vessels and reefer ships, NH_3 is of higher importance than HFCs today /Tec09/.

The use of NH_3 systems is limited to (1) ships that do not carry passengers but professional crew only (toxicity), and (2) ship with a relatively high refrigeration capacity (fishing vessels > 36 m) because of energy efficiency, safety and space reasons. Therefore, use of HFCs refrigerants will continue on cruise and passenger ships, and in general, on small ships of all categories.

Discontinuous systems

Cryogenic (open-loop) systems have been applied in small and large trucks. In one system, liquid CO_2 or N_2 is stored in an insulated tank and injected to an evaporator via a vapour motor driving a fan. Other systems inject liquid N_2 into the cargo space while displacing O_2. Such systems require complex safety mechanisms and gas extraction equipment to protect operators (risk of asphyxiation). All cryogenic systems require recharging with liquid coolant. On the contrary, they offer low noise, reduced maintenance and outstanding refrigeration performance (fast pull-down), which make them excellent systems for vehicles serving local distribution chains. Two aspects shall be considered in energy analyses: the coolant consumption is proportional to the refrigeration need (diesel engines have always a minimum consumption), but energy is needed to produce the liquid coolants.

Eutectic plates are sometimes utilised in distribution vehicles for short distances. They are based on a frozen salt solution, which, while it melts, removes heat from the environment and provides refrigeration. Low pull down capacity and somewhat inflexible temperature management makes them especially suitable for distribution of deep frozen products. Although they must be regenerated periodically (by freezing in an external mechanical refrigeration system), they offer low noise and require almost no maintenance.

Other systems

Cascade systems for trucks, combining a heat driven adsorption system and a vapour compression cycle are still under development. Other alternatives have also been considered in the road transport, but have not been pursued for numerous reasons. Adsorption and absorption systems are also being evaluated.

6.5 Recovery, Reuse and Destructions of Refrigerants

Handling of used refrigerant includes recovery, recycling, reclamation and destruction. All or any of these steps may be required by national legislation. In many countries, however, such requirements are absent. Although voluntary measures may sometimes be implemented, there will still be an opportunity for improvement in many countries as long as legal or monetary measures (incentives or tax to compensate for recycling, reclamation or destruction cost) will not be in place.

6.6 Bank and Emission Data

The estimates of approximate refrigerant banks and emissions in transport refrigeration are summarised in Tables 6-1 and 6-2 (rounded to 10). The data are based on estimates of the fleet size, refrigerant charge per system, refrigerant share in the fleet, and refrigerant emissions per system, which are presented in Tables 6-3 through 6-5.

Except for marine vessels, the total refrigerant banks do not differ substantially from the data presented in the previous 2006 assessment report. Any difference is caused primarily by variation in partial source data (Tables 6-3 through 6-5). The banks reported for vessels are higher also due to the fact that the scope was expanded to smaller vessels down to 100 GT. The 2006 assessment considered merchant, naval and fishing vessels above 300 GT only.

Table 6-1: Estimate of approximate refrigerant banks (t)

	CFC	HCFC	HFC	R-717	R-744	TOTAL
Merchant, naval and fishing vessels	2500	21900	2730	20	110	27260
Road vehicles	160	4860	14380	0	0	19400
Railcars	20	210	80	0	0	310
Interm. containers	0	210	4060	0	0	4270
TOTAL	2680	27180	21250	20	110	51240

Table 6-2: Estimate of approximate refrigerant emissions (t/y)

	CFC	HCFC	HFC	R-717	R-744	TOTAL
Merchant, naval and fishing vessels	1000	6570	270	0	10	7850
Road vehicles	50	970	1440	0	0	2460
Railcars	0	40	10	0	0	50
Interm. containers	0	40	200	0	0	240
TOTAL	1050	7620	1920	0	10	10600

Table 6-3: Estimate of fleet size and refrigerant charge

Category	System type	Share	Fleet	Refr. charge (kg)
Merchant vessels	Direct	90%	90000	200
	Indirect	10%	10000	50
Naval vessels	Direct	100%	5000	200
	Indirect	0%	0	50
Fishing vessels	Direct	70%	35000	200
	Indirect	30%	15000	50
Small trucks	Belt driven	40%	1600000	2
Large trucks	Independent	30%	1200000	6
Trailers		30%	1200000	7.5
Railcars		100%	20000	15
Interm. containers		100%	950000	4.5

System type: Direct = direct expansion; Indirect = secondary loop

Table 6-4: Estimate of approximate refrigerant share

Category	System type	CFC-11	CFC-12	HCFC-22	R-502	R-408A	HFC-134a	R-404A	R-407C	R-717	R-744
Merchant vessels	Direct	5%	5%	80%			7%	2%	1%		
	Indirect			80%			5%	5%			10%
Naval vessels	Direct			90%			10%				
	Indirect										
Fishing vessels	Direct	5%	5%	80%			6%	2%	1%		
	Indirect			80%			5%	5%		2%	8%
Small trucks	Belt driven		5%				85%	10%			
Large trucks	Independent			20%	5%	5%		70%			
Trailers				20%	5%	5%		70%			
Railcars			5%	70%			5%	20%			
Interm. containers				5%			85%	10%			

System type: Direct = direct expansion; Indirect = secondary loop

Table 6-5: Estimate of approximate refrigerant emissions in % of charge, per year, including leaks, total charge losses due to ruptures, service losses and end of live losses.

Category	**System type**	**CFC-11**	**CFC-12**	**HCFC-22**	**R-502**	**R-408A**	**HFC-134a**	**R-404A**	**R-407C**	**R-717**	**R-744**
Merchant vessels	Direct	40%	40%	30%			10%	10%	10%		
	Indirect			30%				10%			10%
Naval vessels	Direct			30%			10%				
	Indirect										
Fishing vessels	Direct	40%	40%	30%			10%	10%	10%		
	Indirect			30%				10%		5%	10%
Small trucks	Belt driven		30%				10%	10%			
Large trucks	Independent			20%	20%	20%		10%			
Trailers				20%	20%	20%		10%			
Railcars			30%	20%			10%	10%			
Interm. containers				20%			5%	5%			

System type: Direct = direct expansion; Indirect = secondary loop

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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, including reversible air heating heat pumps (generally defined as “reversible heat pumps”) ranging in size from 2.0 kW to 420 kW comprise a vast majority of the air conditioning market (the majority are less than 35 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 /ASH08/. 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 400 kW. Air in the space is drawn over a coil containing evaporating refrigerant. Heat transfer occurs between the air and the circulating refrigerant. With heat pump systems, 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 now contains refrigerant undergoing condensation thereby transferring heat to the air.

In 2008, an estimated 553 million HCFC-22 air conditioners were operating world-wide. Refrigerant charge quantities vary roughly proportional to capacity. These 553 million units represent an installed bank of approximately one million metric-tonnes of HCFC-22.

Nearly all air conditioners manufactured prior to 2000 used HCFC-22. The transition away from HCFC-22 is nearly complete in developed countries. The phase-out of HCFC-22 in the manufacturing of new products in the EU was completed in 2004. The phase-out of HCFC-22 was nearly completed (95%) in the manufacturing of new products in Japan in 2004, with the remainder occurring in 2009. The phase-out of HCFC-22 in new systems in North America was completed in 2009. 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 CO2 equivalent emissions. Some Non-Article 5 countries have begun transitioning to non-ODP alternatives ahead of the Montreal Protocol commitment dates. Approximately 85% of the installed unit population currently uses HCFC-22 and approximately 32% of the units produced globally in 2008 used non-ODP refrigerants. In 2006, HFC demand globally represented approximately 9% of the total refrigerant demand for these categories of products /Sab09/.

7.2 Applications

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 and packaged air conditioners (commercial air cooled) /ASH07/, /ASH08/. In each of these categories, the term “air conditioner” includes systems that directly cool or heat the conditioned air.

7.2.1 Small Self-Contained Air Conditioners

Small Self-Contained (SSC) air conditioners are small capacity air conditioners in which all of the refrigeration system components are contained within a single package. These products have cooling capacities typically ranging from 1.0 kW to 10.5 kW. This category of products includes the following common configurations:

- Window Mounted Room Air Conditioner,
- Through-the Wall Air Conditioner
- Portable Air Conditioner [2]
- Packaged Terminal Air Conditioner (PTAC).

Small self-contained air conditioners are designed to heat or cool single spaces--such as bedrooms or small 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, global product shipment data indicates that 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 /JARN08/, /AHRI08/.

Small self-contained air conditioners range in capacity from less than 1.0 kW to approximately 10.5 kW (having an average size of 2.7 kW). These systems have average refrigerant charge levels of approximately 0.25 kg per kW of cooling capacity. All use hermetic rotary, reciprocating or scroll compressors, with the majority using hermitic rotary compressors.

The majority of small self-contained air conditioners historically have used HCFC-22 refrigerant. As non-ODP refrigerants have been applied to these products-the majority have used HFC blends. A small number units (approximately 100,000 portable units per year) are using hydrocarbons /UNEP05/.

7.2.2 Non-ducted (or duct-free) Split 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 can be applied to commercial buildings, schools, apartments and free-standing residences. Non-ducted split air conditioners include 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 one or more fan-coils located inside the conditioned space. Single splits often position the expansion device also within the condensing/outdoor unit.

Non-ducted products can be sub-divided into two sub-categories: single split and multi-split. With single split products a single indoor fan coil unit is connected to an outdoor condensing unit. Small (less than 7 kW) non-ducted split air conditioners with a single indoor fan-coil are sometimes referred to as split type room air conditioners. In multi-split systems, a single outdoor condensing unit is connected to two or more indoor fan coils.

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[2] 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.

Reversible air conditioners (heat pumps) are gaining market acceptance in 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 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 utilise 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. These products range from residential use up to VRF systems, which are used in large commercial applications.

Variable Refrigerant Flow (VRF) systems are a sub-category of the multi-split non-ducted air conditioning systems. VRF systems are distinguished from regular multi-split systems by their ability to modulate the refrigerant flow in response to the system demand. VRF systems normally consist of a number of indoor air handling units connected to a single outdoor air conditioning unit. 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 simultaneously heat and cool separate indoor spaces. The outdoor unit modulates the total refrigerant flow using various compressor capacity control methodologies. VRF systems have capacities ranging from 10 kW to over 130 kW.

Non-ducted split air conditioners use hermetic rotary, scroll or reciprocating compressors. The vast majority of non-ducted air conditioners manufactured prior to 2000 used HCFC-22 refrigerant. Non-ducted single split air conditioners have average HCFC-22 charge levels of approximately 0.25 to 0.30 kg per kW of cooling capacity. The average charge per kW increases as the operating efficiency of these systems increases due to the increased internal volume as the size of the heat exchangers is increased /ICF06/. Typical refrigerant charge levels for multi-split and VRF systems are 0.30 – 0.70 kg/kW of cooling.

7.2.3 Ducted, Split Residential Air Conditioners

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 throughout the building by the duct system. Capacities range from 5 kW to 17.5 kW (average size 10.9 kW) and each has an average HCFC-22 charge of 0.26 to 0.35 kg per kW of capacity.

As the efficiency level of these products is increased, the average charge per kW typically increases unless design changes are made to reduce the product internal volume; such as smaller diameter heat exchanger tubing /ICF06/. In the United States, the minimum efficiency of residential air conditioners that can be manufactured was increased 30 percent in January 2006, from 10 SEER to 13 SEER. Products meeting the new efficiency standards have charge levels approximately 20 to 40% greater than the products designed to meet the prior minimum efficiency levels due to the increased heat exchanger surface added to meet the new minimum efficiency standard /ICF06/. However, considerable research is being conducted to reduce refrigerant charge levels /Pog08/, /Fer05/. Charge reduction technology will become increasingly important as the industry begins to transition to lower GWP alternatives, some of which are flammable.

7.2.4 Ducted Commercial Split and Packaged Air Conditioners

Ducted commercial air conditioners and heat pumps are manufactured in two forms: split system units which are matched with an indoor air handler and heat exchanger and single packaged units which contain an integral blower and heat exchanger section which is connected to the air distribution system of the commercial structure.

The majority of ducted commercial packaged air conditioners and heat pumps are mounted on the roof of individual offices, shops or restaurants or outside the structure on the ground. 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.

Large commercial structures such as hospitals, exhibition halls or high-rise structures generally utilise chillers to produce chilled water or brine which is used to cool and dehumidify air using liquid-to-air heat exchangers (Chapter 9).

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	Evaporator Location	Condenser Location	Capacity Range (kW)	Charge Range (kg)
Window	Small Self-contained	Self-contained	Inside	Outside	1 – 10.5	0.3 – 3
Portable	Small Self-contained	Self-contained	Inside	Inside	1 – 10.5	0.3 – 3
Through-the-Wall	Small Self-contained	Self-contained	Inside	Outside	1 – 10.5	0.3 – 3
Packaged terminal	Small Self-contained	Self-contained	Inside	Outside	1 – 10.5	0.3 – 3
Split (non-ducted)	Non-ducted Split	Remote	Inside	Outside	2 – 15	0.5 – 5
Split (ducted)	Ducted Split	Remote	Inside	Outside	4 – 17.5	1 – 7
Multi-split	Non-ducted Split	Remote	Inside	Outside	10 – 130	5 – 100
Packaged Rooftop	Ducted Commercial	Self-contained	Outside	Outside	7.0 – 350	5 – 100
Ducted Commercial Split	Ducted Commercial	Remote	Inside	Outside	10.5 – 90	5 – 35

7.3 Current Use of HCFC-22

Estimates of the installed base (number of units) and HCFC-22 inventory were made using computer models documented in prior assessments and other reports /Kel04/, /Clo04/, /Sab09/. Table 7-2 lists the estimated 2008 unit populations and HCFC-22 Refrigerant Banks for each of the product categories covered in this chapter.

Table 7-2: Estimated 2008 Unit Population and HCFC-22 Banks

Product Category	HCFC Units Operating[3] (Million)	HFC Units Operating (Million)	Total Units Operating (Million)	Estimated HCFC-22 Bank[4] (m-tonnes)
Window-mounted and Through-the-Wall (Packaged Terminal) Air Conditioners[4]	116	16	132	84,000
Non-ducted or Duct-free Split Residential and Commercial Air Conditioners	332	62	394	423,000
Ducted, Split Residential Air conditioners and Heat Pumps	85	12	97	309,000
Ducted Commercial Split and Packaged Air Conditioners	20	3	23	223,000
Total	553	93	646	1,039,000

7.3.1 Small Self-Contained Air Conditioners

On a world-wide basis, an estimated 10.5 million HCFC-22 based window-mounted[5] and through-the-wall (packaged terminal) air conditioners were sold in 2008 containing on average for the entire population 0.75 kg of HCFC-22.

With service lives over 10 years, it is estimated that more than 116 million HCFC-22 window-mounted and through-the-wall air conditioners remain in operation globally (Table 7-2). The total 2008 global bank of HCFC-22 in the installed population of window-mounted and through-the-wall air conditioners (including portable air conditioners) is estimated to be 84,000 metric-tonnes.

7.3.2 Non-ducted Split Air Conditioners

An estimated 332 million HCFC-22 non-ducted split air conditioners were operating world-wide in 2008. Non-ducted split air conditioners, ranging in capacity from 2.0 kW to 20 kW (average size of 3.8kW). The total inventory of HCFC-22 in the installed population of duct-free split systems world-wide in 2008 has been estimated to be 423,000 metric-tonnes.

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[3] Unit population includes units manufactured with HCFC refrigerant.
[4] HCFC-22 Bank does not include non-ODS refrigerants, HFC Bank not listed
[4] Window mounted air conditioners are also sometimes installed through a penetration of the outside wall. Packaged Terminal Air Conditioners, PTAC, are similar to Window mounted air conditioners but typically contain some form of electric heat. PTACs are typically installed in hotel and motel rooms.

7.3.3 Ducted, Split Residential Air Conditioners

An estimated 85 million HCFC-22 ducted, split residential air conditioners were in service world-wide in 2008. The majority of these air conditioners are located in United States and Canada. The estimated bank of HCFC-22 in the installed population of ducted residential systems has been estimated to be 309,000 metric-tonnes.

Approximately 56% of ducted, split residential air conditioners manufactured globally in 2008 utilised non-ODS refrigerants. Approximately 12 million of the installed population of 97 million (HCFC-22 and HFC) ducted, split residential air conditioners were manufactured with non-ODP refrigerants; such as R-407C and R-410A.

7.3.4 Ducted Commercial Split and Packaged Air conditioner

An estimated 20 million HCFC-22 air-cooled ducted commercial split and packaged air conditioners and heat pumps were operating world-wide in 2008. Ducted commercial air conditioners and heat pumps range in capacity from about 5 kW to as large as 420 kW. The estimated total worldwide bank of HCFC-22 in the installed base of these systems in 2008 has been estimated to be 223,000 metric-tonnes. Approximately 3 million of these 20 million air-cooled ducted commercial units were manufactured with non-ODP refrigerants.

7.3.5 HCFC-22 Bank

On a mass basis in 2008, HCFC-22 accounted for 85% of the refrigerant bank for these product categories. Table 7-2 summarises the total estimated bank of HCFC-22 used in these product categories.

Since the last assessment, there has been a significant increase in the number of new products in these categories, which utilise non-ODS refrigerants. In North America, HCFC-22 was phased out in new products at the end of 2009. Europe and Japan have also completed the shift to non-ODS refrigerants.

The majority of Article 5 countries are still utilising HCFC-22 to produce these categories of products for their domestic markets. However, China and to a lesser extent India have been producing significant numbers of non-ODS products for export to non-Article 5 country markets.

7.4 Options for New Equipment

7.4.1 Methodology

A survey of current product offerings indicates that the majority of non-ODS products available for the product categories covered in this section are using HFC blends as the predominate refrigerant, with a small number of units using hydrocarbon refrigerants (portable and small split system air conditioning units). While HFC-134a and R-744 are technically feasible options, there has been very limited commercialisation of air-cooled air conditioning products using HFC-134a or R-744.

There are several factors that should be considered when selecting an alternative refrigerant for air conditioning applications. These are:

- Safety,
- Zero ODP,
- Climate Change impact (reduced direct and indirect emissions),
- Performance (Capacity and Efficiency) and,
- Impact on Product Cost.

The selection of a refrigerant for a given application should be a process of selecting an optimum solution considering each of the above criteria. Other than Zero ODP, the rest of the parameters will have to be traded-off against one another to arrive at the optimum solutions for each air conditioning application. In particular the carbon Impact will need to address both the "direct" and "indirect" contribution to the carbon footprint of the product over its life cycle. A number of approaches have been documented in the literature including: TEWI, LCCP, MCII and other methods /Kau08/, /UNE05/, /Riv08/, /Kin08/.

Following is a summary of the most viable HCFC-22 replacement candidates for air-conditioners.

7.4.2 Single Component HFC Refrigerants

Several single component HFC refrigerants have been investigated as replacements for HCFC-22. However, HFC-134a is the only single component HFC that has been commercially used in air conditioning systems.

7.4.2.1 HFC-134a

HFC-134a is the only single component HFC that has been commercially applied in this category of products. HFC-134a is not a *drop-in* replacement for HCFC-22. To achieve the same capacity as an HCFC-22 system, the compressor displacement must be increased approximately 40 percent to compensate for the lower volumetric refrigeration capacity of HFC-134a. 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.

While 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. The predominant use of HFC-134a has been in water chillers and mobile air conditioning applications (Chapters 9 and 10 respectively). Therefore HFC-134a has seen limited application in air-cooled air conditioning applications.

7.4.3 HFC Blends

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. R-407C and R-410A have GWPs near HCFC-22 (Table 2-1).

7.4.3.1 R-407C

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 /Li00i/. As R-407C is zeotropic blend, temperature glide is significant. 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.

There are currently R-407C air conditioning products available in Europe, Japan and other parts of Asia. R-407C has also seen some limited usage in the North America, primarily in commercial applications.

Since R-407C refrigerant 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, over time, many of the R-407C designs have been redesigned with R-410A to achieve size and cost reductions.

7.3.3.2 R-410A

R-410A is a binary blend that can replace HCFC-22 in new equipment production. This blend has a low temperature glide (near azeotropic). The normal boiling point is approximately 10°C lower than HCFC-22, resulting in condensing pressures up to 4000 kPa which is approximately 50-60% higher than HCFC-22. R-410A also has favourable thermophysical properties, which enable the design of units, which are more compact than the HCFC-22 units they replace.

R-410A air conditioners (up to 175 kW) are currently commercially available in the US, Asia and Europe. A significant portion of the duct-free products sold in Japan and Europe now use R-410A as the preferred refrigerant. Approximately 55% of the US Ducted Residential Market in 2008 used R-410A as the refrigerant. The US ducted residential market will predominately utilise R-410A as the HCFC-22 replacement refrigerant after 2009.

System pressures with this blend are approximately 50 percent higher than with HCFC-22. 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.), heat exchangers and refrigerant tubing.

7.4.4 Reduced GWP HFC Refrigerants and Blends

7.4.4.1 HFC-32

HFC-32 is one of the primary constituents of both R-410A and R-407C. HFC-32 is an A2L refrigerant having a GWP (675) approximately 70% less than that of R-410A, which makes it a lower GWP alternative to R-410A. HFC-32 exhibits slightly higher capacity and efficiency than R-410A. Because HFC-32 has an A2L flammability rating, the flammability would need to be mitigated in the design of the product by compliance with an applicable safety standard such as IEC 60335-2-40. R-410A systems should be able to be redesigned for HFC-32 with minor modifications.

HFC-32 is not a drop in for HCFC-22 since its pressure is around 60% higher and its capacity is also approximately 60% greater than HCFC-22 /ASH09/. HCFC-22 systems would require significant redesign including: lower displacement compressors and other changes to the refrigeration system components to address the higher operating pressures; which will be nearly the same changes needed to redesign HCFC-22 equipment to use R-410A.

7.4.4.2 HFC-152a

HFC-152a has performance characteristics similar to HFC-134a. It has similar capacity and efficiency performance to that of HFC-134a. HFC-152a has a much lower GWP than HFC-134a, R-410A or R-407C. HFC-152a has Class 2 flammability according to ISO 817, with a relatively high flame speed. The design of HFC-152a equipment should follow the requirements of relevant safety standards such as IEC 60335-2-40, which require limiting the refrigerant charge or under certain circumstances may necessitate the use of indirect systems.

In addition, significant redesign of existing HCFC-22, R-410A or R-407C systems would be required to utilise HFC-152a. Changes would be required to address not only the flammability of HFC-152a but also its low volumetric refrigeration capacity, which is close to that of HFC-134a. The necessary system design changes are similar to those described for HFC-134a.

It is unlikely that HFC-152a will be commercialised in air conditioning systems because its low density and flammability would result in significantly increased costs relative to an HCFC-22 system.

7.4.4.3 HFC-161

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

7.4.4.4 HFC-1234yf

HFC-1234yf is an unsaturated HFC, which has zero ODP and very low GWP. This refrigerant has been proposed as an alternative to R-134a in automotive AC applications /Min08/. HFC-1234yf is not a *drop-in* replacement for HCFC-22 for air-to-air air conditioning applications. Its thermodynamic performance is similar to R-134a. It has a lower volumetric refrigeration capacity than R-22, R-410A or R-407C and thus requires that compressors using this refrigerant have significantly larger displacements. Experimental studies indicate that HFC-1234yf systems will be 40% larger and more costly than HCFC-22 systems /Fuj10/, /Hid10/. The design changes include larger displacement compressors, increased heat exchanger areas and larger diameter interconnecting tubing. These changes are similar to the changes described for HFC-134a in 7.5.2.1. HFC-1234yf has an A2L flammability rating and would need to be applied using an appropriate safety standard such as IEC-60336-2-40.

Because HFC-1234yf is so similar to HFC-134a it will suffer from the same application cost issues discussed for HFC-134a. It is therefore unlikely that unitary air-conditioners using pure HFC-1234yf will be commercially viable.

7.4.4.5 HFC-1234yf Blends

Refrigerant manufacturers have proposed blending HFC-1234yf with other non-ODP refrigerants in order to more closely match the performance of the refrigerants currently being used in these products /Min08/, /Spa10/. Most of these blends contain one or more other HFC refrigerants and exhibit various levels of glide and in some cases flammability depending on the blend composition. These blends can be formulated to have performance characteristics similar to HCFC-22 or R-410A while having much lower GWPs.

7.4.4.6 Lubricants for HFC Systems

The naphthenic mineral-oil-based and alkyl benzene lubricants commonly used in HCFC-22 systems are not miscible with HFC refrigerants. Considerable field experience has resulted in the commercial availability of a number of synthetic lubricants for HFC systems. The two primary lubricants being used in HFC systems are:

1. Polyolester (POE) Lubricants (Synthetic), and
2. Polyvinylether Lubricants (PVE) (Synthetic).

Of these, POE is the most widely used lubricant in HFC refrigerant applications. The selection of the lubricant to be used with a particular HFC is generally made by the compressor manufacturer whom makes the selection after extensive material compatibility and reliability testing.

7.4.5 Hydrocarbon Refrigerants

Hydrocarbon systems are commercially available in a number of low charge air conditioning applications, such as small split, window and portable air conditioners. HC-290 is the most frequently used hydrocarbon refrigerant in air conditioning applications. When used to replace HCFC-22, HC-290 has performance characteristics which yield slightly better performance than HCFC-22 /Dev05i/, /ART01/. Compared to HFCs, hydrocarbon refrigerants have: reduced charge levels (approximately 0.05 - 0.15 kg/kW of cooling capacity), miscibility with mineral oils (synthetic lubricants are not required), reduced compressor discharge temperatures, and improved heat transfer due to favourable thermo-physical properties /Col99/.

The factor that works against the safe application of HC-290 in air conditioning systems is its high flammability, which creates significant safety concerns in application, installation and field service. European and international standards limit the quantity of HC-290 that can be used in a system. IEC-60335-2-40 provides criteria used to determine the maximum allowable charge in a specific application. Section 7.4.7 provides a brief discussion of the methodology used by IEC-60335-2-40 along with examples of the charge limits for typical applications. Charge reduction technologies can reduce the refrigerant charge of hydrocarbon systems; which can increase the range of unit capacities which can use hydrocarbon or any flammable refrigerant.

Risk analyses on the use of hydrocarbons in air conditioners suggest that provided the requirements of safety standards are met, the risk of ignition during normal operation is extremely low /Col04/. 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 consumers and service technicians to the additional risks associated with highly flammable refrigerants.

Another factor that must be considered with flammable refrigerants will be refrigerant reclaim and recovery requirements. Even though hydrocarbon refrigerants have minimal environmental impacts, there may still be a need to recover the refrigerant 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.

The ultimate decision on whether hydrocarbon refrigerants are practical in air conditioning products will be determined by safety standards, local codes and whether the added costs of safety mitigation result in products more costly than those that can be developed using other non-ODS options.

7.4.5.1 Lubricants for Hydrocarbon Refrigerants

A number of researchers and practical experience with hydrocarbon refrigerators confirm that hydrocarbon refrigerants can utilise mineral oil based lubricants /Col99ii/, /Bit04/. Compressor manufacturers' catalogue data indicates that both mineral oil based and POE lubricants are being used in compressors designed for hydrocarbon applications.

7.4.6 R-744

R-744 offers a number of desirable properties as a refrigerant: ready availability, low-toxicity, low GWP and low cost. However, because of the low practical exposure limit of R-744, it needs to be applied using applicable safety standards. R-744 has a low critical point 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; particularly in high ambient climates which could result in higher system costs /Elb08/, /Haf08/, /Joh08/. R-744 air conditioning systems typically operate above the critical temperature of R-744 during heat rejection. Because of this, R-744 systems utilise gas coolers rather than condensers.

R-744 air conditioners operating in warmer climates (design temperatures greater than 30 °C) are likely to have efficiencies 10-15% below best in class HFC based designs /ART03a/. 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, liquid injection, the addition of oil separators, the use of refrigerant ejectors or expanders, various inter-cycle heat exchangers, and cross-counter-flow heat exchangers, which take advantage of the favourable thermophysical properties of R-744 /Xie08/, /Wan08/, /Koy08/, Liu08/, /Peu08/, /Kas08/. 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 as high as 14,000 kPa with a mean system pressure near 5,000 kPa /Ibr03/. The required hydrostatic burst strength of systems operating at these high pressures would have to be approximately 30,000 kPa /Bos08/. 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 combined with significantly increased wall thickness are also necessary to address the high operating pressures of R-744. Design changes required to address the burst pressure requirements of R-744 systems will 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 have been introduced into the market in very limited quantities. R-744 VRF products have been introduced in the European market. 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 improve the capacity, efficiency and reduce the peak electrical power requirements during the cooling mode in high ambient conditions /Jak07/.

7.4.6.1 Lubricants for R-744 Systems

The solubility of R-744 in lubricant is relatively high at the crankcase operating pressures of R-744 compressors /Cas01/. The knowledge base of information on lubricant compatibility in R-744 refrigeration systems is expanding as more researchers conduct studies of R-744 compressors /Hub02/, /Li00ii/, /You03/, /Mul08/. Some of the lubricants being considered for R-744 systems are POEs, PAO, and naphthenic mineral oil or alkyl benzene lubricants /You03/, /See06/. 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 /Mue08/.

7.4.7 Flammability Considerations

When designing systems using flammable refrigerants the designer will need to meet the requirements of applicable safety standards. An example of such a standard is IEC-60335-2-40 /IEC06/. This standard specifies construction requirements, charge limits, ventilation requirements and requirements for secondary refrigerant circuits.

This standard uses the lower flammability limit, LFL, and the specifics of the application (location of equipment, the ventilation of the unit, the volume of the installed space and whether or not the space containing the unit is ventilated) to determine the maximum charge level, ventilation requirements and whether or not a secondary refrigerant circuit is required. Table 7.3 presents an example of the maximum allowable refrigerant charge determined by IEC-60335-3-40 for both a ventilated and unventilated space with all or part of the system installed in the indoor space. The maximum charge for other refrigerants and application conditions can be easily calculated using the equations in Annex GG of the standard.

Table 7-3: Example of Maximum Refrigerant Charge per IEC-60335-2-40, (kg)

Refrigerant	Ventilated Space	Unventilated Space[6]
R-290	1.0	0.3
R-32	8.0	4.0
R-161	2.0	0.7

7.4.8 Not-in-Kind Alternative Technologies

In past assessments, 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 prior assessment has continued to confirm that most of these technologies have not progressed much closer to commercial viability for air-cooled air conditioning applications than they were at the time of the 1990 assessment and three subsequent assessments. While these alternative cycles are feasible they have thus far not been proven to be economically viable. Therefore, it is unlikely that they will significantly penetrate these markets, other than potential niche applications (such as localities where electricity is unavailable), during the next decade. Alternative cycle technologies will therefore have a minimal impact on the HCFC-22 phase-out in both developed and developing countries.

However there are some mature proven alternative technologies, which can provide non-ODP options for some regions and applications. For example, *Evaporative Cooling* technology could provide a very low cost and energy efficient alternative or supplement to vapour compression refrigeration in hot arid climates /ASH07/.

[6] Assumes 15 m^2 floor area with unit mounted 1.8 m above the floor

7.5 Options for Existing Equipment

After the HCFC phase-out occurs in Non-Article 5 or Article 5 countries there will still be a need to service the installed population of products until the end of their useful lives. Servicing of these products can fall into three categories:

1. *Service* field repair
2. *Drop-in Refrigerant* field repair
3. *Retrofit* field repair

All three repair methods will 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 Small Volume Consuming (SVC) countries, which import rather than manufacture air-conditioners. Therefore most of the HCFC consumption in these countries 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. A third less desirable option because of cost, would be to replace the existing equipment before the end of its useful life. The availability of service refrigerants and retrofit options will be very important for these SVC countries during this period.

In Non-Article 5 countries, unit replacement is more common because the costs associated with performing a major repair or retrofit can often be greater than the cost to replace the product.

Service field repair is any repair that can follow normal service practices using new, recycled or reclaimed refrigerant.

Drop-in refrigerant field repair replaces the HCFC-22 with one of the available service blends, without changing the lubricant used in the original equipment. Refrigerants meeting these requirements are sometimes referred to as *Service Fluids or Blends*. In cases where the *drop-in refrigerant* results in a significantly lower capacity or efficiency than HCFC-22, the *retrofit* approach will be more appropriate.

Retrofit field repair techniques range from simply changing the refrigerant, lubricant and filter dryer (if required) to 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. Any refrigerant and lubricant removed from the system should be disposed of in an environmentally responsible manner, in accordance with applicable environmental regulations. Retrofit field repair can be substantially more costly than *service* or *drop-in* repairs or even unit replacement. Refrigerants that require lubricant changes or system component changes are often described as *retrofit* refrigerants. *Retrofit* refrigerants will probably not be cost effective if either the compressor or heat exchangers must be replaced.

In the case of *retrofit* or *drop-in* replacement in HCFC-22 systems, the global warming impact of the replacement refrigerant should also be given consideration.

7.5.1 Service Blend Refrigerants

There are several *Service Blends* currently being introduced to replace HCFC-22 for servicing. These refrigerants are primarily being promoted as a *drop-in* and *retrofit* refrigerants for HCFC-22 in air conditioning applications. They generally combine two or more HFC refrigerants with a small amount of hydrocarbon refrigerant. The hydrocarbon refrigerant is 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. The S*ervice Blend* refrigerants attempt to mimic the performance of HCFC-22. However, these refrigerants generally do not perform as well as HCFC-22; having either lower capacity, efficiency or both in drop-in applications. A sampling of the many commercially available HCFC-22 *Drop In Refrigerant* blends are: R-422D, R-438A, R-424A and R-417A (Chapter 2). Information on the application of these blends can be obtained from their manufacturers.

7.5.2 Retrofit Refrigerants

R-407C has been demonstrated to be an acceptable retrofit refrigerant for HCFC-22 systems. It has seen widespread use as a retrofit refrigerant in some locations with some loss in capacity and efficiency. Its performance is very similar to HCFC-22 but it does require that the existing naphthenic mineral oil or alkyl benzene synthetic oil lubricant be replaced. R-407C compatible filter driers should be installed on HCFC-22 systems retrofitted to R-407C. 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 moderated glide, laboratory and field experience with R-407C systems indicates R-407C systems can be serviced without replacing the entire refrigerant charge with minimal impact on performance.

7.5.3 Anticipated Market Impact of *Drop-in* and R*etrofit* Refrigerants

The need for, and market impact of, *drop-in* and *retrofit* refrigerants will largely be determined by the size of the installed population of HCFC-22 products, HCFC phase-out schedule, allowed *service tail,* the availability of service HCFC-22 and the recovery and reclaim practices in place leading up to the phase-out. 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. It is anticipated that *service* (reclaimed or recycled HCFC-22), *retrofit* and *drop-in* refrigerants will be important for Article 5 countries, because of the limited capital available to manufacture new non-ODS systems and the longer useful lifetimes which are the result of the common practice of servicing rather than replacing a product when major failures occur.

The installed population of air conditioners and heat pumps has an average service life in non-Article 5 countries of 15 to 20 years. The average useful life of these products in Article 5 countries may be longer. Therefore, implementing recovery and reclaim programs coupled with the availability of *drop-in* and *retrofit* refrigerants could help reduce the demand for HCFC-22.

7.5.4 Hydrocarbons as Conversion/*Drop-in* Refrigerants

It has been reported that HC-290, HC-1270 and HC-290/HC-170 blends have been used as conversion/*drop-in* replacements for HCFC-22 in some locations. While these refrigerants may provide capacity and efficiency close to HCFC-22, this practice creates a significant safety concern because of the high flammability of these refrigerants. If hydrocarbons are being considered; all relevant safety standards and codes-of-practice should be strictly followed. The GTZ Handbook for HC Safety is one source of information on the utilisation of HC refrigerants /GTZ10/.

7.6 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 (above 40 °C). 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. Currently, the most widely applied replacements for HCFC-22 in unitary air conditioning applications are HFC blends, primarily R-410A and R-407C. Hydrocarbons are also being used in some low refrigerant-charge applications. This material summarises the information in: Decision XIX/8: Alternatives to HCFCs at High Ambient Temperatures /UNE10/.

R-410A and R-407C both have lower critical temperatures than R-22. This occurs because HFC-125 (a component of both R-407C and R-410A) has a comparatively low critical point temperature of 66.0°C (150 °F). The critical point temperature is important because refrigerants having a low critical point temperature will exhibit a steeper decline in capacity with increased ambient (outdoor) temperatures than refrigerants having higher critical point temperatures. This steeper decline in capacity is of particular importance in geographic regions, which have cooling design temperatures approaching the critical point temperature of the refrigerant.

7.6.1 R-410A in High Ambient Applications

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) as shown in Table 7.4 /UNE10/.

Table 7-4: High Ambient Performance Relative to HCFC-22, %

Refrigerant	Condensing Temperature (°C)			
	40	**50**	**60**	**65**
HCFC-22	100	100	100	100
HFC-32	100	100	99	98
HFC-134a	100	99	97	96
HC-290	100	98	96	95
R-407C	100	97	94	92
R-410A	100	97	93	90
HC-600a	100	100	99	97

Units designed for equal capacity at 40 °C

The optimum selection of compressor, airflow, condenser design and expansion device can reduce the performance losses at high ambient temperatures /Bat04/. Even with optimised designs, when applying R-410A 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 following rule of thumb should be sufficient in estimating the cost impact.

7.6.2 HC-290 in High Ambient Applications

HC-290 has performance characteristics similar to HCFC-22. 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 /Dev09a/. HC-290 shows a 5 percent reduction in capacity at 65 °C, Table 7-4.

IEC standard 60335-2-40 has established the criteria for determining the maximum charge limit for highly flammable refrigerant applications. This standard also establishes mechanical and electrical design requirements and maximum charge limitations for flammable refrigerants. Safely and cost effectively applying hydrocarbons to larger unitary systems will be a significant technical challenge.

7.6.3 R-407C in High Ambient Applications

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 65 °C (Table 7-4). Since R-407C refrigerant requires only modest modifications to existing HCFC-22 systems, it has also been used as a transitional refrigerant in equipment originally designed for HCFC-22.

There are currently R-407C air conditioning products widely available in Europe, Japan and other parts of Asia.

7.6.4 HFC-32 in High Ambient Applications

HFC-32 is being considered as an alternative to R-410A. HFC-32 will have higher efficiency and capacity at high ambient temperatures. HFC-32 will have a capacity approximately 2 percent less than an HCFC-22 system at 65 °C condensing temperature (Table 7-4). HFC-32 is likely to become a longer-term replacement for R-410A. It has a GWP approximately 32% that of R-410A and exhibits much better high ambient performance than R-410A. However, it has an A2L flammability, which will need to be addressed in the design and application of the product using appropriate safety standards. The design changes required to convert from R-410A to HFC-32 should be straightforward. While HFC-32 systems are currently under development, none are currently available in the market.

7.6.5 HFC-134a and HC-600a in High Ambient Applications

HFC-134a and HC-600a would seem attractive from the point of view that they have similar performance to HCFC-22 at high ambient temperatures. However, both of these refrigerants are low-pressure refrigerants. Therefore, extensive redesign of the base system components would be required in order to achieve the same capacity and efficiency of the HCFC-22 system. Design changes would include larger displacement compressors, increased heat exchanger areas and increases in the piping sizes used in heat exchangers and inter-connecting tubing. All of these changes would lead to substantial increases in the product cost. In addition, additional design changes would be required with HC-600a to address the high flammability of this refrigerant. Therefore, HFC-134a and HC-600a are not considered the most viable options to replace HCFC-22 in unitary air-conditioning applications.

7.6.6 R-744 in High Ambient Applications

R-744 offers a number of desirable properties as a refrigerant: readily available, low GWP and low cost. These desirable characteristics are offset by the fact that R-744 has a very low critical temperature (31°C) and will operate above 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).

7.6.7 HFC Replacements for High Ambient Applications

Alternatives to HFC refrigerants for air-conditioning applications are in the early stages of development. A number of new refrigerants are being investigated to replace R-407C and R-410A, including HFC-1234yf and blends of other HFC refrigerants with HFC-1234yf. While refrigerant manufacturers are believed to be working to qualify other chemicals or blends that might be new, their development has not progressed to the point where they are available to unitary equipment manufacturers for evaluation and equipment development. Therefore, it is premature to recommend alternatives to R-410A or R-407C at this early stage of the development other than HC-290, which may be applicable in low charge applications when appropriate safety and application requirements are considered.

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Chapter 8

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 renewable energy sources, such as ambient heat, water or ground-source heat. Most commonly, the source is air-, water-, or ground heat. The sink can be air or water. This chapter covers only systems where water is the sink. The products for industrial process heating are covered in chapter 5 "*Industrial systems*". Air-to-air heat pumps are the most widely used heat pumps. Their construction and refrigerant use is similar to air conditioners; therefore they are covered in chapter 7 "*Air-to-air air conditioners and heat pumps*".

The difference between the temperature of source and sink (called "lift" or "head") sets the basic pressure rise condition the compressor must meet. The compression energy is a fraction of the total useful energy delivered. The power consumption of the heat pumps is dictated by the heating capacity required of the heat pumps, the lift, and compressor/driver efficiency. The heated water pumping power, and fan power must be included to determine the power consumption of the total heat pump system. In general, heat pump systems will be less efficient under higher lift condition.

Heat pumps are in many applications an alternative to fossil fuel gas or oil combustion boilers, often resulting in a significant reduction in CO2 emission and primary energy consumption.

Air-to-water heat pumps have experienced significant growth in Japan, Europe, China, and Australia during the last five years. In Japan and Europe, this significant growth has been enhanced by government incentive policies encouraging the development and sale of products utilising renewable energy sources /JRA09a/. According to estimates from a leading trade publication in Japan, more than 1 million air-to-water heat pumps were sold world-wide in 2008 /JARN09/. This total can be broken down as 500k in Japan, 300k in Europe, 190k in China, and 10k in USA and Australia /JARN09/. The USA also uses large quantities of water-loop heat pumps in commercial and institutional buildings, with heat addition and removal to the loop as needed seasonally and even diurnally.

8.2 Types of Heat Pumps

Heat pumps are classified by heat source (air, water, and ground) and heat sink (air, water), resulting in the following naming of heat pumps in table 8-1 used in this chapter.

Table8-1 Heat pump classification

<table>
<tr><td colspan="3" rowspan="2"></td><td colspan="3">Heat source (direct expansion or indirect expansion system)</td></tr>
<tr><td>Air</td><td>Water</td><td>Ground</td></tr>
<tr><td rowspan="4">Heat sink</td><td colspan="2">Air</td><td>Air to air</td><td>Water to air</td><td>Ground to air</td></tr>
<tr><td rowspan="3">Water</td><td>Water heater</td><td rowspan="3">Air to water</td><td rowspan="3">Water to water</td><td rowspan="3">Ground to water</td></tr>
<tr><td>Space heating</td></tr>
<tr><td>Combined</td></tr>
</table>

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 used in fewer cases.

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

8.2.1 Heat Pump Water Heaters (HPWH)

Heat pump water heater (HPWH) are a category of heat pumps designed to heat domestic and other service hot water to temperatures between 55 and 90 °C. These operating temperatures must be considered when selecting the refrigerant.
A HPWH 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 and then returned to the storage tank. 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, 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 /Cal84, Koy08/.
In order to obtain high water temperatures at low outdoor ambient temperatures, air to water heat pump systems can utilise a cascade refrigerating system with two different refrigerants.

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

A space heating heat pump using warm 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. In the heat pump unit, the basic components of a heat pump space heating system are a compressor driven by an electric motor, condenser or gas cooler for warming up water, an evaporator, refrigerant, a refrigerant expansion device, and a control unit.

Ground and water source heat pumps are also used for space heating, but they represent a small segment of the total heat pump market.

8.2.3 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 to optimise the seasonal energy efficiency. In most configurations a water storage tank is used to store the domestic hot water and to also act as a short heat buffer for the space heating function.

8.2.4 Capacity Ranges of Water and Space Heating Heat Pumps

Table 8-2 lists the 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

8.3 Heat Pump Implications and Trends

8.3.1 Trends of Heat Pumps Replacing From Gas or Fuel Burning System

Most of the space heating systems and water heating systems globally use fossil fuels. Since fossil fuel burning systems generate CO2 during combustion, they contribute to global warming. Heat pumps also contribute to global warming but in a different way. Heat pumps transfer heat from lower temperature source to a high temperature sink. The contribution to global warming is only related to CO2 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 for heat pumps. Efficient heat pumps can reduce global warming impact compared with fossil fuel burning systems significantly. 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 year by year. Also the efficiency levels of heat pumps are improving year by year. However, heat pumps tend to be higher in cost than fossil fuel systems because they employ complicated refrigerant circuits, 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.

However, government support programmes in Europe and Japan to promote heat pump systems have resulted in rapid growth of heat pump system sales in recent years.

In Europe around 40 % of all primary energy is used in buildings from which nearly 75% is used for space and domestic hot water heating. Energy use accounts for nearly 80% of all CO_2 equivalent emissions /EHPA09/. In Europe, heat pumps are expected as the best available technology for space heating. It contributes to reduction in both primary energy use and CO_2 emissions. Some believe that there will be a rapid increase of heat pump applications in

Europe. In Sweden more than 75 % of all new building heating systems now are installing heat pumps /EHPA09/.

As a result of recent technology developments, 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 energy efficiency benefits. The positive environmental aspects and potential market growth of heat pumps must be taken into account when refrigerant options and limitations are considered. Compared to 2008 figures the heat pump market in Europe is expected to double by 2015 and to grow by 7 times by 2030. The total installed equipment in Europe will, compared to 2008, become 3 times in 2015 and 16 times in 2030 /EHPA09/.

Predicated on the new efficiency standards and analyses used in development of these 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 /Amr10/.

8.3.2 CO_2 Heat Pump Water Heaters

Heat pump water heater using R-744 refrigerant have become very popular in recent years in Japan under the trade name “Eco-cute” and are also introduced in Europe. These R-744 heat pump water heaters were launched in 2001. From 2001 till October 2009 a total of 2.0 million units have been sold in Japan, with annual sales of 500,000 units in 2008. Target for 2020 is 10 million units /JRA09a, JRA09b/

This growth is the result of; its relative high efficiency for heating water up to 90 °C (without supplementary heater), a very low night tariff for electricity, and government incentives, in the capacity range up to 12 kW. The Japanese have a culture of daily hot bathing. This results in a significant demand for hot water. To satisfy this large demand within a limited time (at late night when electrical tariffs are lower) and with limited storage tank capacity, a water temperature of approximately 90 °C is required. R-744 as refrigerant performs very well at conditions requiring a large temperature difference of the water to be heated. Therefore, R-744 is ideally suited for small tank storage type heat pump water heaters. The “Eco-Cute” performance has been improved by using existing and new technologies such as counter flow heat exchanger to achieve high temperatures by utilising the large temperature glide of R-744, variable speed compressor, internal heat exchanger and ejector to improve efficiency /Koy08/.

Recently, 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.

HPWHs for commercial use with R-744 are produced by several manufacturers inside and outside Japan.

8.4 Current Refrigerant Options for Water and Space Heating Heat Pumps

Dedicated heat pump water heaters (HPWHs) - uniquely for domestic and other service water heating - were first introduced commercially in the 1950’s in the USA, but production was halted. Interest re-kindled in the mid-1970s after the first OPEC Oil Embargo, and there were at least 17 manufacturers by the early 1980s with more than 23,000 units in use in the USA /Cal84/. Most employed HCFC-22 as the refrigerant.

Interest in the technology again dwindled primarily due to higher equipment costs, though studies showed good performance and energy savings averaging 48% /Cal84, Dob84/.

Commercial interest in the USA 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 /Amr10/.

Space heating heat pumps have been developed (mainly in Europe) as a replacement for fossil fuel burning systems or direct resistive space heating systems. Space heating heat pumps are designed to supply water at different temperatures depending on the type of indoor heat, emitter such as radiators for high or moderate temperature water, fan coils for moderate temperature water or under floor heating for low temperature water.

High and moderate temperature space heating heat pumps were offered with HCFC-22 as refrigerant. With the implementation of the Montreal Protocol, HFC blends R-410A and R-407C have been used as alternatives for HCFC-22, mainly in Europe.

8.4.1 HCFC-22

HCFC-22 is an ODS which has a high global warming potential. HCFC-22 has favourable thermodynamic properties and high efficiency in these applications. Therefore, HCFC-22 is being used for high and moderate temperature water and space heating heat pumps in the A5 countries mainly in China.

8.4.2 HFC-134a and HFC blends R-407C and R-410A

HFC-134a and HFC blends R-407C and R-410A are non-ODS and have GWPs in the same range as HCFC-22. 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. R-134a and R-410A also are used in Japan, 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. R-410A has been used primarily for new products, because design changes are necessary to address its higher operating pressures and higher density and to take advantage of its higher performance.

Recently, cascade heat pumps using HFC-134a and R-410A have been 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 resistive heaters.

The heat pump can supply water at temperatures approaching 80 ºC.

8.4.3 Hydrocarbons

Hydrocarbons HC-290 and HC-600a are non-ODS refrigerant with a very low GWP, but these refrigerants have high flammability classified as an A3 refrigerant under ASHRAE standard 34. HC-290 has refrigerant properties similar to those of HCFC-22. Today, HC-290 and HC-600a are used in a limited number of high and moderate temperature space heating heat pumps in Europe. Until 2004 almost half of the heat pumps sold in the EU used HC-290. Use in Europe has declined due to introduction of the Pressure Equipment Directive /Pal08/.

8.4.4 R-744 (Carbon Dioxide)

R-744 is a non-ODS refrigerant with a very low GWP. Development of R-744 heat pumps started around 1990 /Nek98/. R-744 heat pump water heaters were introduced to the market in

Japan 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 HFC-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. It can achieve high efficiency when heating water to a high temperature (90 °C). However, R-744 has not been used much in space heating because space heating heat pumps do not need to operate at such high temperatures. Compared to HFC refrigerants many design modifications are required to get equivalent performance with R-744 for space heating alone /Nek10/.

The market for heat pump water heaters in Japan is steady growing at a rate of about 10 to 20% per year. This is because of the high efficiency when requiring high temperature water, such as 90 ºC.

Support from government enhancing programs is also an important element. Recently, some water heating heat pumps using R-744 also have been introduced in the European market.

Although the current market for space heating heat pumps for commercial buildings with combined radiator and air heating systems is limited, R-744 is consider to be a promising refrigerant /Nek02/.

8.4.5 R-717 (Ammonia)

R-717 is a non-ODS refrigerant and has a very low GWP, but it has higher toxicity and lower flammability characteristics. R-717 is used mainly for large capacity systems. It has also been used in a small number of reversible heat pumps.

8.4.6 Refrigerant Charge Levels

Table 8-3 below shows approximate charge levels for HPWHs and space heating heat pumps with 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, etc.

Table 8-3: HPWH and space heating heat pumps refrigerants and average charge levels

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 Future Refrigerant Options for New Heat Pumps

When selecting alternative refrigerants, both the direct and indirect climate impacts must be considered. The direct effects to be taken into account are ozone depletion and global warming performance resulting from refrigerant emissions. Indirect climate effects that must be taken into account are the carbon emissions resulting from the generation of the electric

power required to operate the equipment. These should be evaluated over its lifetime. For heat pumps, the reduction in emission resulting from replacing fossil fuel burning may be the most important factor regarding greenhouse gas emissions. The Life-Cycle Climate Performance (LCCP) method can be applied /UNE05/ to evaluate the combined effects. Also properties such as toxicity, flammability, thermo-physical properties, chemical stability, aquatic toxicity of decomposition product, pressure and density must be taken into account.
Future refrigerant options for new heat pumps include current options R-410A, HFC-134a, HC-290, HC-600a, R-744, R-717, as well as HFC-32 and new refrigerants.

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.

8.5.1 HFC-134a and HFC Blends R-407C and R-410A

Most new heat pump products are using the refrigerant R-410A because it results in more compact and efficient systems when they are optimised. The transition away from HCFC-22 to R-407C and R-410A in heat pumps is well underway in developed countries. The transition is just beginning in Article 5 countries, which have later phase-out dates for HCFC-22. But, still much HCFC-22 refrigerant is used in these countries.

Recently air to water split cascade systems are put on the market using R410A 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 resistive heaters. They are most useful for combined space and hot water heating to replace existing boiler systems.

8.5.2 HFC-32

HFC-32 is a non-ODS refrigerant. It is one of the primary constituents of R-410A. It has a lower GWP than HCFC-22 or R-410A, approximately one third of HCFC-22 and R-410A. In addition, HFC-32 has a higher operating efficiency than HCFC-22 and R-410A /Shi01/. 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 R22 and 37% less than for R410A while the energy efficiency is the same or higher/YAJ01/. It has low flammability with a low burning velocity.

8.5.3 HFC-1234yf and Other Low-GWP HFC Blends

HFC-1234yf is a non-ODS and is similar in thermophysical properties to HFC-134a, but has a very low GWP of about 4 /Min08/. 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 interconnecting and heat exchanger tubing and additional heat exchanger surface to offset lower heat transfer. 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 the high temperatures typical for heat pump water heaters. HFC-1234yf has a low flammability with a low burning velocity.
A number of other unsaturated chemicals are being identified in the patent literature as possible low-GWP refrigerants for heat pumps. Blends with R-32 or R-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 in heat pump systems.

8.5.4 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 /Fer08/. After water heating heat pumps were introduced in Japan in 2001, their market in Japan has experienced a steady growth of around 30% per year with help from a government enhancement programme /JRA09a/. R-744 as refrigerant enables high efficiency domestic water heating up to temperatures as high as 90 ºC without use of an auxiliary resistive 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 /Ste08/. 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. Continued growth of market is expected in Japan. In addition, it is expected that these products may experience market success in other countries.

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 /Nek10/. However, recently, R-744 heat pumps have been developed in Europe for use in cold climates if combined with very high temperature radiator type space heating are used. For commercial buildings with combined radiator and air heating systems, R-744 is a very promising refrigerant /Nek02/. 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 and its Life Cycle Climate Performance.

8.5.5 Hydrocarbons

At present HC-290 is sold in a relative 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. In these applications larger capacity systems can be used with hydrocarbons.

8.5.6 R-717 (Ammonia)

Ammonia is used mainly for large capacity systems. It has also been used in a small number of reversible heat pumps. It is not expected to be used in small capacity water and space heating heat pumps, because of the cost that makes it not viable as well the possibility to make so small systems due to the unavailability of hermetic compressor for ammonia and incompatibility with copper.

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Chapter 9

Chillers

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9 Chillers

9.1 Function of Chillers

Comfort air conditioning in large commercial buildings and building complexes (including hotels, offices, hospitals, universities, and other central systems) is commonly provided by chillers. Chillers cool water or other heat transfer fluid (such as a water-antifreeze mixture) that is pumped through heat exchangers in air handlers or fan-coil units for cooling and dehumidifying the air. Chillers also are used for process cooling in commercial and industrial facilities such as data processing and communication centers, electronics fabrication, precision machining, and moulding. District cooling is another application that provides air conditioning to multiple buildings through a large chilled water distribution system, as opposed to air conditioning each building with separate systems. Chiller operation is driven by cooling requirements but provision for heat recovery may be included.

9.2 Types of Chillers

Two types of chillers are available – mechanical vapour-compression chillers and absorption chillers.

9.2.1 Mechanical Vapour-Compression Chillers

The principal components of a vapour-compression chiller are one or more compressors driven by electric motors (or less commonly, engines or turbines using open drive compressors), a liquid cooler (evaporator), a condenser, a refrigerant, a lubrication system, a refrigerant expansion and flow control device, a power handling device (commonly a starter or variable speed electronic drive), and a control and protection unit. The complete chiller usually is factory assembled and tested; no connection between refrigerant-containing parts is required on site by the installer except for very large chillers which may be shipped as multiple assemblies. Installation is accomplished by connection to water, power, and control systems.

Vapour-compression chillers are identified by the type of compressor they employ; centrifugal or positive displacement compressors. The positive displacement category includes reciprocating piston, screw, and scroll compressors. Chillers can be further divided according to their condenser heat exchanger type, the most common being water-cooled or air-cooled. Less common are evaporatively-cooled condensers and dry coolers.

Water-cooled chillers generally employ cooling towers for heat rejection from the system. In some cases, the condenser cooling water may come from surface water such as lakes, rivers, or groundwater. Dry coolers function like cooling towers but water is not employed on the external heat transfer surfaces. Air-cooled chillers are factory-equipped with refrigerant-to-air condenser coils and fans to reject heat to the atmosphere.

For evaporatively-cooled condensers, heat from the condensing refrigerant is rejected to the air in a coil that is continually wetted on the outside by a recirculating water system. Air is directed over the coil causing a small portion of the water to evaporate to help cool the coil. There is no circulation of water from the condenser to the chiller. Most of these chillers are supplied without the condenser which is added in the field. This requires refrigerant piping at the installation site.

The different methods of heat rejection can be associated with differences in initial cost, installation cost, maintenance requirements, and the saturated condensing temperature created in the refrigerant circuit. The condensing temperature is driven by weather – the dry bulb and/or wet bulb temperatures. The difference between saturated condensing temperature and the saturated evaporator temperature (called "lift" or "head") sets the basic pressure rise condition the compressor must meet. The power consumption of the chiller is dictated by the cooling capacity required of the chiller, the lift imposed by the weather (or heat recovery condition), and compressor/driver efficiency. The chilled water pumping power, cooling tower water pumping power (water cooled chillers), and fan power (in the tower or for air cooled chillers) must be included to determine the power consumption of the total chiller system.

In general, water-cooled and evaporatively-cooled systems can be more efficient than air-cooled systems under many operating conditions due to the lower condensing temperatures involved. The selection of water-cooled, air-cooled, dry coolers, or evaporatively-cooled chillers for a particular application varies with regional conditions, power costs and demand costs, owner preferences, maintenance requirements, and project budget.

9.2.1.1 Centrifugal compressor chillers

Centrifugal compressors with one, two, and three compression stages are employed in chillers according to engineering selection and manufacturer preferences. Two and three stage compressors allow addition of an economiser with interstage cooling to improve energy efficiency. Other features that can be used to enhance chiller operation over a range of cooling loads and ambient conditions are inlet guide vanes, variable-speed drives, variable-geometry diffuser passages, lubricant-free magnetic bearings, optimal staging (loading and control) of multiple chillers, and off-peak energy storage. The application of variable-speed drives lowers annualised energy consumption but can decrease full-load efficiency because of inverter and drive losses.

Centrifugal compressors most commonly are used in water cooled systems, especially those with capacities exceeding 1 MW (300 RT). Air cooled centrifugal chillers are less common. They generally require at least two compressor stages because of the higher lift.

Centrifugal chillers typically use flooded or pool-boiler type evaporators with the refrigerant on the shell side of the tubes although some designs use falling film sprayed evaporators. Chilled water is confined to the inside of the tubes, facilitating periodic cleaning of the water tubes to eliminate efficiency-reducing mineral build-up. Refrigerant-in-tube evaporators with chilled water on the shell side, sometimes called DX evaporators, are not practical in the large chiller systems that use centrifugal compressors. Accordingly, there is a limit on refrigerant selection. Zeotropic refrigerants such as R-407C with high temperature glide can fractionate in flooded evaporators during evaporation or condensing, creating significant performance issues (see Section 9.4.1.2.).

9.2.1.2 Screw compressor chillers

Air-cooled and water-cooled screw chillers below 700 kW commonly employ direct-expansion (DX) evaporators.

Chillers with capacities above 700 kW generally employ flooded evaporators. Flooded evaporators generally require higher charges than DX evaporators but permit higher efficiencies due to closer approach temperatures (the difference between the leaving water temperature and the saturated evaporator temperature). Air-cooled chillers employ fin-and-tube condenser construction or microchannel condensers derived from automotive practice. Microchannel condensers are more compact for a given heat transfer capacity and allow the use of lower refrigerant charge in a chiller.

Screw compressors can be equipped with unloading devices such as slide valves or a port unloading mechanism that permit efficient operation at reduced volume flow rates. More recently, manufacturers are employing variable-speed drive devices with screw chillers. The application of variable speed lowers annualised energy consumption by eliminating the slide valves and associated losses, but can decrease full-load efficiency due to electronic drive losses. The benefits of screw compression (lack of surge limits present in centrifugal compressors) are combined with the benefits of variable-speed drives (efficient part loading and simpler screw compressor design) in properly designed systems to yield reduced seasonal energy consumption in water-cooled systems and air-cooled systems.

Screw compressors can be fitted with intermediate pressure ports to accommodate an economiser in the chiller system. An economiser increases the energy efficiency and the cooling capacity of a chiller for a given compressor displacement. Economisers become more effective at higher lift conditions such as low temperature cooling or heat recovery (hot water supply) applications.

9.2.1.3 Scroll compressor chillers

Scroll compressors are available in capacities from 20 kW to 150 kW for a variety of refrigerants. Many scroll compressors are fixed speed machines with no unloading mechanism. However, they are frequently used in manifolded sets for a refrigerant circuit. This allows multiple scroll compressors to be used in chillers up to 1400 kW. Individual circuits and compressors can be turned off, making efficient capacity modulation possible. Scroll compressors with electromechanical mechanisms for unloading are available as are compressors with variable-speed electronic drives.

Scroll compressor chillers are produced in both water-cooled and air-cooled versions. For capacities below 500 kW, brazed plate heat exchangers are commonly used for evaporators instead of the shell-and-tube heat exchangers employed in larger chillers. Brazed plate heat exchangers reduce system volume and refrigerant charge. They also are used as condensers for small water-cooled chillers.

9.2.1.4 Reciprocating-piston compressor chillers

Reciprocating compressors are similar in many ways to automobile engines and can be maintained and rebuilt in a similar manner. Reciprocating compressors have some advantages for units that operate over a variety of lift conditions because, unlike screw, scroll, and rotary vane compressors, they do not have a fixed volume ratio. Chillers with reciprocating compressors are produced in both water-cooled and air-cooled versions. Reciprocating chiller sales continue to decrease year by year although production still is significant, especially for lower capacities and for ammonia chillers. There is a relatively large inventory of older reciprocating chillers throughout the world.

9.2.2. Absorption Chillers

The energy source for absorption chillers is heat provided by a fuel-fired burner, steam, or hot water, though electricity still is required for internal solution pumps and controls. The steam or hot water generally is provided by a fuel-fired boiler or, less commonly, by heat recovered from industrial processes or cogeneration. In absorption chillers the compressor and motor of the mechanical vapour-compression cycle are replaced by two major heat exchangers (a generator and an absorber) and a solution pump. Absorption chillers also have condenser and evaporator heat exchangers. The refrigerant in large absorption systems commonly is water and the absorbent usually is lithium bromide, though lithium chloride also was common in the past and is still used though very infrequently. Absorption chillers may use an alternative fluid pair: ammonia as the refrigerant and water as the absorbent, particularly in smaller capacities.

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 utilise 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. Hot fluid input temperatures typically range from 115^o C to 135^o C, although some machines can use temperatures as low as 90^o C.

Double-effect machines have an additional heat recovery heat exchanger and can be driven by hot water or steam or can be direct-fired. Typical steam input temperatures are 150^o C to 205^o C (steam pressures from 650 to 1100 kPa). 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. Small double-effect gas-fired absorption chillers with capacities below 105 kW (30 RT) are used in Japan with water as refrigerant and lithium bromide as absorbent.

Triple-effect machines have been developed and commercialised but are not used widely. The direct-fired high temperature generator in these machines operates at a temperature level of 205^o to 230^o C which increases the cost and pressure level within the vessels. 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).

Centrifugal chillers were the most common type of chillers above 700 kW capacity for many years. Reciprocating compressors were used in smaller chillers. Screw compressors have largely replaced reciprocating compressors in the range from 140 kW to 700 kW and are alternatives to centrifugal compressors up to about 1800 kW. Scroll compressors are alternatives to reciprocating compressors in the range from 10 to over 100 kW per compressor. Scroll compressors are used in chillers up to 1400 kW with 1 to 12 compressors per unit and multiple refrigerant circuits. Features such as novel unloading mechanisms and variable-high-speed electronic drives have been introduced on almost all compressor types, though not on all sizes. Lubricant-free operation and high–speed direct drive have been introduced with centrifugal compressors.

Table 9-1: Chiller Capacity Ranges

Chiller Type	Approximate Capacity Range (kW)
Scroll and reciprocating water-cooled	10 - 1,200
Screw water-cooled	100 – 7,000
Screw, scroll, and reciprocating air-cooled	10 – 1,800
Centrifugal water-cooled	200 - 21,000
Centrifugal air-cooled	200 – 7,000
Absorption (generally ammonia-water)	15 - 90
Absorption (generally water-lithium bromide)	20 – 18,000

9.3 Developments and Trends in Chiller Markets

9.3.1 Measures of Chiller Efficiency or Energy Use

Energy efficiency, or the total power consumed annually, is the primary environmental consideration for chillers. While refrigerants each have an inherent Global Warming Potential (GWP) relative to CO_2 (see Chapter 2, *Refrigerants*), refrigerants cannot contribute directly to global warming unless they are released to the atmosphere. Properly-maintained chillers of modern design emit very little of their refrigerant charge during operation. The dominant global warming effect caused by chiller operation is the CO_2 and other greenhouse gases emitted in the combustion of fossil fuels generating the electricity to drive them. High annualised chiller efficiencies reduce global warming proportionally. /Cal93, San 97/

Key parameters used in describing the environmental effects of chiller operation are Total Equivalent Warming Impact (TEWI) or the similar and conceptually more complete Life Cycle Climate Performance (LCCP). These parameters are defined in Chapter 3 of /IPCC05/ and data for chillers are included in Chapter 5.2.4 of /IPCC05/.

Other measures of chiller performance include the coefficient of performance (COP) which is the ratio of cooling capacity to the electrical input, both expressed in consistent units of energy or power. The COPs can be stated for any operating condition, but are commonly cited for full rated capacity. This condition establishes peak electrical demand which influences both overall power supply costs and the electricity demand costs paid by users as well as on-site transformer, switchgear, and related power supply costs.

Each type of chiller and refrigerant combination has a best-in-class benchmark COP level that can be purchased. The benchmark COP level tends to increase as time passes and products are improved. The chillers with the best COPs tend to cost more because they employ larger heat exchangers and/or other special features. Many purchasers buy lower-cost, lower-COP chillers that meet or only slightly exceed minimum efficiency levels imposed by regulations, codes, or standards. With concern about increasing energy costs and growing interest in sustainability and "green buildings," the trend is to select more efficient equipment.

An additional measure of performance for individual chillers is called the Integrated Part Load Value (IPLV). This is described in ARI (now AHRI) Standard 550/590 /ARI03/. The IPLV metric is a weighted average of four COP values for an individual chiller, based on weighting by the percent of Ton-Hours assumed to be spent in each of four unequal size bins for load fraction, where the COP value for each bin is represented by one of four load fractions (25%, 50%, 75%, and 100%) each with different operating lift conditions. In Europe a similar part load parameter, ESEER, has been developed by Eurovent. This will be replaced in coming years by legal requirements coming from the Ecodesign directive for energy related products where seasonal efficiency methods for cooling, heating, and refrigeration applications for chillers are currently established. The publication prEN14825 includes SEER and SCOP values for comfort cooling and heating applications. China implemented an IPLV standard in 2005 (GB 50189-2005).

The IPLV concept provides a measure of performance over the seasons at part loads and/or reduced lift conditions. IPLV can be used as a basis for comparison of individual chillers and as a means for establishing a minimum energy efficiency parameter for code enforcement. The ARI Standard applies to an individual chiller serving a North American space conditioning load. It may not be the most accurate seasonal performance indicator for chillers serving other load profiles such as data centers, optimally-controlled systems using multiple chillers, or chillers operating in other climate conditions.

9.3.2 Developments in the Market – Vapour-Compression Chillers

Overlaps in the capacity range served by screw and centrifugal chillers, and scroll vs. screw chillers, are becoming larger. Reciprocating chillers are losing market share rapidly to scrolls and screws in small and large capacities respectively. Screw compressor development led to higher capacity and higher efficiencies in these machines.

Larger scroll compressors and tandem scrolls are being used in multiples and in linked combinations of modular chillers to achieve capacities up to 1400 kW. These chillers increasingly are using R-410A refrigerant, displacing HCFC-22 use.

The centrifugal chiller market has grown because of new construction and the need to replace chillers in developed markets, satisfy expanding infrastructure in emerging markets, and serve large process cooling and factory air conditioning applications. Higher capacity has been achieved by using dual compressors in a chiller and by use of multiple chillers. Counter-flow heat exchangers with dual compressors are used to improve efficiencies for large capacity chillers. Higher condensing temperatures in hot climates or for heat recovery/heat pump service are accommodated by multistaging compressors.

In Southern Europe hydronic cooling systems (smaller capacity air-cooled chillers or air source heat pumps) are widely used. They are combined with fan coil units as low as 10 kW capacity for residential and light commercial buildings.

In northern Europe, chillers of the scroll or screw types are widely used with air handling units and fan coil units in commercial buildings.

While production of HCFCs is permitted in the developing countries beyond 2010, HCFC-22 use in new equipment is decreasing, enabling these countries to benefit from the latest designs and technologies available. Developing countries that wish to export products to developed countries have a further incentive to accelerate their transition away from HCFC-22.

China is now a large and growing market for chillers. The main market is East China with both a new construction and emerging replacement market. Screw and scroll chillers mostly still use HCFC-22, but new generations of scroll chillers are being designed to use R-410A and new screw chillers are employing HFC-134a. China has a major residential market for small chillers with fan coil units.

9.3.3 Developments in the Market – Absorption Chillers

Absorption chillers are manufactured and marketed primarily in Japan, China, India, South Korea and, additionally for capacities below 100 kW, Germany, Austria, and Italy.

Absorption systems inherently are physically larger and have higher primary energy requirements and higher initial cost than vapour-compression chillers. They can be cost-effective in applications where waste heat is available in the form of steam or hot water, where adequate or reliable electricity is not readily available for summer cooling loads, or where high electricity cost structures, including demand charges, make gas-fired absorption a lower-cost alternative. Absorption chillers can supply heating and cooling from one unit year-round without using fluorocarbon refrigerants and with a less expensive power supply system than mechanical chillers.

High natural gas prices have slowed market development of direct-fired absorption systems in Japan, China, and Korea /JAR 08/. Concerns about the higher CO_2 emissions from direct fired systems compared to the global warming impact of vapour compression chillers also is affecting the market.

Trigeneration is the concept of deriving three different forms of energy from the primary energy source, namely, heating, cooling and power generation. Use of water-lithium bromide absorption chillers in trigeneration systems has been implemented in some countries. This concept also is referred to as CCHP (combined cooling, heating, and power generation). This option is particularly relevant in tropical countries where buildings need to be air-conditioned and many industries require process cooling and heating. Although cooling can be provided by conventional vapour-compression chillers driven by electricity, low quality heat (i.e. low temperature and low pressure) exhausted from the cogeneration plant can drive the absorption chillers so that the overall primary energy consumption is reduced.

9.4 Current Refrigerant Choices and Options for Mechanical Vapour-Compression Chillers

9.4.1 Positive Displacement Chillers

9.4.1.1 HCFC-22

Chillers that use positive displacement compressors (screw, scroll, and reciprocating compressors) employed HCFC-22 as the refrigerant of choice when they were first produced. Due to its low ozone depletion potential (ODP), HCFC-22 was viewed as a transition solution to phase-out of CFC-12 and other CFCs. Phase-down of HCFCs in developed countries started in 2004 leading to national regulations for HCFC-22 phase-out for new equipment by 2010 or earlier. Europe phased out HCFC-22 beginning in 2000. Installed refrigerants, stocked inventories, and amounts recovered from retired equipment may be used to service existing equipment indefinitely if national rules permit. HCFC-22 still is offered for chillers in Article 5 countries. HCFC consumption must end by 2030 in developed countries and 2040 in developing countries.

9.4.1.2 HFC-134a, R-410A, and R-407C

HFC-134a screw chillers were introduced early in the 2000s by a number of manufacturers in anticipation of the phase-out of HCFC-22 in 2010. Screw chillers using a higher pressure HFC refrigerant, R-410A, also have been introduced. For scroll compressor chillers, refrigerants being offered include HFC-134a, R-410A, and R-407C. R-410A now is the dominant refrigerant, especially for new scroll chillers.

The zeotropic mixture R-407C served as a transition refrigerant, especially in European countries where HCFC-22 was phased out by regulations in advance of the Montreal Protocol deadlines. It allowed manufacturers to offer chillers with an HFC refrigerant (zero ODP) instead of HCFC-22 by making modest changes in their products. Unfavourable changes in heat transfer with R-407C necessitate larger, more expensive heat exchangers to maintain performance. R-407C has an appreciable temperature glide (5-7 K) so is not suitable for use in flooded evaporators that predominate in larger chillers. R-407C still is used in Europe and Japan as a replacement for HCFC-22 and elsewhere as one of a number of aftermarket service fluid options for retrofit.

9.4.1.3 R-717 (Ammonia)

Chillers employing R-717 as a refrigerant have been available for many years and are widely used in industrial systems (see Chapter 5, *Industrial Refrigeration*). 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 HCFC and HFC chillers. Plate-and-frame steel heat exchangers are common in R-717 systems. Open drive compressors are used to avoid exposing copper motor windings to R-717. Semi-hermetic screw compressors have been developed with motors up to 110 kW using aluminium windings but are not common outside Japan.

The current market for R-717 chillers is of the order of a thousand units annually compared to tens of thousands of chillers employing HCFC-22 and HFCs. 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 /Pea08a and Pea08b/.

9.4.1.4 Hydrocarbons

Chillers employing hydrocarbons as a refrigerant have been available for over 10 years, though typically only in small capacities (up to 200 kW) per refrigerant circuit. HC-290 (propane) is used in chillers in air conditioning and industrial applications. HC-290 and another hydrocarbon, HC-1270 (propylene), are used in a limited number of small (<600 kW) air-cooled chiller installations in Denmark, Norway, the United Kingdom, Germany, 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.

Standards and guidelines for the use of hydrocarbon refrigerants in stationary refrigeration and air conditioning systems are provided in /ASH10a/ and /EN08/. EN 378 specifies maximum refrigerant charge sizes for systems located within occupied spaces of 1.5 kg and 2.5 kg depending upon whether it is a public or private occupancy. For all refrigerant containing parts located outside, the upper charge size is 25 kg in public spaces. There is no limit if located in areas with authorised access only. International Standard IEC 60335-2-40 permits up to approximately 5 kg of HC within a dwelling provided it is contained within a special enclosure /EN08/. Local authorities can impose different charge size limits or require special considerations.

9.4.1.5 R-744 (Carbon dioxide)

R-744 chillers have been introduced to the market by manufacturers in Europe. Both air- and water-cooled gas cooler versions are available. For rating purposes the chilled water range is +12/+7 ^{o}C. The discharge temperature from the gas cooler is 30^{o} C. Models with cooling capacities from 40 to 500 kW are offered.

9.4.2 Centrifugal Chillers

In the 1960s through early 1990s centrifugal chillers were offered with CFC-11, HCFC-22, CFC-113, CFC-12, CFC-114, and R-500 refrigerants. Of these, CFC-11 was by far the most common because it was the most efficient refrigerant for centrifugal chillers. With the implementation of the Montreal Protocol, production of chillers using CFCs or refrigerant blends containing CFCs (such as R-500) essentially ended in 1993 in developed countries and 2005 globally. Centrifugal chillers using HCFC-22 were rarely produced after the late 1990s.

The primary refrigerants used in centrifugal chillers today are HCFC-123 and HFC-134a. These alternative refrigerants began to be used in centrifugal chillers in late 1989 and continue to be used in new production chillers. HCFC-123 replaced CFC-11 and offers an efficient low ODP and very low GWP option. HFC-134a is a high GWP refrigerant but with only 13% of the ultra-high GWP of CFC-12 which it replaced. HFC-245fa, a foam blowing agent in the high GWP category, also can be used as a refrigerant in centrifugal chillers, but its use has been very limited. Table 9-2 shows the range of cooling capacities offered for centrifugal chillers with the refrigerants that replaced the CFCs.

Table 9-2: Centrifugal Chiller Refrigerants

Refrigerant	**Capacity Range (kW)**
HCFC-123	700 - 17,000
HFC-134a	200 - 21,000
HFC-245fa	2,600-8,800

Centrifugal chillers also find application in naval submarines and surface vessels. These chillers originally employed CFC-114 as the refrigerant in units ranging in capacity from 440 to 2800 kW. A number of CFC-114 chillers were converted to use HFC-236fa as a transitional refrigerant. (HFC-236fa has a very high GWP so has not been used in other chiller applications.) New naval chillers primarily use HFC-134a.

9.5 Refrigerant Options for New Chiller Equipment

The selection of alternative refrigerants to replace CFCs and HCFCs required a balance among thermophysical properties, chemical and thermal stability, global environmental issues of stratospheric ozone depletion and global warming due to refrigerant release and energy-related effects, local safety issues such as toxicity and flammability, performance, and cost /Cal97/.

Through better manufacturing techniques, all manufacturers are reducing leakage and minimising the direct effects of refrigerant releases on global warming. Average annual leak rates of 0.5% on a life cycle basis (including manufacturing, start-up, testing, operation, service, amortised catastrophic losses, and retirement) can be achieved by the best centrifugal chillers /Cal99/. Average annual leak rates of many chillers are higher, especially if they are not well maintained. Manufacturers are modifying chiller designs to reduce the refrigerant quantity that they require.

9.5.1 Options for New Positive Displacement Chillers

9.5.1.1 R-407C

R-407C had a role as a transition refrigerant during the phase-out of HCFC-22. The development of new chiller products to use this HFC blend effectively has ended for reasons given in Section 9.4.1.2.

9.5.1.2 Primary HCFC-22 replacements: HFC-134a and R-410A

The transition away from HCFC-22 to HFC-134a in screw compressor chillers and to R-410A in scroll compressor chillers was under way by 2005 or earlier in developed countries. The transition is at an earlier stage in Article 5 countries. HCFC-22 refrigerant is less expensive than those alternatives, and development expenditures for new chillers and new compressors to use those alternative refrigerants can be postponed in these countries because they have later phase-out dates for HCFC-22. On the other hand, conversion to lower GWP refrigerants in higher efficiency systems would reduce climate change impacts.

9.5.1.3 HFC-32

The refrigerant HFC-32 is used as a component in blends such as R-410A. It has been proposed for use as a refrigerant in positive displacement chillers by itself and in azeotropes with R-600 (n-butane), R-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 operating pressure levels higher than for HCFC-22 and flammability. HFC-32 is classed as an A2 refrigerant under ASHRAE Standard 34. /ASH10b/. A new rating for "low flammability" has been adopted (see Chapter 2, *Refrigerants*) and HFC-32 may be reclassified as A2L. Chillers using HFC-32 (other than as a blend component) have not been commercialised yet.

9.5.1.4 Additional HFC refrigerants: R-404A, R-507A, and other HFC blends

High GWP refrigerants R-404A and R-507A have been considered as possible HCFC-22 replacements in low temperature commercial refrigeration units. However, no non-flammable azeotrope has been commercialised for chillers for air conditioning that matches the pressure-temperature relationships of HCFC-22.

Other HFC blends have been proposed by chemical manufacturers. Most of these blends have significant temperature glides (2 K or larger) and do not appear to offer performance benefits compared to HFC-134a or R-410A. Their market penetration in new equipment has been very small. Barriers to entry of new blends that do not offer significant performance or cost benefits include the challenges of developing long-term supply sources for chillers located around the world.

Low GWP Refrigerants

9.5.1.5 R-717

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 but could be revised if acceptable safety is demonstrated with new approaches.

The market for R-717 chillers is likely to grow in the future in regions where concerns about the control of high-GWP refrigerants are strong. However, perceived safety concerns in comfort cooling applications may increase installation costs and restrict installation arrangements.

9.5.1.6 Hydrocarbons

Use of HC-290 and HC-1270 for comfort cooling and heat pump applications is limited primarily by flammability concerns.

There are hydrocarbon refrigerants with properties similar to those of HCFC-22 and HFC-134a that allow use in new equipment of current design after appropriate adjustments for different material compatibility, lubricant, and safety aspects. Chillers employing hydrocarbon refrigerants are higher in cost than HFC chillers because they are manufactured in smaller quantities, though modification of equipment originally designed for HCFC-22 is fairly straightforward.

Safety codes impose stricter requirements on hydrocarbon use for large refrigerant charges in chillers, particularly for indoor chiller installations (e.g., water-cooled chillers in machinery rooms). In regions where companies, government, and the public support hydrocarbon solutions, these safety concerns have been largely overcome by engineering, technician training, and changes in standards. In these regions, the use of hydrocarbon chillers is likely to grow in the future. However, in countries such as the U.S.A., regulations, building codes, and legal environments continue to pose difficulties for hydrocarbon use in commercial chillers.

9.5.1.7 R-744

R-744 air-cooled chillers have been introduced in the northern European market. In climates where the dominant cooling requirement is at an average ambient temperature of 15^0 C or less, these systems can be equivalent in energy efficiency and LCCP with systems employing HFCs, R-717 or HCs. R-744 chillers will likely be less attractive at higher ambient temperatures due to decreasing efficiency with increasing ambient temperature.

Where heat recovery to generate hot water at temperatures of 60^o C 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.

9.5.1.8 HFC-1234yf and other unsaturated hydrofluorochemicals

Chemical manufacturers are offering unsaturated hydrofluorochemicals (see Chapter 2, *Refrigerants*) to replace HFC-134a in mobile air conditioning (see Chapter 10, *Vehicle Air Conditioning*). If adopted widely in the mobile sector, further exploration of possibilities for use in stationary air conditioning (including chillers) and refrigeration is expected. Initial studies based on thermodynamic properties suggest that the COP of chillers using HFC-1234yf refrigerant is not as good as for HFC-134a /Kon09 and Lec10/. Further development of unsaturated HFCs for chillers is under way /Kon10a, Kon10b, Kon10c and Spa08/ . It is not possible at this time to know whether HFC-1234yf and other such new refrigerants or blends will find significant acceptance for use in chillers.

9.5.2 Options for New Centrifugal Chillers

Centrifugal compressors are the most efficient technology in large units, namely those exceeding 1700 kW capacity. Water chillers employing these compressors are designed for specific refrigerants.

9.5.2.1 Commonly used refrigerants: HCFC-123 and HFC-134a

HCFC-123 and HFC-134a are the primary, well-proven current choices for new centrifugal compressor chillers.

9.5.2.2 HFC-245fa

HFC-245fa can be used as a centrifugal chiller refrigerant and at least one manufacturer markets chillers using this refrigerant /JAR08/. HFC-245fa is more commonly used for appliance insulation foam blowing. It went into commercial production in 2003. HFC-245fa has operating pressures higher than for HCFC-123 but lower than for HFC-134a.

9.5.2.3 Design issues with zeotropes, hydrocarbons, and R-717 for centrifugal chillers

Zeotropic refrigerants with significant temperature glides are not suitable for use in the flooded evaporators that are used in all centrifugal chillers. The discussion of refrigerant R-407C in Section 9.4.1.2 explains the issues.

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, *Industrial Refrigeration*). Hydrocarbon refrigerants have not been used in centrifugal chillers for air conditioning due to safety code restrictions and concerns with large charges of flammable refrigerants.

R-717 is not a suitable refrigerant for centrifugal chillers because it requires a large number of compressor stages to produce the pressure rise ("lift" or "head") required for the R-717 chiller cycle. Alternative designs using axial compressors are not commercialised for refrigeration systems.

9.5.2.4 R-718 (water)

The low pressures, high compression ratios, and high volumetric flow rates required in water vapour compression systems require compressor designs that are uncommon in the chiller field, though several companies and research projects have attempted their commercialisation. 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, Israel, and South Africa /Jah96, Oph08, and She01/.

9.5.3 Issues with HCFC-123, HFC-134a, R-410A, and Other HFC Chiller Refrigerants

Under terms of the Montreal Protocol, use of HCFC-123 in new equipment will end in most developed countries by 2020 and by 2030 in Article 5 countries. It already has stopped in Europe. Existing chillers may use installed, recovered, and stocked quantities of HCFC-123 indefinitely (except in Europe).

Controls on the high GWP HFC refrigerants are beginning to be discussed by some countries and by international bodies. For stationary air conditioning applications such as chillers, the regulatory threshold defining high GWP has not been established yet. The GWPs of HFC-134a, HFC-245fa, and R-410A make these refrigerants potential candidates for regulation (see Chapter 2, *Refrigerants*, for latest GWP values). Other HFC refrigerants discussed in this section 9.5 also have GWPs that make them potential candidates.

There is no new refrigerant that has been commercialised yet to replace HCFC-123 or R-410A. HFC-1234yf and other unsaturated hydrofluorochemicals, described in Section 9.5.1.8. above, are in early stages of evaluation for use in stationary air conditioning. It is not possible at this time to know whether these chemicals will find significant usage as a refrigerant in positive displacement chillers or as replacements in centrifugal chillers.

A wide-ranging discussion of the progression of refrigerants from early uses to the present, addressing future directions and candidate refrigerants including "natural refrigerants", is found in /Cal08/.

9.5.4 Alternatives to Vapour Compression Systems (Absorption Chillers)

Absorption water chillers driven by hot water, steam, or direct firing are a viable alternative to the vapour-compression cycle for some installations. Absorption chillers have been described in Sections 9.2.2 and 9.3.3.

9.6 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 to reduce emissions.

Retrofit: modification to allow operation with alternative refrigerants (HFCs) 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 /ASH10a, EN08/ or proposed international standards such as ISO/DIS 5149. It is also recommended that the manufacturers of the equipment be consulted in any retrofit program.

The number of annual chiller retrofits is expected to decline significantly in developed countries where most economically-viable refrigerant conversions from CFC use have been completed.

Today's average centrifugal chillers use 20% less electricity than the average of chillers produced just two decades ago and the best chiller today uses less than 65% of the electricity of the average 1976 chiller /ICF03 and TEA04/. Building owners typically can pay back the investment cost of replacing an old CFC chiller in three to five years (or less) in many regions that require cooling for more than three months a year.

9.6.1 Positive Displacement Chillers

A positive displacement compressor inherently can be applied to handle a number of different refrigerants and pressure ratios in a chiller so long as 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.

9.6.1.1 HFC-134a as a replacement for CFC-12

The operating pressure levels and cooling capacities of HFC-134a and CFC-12 are similar. Thus, HFC-134a can be used as a retrofit refrigerant for CFC-12 chillers. The mineral oil lubricant used with CFC-12 must be carefully flushed from the system and replaced with a suitable synthetic oil that is compatible with HFC-134a (mineral oil is not miscible with HFCs, so cannot be used in HFC systems). If mineral oil and chlorides contained in the oil are not adequately flushed from the system, viscous deposits of contaminants may be formed in the system and clog small passages and controls. Other materials such as gaskets, elastomeric seals, and filter-driers must be checked for compatibility with HFC-134a and replaced if necessary. Control of moisture content in HFC-134a systems with synthetic oil requires more attention than with CFC-12. The chiller manufacturer should be consulted about the requirements for a successful retrofit.

After conversion, the cooling capacity and energy efficiency of the system will be close to those of the system when charged with CFC-12.

9.6.1.2 R-407C, HFC-134a, proprietary blends, and hydrocarbons as candidate replacements for HCFC-22

Refrigerant HCFC-22 was employed in most new positive-displacement chillers until the latter half of the 1990’s. Based on a very extensive search of alternatives, it became clear that there is no direct substitution for HCFC-22 in chillers with flooded evaporators.

Retrofit refrigerants for HCFC-22 initially used were R-407C and HFC-134a. A conversion of a chiller from HCFC-22 to HFC-134a will reduce cooling capacity by approximately one-third unless the compressor is replaced with one having about 50% greater displacement. In a conversion from HCFC-22 to either R-407C or HFC-134a, the mineral oil lubricant in the system must be removed and replaced with a synthetic lubricant compatible with HFCs. It is recommended that the manufacturer of the chiller be actively involved in any retrofit program.

Alternative retrofit refrigerants for HCFC-22 equipment with DX evaporators include proprietary zeotropic and azeotropic blends of HFCs that have been and continue to be developed. The comments in Section 9.4.1.2 on R-407C explain problems with zeotropic blends which cause their use as an alternative in many HCFC-22 chillers to be accompanied by losses in capacity and energy efficiency. Some blends contain a small amount of hydrocarbon refrigerant so the blends may be used with mineral oil. Some blends are more suitable for air conditioning duty while others may be more appropriate for heat pump or refrigeration applications. When considering a blend for replacing HCFC-22 in a system, attention must be given to the effects of the blend upon cooling capacity and energy efficiency.

New refrigerant blends coming into the market may have limited penetration because of concerns about long-term availability for service purposes and the reluctance of chiller manufacturers to warrant their equipment with refrigerants (and lubricants) they have not tested thoroughly. Such testing is an expensive process.

Retrofit of hydrocarbon refrigerants into CFC or HCFC chillers is not permitted in many countries. However, in some jurisdictions (notably in South East Asia) numerous conversions have been completed. Cost may be incurred to incorporate safety features in the equipment and to modify the machinery room to meet safety standards. Conversion should only be planned and performed by suitably qualified engineers and technicians.

9.6.1.3 R-404A or R-507A as replacements for HCFC-22

Refrigerant blends R-404A and R-507A were developed for refrigeration applications as replacements for R-502, a blend that contains a CFC. The new blends have been successful as R-502 replacements for refrigeration duty. However, they are not attractive as replacements for HCFC-22 in chillers. Their energy efficiency for chiller operating conditions is lower than that of HCFC-22 and other alternatives discussed above.

9.6.2 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.

In principle a refrigerant blend can be produced to accomplish substitution, but blends with significant temperature glide are unacceptable in the flooded evaporators of centrifugal chillers for reasons previously discussed. In practice, refrigerant substitutions are uncommon. R-423A has been used successfully as a replacement for CFC-12 in centrifugal chillers without the need for mechanical changes to the compressor in situations where the condensing temperature is not extreme.

Complete replacement of a compressor by a design that is developed for an alternative refrigerant can be done, but this is uncommon because of the high cost of conversion. The primary alternative is to replace the chiller.

9.6.3 Not-in-Kind Chiller Replacements – Absorption

A factor which limits changeovers from CFC or HCFC vapour-compression chillers to absorption is the inability to retrofit in many existing buildings because the access ways are not large enough to allow for the absorption chiller to be delivered to the existing machine room. It is likely that the cooling tower capacity will need to be increased significantly. A suitable gas piping system should be prepared if a gas-fired absorption system is to be used.

9.7 Banks and Emissions Relating to Chillers

An annex entitled "Global inventories of the world-wide fleets of refrigerating and air-conditioning equipment in order to determine refrigerant emissions: The 1990 to 2006 updating, Extracts from the FINAL REPORT" is provided with this RTOC report. The annex was prepared by Denis Clodic, Stephanie Barrault, and Sabine Saba of ARMINES in Paris, France, in April 2010. Section 8 of the annex presents information on chillers. Section 8 of the annex has not been reviewed or edited by the authors and contributors to this RTOC report's Chapter 9.

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Chapter 10

Vehicle Air Conditioning

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10 Vehicle Air Conditioning

10.1 Introduction

Vehicles (cars, trucks, and buses) built before the mid-1990's used CFC-12 as the refrigerant. Since then, in response to the Montreal Protocol, new vehicles with air conditioning have been equipped with systems using HFC-134a. (Abbreviation: A/C. In this report the abbreviation MAC for Mobile Air Conditioning is used). This chapter also covers the heat pump mode of the air conditioning cycle, for example systems used for heating BEVs– (battery-driven electric vehicles). By the year 2000, the transition from CFC-12 to HFC-134a as an OEM refrigerant, for factory installed AC systems, was complete in all developed countries. A US survey conducted by the Mobile Air-Conditioning Society Worldwide [MACSW] done for the IMAC project, indicates that even in 2005, approximately 19% of the US fleet still contain CFC-12 refrigerant. The survey includes vehicles that may have been equipped with CFC-12 when sold, but were later retrofitted to HFC-134a. Considering scrap rates and continued retrofitting, this percentage has likely dropped below 10% in 2010. Hence, it is expected that the demand for CFC-12 as a service refrigerant will be nearly eliminated in the next few years. 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.

10.1.1 Regulatory Actions affecting Vehicle Air Conditioning and Refrigerants

EU regulations, which control Mobile AC system direct emissions fall into two groups, controlling leaks and phasing out high GWP fluorinated GHG's. Directive 2006/40/EC 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 2017. EU Commission Regulation (EC) No 706/2007 includes a harmonised test for measuring leakages from mobile air conditioning systems. Commission Directive 2007/37/EC amends Annexes I and III to Council Directive 70/156/ clarifying some terms. Furthermore, this same regulation 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.

European EU6 regulations were recently passed to limit the grams of GHG Green House Gas] (changed from CO2) emissions per kilometre initially to 130 gCO2/km and in 2012 down to 95gCO2/km. Current directive 80/1268/EC is merged in EURO 5&6. This regulation also allows for a small credit for mobile air conditioning systems with efficient operation. In 2011, the EU will publish a new Directive concerning measurement of MAC based CO2 emissions.

In Australia, a tax of about A$30/kg is proposed for HFC-134a from year 2011.

In the USA, the state of Minnesota has passed a regulation requiring all manufacturers to report the leakage of the systems they sell in the USA as calculated as described in SAE standard J2727. The 2009 industry single evaporator MAC system data listed the average fleet emission loss at 14.1 g/y. This data is reported to consumers through a State of Minnesota website. Data is required to be updated with each model year. [http://www.pca.state.mn.us/climatechange/mobileair.html#leakdata]

Beginning 1 January 2009, all vehicles sold in California must carry a SMOG label indicating the level of Pollution attributed to each vehicle sold in California. This regulation [AB1229] also provides a level of credits for efficient and low leakage mobile air conditioning systems.

The State of California also has a regulation [AB1493], which takes effect in the 2010 model year to restrict CO2 emissions of vehicles. This bill provides credits for AC direct and indirect equivalent CO2 emissions. Seventy percent of the allowable credit is related to indirect emissions and 30% is related in direct emissions. Early AC credits are available for model years 2009-2011.

On October 30, 2009, the EPA published a final rule in the Federal Register (www.regulations.gov) under Docket ID No. EPA-HQ-OAR-2008-0508-2278 on the reporting of Greenhouse Gas emissions. This became effective December 29, 2009, with first reporting in March, 2010. As this relates to vehicle sources of HFC emissions, the reporting is delayed until 2011 and SAE J2727 is the proposed mechanism to report these emissions. [http://www.epa.gov/climatechange/emissions/ghgrulemaking.html]

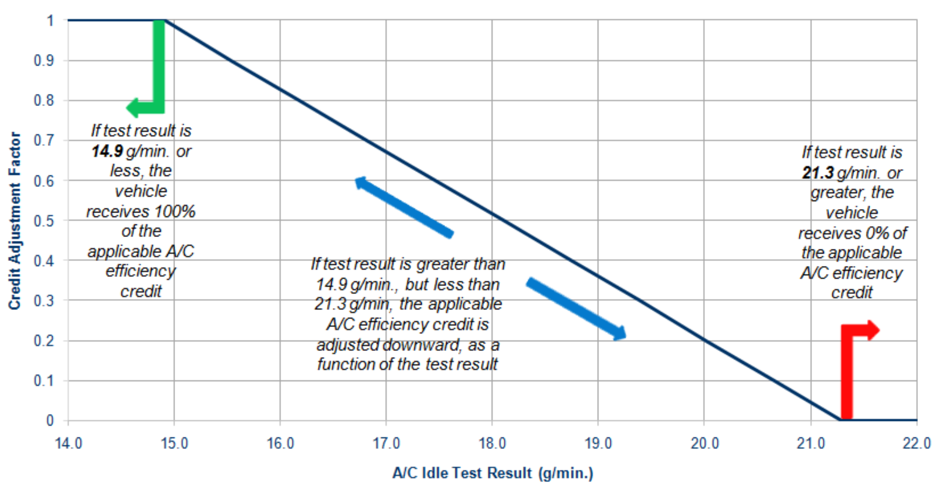
On September 15, 2009, the US EPA and the National Highway Transportation Safety Administration (NHTSA) proposed an historic National Program that would dramatically reduce greenhouse gas emissions and improve fuel economy for new cars and trucks sold in the United States.
[http://epa.gov/otaq/climate/regulations.htm]

The combined EPA and NHTSA standards will apply to passenger cars, light-duty trucks, and medium-duty passenger vehicles, covering model years 2012 through 2016. This rule requires fleet-wide net CO2 emissions reductions over the period 2012-2016. Regarding the impact on mobile air conditioning, a credit system for indirect CO2 emissions has been established. This credit system is based on a technology “menu” as shown in the table below. This rule provides credit for HFC-134a leakage reduction and use of low GWP refrigerant. Early A/C-credits will be available for model years 2009 to 2011.

Table 10-1 Efficiency-Improving A/C Technologies and Credits

Technology Description	Estimated Reduction in A/C CO_2 Emissions	A/C Efficiency Credit (g/mi CO_2)
Reduced reheat, with externally-controlled, variable-displacement compressor	30%	1.7
Reduced reheat, with externally-controlled, fixed-displacement or pneumatic variable-displacement compressor	20%	1.1
Default to re-circulated air with closed-loop control of the air supply (sensor feedback to control interior air quality) whenever the ambient temperature is 75 °F or higher (although deviations from this temperature are allowed if accompanied by an engineering analysis)	30%	1.7
Default to re-circulated air with open-loop control air supply (no sensor feedback) whenever the ambient temperature 75 °F or higher lower temperatures are allowed)	20%	1.1
Blower motor controls which limit wasted electrical energy (*e.g.*, pulse width modulated power controller)	15%	0.9
Internal heat exchanger	20%	1.1
Improved condensers and/or evaporators (with system analysis on the component(s) indicating a COP improvement greater than 10%, when compared to previous industry standard designs)	20%	1.1
Oil Separator (with engineering analysis demonstrating effectiveness relative to the baseline design)	10%	0.6

A new idle test cycle has been added starting in 2014 to qualify indirect MAC system credits. This idle test will quantify the amount of indirect CO2 emissions related to the MAC system. The indirect credit determined from the table above will be adjusted based on the results of the CO2 emissions related to MAC on the idle test on a sliding scale as described in the graph below.



This graph and the table above were presented y the US EPA at the 2010 SAE Alternative Refrigerant and System Efficiency Symposium.

There will also be a direct emissions credit as well based on the measurement of leakage as determined using the SAE standard J2727. This credit will represent about 50% of the total credit for MAC systems.

In July, 2010, there was a workshop held as part of the SAE Alternative Refrigerant and System Efficiency Symposium. In this workshop, regulators, suppliers, and vehicle OEMs, discussed ideas of how MAC indirect emissions could be measured. The timing to introduction of the planned regulation in the USA is model year 2017. From the discussions in the workshop, it is considered likely that this continued co-operation will lead to a global unified approach regarding this matter.

10.2 Technical Progress

For sake of this report, mobile air conditioning systems are those used in passenger cars, light duty trucks, buses and rail vehicles. Passenger cars and light duty trucks have refrigerant charge amounts from 0.4-1.2 kg. Bus and rail vehicles can have refrigerant charge amounts from 2 kg to 15 kg and some even more. This report covers the new developments in this field since the 2005 IPCC TEAP report on Ozone and Climate and the RTOC 2006 report. For more details on the detailed system design and the history of refrigerant system development for these vehicles prior to 2005, see these reports.

Driven by legislation (described in section 10.1.1) and competition with systems using alternative refrigerants (described in section 10.4) car air conditioning systems using HFC-134a have become increasingly more leak tight and energy efficient. This has resulted in the introduction of new system concepts, including the use of internal heat exchangers, oil separators, and ejector cycles. New sealing concepts and improved hose materials are also being developed to reduce refrigerant direct emissions. Advanced research is being conducted on compressor expanders and there are increased applications of MAC to vehicle battery cooling.

The rapid evolution of hybrid electric vehicles and electric vehicles with electrically driven compressors introduces new challenges for HFC-134a vehicle air conditioning systems. For these future mobility concepts a refrigerant has to be compatible with the electric motor of the compressor and with the oil used in these systems. Especially for battery driven electric vehicles, vehicle air conditioning systems for cooling as well as heat pump systems for heating have to be highly energy efficient because power consumed by MAC can significantly impact the vehicle driving range. Not only a HFC-134a system but any system using a new alternative refrigerant (described in section 10.4) faces these new challenges.

10.3 Existing Mobile Air Conditioning Systems

10.3.1 HFC-134a

As already described in section 10.1.1 HFC-134a systems have become increasingly more leak tight. In some cases joint sealing technologies developed for R-744 have been adapted for use in HFC-134a systems. Hose materials and coupling designs for hoses have also been improved. In addition to that, HFC-134a systems show improved energy efficiency and fuel consumption (as mentioned section 10.2) to meet new regulatory requirements in the USA and driven by increased awareness of fuel consumption of MAC in the EU. For more details see also section 10.4.1.1.

10.3.2 Retrofit of CFC-12 systems

CFC-12 MAC systems continue to be retrofitted to HFC-134a as mentioned above. Furthermore, there are 14 other blend refrigerants that are approved by the USEPA under the SNAP regulation for retrofit of CFC-12 systems. 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. In the USA, the sale of CFC-12 is restricted to certified technicians. However, HFC-134a is available to the general public.

Retrofitting of CFC12 vehicles has declined after 1997 due to availability and price of CFC-12. Retrofit cost in 1997 was $89.51and increased to $176.05 in 2003. Some vehicle MAC systems have also had control problems when retrofitted to HFC-134a causing a loss in system cooling performance

10.4 Options for Future Mobile Air Conditioning Systems

This report concentrates on vapour compression refrigeration cycle technology for vehicle air conditioning. The development status of other refrigeration technologies, like sorption or thermoelectric systems, are still far away from serial production and presently show very poor price competitiveness and poor system cooling performance and efficiency.

10.4.1 Passenger Car and Light Truck Air Conditioning

As seen in section 10.1, there is a large amount of regulatory activity related to passenger car MAC systems. The more recent focus is on the indirect impact of MAC vehicle emissions which is expressed for example in a paper by two European vehicle OEMs at the SAE ARSES meeting in July, 2010. An updated version of this was presented in European Commission workshop (Brussels, Oct 7th 2010). This may increase the importance of system efficiency as alternative low GWP refrigerant choices are made for MAC systems. This section covers the various refrigerants considered for use in passenger cars and light trucks that use refrigerant systems similar to passenger cars. All of the choices presented below have similar global warming impact, using the various methods of TEWI, LCCP, or LCA described in chapter 2 of this report. The comparison of the choices is often impacted more by the method and assumptions used than the actual performance.

10.4.1.1 Improved HFC-134a Systems

As the list of regulations grows limiting the use of HFC-134a, this may not be an option for mobile air conditioning systems in the future. HFC-134a systems with improved leakage rates and energy efficiencies might still be an intermediate option for some developing countries.

In the year 2006 about 20 percent of the total global refrigerant emissions (CFC, HCFC, and HFC) are from passenger car MACs including the emissions in production, use, servicing, and end-of-life. Looking at HFC refrigerant emissions alone, emissions of MAC systems contributed to the total HFC refrigerant emissions with a 60 percent share in 2006 (see Annex Banks and Emissions).

Significant research has been undertaken with regards to regular leakage rates of HFC-134a mobile air conditioning systems over the last five years. JAMA and ACEA conducted fleet tests, where the average leakage rate for these vehicles was 9.7-11.1 g/y. ACEA also sponsored laboratory investigations, which resulted in the development of the test procedure that is currently specified to meet the EU leakage regulation. Additional work was done by the SAE IMAC CRP [Improved Mobile Air Conditioning Co-operative Research Program] in the USA. The average leakage in the four systems evaluated by IMAC was 12.9 g/y. This project went further to evaluate alternative improved technologies and demonstrated that a 50% improvement in leakage rate is feasible based on three single evaporator systems and one dual system tested. The average result is similar to the ACEA/JAMA studies. Further work was done for the California Air Resource Board (CARB) analysing five different systems typical of those in high volume use in California and these laboratory results indicate predicted average field leakage of 8.9 g/y. From all this work one could draw the conclusion that much of the atmosphere loading that has been reported for HFC-134a is not due to regular leakage, but due to emissions from irregular leakage, improper service, inadequate end of life recovery and the service of CFC-12 systems with HFC-134a; much of this is controllable by improved service and enforcement of vehicle end-of-life reclamation procedures. A recent paper by Stella Papasavva, et al. does a good job of examining some low and high leak scenarios, summarising many of the other leakage studies. This analysis compares well when examining the sales of HFC-134a that has occurred in recent years. The table below summarises the analysis of leakage from different sources from this paper:

Leakage Type	Low Leak Scenario [g/y]	High Leak Scenario [g/y]
Regular Leakage Rates	13.6	15.0
Irregular Leaks	17.0	17.0
Service Leaks	4.4	7.8
End-of-Life leaks	11.1	50.0
Total	46.1	89.8

These results might also be modified based on the local rules for recovery and recycling. One difference to other older studies is that the assumption of average system charge is lower with this analysis [550 grams]. This has been the trend over the last ten years as vehicle OEMs have strived to reduce system size and charge to reduce mass and cost.

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. The SAE IMAC co-operative research group demonstrated that 30% reduction in energy consumption of the MAC system is possible. Many of these 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.

10.4.1.2 Carbon Dioxide (R-744) Systems

R-744 refrigerant charge amounts are typically reduced by 20-30% as compared to HFC-134a systems. The SAE CRP1234 performed a risk assessment of R-744 systems as compared to HFC-1234yf and determined that the risks are low and similar. R-744 demonstrated slightly higher risks than HFC-1234yf. SAE standards have been developed to cover service best practices, safety practices, and refrigerant purity of R-744. At present, the US EPA is considering the application of R-744 as a refrigerant for MAC with use restrictions under the US Clean Air Act's Significant New Alternatives Policy (SNAP) Program. The EPA indicated that the final ruling should be issued early in 2011.

R-744, with appropriate system design and control changes, has been shown to be comparable to HFC-134a with respect to cooling performance and total equivalent CO2 emissions due to MAC systems, and qualifies for use in the EU under the current impending regulation (Directive 2006/40/EC).

Currently, technical hurdles (reliability, leakage, NVH especially system noise) and commercial challenges (additional costs) exist that will require resolution prior to the implementation of R-744 as a refrigerant for car air conditioning.

At present, no OEMs or suppliers are working on R-744 as an alternative refrigerant solution. R-744 heat pumps are presented as possible heating systems for hybrid and battery driven electric vehicles. In comparison to electric resistance heaters (PTC heaters) which reduce significantly the vehicle driving range, heat pumps operate at a higher level of efficiency and offer the advantage of reducing only moderately the vehicle driving range.

10.4.1.3 HFC-152a Systems

Because of its flammability, HFC-152a would require additional safety systems. Refrigerant charge amounts in a direct expansion system could be reduced by 25-30% as compared to HFC-134a and with a secondary loop system, typically 50%. Industry experts have discussed using R-152a, but only in a secondary loop type system. The added costs, system weight increases and size constraints present obstacles to implementation. 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 refrigerant with the following use condition:

- 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.

HFC-152a in a secondary loop system has been shown to be comparable to HFC-134a with respect to cooling performance and equivalent CO2 emissions due to MAC systems and qualifies for use in the EU under the aforementioned regulations.

At present, no car manufacturer has selected HFC-152a as the refrigerant for MAC serial production due to technical or commercial issues related to the secondary loop system. Most development activity has been focused on using this refrigerant in a secondary loop system (SLS) as a means of assuring safe use. A secondary loop system utilises glycol and water as the direct coolant in the passenger compartment with this coolant being cooled under-hood by the refrigerant. Prototype vehicles have been demonstrated by several of the OEMs. At the 2010 SAE 2010 ARSES meeting, an USA OEM indicated they still have some development on-going with this alternative. An Italian OEM presented an EU financed project with R-134a SLS (not R-152a) not yet finalised development for mass production. 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 required for multi-evaporator installations since chilled coolant is circulated throughout the vehicle not refrigerant.

10.4.1.4 Blend Alternatives

In early 2006, several chemical companies announced new non-flammable refrigerant blends to replace HFC-134a in Europe. One was an azeotropic blend of CF3I and HFC-1234yf (2,3,3,3-tetrafluoroprop-1-ene). Two other formulations were zeotropic blends of HFC-1234yf, HFC-1225ze, HFC-1225ye, HFC-32, and minor concentrations of HFC-134a. These refrigerants were never classified by ASHRAE or proposed to the USEPA for SNAP approval. All the blend alternatives had a GWP less than 150 meeting EU requirements for low GWP refrigerants.

In 2006, the ACEA, VDA, SAE, and Japanese Automobile Manufacturers Associations assisted in co-operative efforts to evaluate these refrigerants. The refrigerant blends were withdrawn by chemical companies in the fourth quarter 2007 after discovering chronic toxicological effects and some stability effects.

Other low GWP blend alternatives are still under consideration for mobile air conditioning as well as for other stationary applications.

10.4.1.5 Hydrocarbons and Blends containing Hydrocarbons

In Australia and the USA, hydrocarbon blends have been introduced as drop-in refrigerants to replace CFC-12 and to a lesser extent for HFC-134a. The real number of cars that have been retro-fitted with such HC refrigerant blends is unknown but it seems to be a significant number. 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, providing safety issues are 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 systems. Some studies have been carried out using hydrocarbons in indirect systems (same system as the secondary loop system presented above for HFC-152a). Nevertheless, even with indirect systems, HCs are so far not seen by vehicle manufacturers as replacement fluids for mass-produced AC systems due to safety concerns.

10.4.1.6 HFC-1234yf Systems

The unsaturated HFC-1234yf, qualifies for use in the EU under the aforementioned regulations. Due to increased density of HFC-1234yf versus HFC-134a, it may be possible to reduce charge amounts. HFC-1234yf performance could also benefit from use of an internal heat exchanger. In this case, HFC-1234yf charge amounts could be expected to increase 5-15%. Manufacturers are working now on ways to reduce the system volume to reduce refrigerant charge further due to the cost of HFC-1234yf as compared to HFC-134a. HFC-1234yf is a new chemical which recently received EPA Pre-manufacture Notice (PMN) and is currently undergoing EPA SNAP review. The EPA is expected in the near future to issue their final rule on this substance and potentially associated use restrictions. It has been registered for high volume applications by REACH review/regulation in the EU. The high volume REACH application was submitted in February 2009. As with HFC-152a, use of any flammable substitute is subject to US state safety conditions on flammable refrigerants. The US EPA has reported that barriers to EPA SNAP listed refrigerants have been removed in all states.

The German Federal Institute for Materials Research and Testing (BAM) has investigated the flammability of HFC-1234yf. They found that in the case of HFC-1234yf leakages the probability to produce explosive atmospheres in the presence of hydrocarbons (less than 1%, which can occur in the engine compartment due to gasoline or cracked oil) is larger than that of HFC-134a leakages, but this explosive atmosphere is less than that which exists with pure hydrocarbons. They also found that the formation of hazardous amounts of HF when HFC-1234yf is exposed to ignition sources (like open flames and hot surfaces with temperatures of, for example, 350°C or 500°C) is critical. Their tests were carried out in comparison to HFC-134a which can also form HF when exposed to ignition sources. The BAM report states that HFC-134a is not as reactive as HFC-1234yf so that the hazards regarding HF formation is judged to be lower for HFC-134a than for HFC-1234yf. Vehicle manufacturers have explained that these tests were not done in a way that is typical of the under-hood environment as most of the tests were done in a sealed chamber. Only a few of these tests were actually done in a real car.

HFC-1234yf in a direct evaporation system has been shown to be comparable to HFC-134a with respect to cooling performance and equivalent CO2 emissions due to MAC systems with some system modifications, and qualifies for use in the EU under the aforementioned regulation.

In a global Cooperative Research Program administrated by SAE the refrigerant was tested in numerous laboratories concerning material compatibility, thermo-chemical stability, toxicity of refrigerant, and decomposition products, and flammability of the refrigerant. The results showed no compatibility and stability issues. A detailed Fault Tree Analysis (FTA) focussing on potential risk due to refrigerant flammability, toxicity and decomposition products has been completed. Based on the results it is concluded that HFC-1234yf is acceptable for use in mobile air conditioning from a toxicity perspective. Risk assessments have concluded there is an extremely low probability of ignition of refrigerant associated with HFC-1234yf during an accidental release. With the application of new safety standards, the specific requirements of HFC-1234yf are considered to maintain the safety of the vehicle at today's level.

In November 2009, all major global car OEMs have concluded after extensive testing and analysis that HFC-1234yf can be used as a global replacement refrigerant in future mobile air conditioning systems and it can be safely accommodated through established industry standards and practices for vehicle design, engineering, manufacturing, and service.

Currently, still hurdles (miscibility with oil, stability problems in the presence of small amounts of water and air in the air conditioning system, mixing with HFC-134a, additional costs) exist that will require resolution prior to the commercial implementation of HFC-1234yf as a refrigerant for passenger car air conditioning.

HFC-1234yf requires a different chemical process route in comparison to that of HFC-134a and a simple conversion of existing assets is not possible. Two North American chemical companies have announced the installation of a new HFC-1234yf production plant in order to supply market demand after regulatory approval. These companies now share patents on the use of this refrigerant in MAC systems and other manufacturers will have to purchase a license to manufacture.

One US American OEM has announced its intention to use HFC-1234yf in serial production vehicles from 2013. Other vehicle OEMs have expressed their interest in HFC-1234yf but have not yet officially announced a commitment to use HFC-1234yf as refrigerant for A/C serial production. OEM's indicate that they will design HFC-1234yf MAC systems in that way that these systems can safely be used with the refrigerant HFC-134a as well. This will affect the world-wide transition from HFC-134a to HFC-1234yf for MAC systems. The emerging choice for global car manufacturers' seems to be HFC-1234yf at this time. Based on the previous industry transition from CFC-12 to HFC-134a, it can be seen that HFC-134a will be used as a service refrigerant for 10-15 years after regions convert to HFC-1234yf.

10.4.2 Bus and Rail Air Conditioning

World-wide, approximate 50% of the bus and train fleet is still equipped with HCFC-22 systems. The rest use mostly HFC-134a or R-407C systems. Most new bus or train air conditioning systems are equipped with the refrigerants HFC-134a or R-407C. The only reported low GWP refrigerant activities are on-going fleet tests of R-744 systems in buses.

Currently, reliable leakage data on mobile air conditioning systems for short and long distance buses and railway vehicles is only reported for Europe, based on a study conducted on behalf of the European Commission. The study is based on 2,000 report forms on inspections of systems installed in short and long distance buses in Sweden. It empirically established the annual leakage rate for the use phase of the vehicles. In buses recharges or topping-off (gas-and-go) are carried out in relatively short service intervals to compensate for leakages whatever their nature. Such refills are recorded over a sufficiently long time and in appropriate detail in Sweden where annual inspection is mandatory for every installation with a refrigerant charge of HFCs of more than 3 kg.

Based on a statistical analysis of the recorded refill data, the study concludes that the average leakage rate of new MACs (2000 and newer) in diesel driven long distance buses is 1.20 ± 0.74 kg/y and is of the same magnitude as leak rates from MACs of new short distance buses with diesel drive, with 0.92 ± 0.40 kg/y. Taking into account that typical refrigerant charges of bus air conditioning systems are about 10 kg that means that the annual leakage rates of new buses are about 10 % of the original charge. However, as the buses age the leakage rates increase. Buses built before 2000 had leakage rates at least twice as high.

In comparison to short and long distance buses leakage rates of air-conditioning systems of rail vehicles are much lower, with 5% of the original refrigerant charge per year for the vast majority of the vehicles. Typical charge amounts of rail air-conditioning systems are higher than 10 kg per system. Depending on its length, a train might be equipped with several of these systems.

At present, no regulation exists worldwide on fluorinated greenhouse gases used as refrigerants for MAC systems in buses and trains. It is likely that the choice of refrigerant of passenger car air conditioning systems will influence the choice of refrigerant for air conditioning systems in buses and trains.

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Chapter 11

Refrigerant Conservation

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11 Refrigerant Conservation

11.1 Introduction

Refrigerant conservation may be viewed as both an effort to extend the life span of refrigeration and air-conditioning equipment by establishing efforts to recover, recycle, and reuse refrigerants. Refrigerant conservation also involves practices to ensure access to and proper disposal of so called “refrigerant banks” held in existing equipment. Refrigeration system leak elimination is fundamental to refrigeration conservation and should be emphasised through appropriate practices."

Recovery means the removal and temporary storage of refrigerant that has been removed from a system undergoing service or disposal. Recycling means the passing of recovered refrigerant through filters in order to make the refrigerant suitable for reuse. Such practice is generally not intended for used refrigerant that will be repackaged and placed back into commerce. Reclamation involves processes that remove impurities (such as non-condensables, moisture, or acid), in essence, reprocessing used refrigerant back to virgin specifications based on industry purity standards (e.g., AHRI Standard 700-2004 and SAE J1991). Whereas, destruction involves Protocol accepted technologies (typically thermal incineration) that effectively destroy ODS to established destruction removal efficiencies.

Conservation efforts should be placed on refrigerant recovery at the point of installation and continue throughout service and ultimate equipment end-of-life. Conservation is achieved by incorporating efforts of governments, equipment and chemical manufacturers, as well as equipment owners/operators to develop life cycle approaches aimed at reducing refrigerant emissions. Conservation efforts have also included taxation of banked refrigerants, required training of service personnel, limited access to ozone-depleting refrigerants, mandated service practices that reduce emissions by maintaining leak tight systems, recovery of refrigerant during equipment service and equipment end-of-life, established market for the resale and reuse of used refrigerants, and providing for the destruction of stockpiled or banked refrigerants.

The continuing phase-out (or as the case for many Parties to the Protocol a phase-down) on the consumption and production of ozone-depleting HCFC refrigerants has resulted in the use of zero ODP and in many instances low GWP refrigerants as a service fluid for existing systems via a retrofit or conversion from an ODS to a non-ODS refrigerant.

Recovery/recycling/reclaiming requirements have been implemented for a few years in different countries and have demonstrated proven results. These requirements have been established in conjunction with phase-out requirements of ODS refrigerants. However, many countries have yet to implement such requirements. Few countries have developed comprehensive conservation policies including recovery, leak tightness, and destruction of stockpiles.

Refrigerant emissions to the atmosphere are often called losses without identification of the cause. The specific identification of refrigerant emissions is necessary to limit fugitive emissions. Refrigerant emissions consist of the following:

- Fugitive emissions whose source cannot be precisely located
- Tightness degradation due to temperature variations, pressure cycling, and vibrations that can lead to unexpected and significant increases of leak flow rates
- Component failures from poor construction or faulty assembly
- Losses due to excessive equipment vibration
- Losses due to refrigerant handling during maintenance (e.g., charging the system), and servicing (e.g., opening the system without previously recovering the refrigerant)
- Accidental losses (e.g., natural disasters, fires, explosions, sabotage, and theft),

- Losses at equipment disposal that is due to venting, rather than recovering refrigerant at the end of the system's life

11.2 Recovery, Recycling, and Reclamation

The need to conserve or recovery refrigerant has led the industry to develop a specific terminology which is used in this section /ISO/:
- **Recover** means to remove refrigerant in any condition from a system and store it in an external container.
- **Recycle** means to extract refrigerant from an appliance and clean it 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** means to reprocess used refrigerant, typically by distillation, to specifications similar to that of virgin product specifications. Reclamation removes contaminants such as water, chloride, acidity, high boiling residue, particulates/solids, non-condensables, and impurities including other refrigerants with different boiling points. Chemical analysis of the refrigerant shall be required to determine that appropriate specifications are met. The identification of contaminants and required chemical analysis shall be specified by reference to national or international standards for new product specifications. Reclamation typically occurs at a reprocessing or manufacturing facility.
- **Destruction** means to destroy used refrigerant in an environmentally responsible manner.

11.3 Refrigerant Recovery and Recycling Equipment

The purpose of refrigerant recovery and recovery/recycling equipment is to help prevent emissions of refrigerant by providing a means of temporarily storing refrigerants that have been removed from systems undergoing service or disposal. Such equipment is used to temporarily store recovered refrigerant until the system undergoing repair is ready to be recharged or is prepared for disposal. Refrigerant recovery equipment may have the ability to store (recovery only) or the added capability of recycling (recovery and recycling) refrigerants. The temporary storage capability of the equipment prevents the release of refrigerants into the atmosphere that may otherwise exist if the refrigeration and air-conditioning equipment were opened to the atmosphere for service.

The use of refrigerant recovery and recycling equipment is the most essential means of conserving 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. Please note that due to incompatibility issues and the array of refrigerants used in different sectors that refrigerant recovery/recycling equipment intended for use with one type of air-conditioning system, such as motor vehicle air conditioners, may *not* be adequate to service air-conditioning and refrigeration equipment in the domestic, unitary, or commercial refrigeration and air-conditioning sectors. The types of refrigerants used in these sectors vary and all recovery/recycling equipment is not capable of meeting the same requirements. This important note should be made known to users to make certain that their recovery equipment is capable of handling the specific refrigerants that are used in the system. The specific identification of the equipment is important throughout its service, disposal or end-of-life.

Recycling equipment is expected to remove oil, acid, particulate, moisture, and non-condensable (air) contaminants from used refrigerants. These recycling performances can be measured on contaminated refrigerant samples according to standardised test methods /ARI 700/. Unlike reclaiming, recycling does not involve analysis of each batch of used refrigerant and, therefore, it does not quantify contaminants nor identify mixed refrigerants /Kau92/. Consequent restrictions have been placed on the use of recycled refrigerant, because its quality is not proven by analysis.

A variety of recycling equipment is available over a wide price range. Currently, the automotive air-conditioning industry is the only application that prefers the practice of recycling and reuse without reclamation. Acceptance in other sectors depends on national regulation, recommendation of the cooling system manufacturers, existence of another solution such as a reclaim station, variety and type of systems, and the preference of the service contractor. Reuse of recovered without strict adherence to refrigerant type-specific service fittings may result in unintended releases of mixed refrigerants. Mixed refrigerants are often costly to separate which may provide incentive for intentional release of cross contaminated refrigerants. Recycling with limited analysis capability may be the preference of certain developing countries where access to qualified laboratories is limited and shipping costs are prohibitive. For most refrigerants there is a lack of inexpensive field instruments available to measure the contaminant levels of reclaimed refrigerant after processing. At the same time the use of reclamation equipment which provides maximum separation of oil, acid, hard particle contaminants, moisture and air is to be preferred in countries where verification of processed refrigerant by proper chemical analysis is available.

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 exist for recovery of flammable refrigerant. Testing standards have been developed to measure equipment performance for automotive /SAE/ and non-automotive /ISO/ applications. Although liquid recovery is the most efficient, vapour recovery methods may be used alone to remove the entire refrigerant charge as long as the time is not excessive. Excessive recovery times should be avoided, since extended recovery time periods may increase the service call time of technicians. Extended service call times may limit the number of service calls that technicians can perform, which in turn may limit the practical usage of recovery equipment. In order to reach the vacuum levels that are required in some countries for larger systems, vapour recovery will be used after liquid recovery /Clo94/. Performance standards for refrigerant recovery equipment are available for service of both motor vehicle air conditioners (e.g., SAE J1990), and stationary refrigeration and air-conditioning systems (e.g., ARI Standard 740-1998 and as are AHRI Standards for certifying. Adoption of such standards as a part of common service procedures should be adopted by regulating authorities.

11.4 Technician Training and Service Certification

An increasing number of governments have realised the need for technician certification programs and /or certified companies to ensure proper handling of regulated products. Training requirements may differ depending on the type of equipment being serviced. Training programs should be structured on the type of equipment that the technician intends to service. For example, the level of training for the service of residential refrigerators should differ from that for centrifugal chillers.

HFCs blends have seen increased usage in multiple end-uses sectors. It is imperative that technicians are properly trained in the proper use and handling of all refrigerant alternatives.

Hydrocarbons have wide acceptability in many small appliances. As a means of making certain that only trained personnel have access to refrigerant, many countries have implemented sales restrictions on refrigerants to certified technicians.

In the U.S., a technician certification program has been established. This program is for individual technicians, as well as companies, that perform maintenance, service, repair, or disposal of refrigerants reasonably expected to release those refrigerants into the atmosphere. The program requires different levels of certification depending on the type of equipment that the technician intends to service or dispose: motor vehicles; small household appliances; or low-pressure, high-pressure, and very high-pressure appliances. The U.S. emphasises this technician certification by limiting the sales of ODS refrigerants to certified technicians.

In many countries strict training and certification requirements for refrigeration technicians who handle refrigerant gases are already a legal requirement. {Insert text on the EU F-Gas Regulations (EC 842/2006) and the associated Regulation for training and certification of individuals and companies (EC 303/2008). The F-Gas Regulations were introduced from 4 July 2007. Member states were required to establish training and certification requirements for individuals by 4 July 2008 and companies were required to be certified by 4 July 2009. In addition the EU ODS Regulations (EC 2037/2000) were re-cast as Regulation EC 1005/2009 with effect from 1 Jan 2010.

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In Japan, obligations of recovery operators are specified by the Fluorocarbons Recovery and Destruction law. As one of the obligations, recovery operators must be authorised as "registered recovery operators." Recovery operators must also have technicians certified by a government recognised authority. The technician training and certification program was started in 1994 by the concerned associations of installers, equipment manufacturers and refrigerant manufacturers. Since the program's inception, the training seminars have been held for the staff of recovery operators throughout the country. The total number of technicians who have passed the final examination and received the certificate during the past 12 years reached nearly 50,000.

In Poland, a total 1,840 persons were trained, out of which nearly 94% passed the final examination and received the "Green Card". This certificate ascertains the serviceman's ability to repair and execute the maintenance of refrigeration and air-conditioning equipment in accordance with all the ecological requirements. Those who successfully pass the training and certification procedure acquire important information (the new types of ecological refrigerants, the main international agreements aiming at protecting the ozone layer) /BU01/.

One key element of RMP and RMP-update programs accomplished in countries of Eastern Europe, Caucasus and Central Asia was to initiate training in Good Practices to reduce the CFC demand through introduction of proper methods for leak reduction and recovery. As an example, Republic of Georgia improved training capacities of vocational schools that educate technicians in refrigeration or air conditioning field through upgrading of vocational schools curriculum and equipment and competency of teachers.

Belize reported to the UNEP in 2004 that their CFC consumption is below the level required in the approved action plan. Since its implementation, the National Ozone Unit has successfully implemented a Refrigerant Management Plan, enacted a comprehensive legal framework to address ozone depleting substances, conducted a public awareness programme, and reduced national CFC consumption by half, from 24.89 ODP tonnes in year 1998 to approximately 12 ODP tonnes in 2005. The country's success can be partially attributed to its establishment of a certification and licensing scheme for refrigerant technicians.

11.5 Refrigerant Reclamation, Separation, Destruction

11.5.1 Reclamation and Separation

One means of conservation is the establishment of a reclamation scheme. Reclamation involves the recovery and reclamation of used refrigerant back to virgin specifications. Once reclaimed, used refrigerants are repacked and sold to new users. Reclamation is essentially, a market-based 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 on with refrigerant supply companies to support the take back of used refrigerant. Many service establishments (particularly for motor vehicle air-conditioning) will not be able to afford storage for recovered refrigerants awaiting reclamation. The cost of sending small quantities of recovered refrigerant to reclamation facilities is a disincentive to reclamation efforts. Such disincentives promote venting 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.

Reclamation practices, which process used refrigerant back to near virgin specifications, are necessary to protect the quality of the refrigerant stock as well as the equipment containing the refrigerant. Likewise, reclamation also extends the lifespan of the refrigerant and decreases the dependency on virgin refrigerant by placing it back into service and prolonging the use of used refrigerants.

Countries that have implemented mandatory reclamation requirements have found incremental increases in the amount of refrigerant reclaimed. France, where reclaimed refrigerant totals have been gathered, shows an evolution in the efficiency of the recovery program /SAU96/. In 1992, without any regulation, 200 metric tonnes of recovered refrigerant (CFCs & HCFCs) were reclaimed. In 1993, after making recovery mandatory and carrying out a deposit-refund scheme, the quantity grew to 300 tonnes and the number of refrigeration companies concerned doubled from 200 to 400 out of 2500. In this example government incentives were necessary to reach full development of recovery schemes. It also shows that making recovery a habit requires some time.

An extensive survey conducted in Australia /BEN01/ traced the paths of imported refrigerants through the sales and application chain. The survey assessed the amount and type of product that may be placed back into service, and concluded that service contractors are recovering approximately 400 MT of product (CFCs and HCFCs) annually from systems during servicing.
Reclaimed refrigerant refers to refrigerant which has been processed and verified by analysis to meet specifications that are similar to newly manufactured product specifications, such as those provided in ARI 700 /ARI700/. There is technically very little difference between virgin and reclaimed refrigerant. One exception is the allowable content of specific hazardous or toxic components that result from the manufacture or decomposition of virgin fluorocarbons.

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 often has the support of equipment manufacturers who maintain guarantees on their equipment. One advantage to reclaiming is that the measurements of refrigerant, which have actually been recovered, are easily obtained. However, reclamation does require a costly infrastructure, which may only prove viable when potential for financial return of recovered refrigerant is sufficient to overcome the initial investment of the company performing reclamation.

Mixed refrigerants, meaning refrigerants that are cross contaminated during the recovery process, are of concern due to their negative impact on systems' performances, possible equipment damage if reused in another system, and the high cost for their disposal. This condition of mixture can be caused by chemical reactions such as in a hermetic compressor motor burnout, but more likely by bad service practices. The following steps can be taken to minimise the probability of mixing refrigerants:

1. Properly clean recovery units, including all hoses and cylinders in accordance with manufacturer's suggestions or dedicate a piece of recovery equipment to equipment suspected to contain mixed refrigerant;
2. Test and identify suspect refrigerant (for example, by using a refrigerant identifier) before consolidating into larger batches and before attempting to recycle or reuse the refrigerant;
3. Keep appropriate records of refrigerant inventory;
4. Label refrigeration and equipment systems with the identity of their refrigerants, especially upon retrofit of older systems to new refrigerant; and
5. Mark cylinders used for recovered and/or recycled refrigerants.

It is very difficult to determine the presence of mixed refrigerants without a laboratory test. If the nature of the refrigerant is in doubt, the saturation pressure and temperature may be checked and compared with published values. However, this method may be rendered unreliable by inaccurate pressure gauges or contamination by non-condensables. A thorough review of the service history, if existing and an understanding of the current problem may provide additional insight. Field instruments capable of identifying R-12, R-22 and R-134a refrigerants at purity levels of 97% or better are now available.

In automotive applications where R-12 and R-134a dominate the market, standards have required separate recycling equipment. In addition they have adopted unique vehicle service ports, service hoses, and service equipment fittings to prevent inadvertent mixing. Hoses have separate connectors for R-12 and R-134a cooling systems and must be properly labelled /SAE/.

The development and wide distribution of replacement refrigerant blends has increased the risks of mixtures, and the complexity of separating them. Currently, the high cost of refrigerant blends has limited the profitability of separation.

The U.S. has mandated that refrigerant reclaimers return refrigerant to the specifications (including the purity level) specified in ARI Standard 700 and verify the specifications using the laboratory protocol set forth in the same standard. In addition, reclaimers must release no more than 1.5% of the refrigerant during the reclamation process and must dispose of wastes properly. This mandate limits the number of persons allowed to reclaim refrigerant, and reinforces the U.S. mandate that used refrigerant be reclaimed prior to resale to a new owner.

Japan reported that 690 tonnes/year of CFCs are recycled or reclaimed for reuse in refrigeration and air-conditioning equipment. This represents 56% of the total estimated recovered quantity of 1230 tonnes/year.

The United States government has mandated reclamation and certification of refrigerant reclaimers since 1993. The U.S. has seen an increase in the reclamation of HCFC refrigerants, but a decline in the amount of CFC refrigerants reclaimed due to the phase-out of the manufacture of CFCs in the U.S.

Care should be taken to not cross-contaminate recovered refrigerant. Refrigerants that are combined after recovery, such as hydrocarbons with CFC refrigerants, will require separation (normally via distillation) prior to reclamation. High costs and the lack of availability of separation facilities provide disincentives to the proper recovery of refrigerant.

11.5.2 Destruction

During the past four years, since the 2006 Assessment, increased interest in the potential environmental benefits of destruction of ODS refrigerant banks has occurred. This is due in part to the recognition of environmental benefit gained from the potential ozone and climate benefits from the avoided emissions of ODS still remaining in refrigeration and air conditioning equipment world-wide. As a result of these benefits, global carbon trading markets have emerged that might provide incentives for early retirement of “banks” of ODS in equipment. There is potential for this equipment to be retired or replaced with more energy efficient equipment with lower refrigerant charge sizes.

ODS refrigerants (specifically CFCs) have high GWPs in addition to their ozone impacts. 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 (i.e., Clean Development Mechanism or CDM) or national and regional level (i.e., European Union Emission Trading Scheme of EU ETS), those participating countries and/or states 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 targets or commitments.

Presently, the voluntary market operates outside of the compliance market where individual companies or organisations voluntarily commit to actions and projects to offset their GHG emissions.[7] Currently, only the voluntary carbon market has established standards for ODS destruction as carbon offsets projects. To date, there are three voluntary standards that recognise and/or have established project protocols to provide carbon credits for ODS destruction. Two installation types are available to destroy CFCs:

(1) Public or commercial installations are accessible, in return for payment. These installations are often capable of treating several families of chemical products; and

(2) Private facilities that are designed for the internal needs of ODS manufacturers. These facilities are not always adapted to the needs of outside groups. Normal conditions where recovery, recycling, and reclamation are prevalent should lead to fairly low requests for destruction in the refrigeration industry. This is especially the case where the demand for CFCs will remain high. A need for destruction facilities may be created in instances where regulations forbid the use or export of CFCs.

The general method of destruction is based on incineration of refrigerants and on scrubbing combustion products that contain particularly aggressive acids, especially hydrofluoric acid (HF). 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.

Belgium, Brazil, Finland, Japan and Switzerland possess the rotary kiln incineration technology to destroy CFC's, halon, and HCFC's. These incineration facilities do accept substances for destruction from outside countries. Currently, there is little experience with rotary kiln incineration within North America. These facilities are expensive to build, maintenance costs are high, and the expense is usually only justified where a variety of hazardous wastes must be destroyed.

Destruction is a viable alternative for handling unwanted banks of refrigerants. There is currently a lack of commercially available companies that destroy refrigerants. As A5 countries start their phaseout programs, commercial opportunities for destruction may become available. Australia, United States, and Japan currently have the capacity to destroy recovered ODS. However, this trend appears to be changing with increased interest in both voluntary and regulatory ODS destruction initiatives.

11.6 Equipment Design and Service

Refrigerant emissions from cooling systems must be minimised to protect the environment. Fortunately, conservation is consistent with good functioning and efficiency of air-conditioning and refrigeration systems. Cooling systems are designed as sealed units to provide long term operation. Conservation is affected by the design, installation, and service of the refrigerating system. Guidelines and standards are being updated with consideration to environmental matters and improved conservation.

Conservation is defined by an emission rate, which can be measured and limited. Cooling system manufacturers have defined minimum tightness requirements to guarantee permanent operation during defined periods. The American Society for Testing and Materials (ASTM) E 479 "Standard Guide for Preparation of a Leak Testing Specification" serves as a manufacturer's reference document. The standard has a large influence on the maximum allowable leakage flow for a cooling system based on the period during which the system must operate without refrigerant recharge. The refrigerant

[7] In the United States, the state of California plans to pursue a compliance market that would accept credits generated from a voluntary carbon market that includes credits for ODS destruction projects.

quantity may be lost by leakage during this period without significantly affecting the operational efficiency of the system.

11.6.1 Design

Every attempt should be made to design tight systems, which will not leak during the life span of the equipment. The potential for leakage is first affected by the design of the system; therefore, designs must focus on minimising the service requirements that lead to opening the system. Manufacturers select the materials, the joining techniques, and service apertures. They also design the replacement parts and provide the recommended installation and service procedures. Manufacturers are responsible for anticipating field conditions and for providing equipment designed for these conditions. Assuming that the equipment is installed and maintained according to the manufacturer's recommendations, the design and proper manufacturing of the refrigerating system determines the conservation of the refrigerant over the intended life of the equipment.

Among recommendations for conservation, leak tight valves should be installed to permit removal of replaceable components from the cooling system. The design must also provide for future recovery, for instance, by locating valves both at the low point of the installation and at each vessel for efficient liquid refrigerant recovery.

11.6.2 Charge Minimising

Minimising the refrigerant charge will also reduce the quantity of possible emissions that could be emitted during catastrophic leak events. Historically, little attention has been given to the full charge of equipment, thus, its quantity is not often known (except for small equipment in which the units are shipped charged with refrigerant from the original equipment manufacturer). It should be noted that there are negative effects of charge minimisation, for example the system may be more sensitive to a charge deficit leading to an increase in energy consumption.. There is a balance to ensure good efficiency despite minor leakage and reduced direct emissions.

Overcharging of equipment is common, 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. For such equipment, field charging is often continued until the evaporator supply is considered satisfactory. Without the check of weighing the charge, installation 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.

11.6.3 Installation

Proper installation of refrigerating systems contributes to the proper operation and conservation during the useful life of the equipment. Tight joints and proper piping materials are required. Proper cleaning of joints and evacuation to remove air and non-condensable will minimise the future service requirements. Proper charging and weighing techniques, along with careful system performance and leak checks, should be practised during the first few days of operation. The installer should also seize the opportunity to find manufacturer defects before the system begins operation. The installation is critical for maximum conservation over the life of the equipment.

11.6.4 Servicing

Service must be improved in order to reduce emissions. Such improvement, however, depends in part on the price end-users agree to pay, as emission reduction has always proved, so far, more expensive than topping-off cooling systems with refrigerant. It is necessary to make end-users understand that their previous practice of paying to top-off systems must cease, and those funds must be spent on improved maintenance. It is to be noted that such a step has already been taken in some cases, especially in countries like the U.S. where an annually increasing tax on the quantities of ozone-depleting refrigerants that remain in stock at the end of the calendar year makes conservation or conversion to ozone-friendly refrigerant alternatives more cost-effective.

Technician training is essential for the proper handling and conservation of refrigerants. Such training should include information on the environmental and safety hazards of refrigerants, the proper techniques for recovery, recycling and leak detection, and local legislation regarding refrigerant handling (if applicable).

Refrigerating systems must be tested regularly to ensure that they are well sealed, properly charged, and operating properly. The equipment should be checked in order to detect leaks in time and thus to prevent loss of the entire charge. During maintenance and disposal of the system, refrigerant should be isolated in the system or recovered.

The technician must study the service records to determine history of leakage or malfunction. The technician should also thoroughly check for leaks and measure performance parameters to determine the operating condition of the cooling system. The technician will want to determine the best location from which to recover the refrigerant and assure that proper recovery equipment and recovery cylinders are available. The existence of a maintenance document enables the user to monitor additions and removals of refrigerant with recovery as well as the searches and repairs of leaks.

11.6.5 Reduction of Emissions through Leak Tightness

Leak detection is a basic element, both in constructing and servicing 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, and during regularly scheduled maintenance of equipment.

There are three general types of leak detection: 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 alerting operators to changes in equipment performances (see Appendix 1).

Governments should take a sector based approach aimed at adopting service requirements that reduce use and emissions of ODS. The major refrigeration and air-conditioning sectors include the following:

Refrigeration sectors include:

- Residential applications-refrigerators, freezers, window air-conditioners
- Commercial refrigeration-convenient stores, warehouses, supermarkets, and grocery stores
- Large size refrigeration-industrial process refrigeration systems used in an array of manufacturing and food processing applications
- Transport refrigeration-refrigerated transport vehicles
- Unitary air-conditioning-residential and light commercial air conditioners and heat pumps
- Chiller/comfort cooling application-chillers
- Mobile air conditioners.

Various countries have demonstrated improvement in the air-conditioning and refrigeration equipment manufactured over the past few years. The new equipment has been designed to be tighter than air-conditioning and refrigeration equipment previously manufactured. Existing 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 in response to growing environmental, regulatory, and economic concerns associated with refrigerant emissions.

For instance, research performed by the U.S. EPA indicates that the reduction in leak rates in the U.S. has been most dramatic in comfort cooling chillers. Leak rates have been lowered from between 10 and 15% per year, to less than 5% per year in many cases, through design changes.

In the Netherlands, the results of some earlier monitoring projects have been previously reported. Those earlier studies involved a large sample of transport refrigeration units and commercial refrigeration systems. Earlier refrigerant emissions were compared over time for units built before and after introduction of the Dutch regulatory program. Comparison found that in the case of transport refrigeration, the refrigerant emission rate was reduced from an average of 6% to 3% of the charge per year. For selected commercial supermarket systems the average emission rate was reduced from 15% of refrigerant charge to 3%, on an annual basis. In another monitoring project, large refrigerating systems (average charge of 2 metric tonnes) up to 10 years old were inspected during 1994-1996. The average annual leakage rate was found to be 8.6%. Information on similar but older equipment built over the period 1986-1992 indicated an average leakage rate of 12.2% The report concluded that the reductions in refrigerant losses experienced for the more recently constructed systems was attributable to the more stringent technical requirements specified under the 1994 Regeling Lekdichtheidsvoorschriften Koelinstallaties (RLK) technical requirements for refrigeration equipment.

More recent monitoring data has been gathered from the detailed National Survey of Refrigerant Flows NOKS study which was conducted for the government to investigate the volumes of CFCs, HCFCs, and HFCs being used throughout the country for refill purposes in all application sectors (excluding auto air-conditioning and marine installations). Relating this data directly to refrigerant emissions, it was concluded that the average annual leakage rate for the reference year 1999 was 4.8% (equivalent to approximately 615 tonnes nation-wide). Furthermore, the NOKS study revealed that the emissions were attributable to only 8% of the installations, and 92% had no emissions that year /IEA02/.

11.7 Direct Regulation as a Means of Refrigerant Conservation

Refrigerant emissions are already regulated in a number of countries, mostly as a component of the implementation of the CFC phase-out. Government actions such as introducing and enforcing direct regulations or legislation are necessary to ensure refrigerant conservation. Existing regulations include service technician certification, required equipment service and disposal practices, leak tightness requirements, restrictions on the sales of refrigerants and certification schemes for service companies. For purposes of refrigerant conservation, direct regulation may include governmental efforts establishing the following:

- Mandatory service and disposal practices for air-conditioning and refrigerating equipment
- Certification programs for air-conditioning and refrigerating equipment and recovery/recycling equipment
- Required training and/or operator certification programs for service technicians
- Restrictions or limitations on who can purchase or sell ODS refrigerants

As is the case for financial incentives, care should be taken to set standards that maximise conservation without being unduly burdensome. Direct regulations establish "floor" standards and practices across industry, and training and/or certification requirements increase general knowledge of both how and why to contain the refrigerant. However, these regulations are often less flexible than financial incentives, and more difficult to develop and enforce, given the large quantities and wide distribution of air-conditioning and refrigerating equipment.

Article 2 countries have taken a number of steps aimed at reducing emissions of ODS refrigerants via direct regulation. Some regulations include the restriction of the supply of refrigerants through limits in imports and sales. As well as requirements for emissions reduction practices, during the service and disposal of appliances, and mandating the recovery, recycling, and reclamation of used refrigerant.

Such restrictions may also have negative impacts, such as the creation of illegal markets for refrigerants, fraudulent business practices by service companies, refrigerant distributors, and appliance recyclers. The financial impact of enforcing such regulations presents another possible negative impact. Such regulations should not be attempted unless the governmental body is willing to invest in the long-term enforcement of the regulations and strict prosecution of those who violate such regulation.

Countries with established markets have similar national programs and policies in place for the recovery, recycling, and reclamation of refrigerants, but individual approaches to organisation and control mechanisms, responsibility levels, regulatory legislation, financing arrangements, and operating procedures vary considerably from one country to another.

In addition to phasing out production of ODS under the Montreal Protocol, governments chose to reduce ozone-depletion by strongly encouraging conservation through different means. In the first years, research and development (R&D) programs were funded to identify emission sources and develop conservation measures. Other R&D programs were developed to evaluate efficient recovery, recycling, and reclamation equipment. Governments also worked with industry groups to develop recovery techniques, and establish standards for the recovery and reuse of ozone-depleting refrigerants.

Information dissemination was another means used to educate the public on the environmental health and safety issues associated with ozone-depletion. These efforts created a general knowledge of both how and why measures should be taken to contain used refrigerant; thus, these efforts improved conservation where ignorance of environmental issues was the primary problem.

Direct regulation also became a point of emphasis for governments. Many governments improved conservation through direct regulation. Governments have found that adoption of industry standards and R&D results are easily incorporated into regulation as a means of mandating refrigerant conservation. While governments have found direct regulation to be a successful means of conservation, it requires a strong commitment to legal or financial enforcement incentives in order to reach significant results.

11.7.1 Financial Incentives

Financial incentives can encourage conservation by making emissions more costly for users or by making conservation efforts financially beneficial. They may include sales taxes on refrigerants at the point of purchase or import across the country's border, deposit-refund schemes to discourage disposal of refrigerant containers, and/or tax breaks for investing in recovery/recycling equipment or other refrigerant conservation technologies.

In the U.S., the manufacture or import of virgin CFCs is prohibited. In addition, the U.S. annually increases the CFC-excise tax that has been effective in increasing conservation of CFC refrigerants and making retrofits to lower ozone-depleting substances more financially appealing. The tax when combined with the phase-out of the manufacture of CFCs has forced an increase in the recycling and reuse of used CFC-refrigerants. This increase in the recycling and reuse of used refrigerant has addressed a significant source of emissions by inflating the costs of imported CFCs; thus, making it less expensive to reuse CFCs or retrofit equipment to refrigerants with lower ozone-depleting potentials than to buy and use imported CFCs.

Deposit-refund schemes involve collecting a deposit when a product is purchased and paying a refund when the used product is returned. The refund serves as an incentive to the user to collect and return used refrigerants. The deposit not only finances the refunds, but also encourages more careful handling of the product by increasing the cost of new refrigerant. Two issues must be faced in establishing a deposit-refund system: (1) how (or whether) refrigerants are traced back to the original manufacturer for collection of the refund and (2) how refunds for the bank of refrigerants in existing equipment, for which no deposit was collected, can be financed. Industry-sponsored deposit-refund schemes in Australia, Denmark and France resolved these issues by setting up a centralised fund for deposits.

Tax breaks for investing in refrigerant conservation equipment and technologies are another government means of coercing conservation. Since tax breaks that are linked to specific technologies have the potential to limit technology that enters that marketplace, they can leave the market less flexibility than either sales taxes or deposit-refund schemes. Care should be taken to set taxes, tax breaks, and deposit-refund amounts at levels that will maximise conservation without being unduly burdensome. In addition, governments using financial incentives must work to prevent the rise of a black market for untaxed, and therefore, less expensive refrigerant. Left unchecked, such a market will eventually undermine the environmental incentives implemented by the incentive. In order to limit the extent of black market sales, such tax efforts should not be attempted without a strong enforcement component with the power to fine and or imprison violators.

Governments may find that financial incentives are easier and more flexible to develop than direct regulations. Financial incentives allow markets to find the most cost-effective conservation measures and maintain the incentive to innovate. Moreover, governmental financial incentives become more important as refrigerant prices drop. Such is the case for HCFCs and HFCs in many Article 2 countries, and for CFCs in many Article 5 countries, because higher refrigerant prices tend to encourage conservation, while lower prices tend to discourage it. However, it can be difficult to set financial incentives at a level that encourages conservation without being unduly burdensome. Financial incentives will be undermined if a black market for imported refrigerants is allowed to operate.

11.7.2 Required Service Practices and Leak Tightness

In the European Council (E.C.) Regulation no. 2037/2000 on substances that deplete the ozone layer /EC00/, the E.C. requires that all precautionary measures practicable shall be taken to prevent leakage of CFCs and HCFCs; however, the member states may define their own minimum qualification requirements for the servicing personnel involved. An annual leak tightness inspection is made mandatory for installations containing CFCs or HCFCs. Three national programs are summarised below, but regulations also exist in other European countries such as Denmark, Germany and Sweden.

The Netherlands described the conditions for the leak tightness of systems in a decree of December 18, 1994 /DR94/. This text is characterised by detailed requirements for materials and components, design, installation, machinery rooms, tests and maintenance, inspection. It contains requirements dealing with the maintenance, the leak tightness controls, and the installation inspection depending on the charge of refrigerant. The occurrence of leak tightness is also specified: once a year for charges under 3 kilograms, once every 3 months for more than 30 kg, once a month for more than 300 kg. Machinery rooms are mandatory for charges of more than 300 kg, and an area monitor is required when the charge is more than 1,000 kg. The area monitor sensitivity (100 ppm), the minimum number of probes (5), and the installation of the probes (at least one at floor level, at least one in the ventilation exhaust duct) are specified. Certified operators who are equipped with leak detectors of five ppm sensitivity perform the leak tightness tests. Before commissioning new installations or changing refrigerant, leak tightness test must be performed at the maximum working pressure of the equipment.

The United Kingdom Environmental Protection Act of 1990 mandates several measures for the conservation of CFC, HCFC, and HFC refrigerants. These include a prohibition on venting refrigerant during service or decommissioning of systems, a prohibition on adding refrigerant to a leaking system before thoroughly examining the system to locate and repair the leak, a requirement to use a vacuum pump to evacuate moisture and non-condensables from a system before adding refrigerant, a requirement to use a refrigerated purge unit (as opposed to manual purging) to purge non-condensables from the system, and a general requirement to limit emissions during a number of procedures for system servicing and operation.

The Clean Air Act Amendments of 1990 mandate leak repairs, In the U.S., refrigerant emissions are controlled by direct regulations requiring recovery, recycling, and reclamation. The U.S. has also created regulations mandating repairs of equipment that leak above allowable rates. U.S. regulations require that appliance manufacturers provide a service aperture to expedite recovery of refrigerant. As for servicing, before repairing or disposing of air-conditioning and refrigeration equipment, technicians must recover the refrigerant using government approved refrigerant recovery equipment. The percentage of refrigerant that must be recovered or the level of evacuation that must be achieved varies depending upon the type of equipment being serviced. For leak repair, the U.S. regulations require owners of equipment containing charges of more than 50 pounds to either repair, retrofit, or replace their refrigeration and air-conditioning equipment when they leak in excess of an applicable maximum allowable rate. These maximum annual allowable rates are 35% of the charge for commercial and industrial refrigeration and air-conditioning applications and 15% for other applications. To track leak rates, owners of air conditioning and refrigeration equipment with more than 50 pounds of charge must keep records of the quantity of refrigerant added to their equipment during servicing and maintenance procedures.

11.7.3 Restrictions on the sales and imports of ODSs

The U.S. has limited the sales of refrigerant to technicians who have been certified in order to improve the level of awareness against refrigerant emissions. In addition to this sales restriction, the government has placed conditions on the manufacturers of substitute refrigerants. New non-ODS refrigerants, which replace CFCs, must be authorised for specific industry sectors and end-uses. The government also mandates that manufacturers of new refrigerants place unique fittings on containers to prevent unintended mixing of different refrigerants, and subsequent emissions resulting from the mixtures.
The U.S. also restricts the amount of imported ODSs into the country. Only used class I ODSs (primarily CFCs, halons, and methyl bromide) are allowed for U.S. import. The U.S. has banned the import of virgin ODS, with the exception of pre-approved essential uses. Prospective importers must petition the U.S. EPA for approval prior to transport from the country of origin.

Several countries have implemented regulations that require customs officers to complete ODS training programs. The training of customs officers in detection and identification methods helps to control trade in ozone-depleting substances. For instance, the Democratic Republic of Congo and Jordan have recently both taken significant steps to increase their phase-out of ozone depleting substances. These countries now require training programs for customs officers as well as the technicians that handle the refrigerant. Other countries such as Oman, provide training workshops for their customs officers in order to raise the level of awareness regarding the dangers of ODS and methods of refrigerant conservation.

The training of customs officers and identification of refrigerants are considered as the most important part of CFC phase-out program in the countries from Eastern Europe, Caucasus and Central Asia. For instance 115 customs officers have been trained and equipped with Refrigerant Ultima Identifier in

Armenia. In Republic of Tajikistan 98 customs officers have been trained in detection and identification methods and 30 check-points have been equipped with Neutronics RI - 2002PA identifier. The same figures for Uzbekistan are 301 trained customs officers and 21 units of portable identifier ID 1000 used in the country. In Republic of Georgia a special laboratory equipped with Complete Gas chromatograph and Tasco TA400 refrigerant analyser helps customs officers to identify CFCs, HCFCs, HFCs and a wide range of their blends.

Restrictions are also placed on new refrigerant blends, which must be authorised by the U.S. EPA prior to introduction into interstate commerce. Manufacturers of refrigerant blends that are anticipated to replace ODSs are required to submit data to EPA on the health and safety of such substitutes before they can be legally sold in the U.S.

11.8 End-of-life

Safe disposal requirements should mandate disposal of ODS components in residential appliances such as refrigerant and foam. Many household refrigerators and freezers produced prior to 1994 rely on CFC refrigerants that destroy the earth's protective ozone layer, which in turn leads to adverse human and environmental health effects (see text box). After 1996, most newly manufactured household refrigerators and freezers contain hydrocarbon refrigerants or ozone friendly refrigerants (HFCs). Similarly, oil in the compressor is likely to be contaminated with refrigerant, be it CFC or HFC, so it too must be treated carefully. In addition, the foam blowing agents in most in-use refrigerators/freezers also use ozone depleting substances. Ultimately, if these foams are not properly recovered from appliances and properly disposed, additional ODS will be released to the atmosphere, leading to further destruction of the ozone layer. Some of the newest refrigerators/freezers use HFC blowing agent, which can lead to GHG emissions if not properly recovered at end of life. Further, raw materials that make-up refrigerators and freezers—including steel, plastic, glass, and rubber—can all be recycled to reduce the amount of waste that would otherwise be put in a landfill and save energy that would otherwise be required to produce virgin materials. Finally, some chest freezers manufactured prior to 2000 may contain a mercury switch. Mercury is toxic and causes a variety of adverse health effects, including tremors, headaches, respiratory failure, reproductive and developmental abnormalities, and potentially, cancers. Also, older appliances may contain PCB capacitors. PCBs can lead to adverse effects ranging from minor skin irritations, to reproductive and developmental abnormalities, to cancers in humans and wildlife.

Efforts should be taken to make certain that companies involved in the disposal chain are not allowed to destroy.

11.9 Examples of Conservation Approaches

11.9.1 Africa

The refrigeration and air-conditioning sector plays a vital role in many of Africa's economies. The predominant sectors in these economies are the agriculture, tourism, and fishing industry. As a result, refrigeration is necessary to preserve perishable foodstuffs that are both exported abroad and are necessary for local consumption. Likewise, the tourist industry increases the demand for air-conditioning, as visiting tourists prefer comfortable environments.

There has been a reasonable reduction in the consumption of ODS in most African countries. Certain countries have undertaken measures to put a partial or total ban on sales of CFCs. Others have put regulations in place to control imports of new CFCs and CFC-based equipment. It is obvious that existing refrigeration equipment will need servicing and maintenance for a long period of time. However, there is not enough training of refrigeration technicians. In Africa, a well-developed educational program for technicians is non existent, thus, those employed in the refrigeration industry do not receive proper instruction needed to comply with standards Examples from other countries have shown that well-trained technicians could reduce the consumption of CFCs in the refrigeration sector by up to 40%. The other main problem for Africa in its bid to phase-out the CFCs is the influx of used refrigeration equipment and cheap CFCs, some of which are obtained through the Black Market.

Many countries, including but not limited to Benin, Chad, Egypt, Mozambique, Uganda, and Zimbabwe, have established refrigerant recovery and recycling programs that train technicians and make refrigerant recovery equipment and service equipment available. These national programs are responsible for the phase-out of tonnes (ODP-weighted) of CFCs from stationary and mobile sources.

For example, Kenya has banned service on refrigeration and air-conditioning equipment by anyone other than government certified service technicians. The government has also established centralised refrigerant recycling stations. The government has promoted the availability of portable refrigerant recovery units that are affordable for service technicians. The refrigerant recovery units were donated to select workshops that have trained technicians on staff. The government reserves the right to repossess the equipment and ban the technicians from the trade if it is found that good service practices are not employed.

Ghana ratified the Montreal Protocol on 24 July 1992. A Country Program was submitted at the 8th meeting of the Executive Committee in October of the same year. The 8th meeting of the Executive Committee had approved US $328,000 for a program to improve refrigeration servicing and maintenance, Ghana's program looked to establish a National Committee for Improved Refrigeration Practices, technical assistance and delivery of recovery and recycling machines, all to be implemented by UNDP. Ghana's RMP statistics find that the most important consumer of CFCs in the country is the domestic sector. The estimated number of domestic refrigerators was reportedly 1 million in 2000, and had increased by 30-40% in 2003. Total consumption of CFCs from repair and maintenance of domestic refrigerators amounts to about 20 tonnes per year.

In 1996, 3,000 trained technicians were already trained in best practices. An additional 600 technicians have been trained in safe handing, and retrofitting to hydrocarbons. However, certification of technicians is not mandatory in Ghana to practice recovery and recycling activities. The recovery equipment provided under the RMP, have been allocated to workshops according to location, security and quantity of refrigeration used. To improve recovery efforts, the RMP has established an incentive program to encourage refrigeration end-users to replace or permanently retrofit their existing ODS based equipment. In Ghana hydrocarbons are significantly cheaper than CFCs and HCFCs, as hydrocarbons are produced in Ghana and also imported from Lebanon. In view of the prevailing economic conditions, the dominance of the domestic sector, the negligible scrap rate of appliances, and the old age of imported vehicles and other refrigeration equipment, phase-out of ODS proves to be a fairly difficult task.

Senegal ratified the Montreal Protocol in May 1993 along with the London Amendment; the Copenhagen Amendment and the Montreal Amendment were ratified in August 1999. to assist Senegal UNEP provided training for trainers in good refrigeration practices, followed by training of technicians by these trainers under a project approved by the 11th meeting of the Executive Committee. Since 2001, a Refrigeration Management Plan (RMP) has been implemented with the assistance of UNIDO, Switzerland and UNEP.

The remaining users of CFC in Senegal are private companies servicing domestic, industrial and commercial refrigeration systems. The most prevalent barrier to retrofit remains the humid climate of Senegal. The hygroscopic nature of ester oil, not to mention its high price, makes it difficult to prevent humidity entering the system resulting in corrosion and clogging problems.

Under a training program implemented by UNEP, a total number of 140 technicians have been trained in four workshops, addressing issue like these. Previous standard practices like flushing with CFC have been replaced by using nitrogen or compressed air. Charging refrigerants is now measured with manifolds and brazing joints is more common now than using hoses thereby reducing the likelihood of leaks. Additionally a total of 40 recovery units have been made available) as well as, leak detectors, vacuum pumps, empty cylinders, scales, manifolds and other tools were provided, supplied through UNIDO.

CFC-12 remains relatively inexpensive, posing a great threat to effective regulatory control. Increases in the illegal smuggling of CFCs, originating in Eastern Europe, continues to occur. Therefore, continued training of Customs officials is necessary.

Most countries have established national programs to recover and reuse refrigerants. Although there is great potential for the recovery and recycling of CFCs in low volume consuming African countries, the low price of virgin refrigerant has decreased the incentive to recover refrigerant. There has also been a shortage of recovery and recycling equipment, as the cost is considered too expensive for the majority of the common workshops. It is expected that that suitable legislation, regulations, and recovery and recycling schemes currently under development will create the much needed incentives for recycling.

11.9.2 South America

The Brazilian government has established a refrigerant conservation program that banned the use of disposable refrigerant cylinders. The Brazilian Association of Domestic End Commercial Appliances has certified an estimated 1500 service shops, employing nearly 3000 service technicians. It is estimated that these certified shops recycle nearly 3.5 MT of CFC-12 per month from the domestic refrigeration and air-conditioning sector.

Through a National CFC Phaseout Plan, approved in July 2002 by the Multilateral Fund, the Brazilian government is planning to establish eight refrigerant reclamation centres within the next two years. In certain regions of the country, recycling and reclamation activities have begun in advance of the full implementation of the National CFC Phaseout Plan. The national plan anticipates the training of 35,000 refrigeration service technicians and the distribution of refrigerant recovery equipment to the technicians. The national plan includes efforts to establish a CFC recovery program in conjunction with the installation of the refrigerant reclamation centres. In addition, Brazil has a destruction facility that accepts contaminated refrigerant for incineration by rotary kiln.

Colombia ratified the Vienna Convention in 1990, the Montreal Protocol and its London Amendment in 1993, the Copenhagen Amendment in 1997, the Montreal Amendment in 2003 and the Beijing Amendment in 2005. In Colombia, 81% of total CFC consumption can be attributed to the service and maintenance of domestic, industrial, and commercial refrigeration systems. With the aid of MLF-funded conversion projects, the number of CFC-based commercial refrigeration units is expected to be reduced to about 850,000 by 2007. CFC prices remain high in Colombia however the price of alternatives are significantly more expensive. The process of phase-out of ODSs in Colombia consisted of a project-by-project approach concentrating on the large CFC consumers such as manufacturers of domestic and commercial, conversion projects in medium-sized commercial refrigeration units, and finalising projects in the foam and refrigeration sector and starting the implementation of the National Phase-out Plan (NPP). Total funds disbursed by the MLF for these projects from 1994 to 2004 (without including funds for the implementation of the NPP) amounted to US$ 1,112 million. As a result, 1,053 ODP tonnes have been eliminated. Programs within the NPP was planned to recover 123.75 ODP tonnes per year, a large part of which was assumed to be recycled. Actual amounts recovered during 1998-1999 were 41,9 ODP tonnes and 3,5 tonnes recycled. Substantial impediments to the NPP program effected its degree of success. The low price of virgin refrigerant in comparison with the costs of recovered substances meant that neither for end-users nor for the servicing workshops there was an economic incentive to recover and to recycle the refrigerant. Secondly, the equipment distributed under this project was limited to the recovering of

CFC-12 and the type of the machines selected did not take into account the diversity of uses required and the different needs of the technicians.

11.9.3 China

In 2002 China consumed 75% of East Asian share of CFCs and produced almost 100% of the regional share. By January 2003, CFC production in China was reduced by 40% and 32 plants were closed and dismantled.

During 1992, China's State Environmental Protection Agency's (SEPA) established a motor vehicle air conditioning sector program. The program is sets national policies and regulations, including the ban on new CFC-based MAC systems in all new vehicles by January 1, 2002; a technical assistance program for developing of service and refrigerant recycling standards; establishment of testing facilities for motor vehicle air conditioning components and systems; and a new certification system and training for the motor vehicle air conditioning industry.

China is currently seeking financial incentives, such as tax breaks, for refrigerant conservation. Also, the government is exploring options for the enforcement of State Environmental Protection Agency (SEPA) regulations. China Refrigeration and Air-Conditioning Industry Association (CRAA) established the standard: CRAA100-2006 (specifications for fluorocarbon refrigerants. The standard is applicable for new and reclaimed refrigerants, and is not applicable for only recycled refrigerants.

11.9.4 United States

The United States has seen an increase in the degree of community outreach and has seen the implementation of many CFC restricting regulations. There are currently regulations requiring technician certification, restriction on sales, mandatory recycling and servicing requirements, and safe disposal requirements. Proper retrofit procedures from CFCs to substitute substances have been created and distributed by chemical and equipment manufacturers. The U.S. has recognised an impediment in its conservation efforts. While the U.S. bans the import of virgin ODSs, the U.S. does allow used CFCs to be imported once approved by the government. Such efforts have extended the life span of CFC equipment, and have allowed equipment owners to hold off on retiring CFC equipment.

11.9.5 Japan

The recycling law concluded its first year since enforcement in April 2001, with good results in the recovery of CFC and HCFC refrigerants from discarded residential air-conditioners and refrigerators – 603 metric tonnes of CFC and HCFC refrigerants (467 from air conditioners and 136 from refrigerators) were extracted and destroyed in 2001. The amount has continued to rise, reaching 1306 metric tons (995 from residential air conditioners and 311 from domestic refrigerators) in 2004. Recovery of refrigerants from insulators used for refrigerators started in 2004. In a move to accelerate recycling, the Japanese cabinet approved an additional bill, requiring automobile manufacturers and importers to accept used cars to recycle different parts including CFCs. The law went into effect in 2003, and added a consumer-recycling fee to the price of each new car sold in Japan.

With the aim of raising the recovery rate of refrigerants from commercial equipment, the Fluorocarbons Recovery & Destruction Law was amended to be effective from October 2006. By this law, refrigerant recovery from commercial refrigeration and air conditioning equipment is expected to reach a higher level than ever before.

11.10 Article 5 Issues

Although the wide range of conditions in Article 5 countries make generalisation difficult, a few characteristics emerge across the refrigeration infrastructures that distinguish Article 5 countries from those of developed countries. These characteristics argue for the adoption of somewhat different strategies for containing and conserving refrigerant in Article 5 countries than are used in developed countries. Among these characteristics are:

- *The ambiguous situation on the market of CFC refrigerants.* CFCs remain relatively inexpensive in most Article 5 countries. In fact, CFC refrigerants are reportedly less expensive than ever in some Article 5 countries. On the other hand there are Article 5 countries were CFCs are practically unavailable or they are very expensive but very often CFCs are replaced by cheap counterfeited refrigerants that causes breakage of cooling systems and accordingly increase of Emissions. This decreases economic incentives to conserve CFC refrigerants. In order to succeed, conservation approaches must either make efficient use of technicians' time and equipment, or be supported by credible government incentives and/or penalties.

- *The relatively low cost of labour compared to recovery equipment*. Low labour rates may favour conservation approaches that are somewhat more labour-intensive than those historically pursued in developed countries. However, technician training and awareness are essential to the success of such approaches, especially where preventive maintenance procedures have not been routine in the past. Moreover, significant incentives are still necessary for refrigerant conservation because of the low cost of CFCs.

- *Weak refrigerant reclamation infrastructures*. A well-developed infrastructure for reclaiming refrigerant requires large numbers of reusable refrigerant containers, refrigerant purification centres, a system for tracking returned refrigerant, and a means of disposing of irretrievably contaminated refrigerant. The amount of refrigerant to be recovered in countries using small quantities of refrigerant is not likely to justify operation of a centralised reclamation centre. To ensure that refrigerant is adequately cleaned before being reused, developing countries may either devote resources to developing a reclamation infrastructure or emphasise on-site refrigerant recycling. If they choose the latter, screening tests may be used to target severely contaminated refrigerant for destruction. Because of the decentralised nature of on-site recycling, its success (in terms of both the quantity and quality of the refrigerant recycled) is more difficult to evaluate than that of reclamation. Where reclamation facilities are not available, an alternative may be destruction in existing incinerators.

- *Lack of scheduled maintenance*. In the past, for many Article 5 countries, routine scheduled maintenance of air-conditioning and refrigeration equipment has been rare. To successfully implement conservation approaches, which rely heavily on regular maintenance, countries should provide incentives for such routine scheduled maintenance.

- *Unreliable power, parts, and supplies*. In many Article 5 countries, frequent voltage fluctuations increase the occurrence of compressor burnouts, which aggravate refrigerant contamination problems and discourage refrigerant recycling. The same voltage fluctuations may also damage electrical recovery equipment, which in combination with the limited availability of replacement parts, may make it difficult to keep such equipment operational. Recent experience has shown the need to adapt recovery equipment to the requirements of Article 5 countries (such as extreme climatic conditions, lack of spare parts, and higher frailty of electric devices).

Together, these characteristics have certain implications for refrigerant conservation programs in Article 5 countries. Because the ability to recover large amounts of refrigerant in a relatively small amount of time increases the cost-effectiveness of recovery, recovery programs may be most effective if focused either on equipment with large charge sizes (e.g., chillers or large commercial refrigeration systems) or on large groups of equipment with small charge sizes (e.g., motor vehicle air-conditioners).

For other systems, such as those with small size and widespread ownership (e.g. domestic and small commercial refrigerators), experiences indicate that retrofitting and recovery are more difficult to implement and that the emphasis should be put on conservation.

In addition to imposing conservation measures on individual pieces of equipment, countries may reduce emissions of CFC refrigerants by reducing the total stock of equipment containing CFCs. This may be accomplished by selecting systems that use HCFCs or non-ozone depleting refrigerants when installing new equipment or by retrofitting existing systems to use HCFCs or non-ozone depleting refrigerants. The high rate of growth in Article 5 countries makes the selection of new equipment especially important. Labour intensive retrofits may be attractive in some Article 5 countries due to relatively low labour rates. It is important to note that replacement or retrofit of equipment will increase rather than decrease CFC emissions if the CFC refrigerant from the old equipment is vented rather than recovered. This emphasises the fact that for any refrigerant, the first step to take towards conservation is improving the leak tightness of systems.

There is no shortage of leak detection devices, conservation methods, or recovery/recycling equipment available from developed countries /UNE94,95/. However, provision of such equipment will not, in itself, guarantee that refrigerant conservation occurs in Article 5 countries. Experience has shown that in order to be effective, conservation programs must match equipment with training and incentives to use the equipment. These incentives may be financial (e.g., deposit-refund systems similar to those used in Australia and France), professional (building on technicians' pride in completing training and in using the most advanced equipment and techniques), or environmental (showing technicians that they have the power to help heal the ozone layer). The Refrigerant Management Plans (RMPs) which focus on A5 countries consuming low volumes of ODS in critical refrigerant sectors include these different aspects /UNE98/.

In order to meet the target of the CFC phase-out, emphasis should be placed not only on replacing CFCs in new and existing equipment, but also on refrigerant conservation through recovery, recycling, reclamation and leak reduction.

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Annex 2: - Excerpt of the Final Report on Global inventories of the worldwide fleets of refrigerating and air-conditioning equipment in order to determine refrigerant emissions. The 1990 to 2006 updating.

ADEME/ARMINES Agreement 0874C0147 – December 2009

Table of Contents

1. Global results: refrigerant demands, banks, and emissions

1.1 Global demand of refrigerants in year 2006

The quality control of refrigerant bank and emissions is made by comparing the annual refrigerant demand calculated by RIEP and the annual refrigerant sales declared by manufacturers (AFEAS). This comparison is made refrigerant by refrigerant and is presented in Section 2.6.

Note: the RIEP method derives, application by application, the refrigerant needs, i.e. the refrigerants charged in new equipment and the refrigerants charged for re-filling existing equipment. These refrigerant needs are called demand.

Once the refrigerant demand has been calculated, it is cross-checked with refrigerant sales data as declared by refrigerant manufacturers and distributors. In many countries the refrigerant quantities sold are monitored; the refrigerant distributors and manufacturers publish their annual sales of CFCs, HCFCs, and sometimes HFC refrigerants. At the global level, AFEAS (Alternative Fluorocarbons Environmental Acceptability Study) publishes every year the quantities of refrigerants (by type) sold by the chemical manufacturers in developed countries. Those data have been used in the past to forecast global emissions of CFCs, HCFCs, and HFCs.

It has to be underlined once again that 2009 is the last year of published data by AFEAS and so, from now on, no public data will be available for global markets of refrigerants detailed by refrigerant types.

1.1.1 Global refrigerant demand by refrigerant types

The calculation-module linked with the RIEP database allows merging refrigerant quantities by type as well as by application; data are presented for year 2006 in Table 2-1.

This report presents one major change compared to the 2003 report, because of a previous overestimate of Chinese commercial refrigeration based on the references that were used (marketing reports). The consequence is that the CFC-12 demand is reduced by a factor 2 in 2006 compared to that calculated in the 2003 report.

Table and Figure 1-1 - Global refrigerants demand from 1990 to 2006 (in tonnes)

Refrigerant demand (t) in 2006		
CFC	R-11	6 331
	R-12	20 328
	R-502	5 579
HCFC	R-22	376 992
	R-408A	3 443
	R-401A	772
	R-123	6 295
HFC	R-134a	135 569
	R-404A	28 279
	R-407C	24 607
	R-410A	28 922
	R-507	3 986
	R-413A	143
Others	R-717	26 194
	R-600a	2 869
Total	**All**	**670 309**

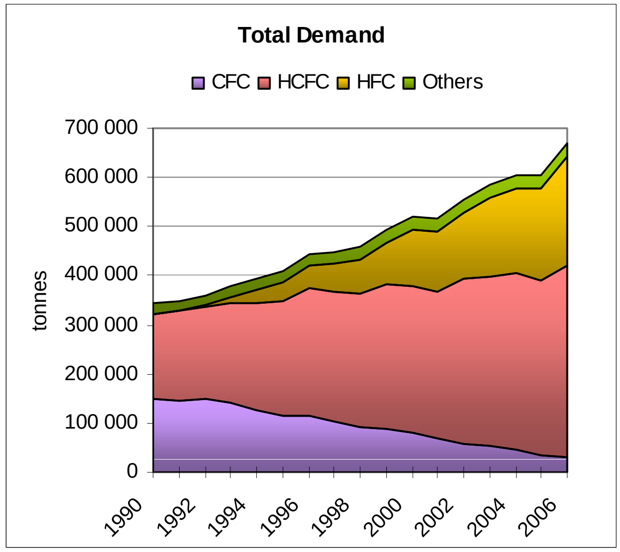


Table 1-1 and Figure 1-1 summarise the essential developments from 1990 to 2006. The total refrigerant demand for all refrigerant types has increased from 345,000 tonnes in 1990 to nearly 670,000 tonnes in 2006, which represents an increase of nearly 100%. This emphasises the impact of the economic growth of fast developing countries on the total, with a special mention to China.

Globally the annual CFC refrigerant demand has decreased from 150,000 tonnes in 1990 to 32,000 tonnes in 2006. The 2006 CFC demand represents about 5% of the total refrigerant demand.

The annual HCFC demand has increased from 174,000 to 387,000 tonnes in 2006 (around 58% of the total demand) and the HFC demand that was negligible in 1990 has raised to about 221,000 tonnes in 2006 (33% of the total demand).

The annual ammonia demand has increased from 22,000 to 26,000 tonnes in 2006, and the HC demand, which was nil in 1990, is in the range of 2,800 tonnes in the year 2006.

1.1.2 Refrigerant demand by application sector and by country

Figures 1-2 and 1-3 present the refrigerant demands, including HCs and ammonia split by application and for the main countries or country groups.

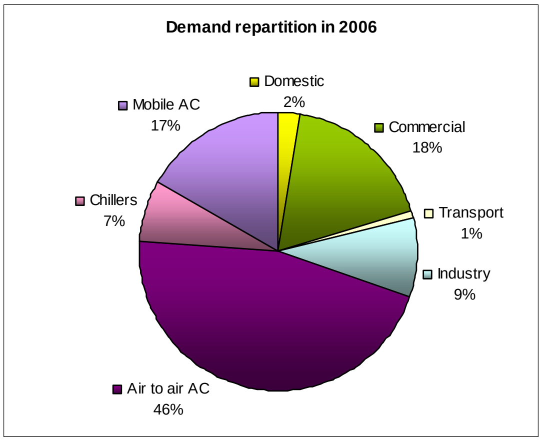


Figure 1-2 – Refrigerant demand split by application.

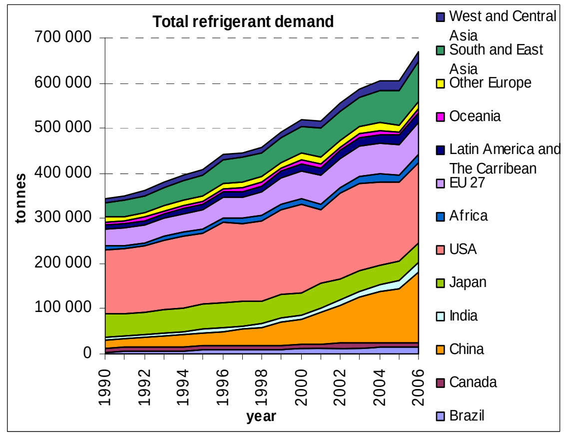


Figure 1-3 - Refrigerant demand split by country and country groups.

Figures 1-4 and 1-5 present HFC demands split by application and by countries.

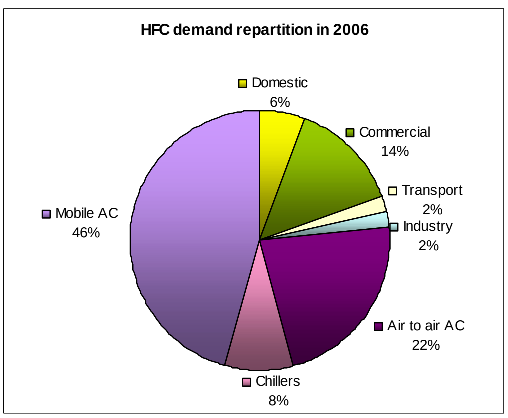


Figure 1-4 – HFC demand split by application.

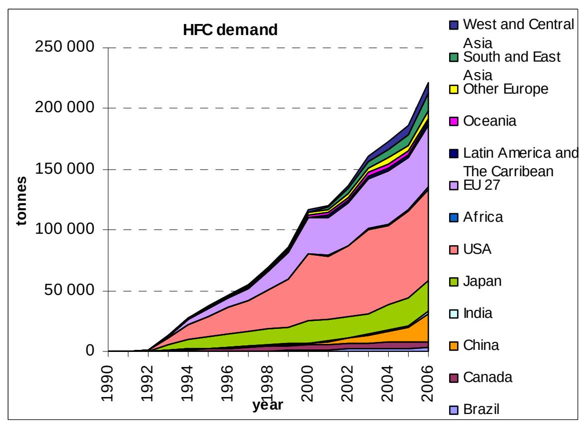


Figure 1-5 - HFC demand split by country and country groups.

Figure 1.2 indicates that when all refrigerants are accounted for, the dominant sectors are commercial refrigeration and stationary air conditioning. For HFC demand, the dominant sector is MAC with 46 % of the HFC demand.

The refrigerant demand in the U.S. is still the dominant one even if the Chinese growth is the main driver of the total refrigerant demand.

EU 25 needs for HFCs are around 40,000 t in 2003. In the U.S., because of the R-134a demand for the MAC sector, the needs are higher: 69,000 tonnes.

1.2 Refrigerant banks, by application sector and by country

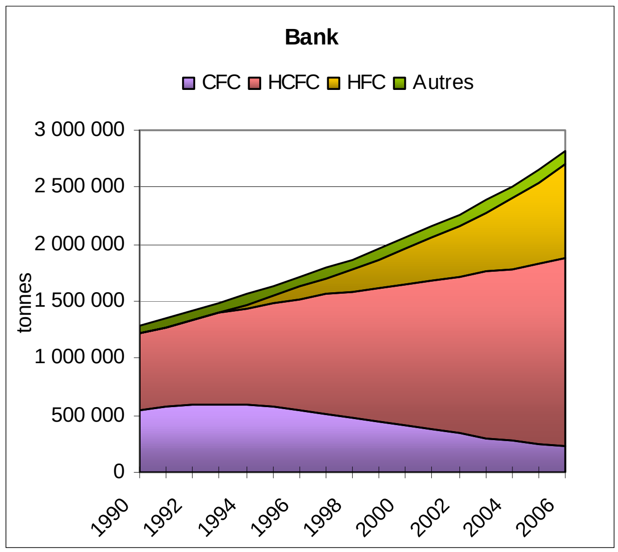
The calculation of refrigerant banks requires the determination of all installed bases and fleets of equipment for their complete lifetime. Banks of refrigerants vary substantially in sizes and in refrigerant types depending on the application sector and the country.

In 2006, the sum of all banks of all refrigerant types (see Figure 1-2) **is calculated at 2,815,000 tonnes.** The global bank is roughly equal to 4.5 times the annual demand. The refrigerant banks and the annual refrigerant demands follow the same trends:

- the size of the CFC bank is decreasing but, it still represents around 230,000 tonnes, which is about 8% of the total refrigerant bank in 2006
- HCFCs represent 1,645,000 tonnes, which equals about 58% of the total bank
- HFCs represent slightly less than 821,000 tonnes, which is around 29% of the total bank
- whereas the remaining 4% of the bank consists of ammonia and HCs.

Table 1-2 – Global refrigerant banks (t)

Refrigerant bank (t) in 2006		
CFC	R-11	36 611
	R-12	173 895
	R-502	17 313
HCFC	R-22	1 585 777
	R-408A	10 592
	R-401A	3 794
	R-123	45 923
HFC	R-134a	576 793
	R-404A	69 354
	R-407C	71 498
	R-410A	93 602
	R-507	8 142
	R-413A	1 979
Others	R-717	109 793
	R-600a	10 325
TOTAL	**ALL**	**2 815 391**



The total refrigerant bank increased by 120% for the period from 1990 to 2006.

Figures 1-6 and 1-7 present the refrigerant banks, including HCs and ammonia, split by application and for the main countries or country groups.

Comparing Figure 1-6, which represents the global refrigerant bank by sector and Figure 1-8, which represents the HFC bank also by sector, it is obvious that the very different schedule of refrigerant changes per application leads to strong differences in the domination of one sector over the others. The emphasis made on mobile air-conditioning (MAC) systems for example is related to the rapid phase out of CFC-12 in this sector as of 1992, which consequently leads to a significant market share of MAC for HFCs. In fact, taking into account all refrigerants, the dominant sectors are stationary air conditioning and then commercial refrigeration. Those two sectors represent about 70% of the total use of refrigerants.

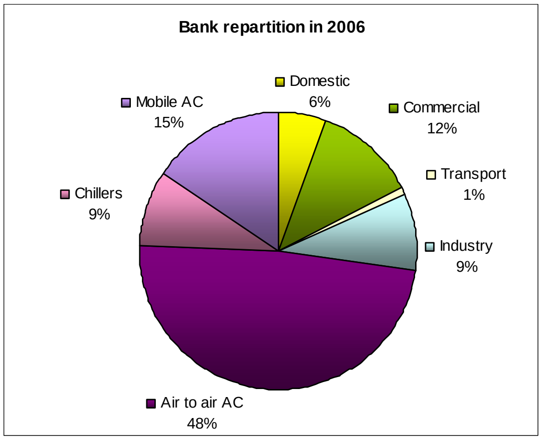


Figure 1-6 – Refrigerant bank in 2006 split by sector

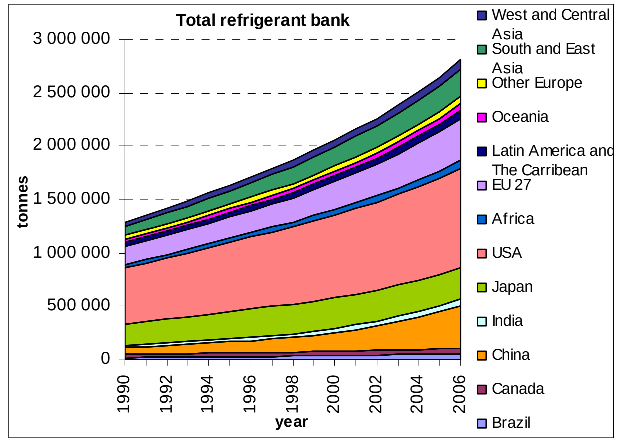


Figure 1-7 - Refrigerant bank - split by country.

Figures 1-8 and 1-9 present HFC demands split by application and countries.

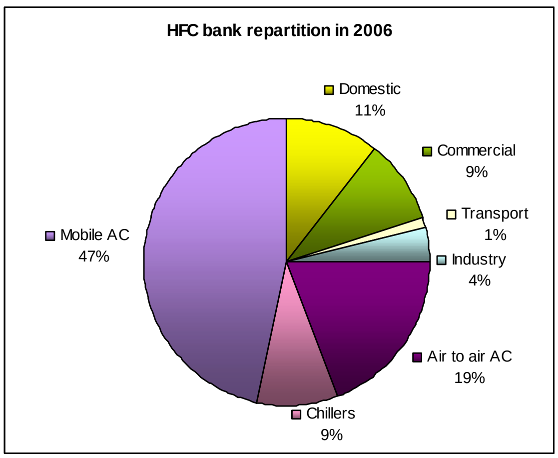


Figure 1-8 – HFC bank in 2006, split by sector.

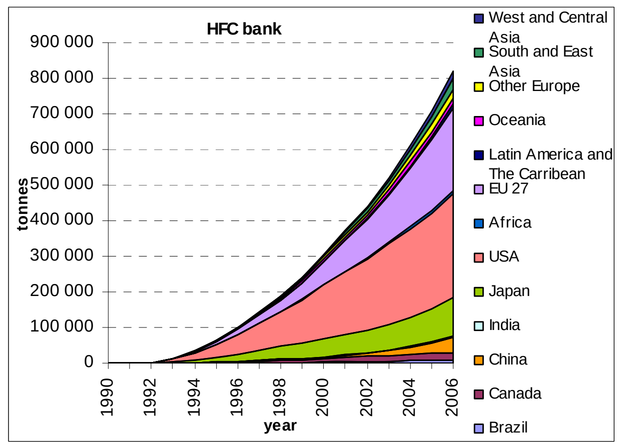


Figure 1-9 - HFC bank - split by country.

57% of the total amount of refrigerants is banked in stationary air-conditioning equipment including chillers (9%) (see Figure 1-6). This confirms the trends observed on the annual refrigerant demand.

Due to the rapid change from CFCs to HFCs, MAC systems (which contain only 15% of the total refrigerant bank) represent 47% of the total HFC refrigerant bank (see Figures 1-8 and 1-9). This important observation indicates the main future trends when the HCFC phase-out has to be accomplished. The HCFC bank is currently the largest bank and 78% (chillers included) of it is contained in stationary air-conditioning systems.

1.3 Refrigerant emissions, by application sector and by country

Based on the bottom-up approach, taking into account all refrigerant types in all refrigerating and air-conditioning systems, it is possible to derive the refrigerant emissions for all refrigerant types for the period from 1990 to 2000.

Table 1-3 – Refrigerant emissions of all refrigerant types (tonnes)

Refrigerant emissions in 2006 (t)		
CFC	R-11	6 958
	R-12	35 195
	R-502	5 430
HCFC	R-22	233 686
	R-408A	3 172
	R-401A	958
	R-123	3 983
HFC	R-134a	82 825
	R-404A	14 663
	R-407C	7 074
	R-410A	7 918
	R-507	2 271
	R-413A	616
Others	R-717	19 562
	R-600a	231
TOTAL	All	**424 542**

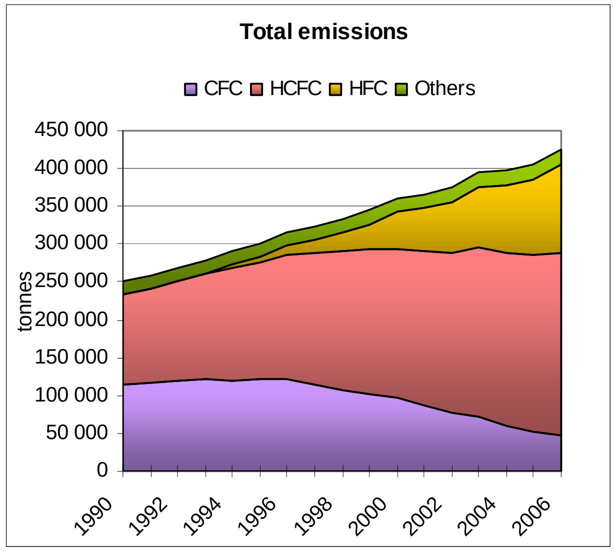


Table 1-3 presents the development of emissions of all refrigerant types from 250,000 tonnes in 1990 to 425,000 tonnes in 2006:

- CFC emissions reach a maximum value in 1995 at 120,000 tonnes, and decrease to 47,000 in 2006 due to their phase out,
- HCFC emissions increase from 156,000 tonnes to 242,000 tonnes, and
- HFC emissions increase from zero to around 115,000 tonnes.

Yet, the sum of the CFC and HCFC emissions equals two third (68%) of all refrigerant emissions.

Note: the management of refrigerant containers that are used every year both for charging new equipment and for servicing of the installed base implies the release to the atmosphere of de minimis quantities; the vapour heel that represents about 3% of the refrigerant charge, and often the liquid heel representing between 5 and 8%. For those inventories, the refrigerant heels are considered of 10% of the annual sales. Those emissions **are not taken into account** in the refrigerant emission figures related to refrigeration and air-conditioning equipment.

Table 1-4 Emissions due to large containers heels (tonnes)

2006	Domestic	Commercial	Transport	Industry	Air-to-Air AC	Chillers	Mobile AC	TOTAL
CFC	129	817	21	484	1	784	568	2 803
HCFC	-	6 766	213	2 206	22 384	1 728	398	33 696
HFC	1 065	2 653	379	409	4 324	1 637	8 794	19 261
Others	249	71	-	2 184	-	29	-	2 534
Total	1 444	10 306	613	5 283	26 709	4 179	9 760	58 294

Figures 1-10 and 1-11 present the refrigerant emissions, including HCs and ammonia, split by application and for the main countries or country groups.

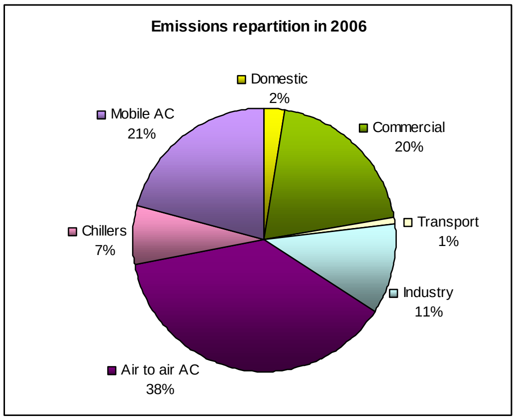


Figure 1-10 – Refrigerant emissions in 2006, split by sector.

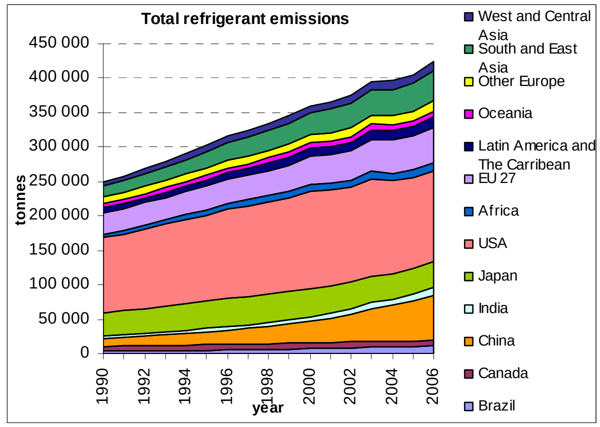


Figure 1-11 – Refrigerant emissions - split by country.

Figures 1-12 and 1-13 present HFC emissions split by application and for the main countries or country groups.

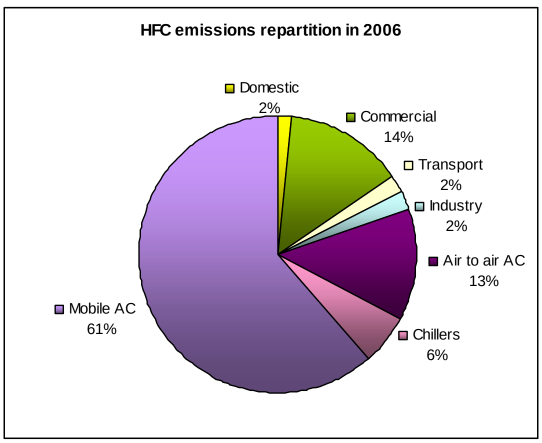


Figure 1-12 – HFC emissions in 2006, split by sector.

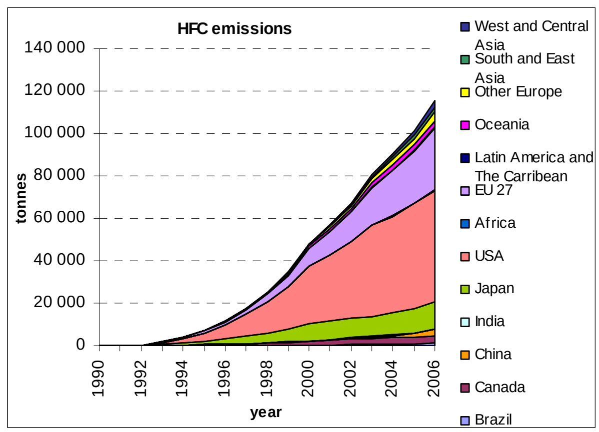


Figure 1-13 – HFC emissions - split by country.

Taking into account all refrigerant emissions (independently of the refrigerant type), 38% come from air-conditioning systems excluding chillers, 20% of emissions come from commercial refrigeration, and 21% from MAC systems. However, when only looking at HFC emissions, the MAC sector represents 61% of HFC emissions. This fact is related to the rapid shift from CFC-12 to HFC-134a, and to the relatively high emission factor, taking into account losses at servicing that apply to MAC equipment.

Commercial refrigeration is also a significant source of emissions characterised by more than 20% of the total refrigerant emissions. Emission rates are three times higher in commercial refrigeration than they are in stationary AC.

Domestic refrigeration, which actually is the sector with the largest number of equipment, is not a significant contributor to refrigerant emissions due to the small refrigerant charges and the low level of emissions.

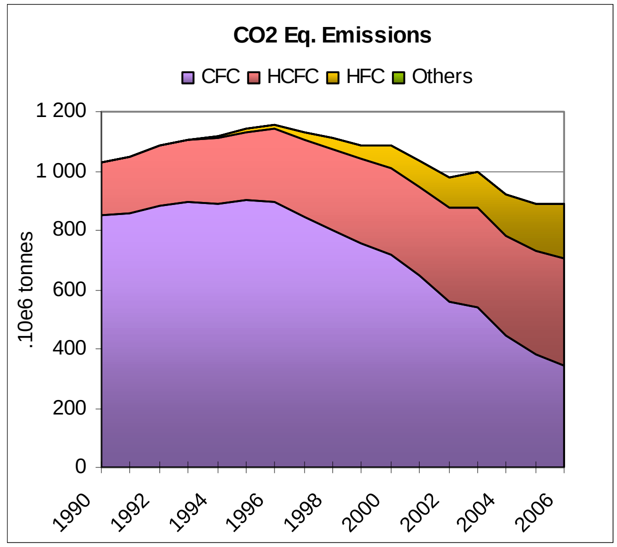
Transportation, even though characterised by a very high emission factor, is a small global contributor due to the relatively small number of equipment.

1.4 Refrigerant CO_2 equivalent emissions, by application sector and by country

The CO_2 equivalent emission calculations are based on GWP values published in the Second Assessment Report of the IPCC.

Table 1-5 Refrigerant CO_2 equivalent emissions of all refrigerant types (tonnes)

CO_2 equiv. emissions (t) 2nd Assessment Report		
CFC	R-11	26 440 153
	R-12	285 086 629
	R-502	29 834 731
HCFC	R-22	350 532 642
	R-408A	8 402 783
	R-401A	932 246
	R-123	358 515
HFC	R-134a	107 673 924
	R-404A	47 802 130
	R-407C	10 794 708
	R-410A	13 699 040
	R-507	7 495 122
	R-413A	1 170 362
Others	R-717	0
	R-600a	4 617
TOTAL	**All**	**890 227 602**



In 2006, the main contributor to global warming is HCFC-22 (39%). CFC-12 represents still 32% of the total contribution of all refrigerants to global warming in the year 2003, whereas the emissions of CFC-12 are only 8% of the total refrigerant emissions in 2006.

HFCs, accounting for 27% of the total refrigerant emissions, contribute to only 21% of the CO_2 equivalent emissions of refrigerants in the year 2006 because of the relatively low GWP of HFC-134a.

Figures 1-14 and 1-15 present CO_2 equivalent emissions for all refrigerants split by application and for the main countries or country groups.

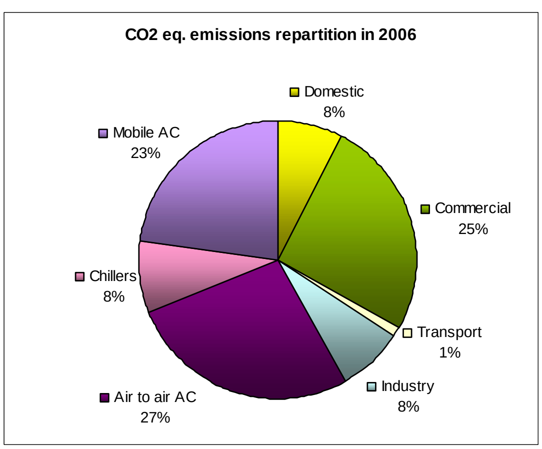


Figure 1-14 Refrigerant CO_2 equiv. emissions in 2006, split by sector.

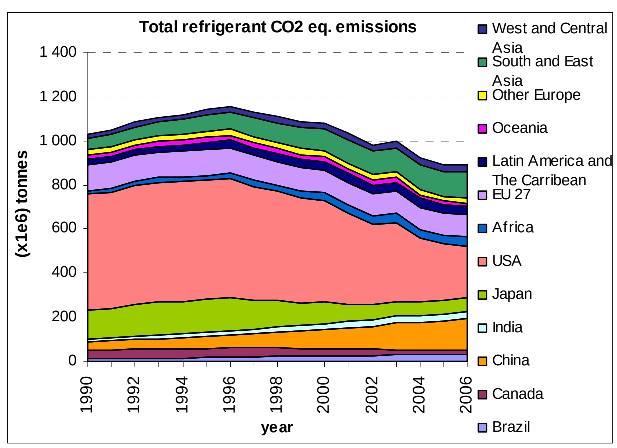


Figure 1-15 Refrigerant CO_2 equiv. Emissions - split by country.

Figures 1-16 and 1-17 present CO_2 equivalent emissions for HFC refrigerants only, split by application and for the main countries or country groups.

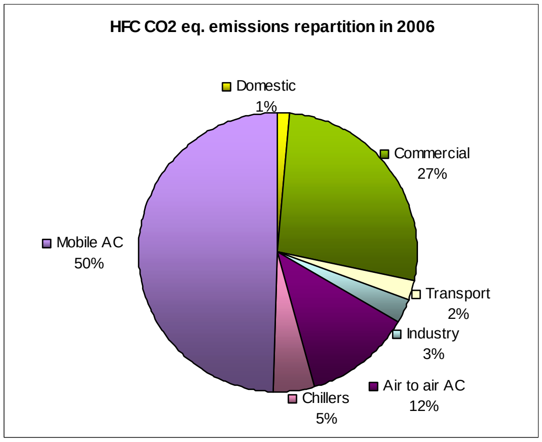


Figure 1-16 – HFC refrigerants, CO_2 equiv. emissions in 2006, split by sector.

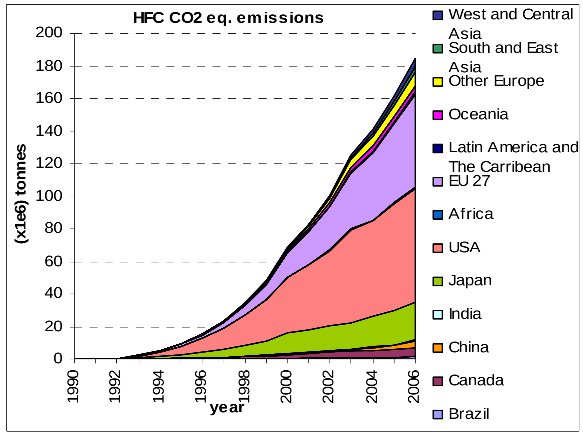


Figure 1-17 HFC refrigerants, CO_2 equiv. emissions - split by country.

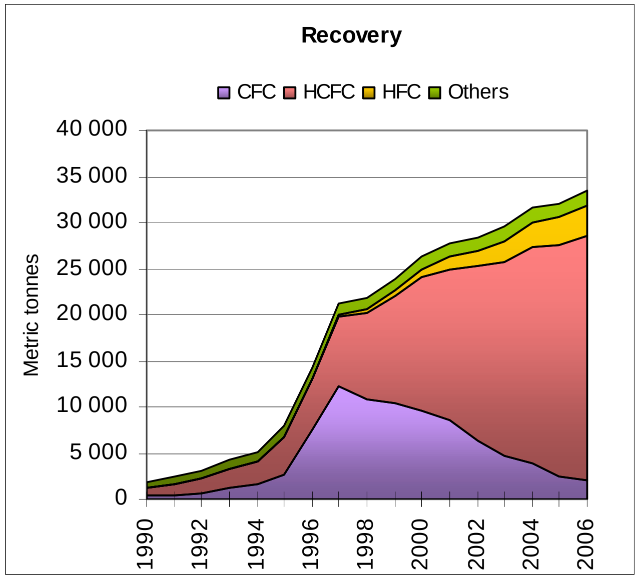
27% of the total CO_2 equivalent emissions come from commercial refrigeration equipment, taking into account all types of refrigerants.

For low temperature applications in commercial refrigeration, the (future) replacement of HCFC-22 by R-404A implies that CO_2 equivalent emissions will significantly increase in this sector. This is due to the high GWP of R-404A (2.2 times higher than the GWP of HCFC-22).

1.5 Refrigerant recovery

Table 1-6 Recovered refrigerants (tonnes)

Refrigerant recovery (t)		
CFC	R-11	851
	R-12	1 040
	R-502	146
HCFC	R-22	25 139
	R-408A	712
	R-401A	219
	R-123	657
HFC	R-134a	2 704
	R-404A	526
	R-407C	0
	R-410A	0
	R-507	0
Others	R-717	1 625
	R-600a	0
Total	**All**	**33,619**



All quantities of recovered refrigerants calculated are directly linked to the assumptions made on an application-by-application basis and for country groups. Very few data are available on the quantity that is effectively recovered. Moreover, and in particular for CFC-12, the recovered refrigerant can be directly re-used in other equipment without being transferred back to the refrigerant reclaim sector. A high level of uncertainty exists here; if real circumstances are different from the assumptions made for calculations, part of the quantity assumed to be recovered could well be emitted.

1.6 Data quality and data consistency

In this report we have taken two complementary approaches, the first one assesses the quality of activity data and emissions factors, the second compare the consistency of refrigerant demand as derived for each type of refrigerant and for all application by RIEP compared to the refrigerant sales as declared at the global level by AFEAS.

1.6.1 Uncertainties

Depending on the application sector, uncertainties are different either because activity data include different uncertainties or because emission factors may vary significantly from one country to the other.

We have taken a simple approach that gives a quality index expressed in percentages. For activity data: the market, the refrigerant charge, and the equipment lifetime are the main elements that define the data quality. For emission factors: fugitive emissions and recovery efficiency at end of life are the two key parameters.

Uncertainties on input parameters are based on expert judgements of the different sectors. These values are given in Table 1-7.

Table 1-7 Uncertainties on input parameters

Uncertainties on input	MAC	SAC	IND	TRA	COM	DOM
Equipment market (a)	2.50%	2.50%	10%	12.50%	7.50%	2.50%
Equipment lifetime (b)	7.50%	2.50%	7.50%	2.50%	7.50%	12.50%
Equipment average charge (c)	2.50%	12.50%	10%	7.50%	7.50%	2.50%
Emission rate (d)	10.00%	7.50%	10%	7.50%	10%	12.50%
Recovery efficiency (e)	10.00%	7.50%	12.50%	7.50%	12.50%	2.50%

The calculation of the lower and upper thresholds for uncertainties is based on simplified equations presented in Table 1-8. It assumes that uncertainties do not change throughout the years.

Table 1-8 Calculation of lower and upper thresholds for banks and emissions

Results	Minimum threshold	Maximum threshold
Bank	1- (a + b + c)	1+ (a + b + c)
EOL	1 –(a + c + e)	1 +(a + c + e)
Fugitive	1- (a + b + c + d)	1+ (a + b + c + d)
Total emissions	(Minimum EOL +Fug)/(EOL +Fug)	(Maximum EOL +Fug)/(EOL +Fug)

Based on those thresholds it is possible to evaluate the uncertainties on banks (activity data) and emissions.

Table 1-9 Uncertainties on results

	BANKS	EMISSIONS
MAC	12.5%	21.2%
SAC	17.5%	24.4%
IND	27.5%	37.1%
TRA	22.5%	29.7%
COM	22.5%	32.0%
DOM	17.5%	12.8%
GLOBAL	18.2%	26.6%

1.6.2 Comparison between refrigerant demands (RIEP calculations) and refrigerant markets (declared by AFEAS)

Annual refrigerant sales have been published by AFEAS since 1990. RIEP allows the calculation of the annual demand of refrigerants including the refrigerant charged into new equipment and refrigerants sold for servicing.

AFEAS publishes data only when the cumulative sales are larger than 5,000 tonnes, and therefore data are not available for some components of new HFC blends, such as HFC-125, and HFC-32. Consumptions of all non-Article 5 countries are traced, and also of some Article 5 countries: Argentina, Brazil, Mexico, and Venezuela.

The comparison of AFEAS data (declared sales) and RIEP evaluation of the refrigerant demand allows crosschecking the consistency of the calculation method at the global level.

♦ CFC demand

Before 1995 the demand is lower than the sales. After the phase-out date of the CFC production, the sales declared by AFEAS decrease rapidly to nearly a zero value in 2000, but the demand still exists during this period. This difference can be explained by a stock-piling effect (end-users buy refrigerant when allowed in order to maintain the CFC-11 chillers after the phase-out date).

The cumulative difference between AFEAS (116,000 t) data and refrigerant CFC-11 need as derived by RIEP (203,000 t) indicates that the CFC-11 has been produced by manufacturers of A5 countries not reporting to AFEAS and the cumulative demand.

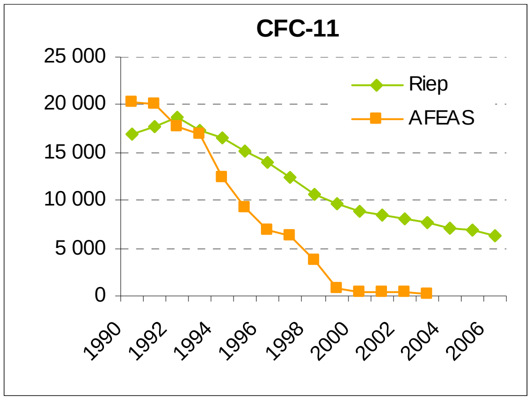


Figure 1-18 – Comparison of CFC-11 demand between AFEAS sales and RIEP calculations

When comparing the sales as declared by AFEAS and the demand as calculated by RIEP, the stock-piling effect from 1990 to 1995 seems obvious. When making the sum of the CFC-12 sold from 1990 to 2006 and the demand as derived also for the same period, RIEP leads to 1,236,000 t and AFEAS leads to 1,069,000 t (1990 to 2003), leading to a negligible difference on those 13 years. This seems to confirm that sales and usages are disconnected when regulation forbids the sales of refrigerant and tolerates the operation of refrigerating systems after the end of refrigerant commercialisation.

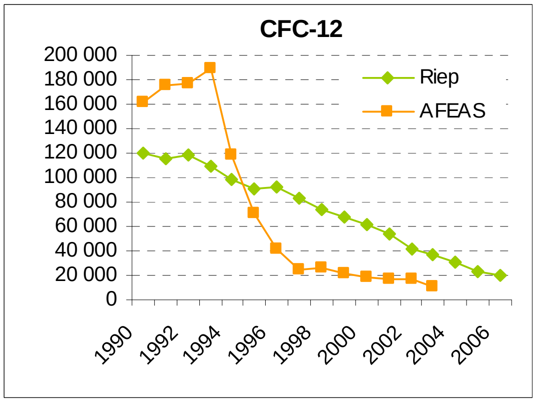


Figure 1-19 Comparison of CFC-12 demand between AFEAS sales and RIEP.

CFC-115 is one of the two components of R-502.

The cumulated demand between 1990 and 2006 is 82,000 t, compared to the cumulated demand of 75,000 t.

Considering a stock-piling effect beginning in 1989, the difference of cumulated demand and demand is very low.

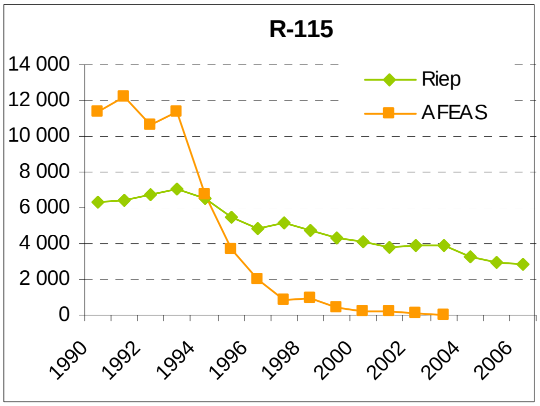


Figure 1-20 Comparison of CFC-115 demand between AFEAS data and RIEP calculations.

♦ HCFC demand

The comparison between the HCFC-22 demand and the HCFC-22 sales by manufacturers reporting to AFEAS shows clearly the impact of HCFC-22 production in developing countries. It is certainly a reason why AFEAS has stopped at the end of 2009 to make this reporting for HCFC-22. It appears that more of it is produced out of AFEAS manufacturers.

The cumulative production as reported by AFEAS from 1990 to 2006 is of 3,245,000 tonnes, and the cumulative needs calculated by RIEP are of 4,600,000 tonnes.

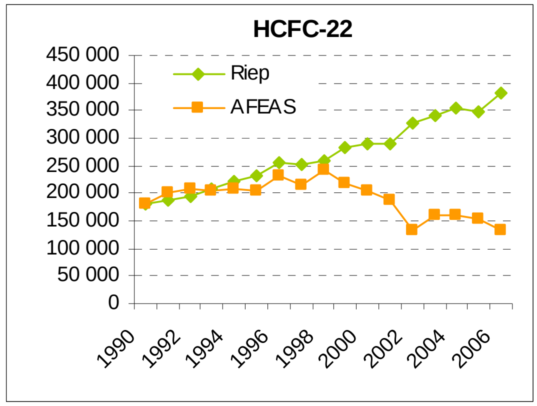


Figure 1-21 — Comparison of HCFC-22 demand between AFEAS data and RIEP calculations

♦ HFC demand

The HFC-134a demand calculated by RIEP is very closed to the declarations of sales.

The growth rate is similar and the cumulated values from 1990 to 2006 are quite the same: 1,181,000 tonnes for the total sales (RIEP) and 991,000 tonnes for the cumulated demand (AFEAS), which is still a difference of about 15%. One of the main issues is to verify if the emission rates of MAC systems have been effectively decreasing as modelled in RIEP since 2000.

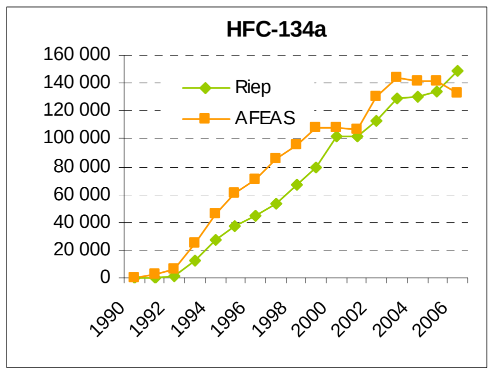


Figure 1-22 Comparison of HFC-134a demand between AFEAS data and RIEP calculations

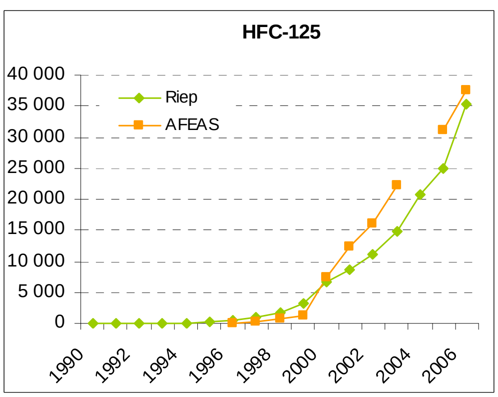


Figure 1-23 Comparison of HFC-125 demand between AFEAS data and RIEP calculations

HFC-125 is used in refrigerant blends such as R-404A, R-507, R-410A, and R-407C.

The trend is the same between sales as reported by AFEAS and the demand as calculated by RIEP. It can be noticed that even if AFEAS data were missing in 2003, the RIEP derivation leads to similar evaluation of HFC-125 needs in 2006. These results confirm that the assumptions for refrigerant changes are good and that HFC-125 is manufactured only AFEAS manufacturers.

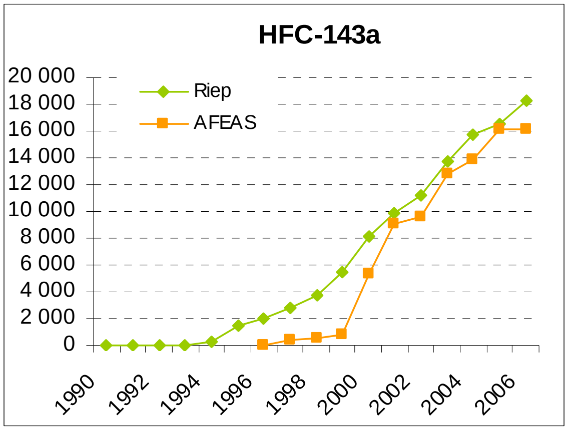


Figure 1-24 Comparison of HFC-143a demand between AFEAS data and RIEP calculations

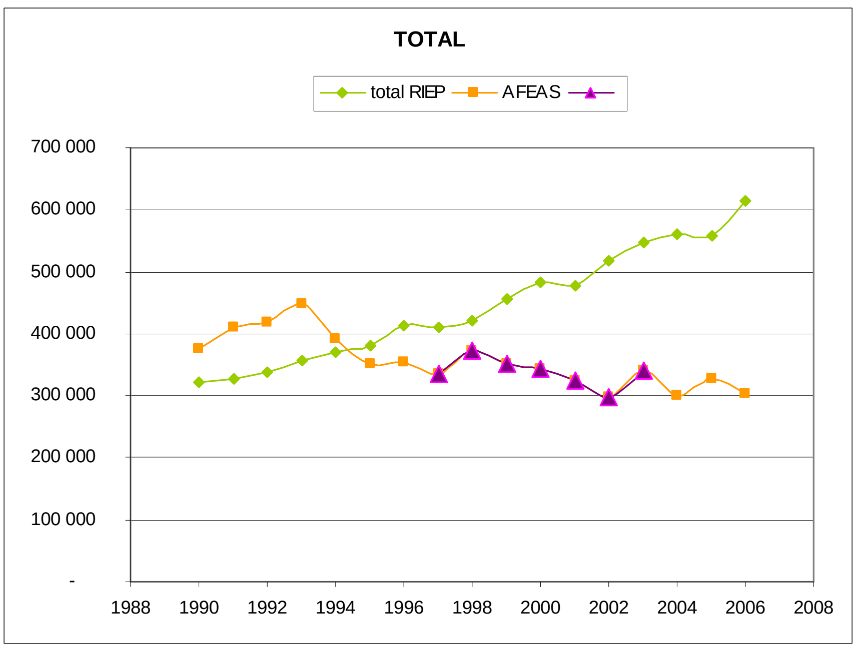
HFC-143a is used in refrigerant blends (R-404A, and R-507) for low-temperature applications, in commercial refrigeration, and mainly in Europe.

The trend is the same between sales, as reported by AFEAS, and the demand as calculated by RIEP. So lessons from the comparison are identical to those drawn for HFC-125.

♦ Total demand

The trend as shown by RIEP indicates the dominance of HCFC-22 sales, which makes the difference between AFEAS data and RIEP calculations since 1998. As shown in the previous charts analysing sales and demand refrigerant by refrigerant, the only significant difference between AFEAS data and RIEP calculation is related to HCFC-22.

Figure 1-25 – Comparison between AFEAS sale data and RIEP calculated refrigerant needs



2. Method of calculation, data and databases

2.1 Refrigerant Inventory methods and emissions calculation for the refrigeration industry

UNFCCC collects every year from signatory countries their national inventories of greenhouse gases. Three methods, Tier 1, Tier 2, and Tier 3 are proposed by the IPCC guidelines to help countries making their inventories. The refrigeration and air-conditioning industry emissions are either inventoried by sales of refrigerants or by sales of all refrigeration and air-conditioning equipment.

The six main sectors for the refrigeration and air conditioning (RAC) are:

- Domestic refrigeration
- Commercial refrigeration (centralised systems, condensing groups, and standalone equipment)
- Industrial and food processes
- Transport refrigeration
- Stationary air conditioning
- Mobile air conditioning.

This section presents the methodologies proposed by the IPCC guidelines for the estimation of GHG emissions. The RIEP model developed by the CEP is a “bottom-up” approach based on the Tier2a methodology. Some improvements have been introduced in this 2006 inventory report.

The Tier 2 IPCC method

The 1996 IPCC Guidelines provide step-by-step instructions for establishing national greenhouse gases inventories: “directions for assembling, documenting, and transmitting completed national inventory data consistently”.

Two calculation methods were developed for the estimation of emissions of fluorinated greenhouse gases and their substitutes for the refrigeration and air-conditioning sectors, the Tier 1 and Tier 2 methods. The Tier 3 method relies on actual monitoring and measurement of emissions from point sources and is not used in the refrigeration since the sources are diffuse [IPC06].

RIEP being based on the TIER 2 and its improvements, the Tier 2 methodology needs to be presented *per se*. This method calculates the actual emissions for each individual chemical in a given year on an application basis. It takes into consideration that there might be a considerable delay between the time where the fluid is produced and charged in equipment, and the time where it is released into the atmosphere.

First, it estimates the consumption of each individual chemical, at an application basis level, in order to establish the global volume from which emissions originate. An application might use several chemicals; typically in refrigeration, blends of refrigerants are used in several applications. They have to be inventoried component by component for UNFCCC reporting.
This method might be implemented in two different ways: the “bottom-up” approach (application based) or the “top-down” approach (national consumption derived).

In a “bottom-up” approach, one evaluates the consumption of a certain refrigerant based on the number of equipment in which the fluid is charged, e.g. refrigerators, stationary air-conditioning equipment, and so on. It requires the establishment of an inventory of the number of equipment charged with inventoried substances, and the knowledge of their average lifetime, their emission rates, recycling, disposal, and other parameters. Annual emissions are then estimated as functions of these parameters during the equipment lifetime.

A “top-down” approach estimates emissions for a given year on the basis of the national consumption of chemicals: it disaggregates chemical consumption data into sectors using distribution factors and then applies time-dependent emission factors. The access to such data might be very difficult due to confidentiality issues. Although in some cases producers might report to their government the quantity of a certain fluid sold into a specific sector, in other cases, when the chemical is sold by many distributors before reaching its application, it might be difficult to collect the corresponding needed data [IPC00]. In such cases, estimating of distribution factors is based on expert judgements.

In the IPCC 2006 guidelines, the mass-balance and the emission-factor approaches were introduced. The Tier 1 method addresses the total refrigeration and air-conditioning sector; the Tier 2 method requires information for each type of equipment in the six application sectors defined above.

For the mass-balance approach, emissions are calculated as follows:

$$\begin{aligned} Emissions = {} & Annual\ sales\ of\ new\ chemical - Total\ charge\ of\ new\ equipment \\ & + Original\ total\ charge\ of\ retiring\ equipment \\ & - Amount\ of\ intentional\ destruction \end{aligned} \quad (2.1)$$

The limitation on the application of Equation (2.1) to MAC systems will be explored in the next paragraphs.

Refrigerant emissions from refrigeration and air-conditioning systems occur at three main levels: emissions during the charging process, emissions from the existing bank, and emissions at the equipment disposal.

The emission-factor approach adds the emissions related to the management of containers $E_{containers,t}$ to those cited above, and equations for this approach are provided below.

The total emissions of a given refrigerant in year t $E_{total,\,t}$ are given by Equation (2.2)

$$E_{total,t} = E_{containers,t} + E_{charge,t} + E_{lifetime,t} + E_{end-of-life,t} \quad (2.2)$$

Where,

$E_{containers,t}$	Emissions related to the management of refrigerant containers
$E_{charge,t}$	Emissions occurring during the charging process of the new equipment
$E_{lifetime,t}$	Emissions occurring during the equipment lifetime
$E_{end-of-life,t}$	Emissions occurring at equipment disposal

Emissions related to the management of refrigerant containers

Emissions at the fluid manufacturing stage occur from the feedstock materials in chemical processing plants. The good design and operation of the plant lead to relatively low emissions [IPC05]. These emissions are not counted within the methods under discussion.

Once manufactured, fluids are loaded in large containers, or in individual cylinders. They are therefore delivered to product manufacturers in bulk quantities or into smaller containers. Emissions can occur at this level of fluid handling: splitting the bulk refrigerant from large containers into smaller volumes of refrigerant. Capacity heels are also considered as a main loss during the refrigerant handling. The “heels” consist of both the liquid and vapour inside the container, which cannot be extracted due to the pressure equilibrium between the vapour (the vapour heel) and the liquid phase remaining in the refrigerant volume (the liquid heel).

Emissions related to the management of containers are considered between 2 and 10% of the total refrigerant market [IPC06].

$$E_{containers,t} = RM_t * \frac{c}{100} \quad (2.3)$$

Where,

RM_t	The refrigerant market for new equipment and servicing in year t
c	The emission factor of the management of refrigerant containers expressed in percentage

Emissions occurring when charging new equipment

At this stage, emissions occur when the refrigerant containers are connected to or disconnected from the equipment being charged. These emissions are usually higher for field-assembled and field-charged equipment than for the factory-produced ones. For example, these emissions include those taking place when hoses and valves are being connected or disconnected [CLO05].

All systems charged in a country in a given year t, including those that are exported are taken into account for the calculation of $E_{charge,t}$ as shown in Equation (2.4). Systems being imported are not considered [CLO05].

$$E_{charge,t} = M_t * \frac{k}{100} \quad (2.4)$$

Where,

M_t	The amount of refrigerant charged into new equipment in year t
k	The emission factor occurring during assembly expressed in percentage; it ranges between 2 and 5%.

Emissions occurring during the equipment lifetime

For most applications, the largest emissions take place particularly during the in-use stage and depend on the application type. For example, domestic refrigerators show very low emission rates during their lifetime, due to their hermetically sealed technology, whereas centralised systems in the commercial refrigeration sector experience the highest annual emission rates, up to 30% of their initial charge. These emissions generally originate from leakage of fittings, joints, and seals but also from ruptures of pipes and from the refrigerant handling during servicing operations. These rates vary among applications and countries depending on the technology, operating conditions, and the servicing quality. These emissions are calculated as shown in Equation (2.5) and include those occurring during servicing.

$$E_{lifetime,t} = B_t * \frac{x}{100} \quad (2.5)$$

Where,

B_t	The bank of refrigerant contained in all existing equipment in year t for all vintages
x	The emission factor of annual leakage from the bank occurring in year t, given in percentage

Emissions occurring at equipment disposal

Emissions from equipment at end of life depend on country regulations affecting the recovery efficiency at disposal. Parameters used for the calculation of these emissions are shown in Equation (2.6).

$$E_{end-of-life,t} = M_{t-d} * \frac{p}{100} * \left(1 - \frac{\eta_{end-of-life,t}}{100}\right) \quad (2.6)$$

Where,

M_{t-d}	The amount of refrigerant charged into new equipment in year t-d, reaching the end of life at age d
p	The remaining charge in the equipment being disposed of, expressed in percentage of the initial charge
$\eta_{end-of-life,t}$	The recovery efficiency at end of life, expressed in percentage of the remaining charge in the system

At the equipment end of life, several scenarios for fluid handling exist:

- The fluid is not recovered ($\eta_{end-of-life,t} = 0$), thus the remaining refrigerant quantity in the equipment constitutes the end of life emissions
- The fluid is recovered. After this, it can be considered as waste, and therefore is either destructed or emitted or disposed of. Alternatively, the recovered fluid can be reclaimed or recycled.

Choice of method for the refrigeration and air-conditioning sectors

Refrigeration and air-conditioning sectors are disaggregated in six sub-sectors. However, due to the diversity of equipment that can be found within the same sector, a more disaggregated level is needed in order to calculate the emission factors and the activity data, such as equipment lifetime, average charge, and refrigerant type. For example, if we consider the commercial refrigeration sector, the emission factor varies widely between the different refrigerating systems that can be found within this sector: the emission factor for standalone equipment is in the range of 1% and, as said before, for large centralised systems it can reach 30%.

The **mass-balance approach** (Equation 2.1) shows limitations especially when the recharge frequency is not on annual basis as for MAC systems: what enters for the servicing in a given year is not equivalent to what has been emitted. A delay of 5 to 8 years could be observed. In a mature market, where the average charge of the MAC system does not change and emission characteristics are also constant along time, this model could be applied since vehicle characteristics are identical, and the refrigerant stock does not change, which means that what is emitted 8 years ago is equal to what is emitted that year. This is not pretty much realistic due to the leak tightness improvements being observed on the MAC systems since the introduction of HFC-134a. Moreover, it is totally unrealistic when the market growth is significant as in Europe since 1995 and now in Asia.

Figure 2-1 shows a comparison of total emissions for MAC systems, as calculated by the emission-factor and the mass-balance approaches.

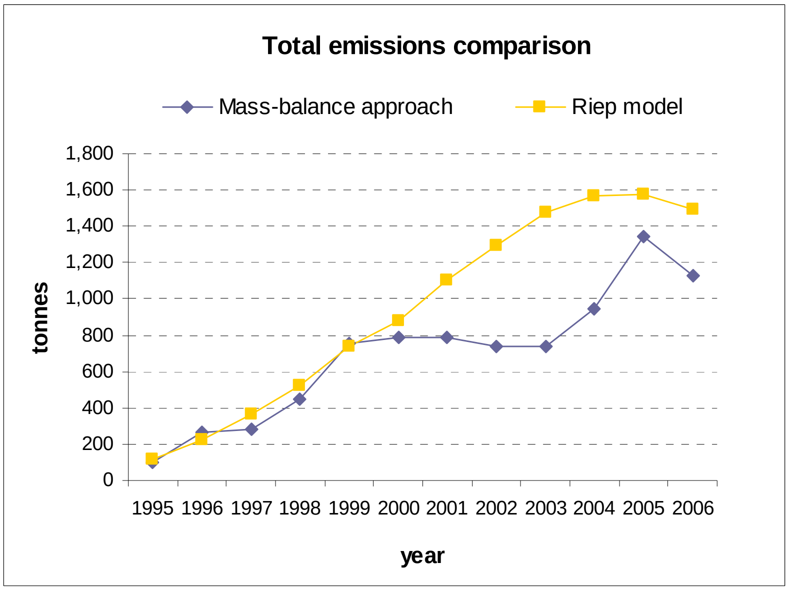


Figure 2-1 - Comparison of total emissions based on the mass-balance and the emission-factor approaches for MAC systems in France.

The mass-balance approach underestimates the emissions coming from the MAC systems as it can be seen on Figure 2- The difference between both methods is mainly due to the time lag between emissions and servicing consumption as explained previously.

The RIEP calculation method

The Center for Energy and Processes (CEP) developed a global database for the refrigeration and air-conditioning application, containing the required activity data and emission factors for the establishment of refrigerant inventories for countries and regions of the United Nations. A calculation model, called RIEP (Refrigerant Inventories and Emission Previsions), was developed based on a bottom-up approach as defined in IPCC 2000 [IPC00]. The work done by the CEP during the last eight years was taken into account for the update of the Tier 2 method as described in the IPCC 2006 guidelines [CLO05], [ASH04]. The covered sub-sectors are those listed previously, defined by the IPCC 2006 guidelines, and the disaggregation leads to the definition of 35 sub-sectors.

Improvements of the RIEP calculation method

A series of improvements of the RIEP calculation method has been done by S. Saba for her thesis work [SAB09]. Those refinements are important in order to figure out more precisely activity data such as equipment lifetime and emission factors.

Emission factors

Equations used for the emission-factor approach of the Tier 2 method are the basis of the general calculation method implemented in RIEP. Still, some particularities might appear for each sub-sector requiring specific input parameters and therefore some modifications to the main calculation algorithm. The method was adapted to the sub-sectors based on the availability of the activity data and the emission factors.

For example, for the commercial centralized systems, chillers, and industrial refrigeration, emission factors are established based on purchase invoices of refrigerants. The amount of refrigerant purchased includes the refrigerant used to replace the losses from leakages and the losses during the system servicing, and therefore both types of emissions are considered within the emission factor, which is then applied to the refrigerant bank. The same methodology is not possible for MAC or stationary air-conditioning systems. Sources of information of emission factors for this sector are scarce; some studies provide numbers on the initial leak flow rate (LFR) and others give numbers on the LFR of a fleet of vehicles from different vintages.

The calculation method implemented in RIEP considers an overall emission factor including “regular” and “irregular” emissions resulting from road accidents and accidents taking places in garages.

Regular leaks are the leaks related to joints, seals, and every location where one can find clearances between metallic parts with an elastomeric seal. Those regular leaks increase along the time due to wear and vibration, so the emission factor increases along the vehicle lifetime. Why a degradation factor has to be taken into account rather than an average value? Because the regular leaks are known from test on new systems, those values are low and do not explain the refrigerant sales dedicated to servicing in the Mobile-Air conditioning sector. Using an initial LFR increasing with time instead of an average value implies a different schedule for the maintenance operations. Taking the assumption of a degradation factor, a vehicle will undergo maintenance at the 6th year, then at the 9th, while assuming single average the vehicle will undergo maintenance every 4 years.

In summary, for MAC systems, the emissions factor is split in two factors:

- the “regular LFR” with an initial value given per vintage associated with a degradation factor, and
- the “irregular LFR” taking into account accidents.

A complementary algorithm is implemented for servicing taking into account emissions occurring during the maintenance $E_{servicing,t}$.

Change of refrigerant by retrofit

The RIEP model identifies retrofit operations for the sectors where they are occurring, and the related emissions $E_{retrofit,t}$.

Refrigeration system retrofit consists in replacing a former refrigerant (CFC or HCFC), which use is no longer possible either due to regulation or due to shortage of sales by a new one adapted to the system and in conformity with the regulation. The operation consists in recovering the “old” refrigerant from the refrigeration system, evacuating the system, and recharging the system with the new refrigerant. For the recovery operation, recovery efficiency is defined, the complementary percentage being emitted. The amount of refrigerant being replaced is calculated based on the retrofit schedule of the remaining bank of this refrigerant; for every year a percentage of this refrigerant bank being replaced.

Retirement curve instead of average lifetime

Another modification applied to the RIEP model is the use of a retirement curve to account for the equipment being disposed of instead of the mean lifetime used in the previous version. The modified equations taking into account the retirement curve are presented now. Equations related to the mean lifetime are taken from Clodic [CL005] and Ashford et al. [ASH04].

Hereafter, equations are given for mean lifetime and retirement curves:

$$B_t = \sum_{v=t-ml+1}^{t} M_v \qquad (2.7)$$

$$B_t = \sum_{v=t-Ml+1}^{t} M_v * r_{v,t} \qquad (2.8)$$

Where,

B_t The bank of refrigerant at year « t » expressed in kilograms

M_v The amount of refrigerant charged into new equipment for vintage v (per application category) expressed in kilograms and calculated by multiplying the national sales of equipment by the average charge of equipment

ml The mean lifetime of the system

Ml The maximum lifetime of the system when using a retirement function

$r_{,v,t}$ The remaining installed base of equipment of vintage v at year t expressed as a fraction of the initial number

Then, it can be seen that the bank calculation requires the knowledge of the mean lifetime for Equation (2.7) or the establishment of a retirement curve for Equation (2.8). The national sales of equipment as well as its average charge should also be known. The access to this activity data might be difficult especially for years before the Montreal Protocol.

For some sectors, such as the commercial refrigeration sector, emission factors are applied directly to the banks and Equation (2.5) is used to calculate emissions along the lifetime, taking indirectly into account the retirement curve for the bank calculation.

For MAC systems, the algorithm presented in Figure 2.2 is used to calculate emissions due to servicing, regular, and irregular emissions.
Emissions during lifetime are calculated as follows, according to the lifetime option:

- mean lifetime, Equations (2.9) and (2.10) are used
- when using a retirement curve, Equations (2.11) and (2.12) are chosen..:

$$E_{regular,t} = \sum_{v=t-ml+1^*}^{t} (N_v * LFR_{v,t}) \qquad (2.9)$$

** If the system is not empty*

$$E_{irregular,t} = \left(\sum_{v=t-ml+1^*}^{t} N_v \right) * EF_{irr,t} \qquad (2.10)$$

** If the system is not empty*

$$E_{regular,t} = \sum_{v=t-Ml+1^*}^{t} (N_v * r_{v,t} * LFR_{v,t}) \qquad (2.11)$$

** If the system is not empty*

$$E_{irregular,t} = \left(\sum_{v=t-Ml+1^*}^{t} (N_v * r_{v,t}) \right) * EF_{irr,t} \qquad (2.12)$$

** If the system is not empty*

Where,

N_v The number of equipment of vintage v

LFR_v The LFR value of vintage v at year t expressed in g/year

$EF_{irr,t}$ The emission factor for irregular emissions at year t expressed in g/year

$r_{v,t}$ The remaining installation of vintage v in year t expressed as a fraction of the initial number

Servicing emissions are calculated by Equations (2.13) and (2.14):

$$E_{servicing,t} = \left(\sum_{v=t-ml+1}^{t} \left(M_v \times \frac{s_{v,t}}{100}\right) \right) * (1 - \eta_{serv,t}) \quad (2.13)$$

** If the vintage requires servicing*

$$E_{servicing,t} = \left(\sum_{v=t-Ml+1}^{t} \left(M_v * \eta_{v,t} * \frac{s_{v,t}}{100}\right) \right) * (1 - \eta_{serv,t}) \quad (2.14)$$

** If the vintage requires servicing*

Where,

$s_{v,t}$	The residual charge of vintage v in year t expressed in percentage
$\eta_{serv,t}$	The recovery efficiency at servicing expressed as a fraction of the amount contained in the equipment being recharged

The algorithm presented in Figure 2.2 describes how emissions during servicing operation are taken into account for MAC systems. This algorithm is applied to all vehicle vintages. The recharge is required when the refrigerant emitted is over a threshold corresponding to 50% of the initial charge.

For every year j, the refrigerant loss is calculated by Equations (2.9) or (2.11). The loss is compared to the threshold of residual refrigerant charge, which requires the AC system maintenance due to the lack of cooling capacity.

If the loss is larger than this quantity, and the MAC system did not reach its end-of-life, the system undergoes maintenance and the amount of refrigerant required for the servicing operation and emissions occurring during this operation are calculated for this year of recharge. After this intervention, the system is fully charged again.

However, if the loss is lower than the threshold leading to maintenance, no maintenance occurs at this year of calculation, which is then incremented. Losses calculated for the following year are then added to those previously calculated, and the threshold for maintenance is then verified. If the condition for maintenance is verified, the maintenance operation takes place as described previously; otherwise, the year of calculation is incremented again until the MAC system reaches its end-of-life. As a result of this calculation algorithm, the $s_{v,t}$ parameter used in Equation (2.13) or (2.14) is calculated dynamically each year the system undergoes maintenance. The same thing applies to the end-of-life emissions that are calculated dynamically for this sector.

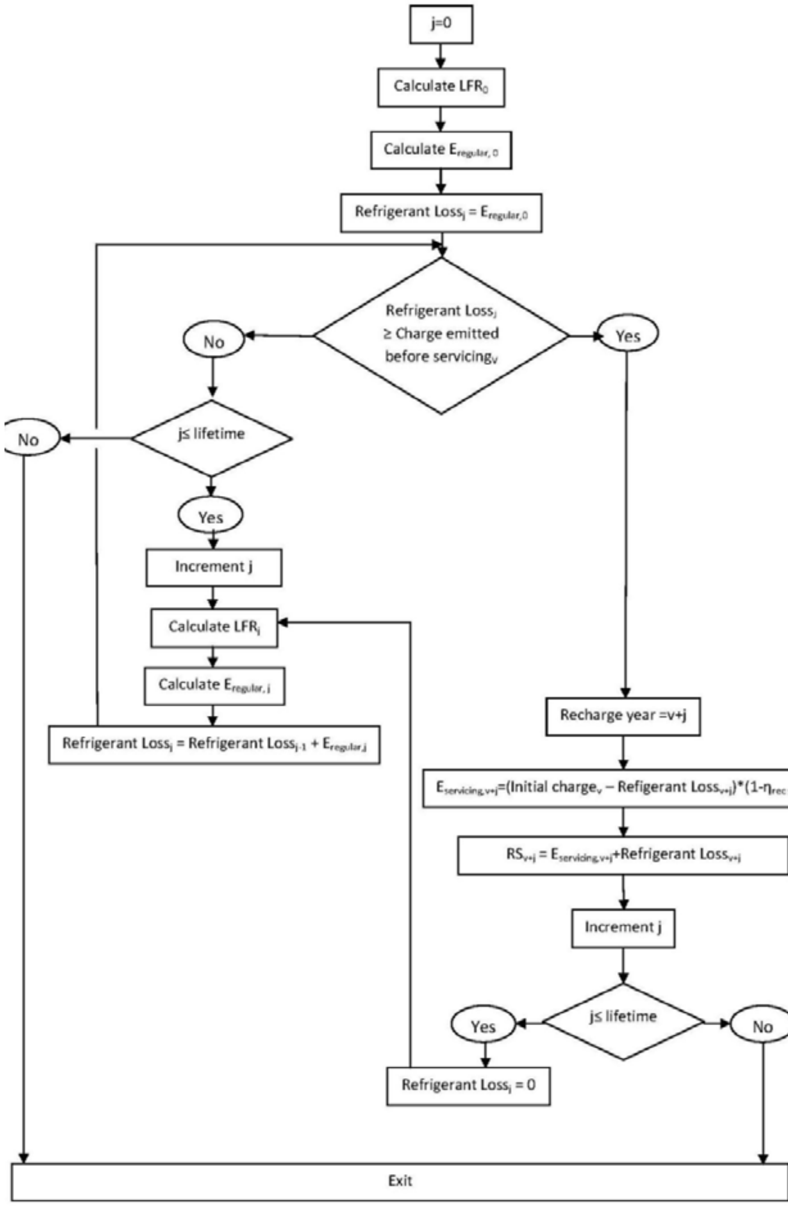


Figure 2.2 - Refrigerant servicing demand and emissions for MAC systems.

Retrofit emissions $E_{retrofit,t}$ are calculated using Equation (2.15)

$$E_{retrofit,t} = M_{refrigerant-out,t} * (1 - \eta_{end-of-life,t}) \quad (2.15)$$

Where,

$M_{refrigerant-out,t}$	The refrigerant being replaced at year t
$\eta_{end-of-life,t}$	The recovery efficiency at end of life in year t expressed as a fraction of the remaining amount of refrigerant being recovered

Total emissions during the lifetime are given by Equation (2.16):

$$E_{operation,t} = E_{regular,t} + E_{irregular,t} + E_{servicing,t} + E_{retrofit,t} \quad (2.16)$$

Emissions during servicing and retrofit given by Equation (2.17) occur during the refrigerant recovery. However, when the refrigerant is being re-introduced, emissions can take place. Those emissions do not appear in equations provided by [CLO05] or the IPCC 2006 guidelines, and can be written as follows:

$$E_{charge(servicing-retrofit)t} = (RS_t + RR_t) * \frac{k}{100} \qquad (2.17)$$

Where,

RS_t Refrigerant demand for servicing at year t
RR_t Refrigerant demand for retrofit at year t
k The emission factor at the charging process expressed in percentage

End-of-life emissions are calculated by Equation (2.6) when an average lifetime is used, whereas they are calculated by Equation (2.18) when using a retirement curve:

$$E_{end-of-life\,t} = \sum_{v=t-N+1}^{t} M_v * (r_{v,t-1} - r_{v,t}) * \frac{p}{100} * (1 - \eta_{end-of-life\,t}) \qquad (2.18)$$

Where,

$r_{v,t-1}$ The remaining installation of vintage v at year t-1
$r_{v,t}$ The remaining installation of vintage v at year t

For MAC systems, the residual charge at end-of-life is calculated for every vintage; therefore the value of p in Equation (2.18) depends on the vintage and on the year of disposal.

2.2 Refrigerants and regulations

The use of CFCs, HCFCs or HFCs and other refrigerants is related to control schedules, which have been continuously adjusted since the Montreal Protocol has been ratified. For the developed countries (the non-Article 5 countries as defined in the Montreal Protocol), the phase-out of CFCs and HCFCs will be earlier than in developing countries (the Article 5 countries). Moreover, where it concerns non-Article 5 countries, the European Union has accepted a much tighter control schedule for phasing out (CFCs in the past and) HCFCs.

The rapid phase out of CFCs in Europe and also the interdiction of use of CFCs for servicing have led to a significant uptake of intermediate blends (HCFC-based blends) for the retrofit of a number of refrigerating systems using CFCs. The retrofit allows keeping the residual value of equipment until its usual end of life. It is likely that the same behavior of equipment owners will be followed for the progressive phase out of HCFCs, which will be replaced by intermediate blends of HFCs. Based on these facts, RIEP includes retrofit options where the refrigerant can be changed during the equipment lifetime.

♦ Non-Article 5 countries

The CFC phase-out schedule as valid for the non-Article 5 countries is presented in Figure 2.3. Via the EU regulation 3093/94, CFCs were phased out one year before the phase-out defined in the Montreal Protocol, i.e. on 31 December 1994.

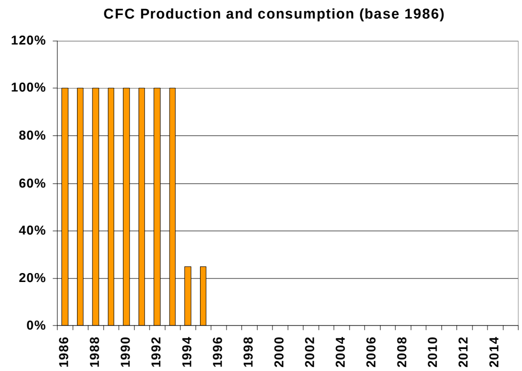


Figure 2.3 – CFCs phase out in non Article 5 countries.

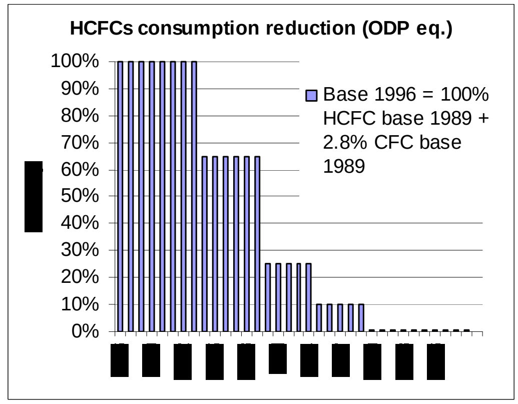


Figure 2.4 – HCFCs phase out in non Article 5 countries (except EU).[MOP07].

As indicated in Figure 2.4, the HCFC consumption base levels refer to the 1989 HCFC consumption plus 2.8% 1989 CFC consumption, ODP-weighted. On the basis of a certain ODP for HCFC-22 and CFCs (0.055 and 1.0 respectively), the factor of 2.8% means that if all CFCs were to be replaced by HCFC-22, about 55% of the CFC consumption in tonnes would be replaced by HCFC-22.

Figure 2.3 clearly shows that, even for non-Article 5 countries, brand-new equipment can be manufactured, charged with HCFC-22, and sold until 31 December 2009. Typically, the U.S. and many developed countries continue to use HCFC-22 for air-conditioning equipment.

As indicated in Figure 2.5, the EU regulation has changed the baseline level for the HCFC consumption by reducing the additional quantities of ODP weighted CFCs by nearly 30% (from 2.8 to 2.0%). Moreover, the time of the HCFC phase-out is been brought forward by about 7 years.

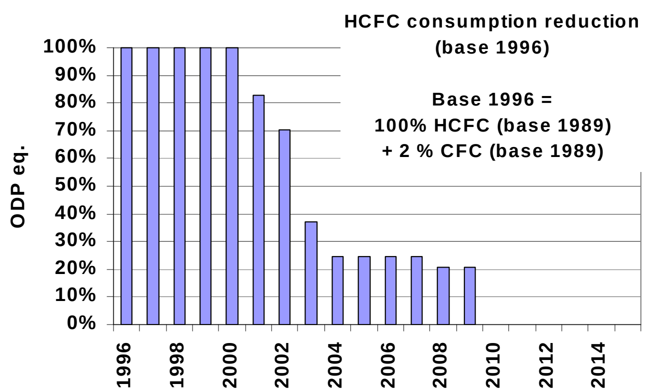


Figure 2.5 - European Union - (European regulation 2037/2000).

♦ **Article 5 Countries**

The CFC consumption and production (see Figure 2.6) for Article 5 countries have a delay compared to non-Article 5 countries of actually 14 years (1996 compared to 2010). There is an additional possibility of production and consumption of 10% compared to the 1996 level for Basic Domestic Needs of developing countries where production can take place in developed countries.

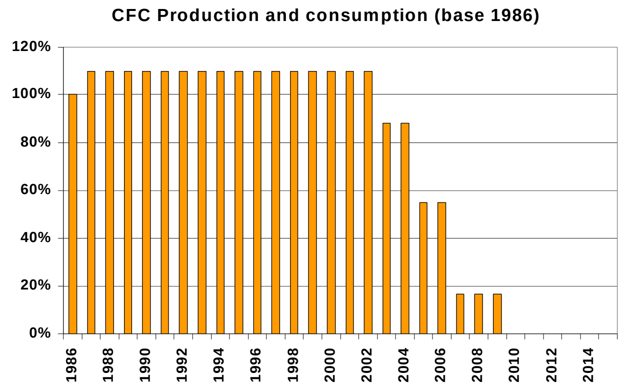


Figure 2.6 - CFC phase-out for Article 5 Countries.

For the HCFC phase-out, the Montreal Protocol schedules are slightly more complicated. Where it concerns the freeze in consumption, Article 5 countries have a delay of about 15 years (freeze by 2016). Where it concerns the phase-out, it is a 10-year delay period (phase-out in 2040 versus 2030) for the developing countries compared to the developed ones.

All these different constraints based on global control schedules and more stringent regional and national regulations imply different refrigerant choices in countries and country groups. The refrigerant choices need to be taken into account on an application by application basis. In this project, additional data, derived from country reports, have been used as well as data available in publications.

2.3 Refrigerant GWPs from the IPCC Second and the Fourth Assessment Reports

Table 2.1 lists the main refrigerant types in use: CFCs, HCFCs, HFCs, ammonia, and different blends, many of them being intermediate blends used for retrofit of CFC equipment. Table 2.1 has been updated taking into account all new blends as declared to ASHRAE 34. Among those blends, the most used of are R-401A, R-409A, and R-413A for the replacement of CFC-12, R-402A and B, and R-408A for the replacement of R-502. The use of those blends can be verified at the global level by the declarations of sales by AFEAS of HCFC-124 and HCFC-142b, which are specific components of those intermediate blends. The list is nearly exhaustive, and takes into account more than 99% of all refrigerant types in use.

The GWP values, as given in the Second Assessment Report of the IPCC (SAR), are used for the calculations of the equivalent CO_2 emissions of refrigerants as shown in Table 2.1. The latest scientific values of refrigerant GWPs are coming from the 4th Assessment Report of IPCC. As it can be observed below, they are virtually all higher than the GWP values published in the 2nd Assessment Report. Nevertheless, in the RIEP calculations, the SAR report values have been kept because they are those used for reporting HFC emissions to UNFCCC. GWPs of mixtures have been calculated from the separate components.

For latest GWP values, based upon the Fourth Assessment Report as well as the 2010UNEP/WMO Scientific Panel Assessment Report reference is made to chapter 2 in this 2010 RTOC report, which contains all latest GWP values for pure substances and for mixtures and blends.

Table 2-1 GWP and physical data of refrigerants [TOC03, IPCC07]

Refrigerant		**Physical data**				**GWP**	
Number	Chemical formula or blend composition – common name	Molecular mass	NPB (°C)	TC (°C)	Pc (MPa)	GWP SAR 1996	GWP AR4 2007
11	CCl_3F	137.37	23.7	198.0	4.41	3 800	4750
12	CCl_2F_2	120.91	-29.8	112.0	4.14	8 100	10890
22	$CHClF_2$	86.47	-40.8	96.1	4.99	1 500	1810
32	CH_2F_2-methylene fluoride	52.02	-51.7	78.1	5.78	650	675
115	$CClF_2CF_3$	154.47	-38.9	80.0	3.12	9 300	7370
116	CF_3CF_3-perfluoroethane	138.01	-78.1	19.9	3.04	9 200	12200
123	$CHCl_2CF_3$	152.93	27.8	183.7	3.66	90	77
124	$CHClFCF_3$	136.48	-12.0	122.3	3.62	470	609
125	CHF_2CF_3	120.02	-48.1	66.1	3.63	2 800	3500
134a	CH_2FCF_3	102.03	-26.1	101.1	4.06	1 300	1430
143a	CH_3CF_3	84.04	-47.2	72.7	3.78	3 800	4470
152a	CH_3CHF_2	66.05	-24.0	113.3	4.52	140	124
245fa	$CHF_2CH_2CF_3$	134.05	15.1	154.0	4.43		1030
290	$CH_3CH_2CH_3$ - propane	44.10	-42.1	96.7	4.25		
401A	R-22/152a/124(53/13/34)-MP39	94.44	-32.9	107.3	4.61	973	
401B	R-22/152a/124(61/11/28)-MP66	92.84	-34.5	105.6	4.68	1 062	
402A	R-125/290/22(60/2/38)-HP80	101.55	-48.9	75.9	4.23	2 250	
402B	R-125/290/22(38/2/60)-HP81	94.71	-47.0	82.9	4.53	1 796	
403A	R-290/22/218(5/75/20)	91.99	-47.7	87.0	4.7	2530	
403B	R-290/22/218(5/56/39)	103.26	-49.2	79.6	4.32	3570	
404A	R-125/143a/134a(44/52/4)	97.60	-46.2	72.0	3.74	3 260	
405A	R-22/152a/142b/C318(45/7/5.5/42.5)	111.91	-32.6	106.1	4.29	4480	
406A	R-22/600a/142b(55/4/41)	89.86	-32.5	116.9	4.96	1560	
407A	R32/125/134a(20/40/40)	90.11	-45.0	81.8	4.52	1770	
407B	R32/125/134a(10/70/20)	102.94	-46.5	74.3	4.13	2290	
407C	R-32/125/134a(23/25/52)	86.20	-43.6	85.8	4.63	1 526	
407D	R-32/125/134a(15/15/70)	90.96	-39.2	91.2	4.47	1430	
407E	R-32/125/134a(25/15/60)	83.78	-42.7	88.3	4.7	1360	
408A	R-125/143a/22(7/46/47)-FX-10	87.01	-44.6	83.1	4.42	2 649	
409A	R-22/124/142b(60/25/15)-FX-56	97.43	-34.4	109.3	4.69	1 288	
410A	R-32/125(50/50)-Suva9100;AZ-20	72.58	-51.4	70.5	4.95	1 730	
411A	R-1270/22/152a(1.5/87.5/11)	82.36	-39.5	99.1	4.95	1330	
412A	R-22/218/142b(70/5/25)	92.2	-38	107.2	4.9	1850	

Refrigerant		Physical data				GWP	
Number	Chemical formula or blend composition – common name	Molecular mass	NPB (°C)	TC (°C)	Pc (MPa)	GWP SAR 1996	GWP AR4 2007
413A	R-218/134a/600a(9/88/3)	103.95	-33.4	96.6	4.07	1770	
414A	R-22/124/600a/142b(51/28.5/4/16.5)	96.93	-33.0	112.7	4.68	1200	
415A	R-22/152a(82/18)	81.91	-37.2	102.0	4.96		
416A	R-134a/124/600(59/39.5/1.5)	111.92	-24.0	107.0	3.98		
417A	R-125/134a/600(46.6/50/3.4)	106.75	-39.1	87.3	4.04		
418A	R-290/22/152a(1.5/96/2.5)	84.60	-41.7	96.2	4.98		
419A	R-125/134a/E170(77/19/4)	109.3	-42.6	79.3	4		
420A	R-134a/142b(80.6/19.4)	101.84	-24.9	104.8	4.11		
421A	R-125/134a(58/42)	111.75	-40.7	82.9	3.88		
422A	R-125/134a/600a(85.1/11.5/3.4)	113.60	-46.5	71.8	3.92		
427A	R-32/125/143a/134a(15/25/10/50)	90.44	-43.0	85.1	4.39	1827	
500	R-12/152a(73.8/26.2)	99.30	-33.6	102.1	4.17	6 014	
502	R-22/115(48.8/51.2)	111.63	-45.2	80.2	4.02	5 494	
503	R-23/13(40.1/59.9)	87.25	-87.8	18.4	4.27	11 700	
507A	R-125/143a(50/50)-AZ-50	98.86	-46.1	70.5	3.79	3 300	
1270	$CH_3CH{=}CH_2$ - propylene	42.08	-47.7	92.4	4.66		
600a	$CH(CH_3)2\text{-}CH_3$ - isobutane	58.12	-11.7	134.7	3.64		
717	NH_3 – ammonia	17.03	-33.3	132.3	11.33		
744	CO_2	44.01	-78.4	31.0	7.38		1

NBP = normal boiling point; Tc = critical temperature; Pc = critical pressure; GWP = global warming potential (for 100-yr integration).

The GWP calculation for blends is based on the GWP values of pure refrigerants, and their mass concentration in the blend. All values for blends are coming from the 2006 TOC Report [TOC06]

2.4 Consistency and improvement of data quality

The refrigerant demand calculated by RIEP for each refrigerant, including charge of new equipment and recharge of the installed base to compensate refrigerant emissions, is compared to refrigerant sales declared by refrigerant distributors.

Equation (2.19) calculates the refrigerant demand, which is then compared to the declared numbers.

$$R_t = \left(1 + \frac{c}{100} + \frac{k}{100}\right) * (RP_t + RS_t + RR_t) \quad (2.19)$$

Where,

R_t	The total refrigerant demand at year t, expressed in kilograms
RP_t	The total refrigerant demand for the new equipment being charged in the country, expressed in kilograms
RS_t	The refrigerant demand for servicing at year t, expressed in kilograms
RR_t	The refrigerant demand for retrofit at year t, expressed in kilograms
c	The emission factor of the management of refrigerant containers, expressed in percentage
k	The emission factor occurring during assembly, expressed in percentage

The refrigerant demand for new equipment is given by Equation (2.20)

$$RP_t = \sum_{i=1}^{6} (S_{prod_{i,t}} * m_{i,t}) \quad (2.20)$$

Where,

$S_{prod,i,t}$	The national production of equipment for the application i at year t
$m_{i,t}$	The average equipment charge for the application i at year t, expressed in kilograms

The refrigerant demand for servicing is given by Equation (2.21) when the emission factor is applicable to the sector bank, and by Equation (2.22) in other cases.

$$RS_t = \sum_{i=1}^{6} E_{lifetime_{i,t}} \quad (2.21)$$

Where,

$E_{lifetime\ i,t}$	The total emissions as calculated by Equation (2.22) when the emission factor is applicable to the bank of the sector I

$$RS_t = \sum_{i=1}^{6} \left[\left(\sum_{v} E_{regular_{i,t\_vintage}} ^{*} + (1 - \eta_{serv_{i,t}}) * RemainingCharge \right) + E_{irregular_{i,t}} \right] \quad (2.22)$$

** If the vintage requires servicing*

Where,

$E_{regular\ i,t\_vintage}$	Losses of vintage v since its last recharge until year t, if the vintage requires recharging, and for application I
$\eta_{serv\ i,t}$	The recovery efficiency at servicing at year t for application I
RemaningCharge	The remaining charge in the equipment at the moment of servicing being recovered
$E_{irregular,t,i}$	The irregular emissions at year t for application I

The refrigerant demand for retrofit RR_t corresponds to the amount of refrigerant being introduced into the system during the retrofit operation.

The refrigerant demands calculated for each refrigerant and for each application, are added up to derive the national demand by refrigerant or the global demand. These demands are compared to the national declarations of refrigerant manufacturers and distributors or compared to the AFEAS sales data at the global level.

Note: It has to be mentioned that AFEAS has decided to stop its yearly publication of refrigerant sales at the end of 2009, because the production of China, India, Russia, and Brazil are not published and so a bias between the "real" sales and the AFEAS data is becoming more and more significant.

The cross-checks can be performed both on a country-by-country basis and globally. If the refrigerant inventories and the related emissions are adequately determined, the difference between the submitted figures and the calculated refrigerant sales will be small. If not, additional analyses are required.

♦ Consistency for refrigerating equipment at the global level

To reach high accuracy in the sizes of refrigerant inventories, the first step required is to gather reliable data for equipment numbers. Fortunately, annual statistical data are available for nearly all mass-produced equipment. Details on the availability of such numbers per application are provided in the corresponding chapters. When data is not available, correlations between sale population and wealth of countries are established to derive the missing data. Some data have been published by manufacturer associations, and some are available from marketing studies that can be purchased from specialised companies. The data on annual equipment sales allow deriving figures on production and sale at the national level for nearly all OECD countries, and also at the global level, when they are based on production data (see Figure 2.7).

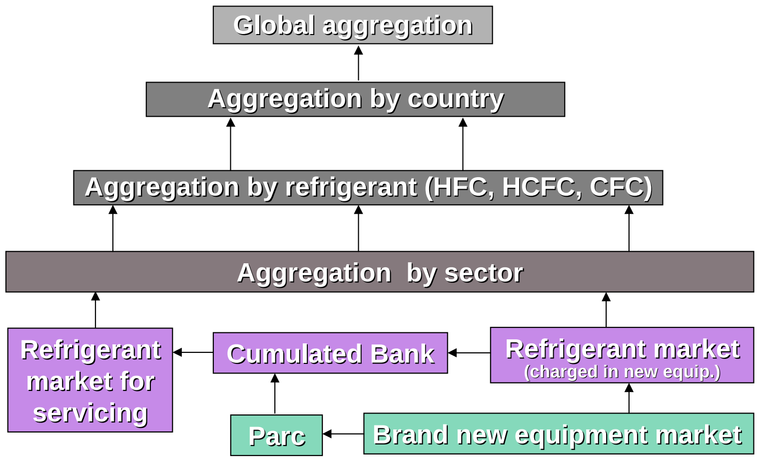


Figure 2.7 – Determination of refrigerant markets.

As shown in Figure 2.7, the derivation of the global demand of refrigerants consists in:

- establishing the annual sales of brand-new equipment and the amount of refrigerants charged in this equipment,
- the derivation of refrigerants banked in the installed bases of the six sectors, as a function of their lifetime,
- the calculation of the refrigerant market for servicing dependent on emission factors,
- then the six application sectors are aggregated
- by families of refrigerants,
- country by country,
- by country groups and globally.

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Appendix 1

1 – Geographical split

Global inventories cover six countries calculated independently and seven groups of countries:

- USA,
- China,
- Japan,
- Brazil,
- India,
- Canada,

- Latin America and the Caribbean,
- European Union 27 (EU27),
- Other Europe,
- West and Central Asia,
- South and East Asia,
- Oceania, and
- Africa.

The subdivision of the groups of countries is based on the geographical regions provided by the United Nations Statistics Division, revised on the 17th of October 2008 [UNS08]. However, the calculation assumptions (CFC and HCFC phase-out...) are not always identical over the countries within the same group. Therefore, some groups are separated in two subgroups in order to take into account the difference in the calculation assumptions.

Table A2.1 provides details about the group subdivisions and the considered calculation assumptions. Calculations are led on one database for those groups that are not subdivided, i.e. the activity data of all countries constituting the group are aggregated in one database. Regions divided in two groups (Oceania, West and Central Asia, EU27, and Other Europe) are separated each in two different databases.

Table A2.1 - Country groups description.

Group	Composition	Assumptions for phase-out of CFCs and HCFCs
Latin America and the Caribbean	Antigua, Argentina, Bahamas, Barbados, Belize, Bolivia, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Rep., Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Saint Lucia, St Kitts and Nevis, St Vincent, Suriname, Trinidad & Tobago, Uruguay, Venezuela	Article 5
Africa	Algeria, Angola, Benin, Botswana, Burkina, Burundi, Cameroon, Cape Verde, Centrafrica, Chad, Comoros, Congo , Congo RD, Côte d'Ivoire, Djibouti, Egypt, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Guinea Eq, Kenya, Lesotho, Liberia, Libyan Arab, Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe	Article 5
West* and Central Asia	Afghanistan, Armenia, Bahrain, Georgia, Iraq, Jordan, Kuwait, Kyrgyzstan, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkmenistan, United Arab Emirates, , Yemen, Azerbaijan, Kazakhstan, Tajikistan, Uzbekistan	Article 5
	Turkey, Israel	
South and East Asia	Bangladesh, Bhutan, Brunei, Cambodia, Indonesia, Islamic Republic of Iran, People's Democratic Republic of Korea, Republic of Korea , Lao, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Viet Nam	Article 5
Oceania	Australia, New Zealand	non Article 5
	Cook Islands, Fiji, Kiribati, Marshall, Micronesia, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu	Article 5
EU 27	**EU 15**: Austria, Belgium, Denmark, Finland, France, Germany , Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United kingdom	non Article 5
	Other EU: Bulgaria, Cyprus, Czech republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia	transition Article 5 -> non Article 5
Other Europe	Andorra, Belarus, Iceland, Lichtenstein, Monaco, Norway, Russian Federation, Switzerland, Ukraine	non Article 5
	Albania, Bosnia and Herzegovina, Croatia, Moldova, Montenegro, Serbia , The Former Yugoslav Republic of Macedonia	Article 5

**Except Cyprus included in EU27*

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