# MONTREAL PROTOCOL

# ON SUBSTANCES THAT DEPLETE

# THE OZONE LAYER

UNEP

## 2006 REPORT OF THE
## REFRIGERATION, AIR CONDITIONING AND HEAT PUMPS
## TECHNICAL OPTIONS COMMITTEE

## 2006 Assessment

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The text of this report is composed in Times New Roman.

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The names, addresses and contact numbers of all chapter lead authors and other authors of the UNEP TOC Refrigeration, A/C and Heat Pumps can be found in Annex I.

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# Table of Contents

# Abstract Executive Summary of the 2006 TOC Refrigeration, Air Conditioning and Heat Pumps Assessment Report

## *Current status*

The required global phase-out of CFCs and later also HCFCs, coupled with steps to reduce global warming, continues to drive transitions away from ODS refrigerants. The technology options are universal, but regional choices are influenced by local laws, regulations, standards, and economics. The primary current solutions are summarised below by application.

- *Refrigerants:* More than 20 new refrigerants were commercialised for use either in new equipment or as service refrigerants (to maintain or convert existing equipment) since publication of the 2002 RTOC report. Additional refrigerants still are being developed, and research continues to increase and improve the physical, safety, and environmental data.
- *Domestic refrigeration:* More than 96% of new production uses non-ODS refrigerants, primarily HFC-134a and isobutane (HC-600a). CFC emissions from the 100,000 tonne bank are dominated by final disposal due to the intrinsic equipment durability.
- *Commercial refrigeration:* Most stand-alone equipment uses HFCs, but hydrocarbon (HC) and carbon dioxide (R-744, $CO_2$) use is growing, especially in Europe and Japan. Use of HCFC-22 (USA and Article 5 countries) and R-404A (Europe) dominate in new supermarket systems. $CO_2$, HCs, and ammonia (R-717) are used in Northern European countries. The ODS refrigerant bank is 185,000 tonnes of CFCs and 240,000 tonnes of HCFC-22. Annual supermarket systems emission rates range from 15 to 30% of their charge.
- *Industrial refrigeration:* Ammonia (R-717) and HCFC-22 are the most common refrigerants for new equipment; costs have driven HFC-use in small systems. $CO_2$ use is gaining in low-temperature, cascaded systems. The ODS refrigerant bank is 20,000 tonnes of CFCs and 130,000 tonnes of HCFC-22. Annual ODS emission rates are in the range of 10-25% of the banked charge.
- *Transport refrigeration:* New production has shifted to non-ODS options, such as HFC-134a, R-404A and R-507A, with recent increases also for R-410A. Nearly all CFC-containing systems will be retired by 2010. The ODS refrigerant bank is 4,300 tonnes of CFCs and 17,000 tonnes of HCFC-22 with estimated annual emission rates of 25%.
- *Air conditioners and heat pumps:* HFC blends, primarily R-410A, but also R-407C, are the most common near-term substitutes for HCFC-22 in air-cooled systems. HCs are an option for low charge systems and limited consideration of $CO_2$ continues. The refrigerant bank is 887,000 tonnes of HCFC-22 with estimated annual emissions at a rate of 18%. HCFC-22 recovery and containment are necessary to ensure adequate refrigerant supply for service.
- *Water-heating heat pumps:* This small but rapidly growing application area is driven by energy efficiency. HFCs, primarily HFC-134a and R-410A, are replacing HCFC-22. $CO_2$ systems have been introduced in Japan and Europe. The ODS refrigerant bank is very small as historical application was at a low level.

- *Chillers:* HCFC-22 continues to be used in small chillers; the use of HFC-134a, R-407C, and R-410A is increasing here. HCFC-123 and HFC-134a are used in larger centrifugal chillers. Ammonia or HC use is limited. The ODS bank is 107,000 tonnes of CFCs and 112,000 tonnes of HCFCs with estimated annual emission rates of 15% and 10%, respectively.
- *Vehicle air conditioning:* HFC-134a has been used almost exclusively since 1994 in new systems in non-Article 5 countries, and now also globally. Environmental pressure such as recently adopted EU MAC directive is driving possible future replacement of HFC-134a in vehicle air conditioning by low GWP alternatives. $CO_2$ and also HFC-152a are currently among important candidates. The ODS-refrigerant bank is estimated to be about 60,000 tonnes of CFC-12 with an estimated annual emission rate of 10%. Few ODS-containing systems will remain in service after 2012.

### *What is left to be achieved*

CFCs and HCFCs still are common in installed equipment. The CFC bank is approximately 450,000 tonnes, 70% of which can be found in Article 5 countries. The annual global CFC demand of approximately 50,000 tonnes per year is decreasing slowly. HCFCs form the dominant refrigerant bank, estimated as more than 1,500,000 tonnes, representing 60% of the total amount of refrigerants in use. Two thirds of this bank can be found in non-Article 5 countries. Current service needs are estimated at 200,000 tonnes per year. Efficient refrigerant recovery at end-of-life and retrofit to non-ODS service refrigerants are essential to avoid HCFC shortages in Article 5 countries. The critical years could be 2009 and 2010 in Europe and later on in the USA and other countries.

The refrigerant demand for service needs can be minimised by preventive maintenance to improve containment and by reusing the recovered and recycled refrigerant. Retrofitting to non-ODS refrigerant is another option. Refrigerant recovery is required in the USA and EU upon equipment decommissioning or retirement; it is receiving increasing attention in other non-Article 5 countries. The countries with successful recovery and recycling have achieved that with technician training, certification programs, and comprehensive containment regulations.

The technological options for air conditioning and refrigeration are expected to be much the same in the next four years as they are today. In applications with high emission rates, such as commercial refrigeration, designs with lower emissions, and conversion to low-GWP refrigerants, such as $CO_2$, are expected.

### *The way forward*

Research will continue to develop additional refrigerant options. Efforts also will increase and refine the physical, safety, and environmental data for refrigerants, to enable screening, to optimise equipment designs, and to determine application requirements. Changing refrigerant options and efficiency goals are likely to drive further innovations in air conditioning and refrigeration equipment. Technical solutions are being developed to lower refrigerant charges in equipment, thereby decreasing refrigerant emissions. Use of indirect systems (applying heat transfer fluids in secondary loops) is increasing to reduce charge sizes, to enable use of sealed systems, and to facilitate application of flammable ODS alternatives. Since the recently adopted EU F-Gas Regulation will ban HFC-134a and other refrigerants with GWPs exceeding 150 in new vehicle models by 2011, the industry will be forced to make a second refrigerant change in mobile air conditioning. Several candidates continue to be evaluated, including $CO_2$ and R-152a as well as new low-GWP refrigerants, some of which may have low ODPs. Development of these low-GWP refrigerants also may have future consequences for the refrigerant choices in other applications.

The use of HCs and $CO_2$ in stand-alone commercial refrigeration equipment is expected to grow, mainly in Europe. HFC blends are the most likely near-term refrigerants to replace HCFC-22 in several applications. The dominant HCFC-22 bank is expected to continue to grow for a number of years, and the HFC bank is expected to increase rapidly, at least during the next decade.

Contrary to non-Article 5 countries, the demand for service refrigerants in most Article 5 countries will consist of CFCs and HCFCs, a tendency driven by long equipment life and with the costs of field conversion to alternative refrigerants. One of the main concerns will be maintaining adequate supplies of HCFCs. Refrigerant conservation programs to be established for CFCs in Article 5 countries will mostly be government sponsored and regulatory in nature. As in many non-Article 5 countries, they may include restrictions on the sale, use, and end-of-life disposal requirements that mandate recovery and recycling of refrigerants. These programs will be expanded in countries without such requirements.

# Executive Summaries of all Chapters

## Refrigerants

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.

The tabular data summaries are updated from prior assessments to reflect current data, from 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 ($\tau_{atm}$), ozone depletion potential (ODP), global warming potential (GWP), and control status. The summary tables also add new blends introduced since the 2002 assessment report. The updated chapter adds guidance for ODPs and GWPs for regulatory reporting.

This chapter also provides similar information for heat transfer fluids (sometimes referred to as “secondary coolants” or “secondary refrigerants”) for air-conditioning, heat pump, and refrigeration systems.

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 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 excellent and 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 the transport properties of many fluids (but especially so for blends). The data situation for the less-common fluids is more variable; there is a need to collect and evaluate the data for such candidates.

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 introduction of new refrigerants, 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.

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

- *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 hydrocarbons, ammonia, and carbon dioxide*
- *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*

This chapter similarly outlines current understanding of materials compatibility data for refrigerant systems as well as safety data and classifications. It notes that efforts are underway to develop recommended refrigerant concentration limits for unplanned exposures and to improve flammability test methods and data.

The expanded update adds information on heat transfer fluids (HTFs) — also referred to as *secondary coolants* or *secondary refrigerants* — for indirect systems. Although HTFs have been used for many years in industrial applications, they have recently become more popular in commercial applications for the purposes of reducing the primary refrigerant charge and/or mitigating emissions of refrigerants that have notable environmental warming impact or when regulatory or safety constraints apply. HTFs are divided into two categories, namely single phase and phase-change fluids.

The use of phase-change fluids in indirect systems is becoming more popular due to favourable thermal and transport properties leading toward energy savings benefits. The most common phase change fluids are carbon-dioxide and ice-slurries, although other suspensions such as water/ice-filled capsules, hydrophilic material slurries, and frozen emulsions have been considered, but these are largely in developmental stages. Phase-change fluids benefit from having much greater heat capacities and generally improved heat transfer coefficients associated with the phase change. Therefore, phase-change fluids offer the potential benefits of lower flow rates and pumping costs, smaller pipe sizes and smaller heat exchangers.

## Domestic Refrigeration

Conversion of new production domestic refrigeration equipment from CFC-12 to non-ODS refrigerants has occurred well in advance of Montreal Protocol requirements. By the end of 2004, more than 96% of new production had converted to non-ODS refrigerants. 63% of these were converted to HFC-134a, 35% were to hydrocarbons (HC-600a or HC-600a/HC-290 blends) and 2% were to all other refrigerants. Original production conversion may be 100% complete by the time this report is published. Broad-based refrigerant alternatives continue to be HFC-134a or HC-600a with regional preference being influenced by multiple local and national codes, standards and regulations.

Conversion of domestic refrigeration field service refrigerant demand from CFC-12 to non-ODS refrigerants is significantly slower than new production conversion. By the end of 2004, only approximately 25% of field service refrigerant demand had converted to non-ODS refrigerants. The distribution of non-ODS service refrigerants is roughly comparable to the new equipment refrigerant selection. Approximately 75% of domestic refrigeration service refrigerant demand continues to be CFC-12. This sluggish conversion is a consequence of long equipment service life and technical difficulties with field-conversion of existing units to alternative refrigerants. Increased use of the binary and ternary blends of HFC, HCFC, PFC and hydrocarbon refrigerants specifically developed for the service industry is expected to somewhat accelerate conversion from CFC-12. These blends have current widespread use in Australasia and North America. The acceleration rate for their global use will be determined by the relative availability and economics of these blends versus CFC-12.

The long product life and low failure rate of the estimated 1200 to 1500 million currently installed domestic refrigerators result in refrigerant emissions from the domestic refrigeration bank being dominated by end-of-life final disposition of these units. This bank is estimated to contain 90,000 to 100,000 tonnes of CFC-12. The management of the potential emissions from this bank is expected to be a global agenda topic for at least another 20 years. Experience with various regulatory and market-driven refrigerant conservation initiatives is discussed in Chapter 11 of this report.

## Commercial Refrigeration

Commercial refrigeration is part of the food chain. Two levels of temperature (medium temperature for preservation of fresh food and storage of beverages, and low temperature for frozen products) may imply the use of different refrigerants.

Commercial refrigeration has benefited from over 10 years of technical efforts, which have reduced refrigerant emissions, drastically lowered the refrigerant charge by developing indirect systems or other concepts, or replaced high-GWP refrigerants with lower GWP alternatives.

Commercial refrigeration is composed of three main categories of equipment: stand-alone equipment, condensing units, and centralised systems. The number of supermarkets world-wide is estimated at 477,000 in 2003 covering a wide span of sales areas varying from 500 $m^2$ to 20,000 $m^2$. The populations of vending machines, stand-alone equipment and condensing units are evaluated respectively at 18.5, 29, and 31 million units.

### *Stand-alone equipment*

The majority of stand-alone equipment is based upon HFC technology. Some well-established beverage companies and ice-cream manufacturers have committed themselves in 2004 to eliminate the HFC use in their applications and so the use of HCs and $CO_2$ is growing in several applications. For existing systems, the conversion from CFC-12 to HFC-134a involves several steps, including the change of mineral oil to POE lubricant. These procedures are now well established but still significant training is necessary in many Article 5 countries to avoid unnecessary repair after retrofit.

*Centralised systems*

The size of centralised systems can vary from refrigerating capacities of about 20 kW to more than 1 MW. The charge of refrigerant is related to the refrigerating capacity and store layout. In order to lower the refrigerant charge, a number of technical solutions have been developed including mainly indirect and distributed systems. An indirect system is composed of a refrigerating system installed only in the machinery room. In a centralised system, a heat transfer fluid (HTF) is cooled in the evaporator of a compact refrigerating system located in the machine room. It is then circulated to the display cases located in the sales area to extract heat from these display cases. The HTF is then returned to the machine room where it is re-cooled so the process can be repeated.

Depending on the country, HFCs, ammonia, HCs, and $CO_2$ are used as primary refrigerants in the refrigerating system entirely installed in the machinery room and/or outside. HFC-404A is the dominant choice in Europe, HCFC-22 is the most used refrigerant still in the US and in all developing countries. The uptake of R-404A and so called “intermediate” HFC blends has begun as of 2000 in the USA for the replacement of HCFC-22. In Europe there is now interest in the development of low GWP refrigerants and increased attention in containment. CFCs (CFC-12 and R-502) are mainly used in Article 5 countries and are needed for servicing of all commercial refrigerating systems. HCFCs are used both for new equipment and for servicing and in all countries except Europe for new equipment.

*Refrigerant banks*

The bank of CFCs has reached about 185,000 tonnes from 1995 to 1999 with a slow decrease by then. The dominant bank as of 1999 is the HCFC-22 bank, which reached more than 240,000 tonnes in 2003. Its growth is expected to continue for a number of years. The HFC bank is increasing rapidly and has reached 50,000 tonnes in 2003.
The refrigerant emissions of CFCs, HCFCs, and HFCs are respectively of 44,000, 78,000, and 10,000 tonnes in 2003 /Clo06/. They are proportional to the size of their respective refrigerant banks.

## Industrial Refrigeration

This chapter has been completely revised and updated from the previous 2002 RTOC report /TOC02/. Market and technology trends are updated and new developments covered. The market for industrial refrigeration covers food and drink processing and distribution, process industries such as pharmaceutical, chemical and petrochemical and some specialist plants in the building services market. It also includes heat pumps using the refrigeration cycle within these market segments. R-717 is widely used for industrial refrigeration in developed countries, but is less common in the developing world, particularly where there are concerns about plant integrity and maintenance capability.

The industrial refrigeration market in the developed countries is estimated to be growing at a rate of 4% per year, and there is also an increasing diversity of requirements in the food and drink market segment. Transition in these markets from CFCs and HCFCs has resulted in a significant investment in new equipment, principally R-717 plants. In some niche markets R-744 has been used in order to achieve specific benefits. It is particularly difficult to estimate the emissions of fluorocarbons owing to the wide variety of system types in this sector. Extrapolation from available information suggests world-wide annual leakage rates for 2006 of 18% of the charge for CFCs, 15% for HCFCs and 13% for HFCs.

## Transport Refrigeration

Transport Refrigeration includes transport of chilled or frozen products by reefer ships, intermodal refrigerated containers, refrigerated railcars and road transport including trailers, diesel trucks and small trucks and vans. It also includes use of refrigeration and air conditioning on merchant ships above 300 gross tonnes.

According to a recent study, transport refrigeration still accounted for 0.8 % of all ODS emissions in 2002, while transport refrigeration equipment contained just 0.5 % of the world refrigerant bank. This indicates that leakage rates of transport refrigeration equipment are still higher than industry average. Since the working environment in all sub-sections of transport refrigeration is under rough conditions, emissions on average are higher than in other areas. To reduce leakages, better quality systems are now on the market, meaning higher costs to the user, but also better conditions for the goods transported.

Rough operating conditions bring about shorter life cycles so that the typical life span of many transport refrigeration systems is lower than for stationary refrigeration and air conditioning equipment. This is the reason that the transport refrigeration sector has already shifted more towards HFCs than other industry sectors.

All over the world, including Article 5 countries, new transport refrigeration systems are commissioned with HFC refrigerants, thus continuously decreasing the bank of ODS containing equipment in the transport refrigeration sector. HFC-134a and R-404A/R-507 have been implemented in many cases. Use of R-410A will advance further.

Since the 2002 Assessment, CFCs have not been used for new equipment in developed countries and a big proportion of CFC-containing equipment has disappeared. There are few remaining CFC-containing systems in the developed world today and they will not last longer than two to five years, thereby being replaced before 2010. Zero ODP will be reached within the next years in transport refrigeration equipment.

The prognosis of 2002, that vapour compression will remain the main cooling method in all the sections of world-wide transport, has proven true up to now. Several companies are working on non-HFC alternatives for applications within the transport sector, but there are still very few commercialised units running on absorption processes, air cycle, liquid air/nitrogen or carbon dioxide.

Efforts have to be increased in order to reduce leakage during lifetime and decommissioning. Very low values can be achieved with the right combination of good practice, legislation and incentives.

## Air Conditioners and Heat Pumps

On a global basis, air-cooled air conditioners and 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 35kW). Nearly all air-cooled air conditioners and heat pumps manufactured prior to 2000 used HCFC-22 as their working fluid. This installed base of units in 2004, represented a bank of approximately 887,000 metric-tonnes of HCFC-22 (see Table 7-1).

Air-cooled air conditioners and heat pumps 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 or duct-free split residential and commercial air conditioners; ducted, split residential air conditioners; and ducted commercial split and packaged air conditioners (commercial air cooled).

This assessment concludes that HFC blends are the most likely near-term refrigerants to replace HCFC-22 in air-cooled air-conditioning systems. Air-cooled air conditioning equipment using HFC refrigerants is already commercially available in most non-Article 5 regions of the world. Commercial availability of systems using HFC refrigerants is also occurring in some Article 5 countries. Hydrocarbon refrigerants may also be considered as replacements for HCFC-22 (with appropriate safety mitigation techniques) in some categories of products--particularly low charge level applications. In addition, there is a significant amount of research being conducted on R-744 ($CO_2$) systems to address efficiency and operating pressure issues. Commercialisations of R-744 air-cooled air conditioning systems will likely lag HC (hydrocarbon) and HFC technologies by many years.

The primary technical concerns of the Article 5 countries are: having adequate supplies of HCFCs to service equipment manufactured before the HCFC Phase-out dates mandated by the Montreal Protocol, and having the alternative refrigerants and technologies needed to transition products to non-ODP options.

As the state of development progresses, the alternative refrigerants and technologies available today in non-Article 5 countries should become readily available in most Article 5 countries. Since common manufacturing processes are increasingly being used throughout the world, we are fast approaching the situation where containment and conservation of refrigerants will become some of the key areas that will need to be addressed by Article 5 countries to ensure refrigerant supplies are available to service the installed base of HCFC-22 air conditioners. Since many of Article 5 countries will be importers and not manufacturers of air-conditioning equipment, the specific issues faced by these countries are mostly related to servicing, training of technicians, and regulation of refrigerants.

## Water-Heating Heat Pumps[1]

Heat pumps are used to heat water for space heating (comfort) and for domestic hot water heating (DHW). Heat pumps have been developed for comfort heating only, domestic water heating only, and for combined service. Most of these heat pumps employ the vapour-compression cycle although absorption heat pumps also are available. Water-heating heat pump markets are significant in Europe, Japan, and China.

### *Recent Trends*

Heating-only comfort heat pumps are manufactured in sizes ranging from 1 kW heating capacity for single-room units to 50-1000 kW for commercial/institutional/industrial applications. Most small to medium capacity heat pumps in buildings are standardised factory-made units. Air-source and ground-coupled heat pumps dominate the market. Larger heat pump installations usually are custom-made.

In countries with cold climates such as northern Europe, some heat pumps are used for heating only. In warmer climates, heat pumps serving hydronic systems with fan coils provide heat in winter and cooling in the summer. Systems are becoming available to provide both floor panel heating and fan coil heating or cooling.

European countries have been using domestic hot water heat pumps for years. The market for DHW heat pumps is growing rapidly in Japan where night-time electricity prices are low. The government in Japan now provides subsidies to introduce high-efficiency DHW heat pumps using R-744 (carbon dioxide) as the refrigerant. In 2006 over 300,000 R-744 heat pump water heaters are expected to be sold. The demand for DHW water heaters using HFC refrigerants, which do not benefit from the subsidy, also has increased as all-electric homes are becoming more common.

HCFC-22 still is used in heat pumps, but models are being introduced using HFC alternatives (HFC-134a, R-410A, R-407C, R-404A,) and hydrocarbons in smaller units in Europe. For larger water heaters for commercial use, R-410A is employed because larger R-744 compressors are not available. For comfort water-heating heat pumps with fan-coil units, water temperatures are in the range from $45^{o}$ to $55^{o}$ C. Hydronic circuits with radiators employ heat pumps delivering temperatures from $55^{o}$ to $75^{o}$ C. Water temperatures of $70^{o}$ to $80^{o}$ C are common for DHW heat pumps.

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[1] These heat pumps also may be called "heat pump water heaters (HPWH)" in the literature

## Chillers

Chillers, also known as water chillers, cool water or heat transfer fluids for air conditioning and process cooling. The heat removed is rejected to ambient air in air-cooled chillers or to water in water-cooled chillers.

### *Recent Trends*

Air-cooled chillers represent about 75% of the annual unit production in the positive displacement category. Scroll compressors are increasingly used in chillers from 7 to 1600 kW. Screw compressors have displaced most reciprocating compressors in chillers up to 2275 kW capacity.

While HCFC-22 still is used in chillers with scroll, screw and reciprocating compressors, R-410A is used in many new chillers up to 350 kW capacity and HFC-134a is used in new chiller designs of larger capacities. R-407C has been employed as a replacement for HCFC-22 in positive displacement chillers but the trends favour R-410A and HFC-134a over the longer term.

For water-cooled chillers, screw chillers frequently are chosen as alternatives to centrifugal chillers in the range from 200 to 2275 kW, while centrifugal chillers are dominant above this range. Centrifugal chillers continue to be offered with HCFC-123 or HFC-134a refrigerants. The production of chillers using CFC-11 (and also CFC-12) essentially has stopped in Article 5 countries. Conversion of existing CFC chillers to use non-CFC refrigerants nearly has ended because most good conversion candidates already have been converted. Existing chillers employing CFC refrigerants (both CFC-11 and -12) slowly are being replaced by new chillers using HCFC-123 or HFC-134a. Today’s new chillers use 20%-35% less electricity than the CFC chillers produced years ago, so the savings in energy costs often justify the replacement of aging CFC chillers.

Two trends continue in chiller development. The first is an effort to reduce refrigerant emissions through design changes and improved service practices. The second trend is to increase seasonal energy efficiency, represented by standard parameters such as IPLV (Integrated Part Load Value), reflecting concerns about indirect global warming effects and annual operating costs. A number of methods are used to achieve higher seasonal efficiencies. These include economisers, use of multiple compressors in a system, continuous unloading capabilities for screw compressors, enhanced electronic controls, and variable-speed compressor drives.

Absorption chillers are an alternative to chillers employing the vapour-compression cycle. The market for absorption chillers remains concentrated in the Asia-Pacific region, primarily in China, Japan, and Korea.

### Vehicle Air Conditioning

Vehicles (cars, trucks, and buses) built before the mid-1990's used CFC-12 as the refrigerant. Since then, all new vehicles with A/C have been equipped with HFC-134a as the refrigerant in non-Article 5 countries; this process is now also virtually complete for new equipment in Article 5 countries. As a result, HFC-134a has now replaced CFC-12 as the globally accepted mobile A/C (MAC) refrigerant and the industry is busy expanding global production to meet the increasing demand. By 2008, almost all vehicles on the road are expected to be using HFC-134a and the transition from CFC-12 will be complete. Vehicles originally built with CFC-12 are expected to continue being serviced with CFC-12 until they are scrapped.

HFC-134a is considered a potent greenhouse gas and, due to concerns about its emission from MAC systems, the European Union has finalised legislation banning the use of HFC-134a in new-type vehicles from 2011 and all new vehicles from 2017. They have also limited replacement refrigerants to those with a maximum global warming potential (GWP) of 150. As a result, vehicle makers and suppliers are fully committed to developing a replacement.

Since 1998, the leading replacement candidate for HFC-134a has been carbon dioxide (R-744) for which many global vehicle manufacturers and suppliers have demonstrated prototype cars. The use of HFC-152a as a replacement was proposed in 2001 and has been publicly demonstrated in several prototype vehicles. Both refrigerants have a GWP below the 150 threshold and adoption of either would be of equivalent environmental benefit, next to other low-GWP substitutes that can be anticipated in the near future. The decision of which refrigerant to choose would have to be made based on other considerations than purely the GWP, such as energy usage, cost, heat pump capability, safety, and ease of servicing.

In early 2006, several chemical companies (others will likely follow) have each announced a new refrigerant blend to replace HFC-134a in Europe. One is an azeotropic blend of CF3I and 1,1,1,2-tetrafluoropropene. Two other formulations have not been publicly released. Since then, due to safety and cost issues of R-744 and R-152a, German carmakers have collectively asked for, and formally organised, a co-operative effort to assess the new candidates with a focus on selecting a replacement for HFC-134a during the second half of 2007. The SAE and Japanese Automobile Manufacturers Association are assisting this effort.

Given the large number of potential replacement options, and the promise of improved HFC-134a systems, it appears there will be at least two refrigerants in the global automotive marketplace in the near future, in addition to the residual use of CFC-12.

### Refrigerant Conservation

Refrigeration conservation is an effort to extend the life span of used refrigerant by establishing efforts to recover, recycle, and reuse refrigerants. Refrigerant conservation is now a major consideration in refrigerating system design, installation, and service. The benefits of refrigerant conservation include not only environmental protection, but they also include a decrease on the dependency on newly manufactured refrigerant. Refrigerant conservation has several basic elements:

1. proper design and installation of new refrigeration and air-conditioning equipment so as to minimise actual or potential leaks;
2. leak-tighten existing refrigeration and air-conditioning systems so as to reduce emissions;
3. improve service practices, including use of refrigerant recovery equipment and technician training; and
4. safe disposal techniques that provide for refrigerant recovery for systems at the point of final disposal.

There has been a great deal of success in the creation and implementation of conservation programs since the 1994-1998 assessment, most visibly in the creation of governmental regulations to restrict the use or reuse of CFCs and mandate training for service technicians.

Developed countries have begun to see the results and consequences of conservation programs. The Japan End-Of-Life Appliance Recycling And Destruction Technologies Program has been established to reduce emissions of ozone-depleting refrigerants. European Union countries have established programs mandating recovery, mandating service technician training, forbidding CFC top-off, forbidding reuse of CFCs, and mandating the use of non-HCFC refrigerants in new equipment. The United States has seen an increase in the number of service technicians certified and the amounts of refrigerant reclaimed and placed back into commerce.

Article 5 countries have the opportunity to leverage the knowledge gained from developed countries during their implementation of conservation programs. If a government plans to create a program to recover, recycle, and reclaim refrigerant or phase-out the use of CFCs, the government has to consider establishing economic assessments that make owners of systems take conservation efforts or enforce government requirements by means of financial or other penalties. Article 5 countries have also seen increases in the number of certified technicians and establishment of conservation programs. For example, Brazil is implementing several reclaim centres capable of handling recovered refrigerant. Several African countries have seen an increase in the use of portable recovery equipment in their efforts to reduce emissions of ozone-depleting refrigerants.

When establishing refrigerant conservation controls, governments must also establish disposal means for systems. The government should include means of properly disposal of refrigeration and air-conditioning systems. Refrigerant containers pose a problem, in that efforts must be implemented to recover remaining refrigerant (commonly called the can heel) at the point of container disposal.

Governments could also be proactive in combating illegal imports and the establishment of illegal markets for CFCs that can be a by-product of conservation efforts. Governments should include training of customs officials as a part of their conservation efforts.

# 1 Introduction

## 1.1 Montreal Protocol Developments

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

Shortly after the 1987 Protocol was negotiated, new scientific evidence conclusively linked CFCs to the depletion of the ozone layer and indicated that depletion had already occurred. Consequently, many countries called for further actions to protect the ozone layer by expanding and strengthening the original control provisions of the Montreal Protocol, and they decided that 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; they extensively dealt with the difficulties experienced by Countries with Economies in Transition (CEITs), in particular several successor states to the former Soviet Union. 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 11th Meeting of the Parties, held in Beijing in December 1999, considered the 1998 Assessment Reports, next to a number of other issues, including quarantine and preshipment uses of methyl bromide, the use of process agents and the replenishment of the Multilateral Fund. Noting with appreciation the excellent and highly successful work done by the three Panels, the Parties decided to request the Assessment Panels to update their Assessment Reports of October1998 and submit them to the Secretariat by 31 December 2002 for consideration by the Open-ended Working Group and by the Fifteenth Meeting of the Parties in 2003.

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. Noting with appreciation the excellent and highly successful work done by the three Panels for the Assessment Reports and the Synthesis Report, the 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".

Together with the Science and Environmental Effects Assessment reports, the 2006 TEAP Assessment Report -together with the 2006 TOC Assessment Reports- forms the direct response to the above-mentioned decision.

The present status (early 2007) is that the Montreal Protocol has been ratified by 191 countries, Parties to the Protocol (where the Vienna Convention has also been ratified by 191 countries). The London Amendment has been ratified by 184 Parties and the

Copenhagen Amendment by 175 Parties. The Montreal Amendment has been ratified by 149 countries, and the Beijing Amendment by 119 Parties.

## 1.2 The UNEP Technology and Economic Assessment Panel

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

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

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

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 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 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 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. Many members of the 2002 TOC Refrigeration have been part of the drafting group membership of this IPCC/TEAP Report. 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 -and still is- the basis for many discussions that take place at the various Meetings of the Parties to the Montreal Protocol and the Kyoto Protocol (a report on measures that result from the information in the Special Report has recently been published by the Ozone Secretariat in September 2006).

The 2006 Technical and Economic Assessment study has been carried out by the Technology and Economic Assessment Panel and the six Technical Options Committees. The six Committees consisted of more than 200 experts from a large number of countries (for a list, see the annex to the Technology and Economic Assessment Panel Report 2006).

The 2006 Technical Options Committees consisted of several members of the 1998 and 2002 Committees and additional new experts, to provide the widest possible international participation in the review. Much attention was 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 2006 assessment work of the Technology and Economic Assessment Panel (requested by the Parties in Nairobi (XV/53)). The information collected (particularly in the form of the Abstract Executive Summary and the Executive Summaries) will also be part of the Technology and Economic Assessment Report 2006, as well as the overall 2006 Synthesis Report composed by the three Assessment Panel co-chairs.

The 2006 RTOC Assessment Report has been drafted in the form of a number of chapters. There are chapters on application areas and on refrigerants, one chapter on refrigerant conservation. The structure of the report was chosen more or less similar to the structure of the 2002 RTOC Assessment Report.

***Table 1-3*** *"Member countries" of UNEP's Refrigeration, A/C and Heat Pumps Technical Options Committee*

Brazil
China
Denmark
France
Germany
Hungary
India
Indonesia
Japan
Kenya
Korea, Rep. Of
Netherlands
Norway
Poland
Russian Federation
Slovakia
Thailand
Tunisia
Uganda
United Kingdom
United States
Vietnam

Each of the chapters was developed by 2-6 experts in the specific sector, and the chapter was chaired by one (or two) experts, -Chapter Lead Authors- who did the larger part of the drafting and the co-ordination. The 2006 RTOC included 37 representatives from African, Asian, European, Latin and North American companies, universities and governments, as well as independent experts (see Table 1-3). These representatives have been full (reporting) members; as resource persons the RTOC also had a small number of consulting members.

Affiliations of the members are listed in Table 1-5 (38 organisations (including consultancies) were involved in the drafting of the report). The names and contact details 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 mid 2004, preliminary draft mid 2005, draft mid 2006, peer review draft October 2006 and final report December 2006). A preliminary committee meeting was held in W-Lafayette, Purdue University, July 2004. Drafting and reviewing meetings were held in the United Kingdom (Glasgow), September 2004, Italy (Vicenza), September 2005, Norway (Trondheim), May 2006, and the USA (Washington, D.C.), December 2006.

As stated, the structure of this RTOC Assessment Report is more or less similar to the 2002 RTOC Assessment Report, except for the fact that the report does now contain separate chapters for heat pumps for water heating and for chillers. With technology proceeding rapidly, the report is not a simple update of the 2002 report, but all options described in 2002 are re-examined taking into account the present scale of technological developments.

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 2006 (see Table 1-4 for the organisations involved). All peer review comments were dealt with by Chapter Lead Authors before the RTOC Meeting in December 2006, and by the RTOC (on a case-by-case basis) in plenary during its meeting in Washington D.C., December 2006. The RTOC greatly acknowledges the voluntary support given by the peer review institutions.

***Table 1-4*** *Organisations that participated in the peer review of the UNEP RTOC Assessment Report*

| | |
|---|---|
| *ARI* | *Air Conditioning and Refrigeration Institute* |
| *IIAR* | *International Institute of Ammonia Refrigeration* |
| *IIR* | *International Institute of Refrigeration* |
| *IOR* | *Institute of Refrigeration, UK* |
| *JRAIA* | *Japanese Refrigeration and Air Conditioning Industry Association* |
| *VDA* | *Verband der Deutschen Automobilindustrie* |

An additional seven organisations were invited to peer review the report; they responded positively to the invitation but did not provide comments.

***Table 1-5*** *Affiliations of the members of UNEP's Technical Options Committee on Refrigeration, A/C and Heat Pumps*

| | |
|---|---|
| Bandung Institute of Technology | Indonesia |
| Braunschweig University | Germany |
| Carrier Corporation | USA |
| Colbourne (Consultant) | UK |
| Daikin Industries Ltd. | Japan |
| Danish Technological Institute | Denmark |
| Dehon Service SA | France |
| Delphi Automotive Systems | USA |
| Department of Industry | Kenya |
| Ecole des Mines Paris | France |
| General Electric, Consumer and Industrial | USA |
| Hungarian Refrigeration and AC Association | Hungary |
| Indian Institute of Technology Delhi | India |
| Inst. Fluid Flow Machinery Gdansk | Poland |
| Investment Centre ODS Phase-out | Russia |
| Jaeggi/ Guentner AC | Switzerland |
| James M. Calm, Engineering Consultant | USA |
| Johnson Controls | USA |
| Karlsruhe University of Applied Sciences | Germany |
| LG Electronics | Rep. of Korea |
| Makerere University, Kampala | Uganda |
| Matsushita Electric Industrial Co.,Ltd. | Japan |
| Maua Institute of Technology | Brazil |
| Ministry of Fisheries, Hanoi | Vietnam |
| National Environmental Eng. Institute, NEERI | India |
| Re/genT b.v. | Netherlands |
| SINTEF Energy Research, Trondheim | Norway |
| Slovak Union for Cooling and AC Technology | Slovakia |
| Sofrifac SA, Tunis | Tunisia |
| Star Refrigeration | UK |
| Technical University Eindhoven | Netherlands |
| Thai Compressor Manufacturing Co. Ltd. | Thailand |
| The Trane Company | USA |
| U.S. Environmental Protection Agency | USA |
| Whirlpool S.A. | Brazil |
| Zhejiang University, Hangzhou | China |
| Zhejiang Environmental Protection Hi-Tech Co Ltd. | China |

## 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 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 the foreseeable future) have been and still are difficult to estimate.

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

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

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

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

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

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

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 Longer Term Options and Energy Efficiency

CFC production has been phased out since a decade in the developed countries, and the CFC phase-out is approaching in the developing countries. In both developed and developing countries, HCFCs and HFCs have so far been the primary substitutes for CFCs. In many applications, alternatives to HCFCs have become commercially available, as blends of HFCs or as non-HFC alternatives. Nevertheless, HFCs have currently gained a large share of the replacement market. In particular the necessary incentives remain to be provided to Article 5 countries to transition as soon as possible from CFCs to non-CFC refrigerants, which will include both HFC and non-fluorocarbon alternatives.

This aspect is in particular valid for chillers, as mentioned above (and already in the 1998 2002 RTOC Assessment Reports). The larger part of the centrifugal chillers in the world (the majority being on CFC-11) has now been replaced or has been retrofitted from CFCs to substitutes. The retrofit or, in many cases, the replacements of chillers have still to occur in many Article 5 countries. The only alternative available for CFC-11 chillers available to date is HCFC-123; blends cannot be used due to the frequently applied flooded evaporator systems. It is clear that there are not only technical but certainly also important economic considerations at stake in the conversion process.

An early HCFC phase-out date (as e.g. decided in the European Union) has given clear signals to the user of HCFC chemicals, however, it cannot be anticipated which consequences it will have for the global and national trade markets if very significant differences in regimes exist in different parts of the world. However, early national phase-out dates will have a significant effect on global trends if the country is an important consumer of HCFCs. These kinds of political decisions cannot and will not be dealt with in the chapters of this report.

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, that currently 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 longer term, there are, in fact, only five important different groups of refrigerants, which are options for the vapour compression cycle in all refrigeration and A/C sectors. Listed alphabetically they are:

- ammonia (R-717);
- carbon dioxide (R-744);
- hydrocarbons and blends (HCs, e.g. HC-290, HC-600, HC-600a, dimethylether etc.);
- hydrofluorocarbons (HFCs, HFC-blends (400 and 500 number designation), hydrofluoroethers, unsaturated hydrofluorocarbons);
- 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, (saturated) HFCs have relatively high global warming potentials, 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 option groups above are in different stages of development or commercialisation. HFCs are widely applied in many sectors, and ammonia and hydrocarbons enjoy growth in sectors where they can be easily accommodated. For certain applications, $CO_2$ equipment has been developed and extensively tested on the market, with an increasing number currently being installed. 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 the 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 2006 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.

A study on the status of HFCs and alternatives to HFCs and PFCs was performed in 2003-2004, as decided by the Parties to the UNFCCC and by the Parties to the Montreal Protocol, in the year 2002.  The efforts for this Special Report “Safeguarding the climate system and protecting the ozone layer; issues related to HFCs and PFCs” were undertaken jointly by the IPCC and TEAP.  Next to members from other TOCs, many members of the 2002 RTOC have been part of the membership.  The Special Report was published mid-2005, and is still the basis for many discussions on fluorochemicals by the Parties to the Montreal and the Kyoto Protocol.

In the Special Report (IPCC TEAP, 2005) 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 between now and 2015.  These activities (such as the requirements for refrigeration, air conditioning and insulation) will involve a number of technologies, including CFCs and HCFCs.  In non-Article 5 countries, the use and emissions of CFCs and HCFCs will decline as obsolete equipment is retired.  In Article 5 countries, ozone-depleting substances (particularly HCFCs) may be used for most of the first half of this century and significant growth is still expected.

Current emission profiles are largely determined by historic use patterns, resulting in a relatively high contribution (now and in the coming decades) 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 between 2002 and 2015.  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.  Banks of ODS substances in refrigeration and air conditioning are relatively small (compared to the others mentioned above) and will be much smaller in the year 2015, mainly due to a decrease in the CFC banks, which can then only be found in the Article 5 countries.

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.

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.

The European Parliament and the Council have adopted two regulations on fluorinated gases in 2006, which may impact global developments in refrigeration and air conditioning. The dates for the entry into force of the F-gas Regulation and the MAC regulation (a directive) were published in the Official Journal of the European Union on 14 June 2006.

The first one is the regulation on F-gases for stationary equipment. The objective of the regulation 2006/842 is to contain, prevent and thereby reduce emissions of fluorinated greenhouse gases covered by the Kyoto Protocol. The Regulation covers the use of HFCs, PFCs and SF6 in all their applications, except Mobile Air Conditioning. The Regulation entered into force on 4 July 2006 and a number of measures will apply from 4 July 2007. In addition to the legal text, additional national measures will be needed to implement its provisions on penalties for non-compliance, to be notified by 4 July 2008. Implicit in the regulation is that, for containment, recovery, certification and reporting, EU Member States can adopt more stringent rules provided that they are notified under the appropriate procedures and demonstrated to be justified. By July 2011, the Commission shall publish a report based on the experience of the application of the Regulation, taking into account further IPCC Assessment Reports and best available techniques and best environmental practices.

The second one is a regulation (a directive) on Mobile Air Conditioning (MAC). The directive 2006/40 covers the use of HFCs in MACs for passenger cars only, will enter into force on 4 July 2006 and will have to be transposed into national law by 4 January 2008. By 4 July 2007, the European Commission will define the administrative provisions for an EC type-approval of vehicles, and a harmonised leakage detection test for measuring the leakage rate of HFC-134a from air-conditioning systems. One year after the definition of the leakage detection test, type-approval for new car models shall only be granted if the leakage of HFC-134a will be less than either 40 g/year in the case of a simple evaporator system or 60 g/year in the case of a dual evaporator system. Two years later, the same leakage limits will be mandatory for all new cars. By 1 January 2011, HFC-134a will be banned for air conditioning systems for new vehicle models. By 1 January 2017, HFC-134a will be banned for all new vehicles. By 4 July 2011, the European Commission will examine whether the directive should be extended to other categories of vehicles.

### 1.4.3 Set up of the 2002 TOC Refrigeration, A/C and Heat Pumps report

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

Chapters 3, 4, 5 and 6 deal with the food chain and investigate the technical feasibility of options. They all consider non-ODP options and deal with aspects such as the use of non-fluorochemicals, the reduction of charges, energy efficiency improvements etc. Particularly the energy efficiency aspect plays an important role in chapter 3 on domestic refrigeration. Chapter 5 deals with industrial refrigeration and cold storage, chapter 6 with transport refrigeration. Chapters 7 and 8 deal with air conditioning and heat pumps. Chapter 9 deals with the various aspects of chillers, which includes important considerations on energy efficiency. Chapter 10 describes the options for mobile air conditioning; in a first instance, it deals extensively with HFC-134a, but it also evaluates the potential the options carbon dioxide, hydrocarbons and (recently introduced) other options will have. Chapter 11 deals with refrigerant conservation in the broadest sense; via adequate practices one can reduce the emission of ODP refrigerants to the atmosphere (recover and recycle, containment) but the same approaches are also valid to reduce the emissions of greenhouse gases (HFC based refrigerants) to the atmosphere.

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

# 2 Refrigerants

## 2.1 Introduction

This chapter summarises data for refrigerants and specifically those addressed in other chapters. It discusses thermophysical (both thermodynamic and transport) properties as well as heat transfer, compatibility, and safety data. The chapter also provides similar information for heat transfer fluids (sometimes referred to as "secondary coolants," "secondary fluids," or "secondary refrigerants") for air-conditioning, heat pump, and refrigeration systems.

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.

## 2.2 Data Summary

Table 2-1 provides summary data for refrigerants, both single compounds and blends, addressed in this report as well as those used historically or under consideration as candidates for future use. 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 new blends introduced since the 2002 assessment report /UNEP02/.

The data in this table were extracted from a summary by Calm and Hourahan /Cal07/ and the *Refrigerant Database* /Cal01/; 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 7.0 /Lem02/ for thermophysical properties, though in most cases with updated fluid and mixture models for planned inclusion in REFPROP 8.0, and new flammability test data /Alp01, Wil02/. 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.

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

- refrigerant number, if assigned, in accordance with ASHRAE Standard 34 /ASH04a, ASH06a, ASH06b, and ASH06c/: An international standard is in preparation, but not yet final, as the primary document for designation and safety criteria /ISO06/, but the proposed designation systems are essentially consistent.

- chemical formula, in accordance with the IUPAC convention /IUP79/ or, for blends, the blend composition in accordance with ASHRAE Standard 34 /ASH04a, ASH06a, ASH06b, and ASH06c/
- molecular mass calculated /Cal07/ based on the updated IUPAC atomic weights /Los03 and IUP05/
- normal boiling point (NBP) or, for blends, the bubble point temperature at 101.325 kPa
- critical temperature ($T_c$) in °C or, for blends, the calculated pseudo-critical temperature
- Threshold Limit Value - Time Weighted Average (TLV-TWA) in ppm v/v assigned by the American Conference of Governmental Industrial Hygienists (ACGIH) or a consistent occupational exposure limit
- lower flammability limit (LFL) in % concentration ambient air, determined in accordance with ASHRAE Standard 34 /ASH04a, ASH06a, ASH06b, and ASH06c/.
- safety classification, if assigned, in accordance with ASHRAE Standard 34 /ASH04a, ASH06a, ASH06b, and ASH06c/: The proposed ISO 817 draft /ISO06/ further splits flammability group 2 ("lower flammability") into "2" and "2L," even though not shown in Table 2-1. Some of the classifications are followed or replaced by lower case letters that indicate:

  d indicates that a prior classification was deleted and that the refrigerant no longer has a safety classification

  p indicates a classification assigned on a provisional basis

  r signifies that SSPC 34 has recommended revision or addition of the classification as shown, but final approval and/or publication is still pending

  Future changes to some classifications are possible with development of the international standard /ISO06/ mentioned above.
- atmospheric lifetime ($\tau_{atm}$) in years: Note that $\tau_{atm}$ normally is not indicated for blends since it is ambiguous whether the time indicated 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 based on the semi-empirical values adopted in the *Scientific Assessment* /WMO06/ or, for blends, the mass-weighted averages /Cal07/ based on the IUPAC atomic weights /Los03 and IUP05/ of the component ODPs: The ODP indicates the relative ability of refrigerants (and other chemicals) to destroy stratospheric ozone.
- global warming potential (GWP) relative to $CO_2$ for 100-year integration based on the values adopted in the IPCC-TEAP special report /IPCC05/ and the Scientific Assessment /WMO06/ or, for blends, the mass-weighted average based on the IUPAC atomic weights /Los03 and IUP05/ of the component GWPs. The values shown are direct GWPs; indirect and net GWPs are discussed in references IPCC05 and WMO06. The GWP values shown as "~20" in Table 1 for hydrocarbons reflect uncertainty in calculation, for which there is no scientific consensus at this time. The approximation shown lies in the range of uncertainty. Further study is needed using three-dimensional (3D) models for a range of release scenarios to determine representative GWPs for chemicals with very short atmospheric lifetimes /IPCC05/, including most saturated and unsaturated hydrocarbons.
- status: Refrigerants restricted (production limitations, phase-out, 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

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

| | | physical data | | | safety data | | | environmental data | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| refrigerant number | chemical formula - common name | molec-ular mass | NBP (°C) | Tc (°C) | TLV-TWA (PPM) | LFL (%) | Std 34 safety group | 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 |
| BCFC-12B1 | CBrClF2 - halon 1211 | 165.36 | -4.0 | 154.0 | | none | | 16 | 7.100 | 1890 | M |
| CFC-12 | CCl2F2 | 120.91 | -29.8 | 112.0 | 1000 | none | A1 | 100 | 1.000 | 10890 | M |
| BFC-13B1 | CBrF3 - halon 1301 | 148.91 | -58.7 | 67.1 | 1000 | none | A1 | 65 | 16.000 | 7140 | M |
| CFC-13 | CClF3 | 104.46 | -81.5 | 28.9 | 1000 | none | A1 | 640.0 | 1.000 | 14420 | M |
| FIC-13I1 | CF3I - trifluoroiodomethane | 195.91 | -21.9 | 123.3 | | none | | ~0.01 | ≤0.018 | ~1 | |
| FC-14 | CF4 - carbon tetrafluoride | 88.00 | -128.0 | -45.6 | | none | A1 | 50000 | 0 | 7390 | K |
| HCFC-22 | CHClF2 | 86.47 | -40.8 | 96.1 | 1000 | none | A1 | 12.0 | 0.050 | 1810 | M |
| HFC-23 | CHF3 - fluoroform | 70.01 | -82.0 | 26.1 | 1000 | none | A1 | 270 | 0 | 14760 | K |
| HFC-32 | CH2F2 - methylene fluoride | 52.02 | -51.7 | 78.1 | 1000 | 14.4 | A2 | 4.9 | 0 | 675 | K |
| CFC-113 | CCl2FCClF2 | 187.38 | 47.6 | 214.1 | 1000 | none | A1 | 85 | 1.000 | 6130 | M |
| CFC-114 | CClF2CClF2 | 170.92 | 3.6 | 145.7 | 1000 | none | A1 | 300 | 1.000 | 10040 | M |
| CFC-115 | CClF2CF3 | 154.47 | -38.9 | 80.0 | 1000 | none | A1 | 1700 | 0.440 | 7370 | M |
| FC-116 | CF3CF3 - perfluoroethane | 138.01 | -78.1 | 19.9 | 1000 | none | A1 | 10000 | 0 | 12200 | K |
| HCFC-123 | CHCl2CF3 | 152.93 | 27.8 | 183.7 | 50 | none | B1 | 1.3 | 0.020 | 77 | M |
| HCFC-124 | CHClFCF3 | 136.48 | -12.0 | 122.3 | 1000 | none | A1 | 5.8 | 0.020 | 609 | M |
| HFC-125 | CHF2CF3 | 120.02 | -48.1 | 66.0 | 1000 | none | A1 | 29 | 0 | 3500 | K |
| HFC-134a | CH2FCF3 | 102.03 | -26.1 | 101.1 | 1000 | none | A1 | 14.0 | 0 | 1430 | K |
| HCFC-142b | CH3CClF2 | 100.50 | -9.1 | 137.1 | 1000 | 6.0 | A2 | 17.9 | 0.070 | 2310 | M |
| HFC-143a | CH3CF3 | 84.04 | -47.2 | 72.7 | 1000 | 7.0 | A2 | 52 | 0 | 4470 | K |
| HFC-152a | CH3CHF2 | 66.05 | -24.0 | 113.3 | 1000 | 4.8 | A2 | 1.4 | 0 | 124 | K |
| HFC-161 | CH3CH2F - ethyl fluoride | 48.06 | -37.6 | 102.2 | | 3.8 | | 0.21 | 0 | 12 | K |
| HC-170 | CH3CH3 - ethane | 30.07 | -88.6 | 32.2 | 1000 | 3.1 | A3 | 0.21 | 0 | ~20 | |
| HE-E170 | CH3-O-CH3 - DME | 46.07 | -24.8 | 127.2 | 1000 | 3.3 | A3 | 0.015 | 0 | 1 | |
| FC-218 | CF3CF2CF3 - perfluoropropane | 188.02 | -36.8 | 71.9 | 1000 | none | A1 | 2600 | 0 | 8830 | K |
| HFC-227ea | CF3CHFCF3 | 170.03 | -16.4 | 102.8 | 1000 | none | A1 | 42 | 0 | 3220 | K |
| HFC-236ea | CHF2CHFCF3 | 152.04 | 6.2 | 139.3 | | none | | 10.7 | 0 | 1370 | K |
| HFC-236fa | CF3CH2CF3 | 152.04 | -1.4 | 124.9 | 1000 | none | A1 | 240 | 0 | 9810 | K |
| HFC-245fa | CHF2CH2CF3 | 134.05 | 15.1 | 154.0 | 300 | none | B1 | 7.6 | 0 | 1030 | K |
| HFE-E245cb1 | CH3-O-CF2-CF3 | 150.05 | 5.9 | 133.7 | | flam | | 5.1 | 0 | 708 | |
| HC-290 | CH3CH2CH3 - propane | 44.10 | -42.1 | 96.7 | 2500 | 2.1 | A3 | 0.041 | 0 | ~20 | |
| FC-C318 | -CF2-CF2-CF2-CF2- | 200.03 | -6.0 | 115.2 | 1000 | none | A1 | 3200 | 0 | 10250 | K |
| R-400 (50/50) | R-12/114 (50.0/50.0) | 141.63 | -20.8 | 129.1 | 1000 | none | A1 | | 1.000 | 10000 | M |
| R-401A | R-22/152a/124 (53.0/13.0/34.0) | 94.44 | -32.9 | 107.3 | 1000 | none | A1 | | 0.033 | 1200 | M |
| R-401B | R-22/152a/124 (61.0/11.0/28.0) | 92.84 | -34.5 | 105.6 | 1000 | none | A1 | | 0.036 | 1300 | M |
| R-401C | R-22/152a/124 (33.0/15.0/52.0) | 101.03 | -28.3 | 111.7 | | none | A1 | | 0.027 | 930 | M |
| R-402A | R-125/290/22 (60.0/2.0/38.0) | 101.55 | -48.9 | 75.9 | 1000 | none | A1 | | 0.019 | 2800 | 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 | molecular mass | NBP (°C) | Tc (°C) | TLV-TWA (PPM) | LFL (%) | Std 34 safety group | atmospheric life (yr) | ODP | GWP 100 yr | status |
| R-402B | R-125/290/22 (38.0/2.0/60.0) | 94.71 | -47.0 | 82.9 | 1000 | none | A1 | | 0.030 | 2400 | M |
| R-403A | R-290/22/218 (5.0/75.0/20.0) | 91.99 | -47.7 | 87.0 | 1000 | 13.0 | A1 | | 0.038 | 3100 | M |
| R-403B | R-290/22/218 (5.0/56.0/39.0) | 103.26 | -49.2 | 79.6 | 1000 | none | A1 | | 0.028 | 4500 | M |
| R-404A | R-125/143a/134a (44.0/52.0/4.0) | 97.60 | -46.2 | 72.0 | 1000 | none | A1 | | 0 | 3900 | 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 | | 0.026 | 5300 | M |
| R-406A | R-22/600a/142b (55.0/4.0/41.0) | 89.86 | -32.5 | 116.9 | 1000 | 8.2 | A2 | | 0.056 | 1900 | M |
| R-407A | R-32/125/134a (20.0/40.0/40.0) | 90.11 | -45.0 | 81.8 | 1000 | none | A1 | | 0 | 2100 | K |
| R-407B | R-32/125/134a (10.0/70.0/20.0) | 102.94 | -46.5 | 74.3 | 1000 | none | A1 | | 0 | 2800 | K |
| R-407C | R-32/125/134a (23.0/25.0/52.0) | 86.20 | -43.6 | 85.8 | 1000 | none | A1 | | 0 | 1800 | K |
| R-407D | R-32/125/134a (15.0/15.0/70.0) | 90.96 | -39.2 | 91.2 | 1000 | none | A1 | | 0 | 1600 | K |
| R-407E | R-32/125/134a (25.0/15.0/60.0) | 83.78 | -42.7 | 88.3 | 1000 | none | A1 | | 0 | 1600 | K |
| R-408A | R-125/143a/22 (7.0/46.0/47.0) | 87.01 | -44.6 | 83.1 | 1000 | none | A1 | | 0.024 | 3200 | M |
| R-409A | R-22/124/142b (60.0/25.0/15.0) | 97.43 | -34.4 | 109.3 | 1000 | none | A1 | | 0.046 | 1600 | M |
| R-409B | R-22/124/142b (65.0/25.0/10.0) | 96.67 | -35.6 | 106.9 | | none | A1 | | 0.045 | 1600 | M |
| R-410A | R-32/125 (50.0/50.0) | 72.58 | -51.4 | 70.5 | 1000 | none | A1 | | 0 | 2100 | K |
| R-411A | R-1270/22/152a (1.5/87.5/11.0) | 82.36 | -39.5 | 99.1 | 1000 | 5.5 | A2 | | 0.044 | 1600 | M |
| R-411B | R-1270/22/152a (3.0/94.0/3.0) | 83.07 | -41.6 | 96.0 | 1000 | 7.0 | A2 | | 0.047 | 1700 | M |
| R-412A | R-22/218/142b (70.0/5.0/25.0) | 92.17 | -38.0 | 107.2 | 1000 | 8.7 | A2 | | 0.053 | 2300 | M |
| R-413A | R-218/134a/600a (9.0/88.0/3.0) | 103.95 | -33.4 | 96.6 | | 8.8 | A2 | | 0 | 2100 | 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 | | 0.043 | 1500 | K |
| R-414B | R-22/124/600a/142b (50.0/39.0/1.5/9.5) | 101.59 | -32.9 | 111.0 | | none | A1 | | 0.039 | 1400 | M |
| R-415A | R-22/152a (82.0/18.0) | 81.91 | -37.2 | 102.0 | | 5.6 | A2 | | 0.041 | 1500 | M |
| R-415B | R-22/152a (25.0/75.0) | 70.19 | -26.9 | 111.4 | 1000 | WCF | A2 | | 0.013 | 550 | M |
| R-416A | R-134a/124/600 (59.0/39.5/1.5) | 111.92 | -24.0 | 107.0 | | none | A1 | | 0.008 | 1100 | M |
| R-417A | R-125/134a/600 (46.6/50.0/3.4) | 106.75 | -39.1 | 87.3 | 1000 | none | A1 | | 0 | 2300 | K |
| R-418A | R-290/22/152a (1.5/96.0/2.5) | 84.60 | -41.7 | 96.2 | | 8.9 | A2 | | 0.048 | 1700 | M |
| R-419A | R-125/134a/E170 (77.0/19.0/4.0) | 109.34 | -42.6 | 79.3 | | none | A2 | | 0 | 3000 | K |
| R-420A | R-134a/142b (88.0/12.0) | 101.84 | -24.9 | 104.8 | 1000 | none | A1 | | 0.008 | 1500 | M |
| R-421A | R-125/134a (58.0/42.0) | 111.75 | -40.7 | 82.9 | 1000 | none | A1 | | 0 | 2600 | K |
| R-421B | R-125/134a (85.0/15.0) | 116.93 | -45.6 | 72.5 | 1000 | none | A1 | | 0 | 3200 | K |
| R-422A | R-125/134a/600a (85.1/11.5/3.4) | 113.60 | -46.5 | 71.8 | 1000 | none | A1 | | 0 | 3100 | K |
| R-422B | R-125/134a/600a (55.0/42.0/3.0) | 108.52 | -41.3 | 83.4 | 1000 | none | A1 | | 0 | 2500 | K |
| R-422C | R-125/134a/600a (82.0/15.0/3.0) | 113.40 | -45.9 | 73.2 | 1000 | none | A1 | | 0 | 3100 | K |
| R-422D | R-125/134a/600a (65.1/31.5/3.4) | 109.93 | -43.2 | 79.8 | 1000 | none | A1 | | 0 | 2700 | K |
| R-423A | R-134a/227ea (52.5/47.5) | 125.96 | -24.1 | 99.5 | 1000 | none | A1 | | 0 | 2300 | K |
| R-424A | R-125/134a/600a/600/601a (50.5/47.0/ 0.9/1.0/0.6) | 108.41 | -39.7 | 86.3 | 1000 | none | A1 | | 0 | 2400 | K |
| R-425A | R-32/134a/227ea (18.5/69.5/12.0) | 90.31 | -38.1 | 93.9 | 1000 | none | A1 | | 0 | 1500 | 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 | molecular mass | NBP (°C) | Tc (°C) | TLV-TWA (PPM) | LFL (%) | Std 34 safety group | atmospheric life (yr) | ODP | GWP 100 yr | status |
| R-426A | R-125/134a/600/601a (5.1/93.0/1.3/0.6) | 101.56 | -28.5 | 100.2 | 990 | none | A1 r | | 0 | 1500 | K |
| R-427A | R-32/125/143a/134a (15.0/25.0/10.0/50.0) | 90.44 | -43.0 | 85.1 | 1000 | none | A1 r | | 0 | 2100 | K |
| R-428A | R-125/143a/290/600a (77.5/20.0/0.6/1.9) | 107.53 | -48.4 | 68.9 | 1000 | none | A1 r | | 0 | 3600 | K |
| R-500 | R-12/152a (73.8/26.2) | 99.30 | -33.6 | 102.1 | 1000 | none | A1 | | 0.738 | 8100 | M |
| R-502 | R-22/115 (48.8/51.2) | 111.63 | -45.2 | 80.2 | 1000 | none | A1 | | 0.250 | 4700 | M |
| R-503 | R-23/13 (40.1/59.9) | 87.25 | -87.8 | 18.4 | 1000 | none | | | 0.599 | 15000 | M |
| R-507A | R-125/143a (50.0/50.0) | 98.86 | -46.7 | 70.5 | 1000 | none | A1 | | 0 | 4000 | K |
| R-508A | R-23/116 (39.0/61.0) | 100.10 | -87.6 | 10.2 | 1000 | none | A1 | | 0 | 13000 | K |
| R-508B | R-23/116 (46.0/54.0) | 95.39 | -87.6 | 11.2 | 1000 | none | A1 | | 0 | 13000 | K |
| R-509A | R-22/218 (44.0/56.0) | 123.96 | -49.7 | 68.4 | 1000 | none | A1 | | 0.022 | 5700 | M |
| R-600 | CH3-CH2-CH2-CH3 - butane | 58.12 | -0.5 | 152.0 | 800 | 1.5 | A3 | 0.018 | 0 | ~20 | |
| R-600a | CH(CH3)2-CH3 - isobutane | 58.12 | -11.7 | 134.7 | 800 | 1.7 | A3 | 0.019 | 0 | ~20 | |
| R-601 | CH3-CH2-CH2-CH2-CH3 - pentane | 72.15 | 36.1 | 196.6 | 600 | 1.4 | | 0.01 | 0 | ~20 | |
| R-601a | (CH3)2CH-CH2-CH3 - isopentane | 72.15 | 27.8 | 187.2 | 600 | 1.0 | A3 | 0.01 | 0 | ~20 | |
| R-702 | H2 - normal hydrogen | 2.02 | -252.9 | -240.0 | | 4.0 | A3 | | 0 | | |
| R-704 | He - helium | 4.00 | -268.9 | -268.0 | | none | A1 | | 0 | | |
| R-717 | NH3 - ammonia | 17.03 | -33.3 | 132.3 | 25 | 15.0 | B2 | 0.01 | 0 | <1 | |
| R-718 | H2O - water | 18.02 | 100.0 | 373.9 | | none | A1 | | 0 | <1 | |
| R-729 | air - 78% N2, 21% O2, 1% Ar, + | 28.97 | -194.2 | -140.4 | | none | | | 0 | 0 | |
| R-744 | CO2 - carbon dioxide | 44.01 | -78.4 | 31.0 | 5000 | none | A1 | >50 | 0 | 1 | |
| R-764 | SO2 - sulfur dioxide | 64.06 | -10.0 | 157.5 | 2 | none | B1 | | 0 | 300 | |
| HC-1150 | CH2=CH2 - ethylene | 28.05 | -103.8 | 9.2 | 1000 | 2.7 | A3 | 0.004 | 0 | | |
| HC-1270 | CH3CH=CH2 - propylene | 42.08 | -47.7 | 92.4 | 660 | 2.0 | A3 | 0.001 | 0 | ~20 | |

NBP = normal boiling point (*sublimation point); Tc = critical temperature; TLV-TWA = ACGIH Threshold Limit Value – Time-Weighted Average, unless preceded by "C" for Ceiling values, or consistent chronic exposure limit (e.g., OSHA Permissible Exposure Limit, PEL); LFL = lower flammability limit (% volume in air), "wcf" signifies that the worst case of fractionation may be flammable; ODP = ozone depletion potential; GWP = global warming potential; STATUS codes of "K" and "M" indicate restricted by the Kyoto or Montreal Protocols

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 source documents before use. JMC-2006.11.10

### 2.2.1 Ozone Depletion Potentials

The ODPs indicated in the Table 2-1 are *semi-empirical* values. 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* variations /Cal07/. 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 hydrochlorofluoro-carbons (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 /UNEP06/.

### 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 provides the “regulatory” ODPs for the Montreal Protocol /UNEP06/. 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: Modelled and Regulatory ODPs for BFC, CFC, and HCFC Refrigerants*

| | ODP | | |
|---|---|---|---|
| refrigerant | modelled | semi-empirical | regulatory |
| 11 | 1.000 | 1.0 | 1.0 |
| 12 | 0.820 | 1.0 | 1.0 |
| 12B1 | 5.100 | 7.1 | 3.0 |
| 13 | 1.000 | | 1.0 |
| 13B1 | 12.000 | 16 | 10.0 |
| 21 | 0.010 | | 0.04 |
| 22 | 0.034 | 0.05 | 0.055 |
| 113 | 0.900 | 1.0 | 0.8 |
| 114 | 0.850 | 1.0 | 1.0 |
| 115 | 0.400 | 0.44 | 0.6 |
| 123 | 0.012 | 0.02 | 0.02 |
| 124 | 0.026 | 0.02 | 0.022 |
| 142b | 0.043 | 0.07 | 0.065 |

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

| | GWP | |
|---|---|---|
| refrigerant | reporting | /WMO06/ |
| 14 | 6,500 | 7,390 |
| 23 | 11,700 | 14,760 |
| 32 | 650 | 675 |
| 116 | 9,200 | 12,200 |
| 125 | 2,800 | 3,500 |
| 134a | 1,300 | 1,430 |
| 143a | 3,800 | 4,470 |
| 152a | 140 | 124 |
| 161 | | 12* |
| 218 | 7,000 | 8,830 |
| 227ea | 2,900 | 3,220 |
| 236ea | | 1,370 |
| 236fa | 6,300 | 9,810 |
| 245fa | | 1,030 |
| C318 | 8,700 | 10,250 |
| 744 | 1 | 1 |

* R-161 GWP is from /IPCC01/

## 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. Data gaps do exist, however, for the thermodynamic and transport properties of blends and less-common fluids as well as the transport properties of many fluids (but especially so for blends). Complete data are desirable for any refrigerant in commercial use.

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 are often limited for the new blends that are being introduced continually. The transport data for these fluids are good for the single-compound refrigerants, but additional data and improved models are needed for the HFC blends. The thermodynamic data for HC-290 (propane), HC-600 (n-butane), and HC-600a (isobutane) are good, but they are not known as well as is commonly assumed and observed inconsistencies should be resolved. Also, the current models should be reviewed in light of more recent data. The status of data for R-717 (ammonia) is similar to that for the cited hydrocarbons, namely much of the data are old, and sometimes inconsistent and/or limited in coverage. The property data for R-744 (carbon dioxide) are excellent.

The commonly used thermodynamic property models are summarised by McLinden et al. /McL98b/; this paper also contains recommended formulations for the most common HCFCs, HFCs, hydrocarbons, R-717 (ammonia), and R-744 ($CO_2$). McLinden et al. /McL98b/ and Lemmon and McLinden /Lem01/ provide a summary of the available data for blends. A new international standard provides thermodynamic properties of ten single-compound refrigerants and four blends /ISO05/. Assael et al. /Ass99/ and McLinden et al. /McL00/ provide references to transport property data for 31 and 14 refrigerants, respectively. The NIST REFPROP database /Lem02/ 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 conditions, and it is compliant with the ISO standard /ISO05/.

The data situation for the less-common fluids is more variable. There is interest in the ethers and particularly the hydrofluoroethers (HFE-E series refrigerants as in, for example, HFE-E245cb1). The available data for them are often scattered among obscure sources. There is a need to collect and evaluate the data for such candidates.

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). Concerted 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.

### 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, state-of-the-art reviews of evaporation and condensation 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. Mention should be made of other representative reports on refrigerant heat transfer technology including Ohada 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 hydrocarbons, ammonia, and carbon dioxide
- 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 such as manufacturers' literature (refrigerant, plastics, and elastomer manufacturers), materials chemical resistance publications, plus 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 include 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/. Essentially all of the MCLR studies were made with fluorochemical refrigerants, especially the major commercialised HFC refrigerants. It was found that HFCs were less reactive than HCFCs such as HCFC-22 or HCFC-123, with the result that most materials compatible with HCFCs were also compatible with HFCs.

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 /Pru95, Pru94, and Pru83/. Since plastics and elastomers contain many types of additives (many being proprietary), specific materials should be tested to ensure compatibility.

Ammonia is not compatible with most types of electrical wiring insulation. Metals of construction inside ammonia systems normally are limited to carbon and stainless 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. Aluminum is compatible with ammonia, but it is sensitive to corrosion in water circuits due to the presence of chlorides.

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/. A photograph of an o-ring shattered by carbon dioxide explosive decompression can be found in /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 POE oil; Buna N, HNBR, Viton, and neoprene performed well while natural, silicon, and 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 ANSI/ASHRAE 15, *Safety Standard for Refrigeration Systems* /ASH04b/, 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 anaesthetic 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, Cal01, and Cal07/. 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, Cal01a, and Sek00/.

Flammability data generally are available /Ric92 and Cal01a/, though data dispersion from different test methods and laboratories leads to a degree of uncertainty in some cases.

## 2.4 Status and Research Needs for Heat Transfer Fluids for Indirect Systems

Heat transfer fluids (HTFs) — also referred to as *secondary coolants*, *secondary fluids*, or *secondary refrigerants* — for indirect systems are employed as a medium for removing heat from a cooling application (e.g. cold storage warehouses) to be discharged to the evaporator of a direct refrigerating system. HTFs have been used for many years in industrial applications. Recently, they have become more popular in commercial applications for the purposes of reducing the primary refrigerant charge and/or mitigating emissions of refrigerants that have notable environmental warming impact or when regulatory or safety constraints apply. HTFs are divided into two categories, namely single phase and phase-change fluids.

Single-phase fluids are in common use and include the following chemical groups:

aqueous solutions

- glycol solutions
- alcohol solutions
- salt solutions
- other aqueous mixtures

non-aqueous liquids

- hydrofluoroethers (HFEs)
- aliphatic hydrocarbons
- aromatic hydrocarbons
- synthetic oils

Table 2-4 lists common HTFs categorised by chemical types. The freezing points /CIS/ and minimum eutectic temperatures /Mel97/ are provided for aqueous solutions and for non-aqueous liquids, respectively. Freezing and eutectic temperatures are approximate as the literature reveals a range of values for many of the HTFs listed. This is largely due to the difficulty in distinguishing between liquid and solid, as a mushy or jelly-like consistency develops as the temperature is depressed. Toxicity is expressed at the TLV-TWA of the vapour where available /CIS/. Similarly the flash point (closed cup) is listed where relevant as a measure of flammability /CIS/. A number of additional HTFs are not listed in Table 2-4 as the pertinent data are held as proprietary and not disclosed.

As with conventional refrigerants, selection and application of HTFs depends largely on compatibility and energetic performance at the given operating conditions. The aliphatic and aromatic hydrocarbon groups are rarely used in refrigeration or air conditioning applications because of flammability issues.

*Table 2-4: Basic characteristics of liquid HTFs*

| Type | Substance | freezing or eutectic point (°C) | toxicity (TLV-TWA) (ppm) | flammability (flash point °C) |
|---|---|---|---|---|
| Aqueous glycols | Glycerol | -50 | 3 | +177 |
| | propylene glycol | -52 | n/e | +99 |
| | ethylene glycol | -54 | 40 | +111 |
| Aqueous alcohols | ethanol | -117 | 1000 | +13 |
| | Methanol | -98 | 200 | +12 |
| | Propanol | -127 | 200 | +15 |
| | Isopropanol | -90 | 200 | +12 |
| Aqueous salts | lithium chloride | -74 | n/e | n/f |
| | magnesium chloride | -33 | n/e | n/f |
| | calcium chloride | -55 | n/e | n/f |
| | sodium chloride | -21 | n/e | n/f |
| | potassium formate | -53 | n/e | n/f |
| | potassium acetate | -53 | n/e | n/f |
| | potassium carbonate | -38 | n/e | n/f |
| other aqueous mixtures | Ammonia | -78 | 25 | +11 |
| | trimethyl glycine (betaine) | -97 | n/e | +46 |
| Aliphatic hydrocarbons | Pentane | -129 | 600 | -49 |
| | Hexane | -95 | 50 | -22 |
| | isoparaffinic naptha, hydrotrated | -100 | n/e | +62 |
| Aromatic hydrocarbons | dipentene (d-limonene) | -97 | 100 | +46 |
| | diethyl benzene (*) | -81 | 10 | +57 |
| | Methylcyclohexane (*) | -127 | 400 | -6 |
| | Trimethylpentane (*) | -107 | 300 | +5 |
| | benzyltoluene (isomeric) | -70 | n/e | +150 |
| hydrofluoroethers | methyl perfluoropropyl ether | -123 | 75 | n/f |
| | methoxy-nonafluorobutane | -135 | 750 | n/f |
| | ethoxy-nonafluorobutane | -138 | 200 | n/f |
| | ethoxy-dodecafluoro-trifluoromethyl-hexane | -100 | n/e | n/f |
| synthetic oils | decene, dimer, hydrogenated | -73 | n/e | +163 |
| | Dimethylpolysiloxane #1 (*) | -40 | n/e | +160 |
| | Dimethylpolysiloxane #2 (*) | -82 | n/e | +64 |
| | Dimethylpolysiloxane #3 (*) | -101 | n/e | +47 |
| | diphenyl ethane (*) | -18 | n/e | +135 |

Notes: n/e – not established, n/f – non-flammable, (*)in various compositions as commercial blends

Use of phase-change fluids in indirect systems is becoming more popular due to their favourable thermal and transport properties, which in isolation can lead to improved system efficiency. There are three broad categories of phase-change HTFs:

- liquid-vapour: A liquid is circulated to, and allowed to vaporise within the secondary heat exchangers, and the vapour re-condensed in the evaporator of the primary circuit. The most commonly adopted fluid is carbon dioxide.
- liquid-permanent solid: A liquid that contains permanent suspensions, such as capsules with contents that melt as they pass through the secondary heat

exchanger and refreeze in the primary evaporator. Most single-phase HTFs can be used as a carrier for the mediums, which include pellets or capsules containing phase-changing mixtures. Aqueous solutions tend to be used with hydrophilic particles that absorb a water-rich mixture.

- liquid-transient solid: A mixture of fluids such that one component (typically water) separates and freezes into solid suspensions as the temperature lowers in the primary evaporator, and then melts and reforms a solution when passing through the secondary heat exchanger. Ice slurry using a variety of aqueous solutions is the most widespread form of this HTF, although emulsions and mixtures forming clathrate hydrates also have been considered /Ina03/.

The thermal transport capacity of phase-change HTFs is generally higher than for single-phase HTFs. Pressure losses and heat transfer capabilities also are improved in many cases. As such, their use offers potential benefits including lower flow rates, lower pumping costs, smaller pipe sizes, and smaller heat exchangers. However, a number of technical issues inhibit broader application. For liquid-vapour HTFs, the problems associated with potentially high system pressures apply, as well as control methods and defrosting. In contrast, the favourable viscosity at low temperatures of carbon dioxide compared to other HTFs provides significant benefits in terms of pump requirements. For ice slurries, elaborate primary evaporators (ice generators) are required and the additional energy required for operating scrape-surface equipment can offset the benefits achieved elsewhere.

In addition to corrosion inhibitors, additives are often used in phase-change HTFs for a number of purposes such as to control particle formation and to avoid agglomeration /Ina05 and Lu02/. While most phase-change HTFs have focused on sub-zero application temperatures, clathrate hydrates have been considered for use in air-conditioning applications /Dar05/. Lower temperature clathrate hydrates using carbon dioxide also have also been considered /Mar06/.

Some important aspects associated with use of HTFs are detailed below.

Material compatibility: Most HTFs can corrode metals in the presence of air (oxygen) and moisture contamination in the case of oils, fluoroethers and single-component hydrocarbons, and may cause deterioration in certain non-metallic materials. Some HTFs, such as salt solutions (brines), are more corrosive than others. Corrosion inhibitors or passivators are required in most cases along with means to removing absorbed air.

Costs: The cost of most HTFs is relatively low compared to that of most primary refrigerants. However, the synthetic oils and fluoroethers can be significantly more expensive, approaching that of conventional refrigerants. The use of additives can sometimes impact on the cost of the HTF, and similarly, there can be a major additional costs associated with the heat exchangers to produce ice slurries.

Thermodynamic and transport properties: Viscosity, density, specific heat, and thermal conductivity are important properties. Energy consumption and component cost are reduced with low viscosity, high density, high specific heat, and high thermal conductivity. HTFs generally become significantly more difficult to implement in low-temperature applications since viscosity increases and pumping power requirements escalate. Some recently developed aqueous salt solutions have shown properties that are more favourable at these conditions, but phase change fluids such as carbon dioxide demonstrate properties most favourable for energetic performance.

Environmental impacts: Most HTFs have high normal (atmospheric) boiling points (NBP), with corresponding low volatility resulting in only limited releases to the atmosphere. However, virtually all fluids will result in some impact if discarded into drainage systems or the environment in general. Safety data sheets will provide environmental impact information and methods of appropriate disposal.

Safety issues: Safety requirements are normally determined by the application, although normally non-toxic, non-flammable fluids are preferred, or required by codes and regulations. In situations where food is involved, "food-safe" grade products are required.

Research needs: The research aspects can be broken down into three key areas:

> Properties of single phase HTFs: Work by Melinder /Mel97/ characterised the properties of many HTFs in use. Melinder /Mel98/ identifies considerable discrepancies among published HTF data, particularly at low temperatures. Similar disagreement is found in freezing point measurements, which is important to estimate ice concentrations in slurries.
>
> Properties of phase-change HTFs: There is significant progress on properties for ice slurries using a broad range of different aqueous solutions of glycols, alcohols, and salts (e.g., /Lot00 and Mee00/). Significant work is also being done on carbon dioxide, although the earlier section on primary refrigerants should be referred to for property aspects. There is also a limited amount of information relating to permanent slurries, such as capsules, given that such technologies offer significant practical benefits over the other phase-change slurries.
>
> Compatibility: The most significant problems encountered by industry are compatibility issues. Inhibitors generally are included in commercialised HTFs. However, such additives vary between manufacturers, and information on them is limited. Since absorbed air is difficult to remove and spillage frequently occurs, further work is required in this field.

Although not directly related to the HTF itself, the literature shows that relatively little work has been produced on the issue of systems, rather than the fluids itself. Particular aspects are effective design schemes, defrost methods, and improving energy efficiency.

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# 3 Domestic Refrigeration

## 3.1 Introduction

Domestic refrigerators are used for food storage in dwelling and non-commercial areas such as offices in every country throughout the world. More than 80,000,000 units are produced annually. The estimated aggregate installed inventory is 1200 to 1500 million domestic refrigerators. Product variations include: *fresh food and beverage storage only*, typically maintained at +1 to +7$^{o}$C; *frozen food storage only*, typically maintained at –6 to –24$^{o}$C; or *products having multiple chambers* maintained at each of these temperatures. Internal storage volumes range from 20 litres to greater than 850 litres. Other feature variations include: manual, cycle or automatic defrosting techniques; natural or forced convection heat transfer; and various consumer convenience features. Products contain a factory-assembled, hermetically sealed vapour-compression refrigeration system typically employing a 50 to 250 watt induction motor and containing 50 to 250 grams of refrigerant. The typical median unit life is about 20 years and the age distribution is extremely broad. Niche market products in some cases apply alternative technologies such as absorption or Stirling cycles.

## 3.2 Technical Alternatives Available through Product Life Cycle

CFC-12 became the universal refrigerant choice for domestic refrigeration production during the 1940s. Conversion from CFC-12 to ozone-safe alternatives was initiated in response to the Montreal Protocol. Conversion in Article 2 countries was complete by the end of 1995. Conversion in Article 5 countries continues with current status being well ahead of Montreal Protocol requirements. Technical alternatives are mature and stable and are briefly reviewed below. In-depth discussion of these alternatives is available in earlier reports of this committee. /UNEP95, UNEP98, UNEP02/

### 3.2.1 Refrigerant Options for Original Equipment

Most new refrigerators or freezers employ either HC-600a or HFC-134a refrigerant. Each of these refrigerants has demonstrated mass production capability for safe, efficient, reliable and economic use. There are no known systemic technical problems with properly designed and manufactured products employing either of these options. HC-600a is flammable, which introduces unique design considerations. HFC-134a is more sensitive to contaminants, which introduces unique manufacturing considerations. Either option can be effectively implemented as indicated by the tens of millions of units annually produced employing each approach. Other key variables influencing refrigerant option selection are refrigerator construction details, building codes, environmental considerations and the relative economics of standards compliance. Energy efficiency of the two refrigerants is comparable with design parameters introducing more variation than the refrigerant selection. An extended discussion of factors influencing refrigerator energy efficiency and this direct nexus to global warming potential is available in the 1998 report of this committee /UNEP98/. Blending HC-600a and HC-290 provides the opportunity to match the volumetric capacity of compressors designed for use with CFC-

12. These are zeotropic blends boiling through a glide of 7 K. This glide introduces manufacturing complications, such as the required use of liquid charging techniques. Liquid charging techniques are also required for service or repair of these units in the field. These hydrocarbon blends were employed in Western Europe during the 1990s and are currently being applied in several Article 5 countries to assist conversion from CFC-12 refrigerant. Their application in Europe was a short interim step toward a final transition to HC-600a using compressors with modified volumetric capacity. HC-600a and HC-600a/HC-290 blends have been combined into a single hydrocarbon category in this report.

### 3.2.2 Original Equipment Not-In-Kind Alternative Technology

Alternative refrigeration technologies continue to be pursued for applications with unique drivers such as portability or absence of dependence on electrical energy supply. Technologies of interest include Stirling cycle, absorption cycle, thermoelectric, thermoacoustic, magnetic and trans-critical $CO_2$. Previous assessments concluded that no identified technology for domestic refrigerator-freezers was competitive with conventional vapour-compression technology with respect to cost or energy efficiency /UNEP95, UNEP98, UNEP02, IPCC05/. These conclusions are still valid for mass-produced domestic refrigeration equipment. However, Stirling technology in portable cool boxes has recently been introduced to the market. In addition, Stirling and trans-critical $CO_2$ technology will be applied in vending machines for packaged beverages.

### 3.2.3 Refrigerant Options for Field Service and/or Retrofit

Field service procedures typically use originally specified refrigerants. The 1998 status report of this committee /UNEP98/ included extended discussion of field repair and conversion options. No subsequent developments, other than increased supply-side restrictions on CFC-12 availability, have significantly influenced that behaviour. These restrictions include the ban of CFC-12 from service use in the European Community. Field service options include service, using original refrigerant; drop-in, where only the refrigerant is changed; and retrofit, where the refrigerant and other product components are changed to accommodate the different refrigerant.

In Non-Article 5 countries the rate of sealed system failures is estimated to be a manufacturing defect driven cumulative 1% during the first five years, and an additional cumulative 1% during the typical remaining 15 years of useful life. In Article 5 countries these rates are estimated to be cumulative 3% and cumulative 7% for the initial 5 years and the remaining 15 years respectively /UNEP98/. The dispersed nature of the field service infrastructure for domestic refrigerators and freezers hampers reporting of service statistics. Each sealed system failure results in the discharge or recovery of the original refrigerant and recharging with new or reclaimed refrigerant. Consequently, the failure rates above are useful to provide first order estimates for refrigerant field service demand when integrated with OEM historic production statistics.

A long useful product life (median life near 20 years with some units exceeding 30+ years /Wes97/), a 1200 to 1500 million unit installed base and high-cost/uncertain-reliability with field conversion to alternative refrigerants result in a strong continuing service demand for CFC-12. Further compounding this is the limited availability of capital resources in Article 5 countries. Restricted capital resources promote rebuilding older, less-efficient equipment versus replacing it. This rebuilding is almost always a cottage industry endeavour and is a prevalent option in many Article 5 countries. The variable quality inherent in this cottage industry rebuilding amplifies failure rates and further extends demand for historic ODS and/or high GWP refrigerants. This rebuilding also maintains the power grid demands of older, less-efficient units through delaying their replacement by newer units which typically will require less than one-half the electrical power to operate.

Statutory CFC-12 production constraints under the Montreal Protocol and country-specific or global-region-specific bans on the use of CFC-12 for service have prompted the development of various binary and ternary blends of HFC, HCFC, PFC and hydrocarbon refrigerants to supplement CFC-12 availability for serving the continuing service demand. Some of these are near-azeotropes, while others exhibit glide or difference in boiling points. There appears to be a regional preference in service blends – for example the use of R-401A or R-413A in Australasia - presumably due to regional availability or marketing strengths. The use of blends or alternative refrigerants for service is expected to significantly increase after 2007. The cost of CFCs is predicted to sharply increase in this time frame and this is expected to provide incentives to convert from CFCs to alternatives. If refrigerants and lubricants that do not meet original design specification are proposed for use, their compatibility with the specific refrigerator-freezer product configuration and its component materials must be specifically reviewed. Properly dealing with refrigerant flammability and solubility in the compressor lubricant are two critical considerations. The manufacturers of these alternative refrigerants and compressor manufacturers are the recommended sources for information regarding their application.

### 3.2.4 End-of-Life Conservation and Containment Concerns

Refrigerant recovery to prevent emissions at end-of-life and during service is required in several countries. Equipment and techniques are readily available to accomplish this recovery. The small amount of refrigerant charge present in domestic refrigerators – typically 50 to 250 grams with up to 500 grams present in some older units – combined with geographically disperse service and disposal needs, constrains commercial incentives to promote recovery and recycling.

If recovered refrigerant is to be reused, it is preferable that it be reclaimed, i.e. restored to original purity specifications. Reclaiming is desirable to avoid repeat failures due to contamination. Chemical processors typically accomplish reclaiming in centralised facilities. The use of multiple refrigerants in a geographic area increases the probability of cross-contamination and complicates the logistics of refrigerant recovery. This further reduces the economic justification for recovery since refrigerant value is dependent upon its purity. Single component reclaimed refrigerant has an intrinsic value, which is discounted as contaminants are introduced. Non-azeotropic blends and significantly contaminated refrigerant have negative value, i.e. there are costs associated with environmentally responsible disposal.

The European Waste Electrical and Electronic Equipment (WEEE) Directive is arguably a paradigm regulation for extending end-of-life product disposal management beyond refrigerant recovery requirements. Analogous regulations have already been enacted in several countries and are being considered in additional countries and regions. These initiatives potentially can improve the effectiveness of refrigerant recovery and conservation efforts. It is likely that incremental attention will be focused on the five-fold or greater content of ozone depleting substances present in foam insulation of older units in the installed base. Elaborating comments on this topic can be found in Chapter 11 of this report, “Refrigerant Conservation, Containment and Destruction.”

## 3.2 Refrigerant Annual Demand

Domestic refrigeration refrigerant annual demand and existing bank are not reported, but can be estimated with reasonable assumptions. Annual OEM refrigeration production statistics are reported. The type of refrigerants used and the amount of refrigerant charge per unit are available from industry sources. Annual OEM refrigerant demand can be estimated from the facts immediately above. Field service refrigerant annual demand can be estimated by integrating production statistics over an estimated 20 years product life, the consensus failure rates discussed earlier in this chapter, and field service purging and charging practices. The refrigerant bank for domestic refrigeration can be estimated similarly by integrating annual OEM units production and refrigerant charging practices over the anticipated unit lifetimes.

### 3.3.1 Original Equipment

The status of the conversion of domestic refrigeration original equipment manufacturing from CFC-12 refrigerant to ozone safe alternative refrigerants is summarised in Table 3-1 /Eur01, Eur05, UNEP02/. This table clearly shows extension of the previously reported trend to complete this conversion well in advance of the Montreal Protocol timetable. 96.3% of new production had been converted by the end of 2004: 61.2% to HFC-134a, 33.3% to hydrocarbons (HC-600a or HC-600a/HC-290 blends) and 1.8% to all other refrigerants. Table 3-1 extends through 2004 the 1992 through 2000 refrigerant demand data previously reported /UNEP02, Eur01/. Domestic refrigerator-freezer production statistics by global region were provided by a commercial data base service /Eur05/. Two compressor manufacturers provided compressor production data tabulated by refrigerant type and global sales region. **[2]** Improved accuracy data are included versus the 2000 original equipment market information

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[2] The cooperation of Matsushita and Whirlpool compressor manufacturing divisions and Euromonitor International Inc. in providing data enabling the construction of Tables 3.3.1 and 3.3.2 is appreciated.

previously reported /UNEP02, Eur05/. The previously reported data have been adjusted to reflect the improved accuracy and the 2004 market information has been included.

### 3.3.2 Field Service

*Table 3-1 Estimated 1992 to 2004 Production of Domestic Refrigerators and Freezers*

| Global Region | Year | New Unit Production, Million Units | | | | | New Unit Refrigerant Use, tonnes | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFC12 | HFC134a | HC600a[1] | Other[2] | Total | CFC12 | HFC134a | HC600a[1] | Other[2] | Total |
| Western 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 | | 1460 |
| 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 |
| 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 |
| 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 |
| Asia and 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 |
| Africa and 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 |
| 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 |

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

The estimated annual demand trend for domestic refrigeration field service over the period 1992 through 2004 is tabulated in Table 3-2. Significant residual service demand for CFC-12 is evident. Drivers for this are the large installed base and long product life plus the planned grace period for conversion from CFC-12 by Article 5 countries. The effects of this delayed conversion are exacerbated for service by the estimated five-fold mature sealed system failure rate for Article 5 countries versus Non-Article 5 countries. This may be somewhat mitigated by expanded use of the binary and ternary blends of HFC, HCFC, PFC and hydrocarbon refrigerants formulated for the service industry which were discussed in section 3.2.3 above. Further counteracting this are systemic improvements in refrigerant containment driven by improved manufacturing and service techniques and improvements in service refrigerant charging practices. Assistance programs funded by the Multilateral Fund have been significant contributors to these systemic improvements. /UNEP05/.

*Table 3-2 Estimated 1992 to 2004 Domestic Refrigeration Service Refrigerant Demand*[1]

| Global Region | Year | Service Refrigerant Demand, tonnes | | | |
|---|---|---|---|---|---|
| | | CFC12 | HFC134a | HC600a[2] | Total |
| Western Europe | 1992 | 68 | | | 68 |
| | 1996 | 52 | 10 | 4 | 66 |
| | 2000 | 34 | 14 | 12 | 60 |
| | 2004 | | 16 | 34 | 50 |
| Eastern Europe | 1992 | 220 | | | 220 |
| | 1996 | 220 | 13 | | 233 |
| | 2000 | 180 | 17 | 4 | 201 |
| | 2004 | 121 | 29 | 32 | 182 |
| North America | 1992 | 130 | | | 130 |
| | 1996 | 110 | 16 | | 126 |
| | 2000 | 60 | 60 | | 120 |
| | 2004 | 17 | 90 | | 107 |
| Central & South America | 1992 | 780 | | | 780 |
| | 1996 | 1080 | | | 1080 |
| | 2000 | 990 | 20 | | 1010 |
| | 2004 | 600 | 117 | | 717 |
| Asia and Oceania | 1992 | 2390 | | | 2390 |
| | 1996 | 2670 | 190 | 0.1 | 2860 |
| | 2000 | 2420 | 230 | 130 | 2780 |
| | 2004 | 1650 | 270 | 291 | 2211 |
| Africa and Mid-East | 1992 | 870 | | | 870 |
| | 1996 | 870 | 120 | | 990 |
| | 2000 | 800 | 50 | | 850 |
| | 2004 | 575 | 120 | | 695 |
| World Totals | 1992 | 4458 | | | 4458 |
| | 1996 | 5002 | 349 | 4 | 5355 |
| | 2000 | 4484 | 391 | 146 | 5021 |
| | 2004 | 2963 | 642 | 357 | 3962 |

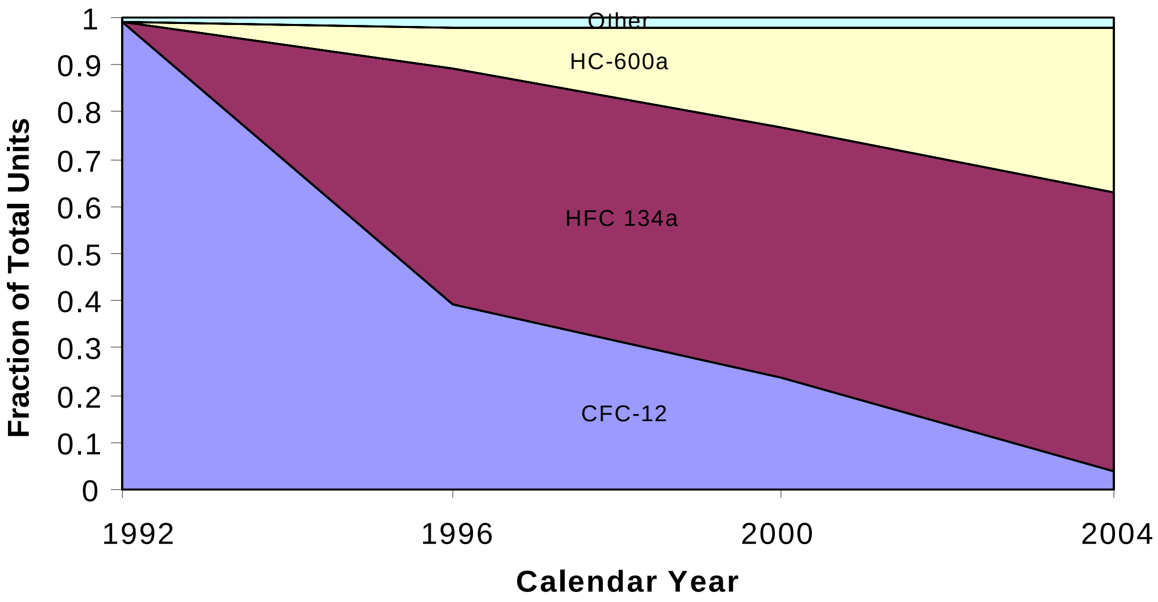
Notes: [1] Demand estimates prepared for three primary refrigerants only.
[2] Includes HC600a/HC290 blends

## 3.4 Future Refrigerant Demand

### 3.4.1 OEM Production Demand

Selected data from Table 3-1 are shown graphically in Figure 3-1 to illustrate the reduced OEM production demand trend for CFC-12. Data are presented as the percent of OEM refrigerators produced using different refrigerants. Parametric curves are included for CFC-12 conversion to either HFC-134a or hydrocarbons, which are considered to be the two long-term refrigerant options. HC-600a and HC-600a/HC-290 blends are treated here as one combined option. Longer-term this is expected to migrate to the pure HC-600a material due to ease of control and application. This simplification has been delayed due to the capital investments required to increase the volumetric capacity of the compressors applied. Figure 3-1 clearly shows the transition of OEM domestic refrigeration use from CFC-12 refrigerant is essentially complete. As stated above, conversion was 96.3% complete by the end of 2004. A modest increase in the share of units using HC-600a is predicted.

*Figure 3-1 New Unit Production* (1)



(1) Includes HC-600a/HC-290 Blends

### 3.4.2 Field Service Demand

Figure 3-2 similarly shows the reduced domestic refrigeration field service demand trend for CFC-12. Curves are included for the three highest demand service refrigerants: CFC-12, HFC-134a and hydrocarbons. Data are shown as the fraction of total service refrigerant demand represented by each refrigerant option. Absolute demand quantities can be seen in Table 3-2. Data are not available to track the usage of refrigerant blends specifically developed to serve the CFC-12 service market demand. Usage of these blends or other alternatives for service of units containing CFC-12 is not believed to have been significant through 2004. Their use is expected to become more significant in the future, driven by reduced favourability in CFC-12 supply and economics. Reduction of the field service demand for CFC-12 is heavily damped versus results for OEM production reduction. This is a consequence of long equipment service life and technical difficulties involved with converting existing units to alternative refrigerants. As a result, CFC-12, or its blended refrigerant substitutes will continue to have significant residual service demand for many years to come.

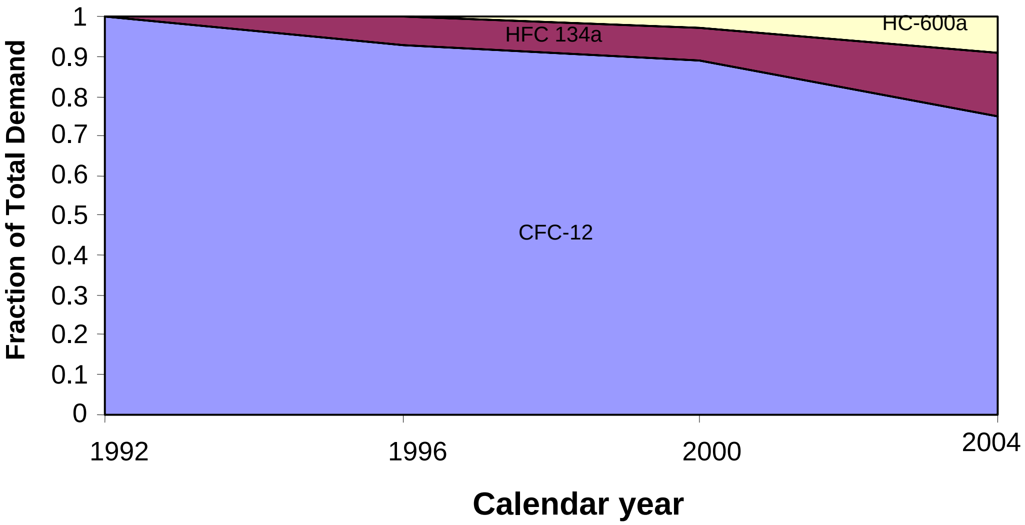


*Figure 3-2 Field Service Demand* [(1)]

(1) Includes HC-600a/HC-290 Blends

## 3.5 Existing Refrigerant Bank

The existing inventory bank is summarised in reports by Palandre and Clodic, et al /Pal03, Clo06/ for the period 1990 through 2003. Data are reported by country or global region and demonstrate a growing bank, spurred by market growth. The aggregate refrigerant bank in 2003 was estimated to be about 155,000 tonnes consisting of approximately 58% CFC-12, 35% HFC-134a and 7% HC-600a. 51% of this bank was installed in Article 5 countries and 49% was in non-Article 5 countries. 2003 aggregate emissions were estimated to be approximately 7 tonnes, or approximately 4.5% of the total bank, consisting of approximately 92% CFC-12, 7.5% HFC-134a and 0.5% HC-600a. Similar to the bank distribution, 52% of these emissions originated in Article 5 countries. Weighting these emissions by relative global warming potentials indicates an even greater influence of the legacy CFC-12 emissions.

It is readily apparent from these data that the conversion of the bank to non-ODS refrigerants is heavily damped. The emissions trend to non-ODS alternatives from this bank is even further damped. This sluggish response to change primarily results from the large, 1200 to 1500 million unit, installed base and long product life; the refrigerant systems being hermetically sealed during manufacture; and the majority of these units never requiring sealed system service because of their intrinsic reliability. These combined factors result in total emissions being dominated by end-of-life final disposition. This statement and Table 3-2 suggest that management of potential emissions from the domestic refrigeration refrigerant bank will be a topic of consideration for more than 20 years in the future.

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# 4 Commercial Refrigeration

## 4.1 Introduction

Commercial refrigeration is essential for food and beverage processing and marketing, for example to prepare beverages, preserve chilled and frozen foods, cool drinks, and store foods at the appropriate temperatures. More and more attention is being paid by customers to food quality, and therefore to its preservation from the source to the end user. Storage temperatures have to be maintained precisely and are controlled by regulations in a number of countries. Two levels of temperature (medium temperature for preservation of fresh food and storage of beverages, and low temperature for frozen products) may require the use of two different refrigerants. Chilled food is maintained in the range of 1 °C to 14 °C and the evaporating temperature for the equipment varies between -15 °C and +1 °C. Most frozen products are kept at temperatures (from -12 to -18 °C). Ice cream is kept between –18 and -20 °C. Usual evaporating temperatures for frozen food are in the range of -35 to -40 °C.

Energy efficiency of commercial refrigerating systems has always been an issue when energy prices are high. With the energy price increases since 2003, many global companies have set new targets to lower energy consumption by 15 to 20% for stand-alone equipment and large centralised systems.

Commercial refrigeration causes more refrigerant emissions /Clo06/ in terms of $CO_2$ equivalent than any other refrigeration application.

Centralised systems with long piping circuits have led to large (1,000 to 2,000 kg) refrigerant charges, resulting in large losses when ruptures occur. Over the last 10 years, a number of technical improvements have been made to limit refrigerant emissions and their environmental impacts and to reduce the refrigerant charge by developing indirect systems and employing refrigerants with lower GWP.

## 4.2 Type of Equipment and Systems

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

Stand-alone equipment consists of systems where all the components are integrated. They are also called plug-in systems because the only thing to be done for the installation is to connect the electric plug in a socket. This equipment is installed in metro (subway) and train platforms, small shops, schools, office buildings, and in supermarkets. Annual growth of the installed system base is significant. Vending machines can be either bought by the establishment owner (end user) or rented by beverage companies; no special attention is paid to the refrigeration system by the end user. Stand-alone equipment, including freezers and all kinds of small equipment are used extensively in many Article 5 countries. In Article 5 countries, refrigerating equipment such as domestic refrigerators or freezers can be found in small shops and are used for commercial purposes.

Condensing units, comprising the second group of commercial refrigeration equipment, are composed of one (or two) compressor(s), one condenser, and one receiver assembled into the condensing unit which is located external to 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 (up to 20) of condensing units installed side-by-side in a single machinery room. Systems employing condensing units are installed in many Article 5 countries.

In order to cover the wide variety of refrigerating systems developed for supermarkets in the last ten years, a new concept "full supermarket system" has been introduced in the IPCC TEAP Special Report /IPCC05/. It includes both direct and indirect systems as well as hybrids of them.

Centralised systems employ racks of compressors installed in a machinery room. A number of possible designs exist (see 4.5.3). Two main design options are used: direct and indirect systems.

Direct systems are more widespread. The refrigerant circulates from the machinery room to the sales area, where it evaporates in heat exchangers in display cases, and then returns in vapour phase to the suction port of the compressor racks. The supermarket cold rooms are also cooled in the same way. In the machinery room, racks of multiple compressors are installed with common suction and discharge ports, and each rack is usually associated with an air-cooled condenser. Specific racks may be dedicated to low temperature and others to medium temperature with a common connection for each level of temperature.

Indirect systems are composed of primary heat exchangers where a heat transfer fluid - HTF (also called a “secondary refrigerant” or a “secondary coolant”) is cooled and pumped to the display cases, where it absorbs heat, and then back to the primary heat exchanger. HTFs have received much interest in recent years because indirect systems allow for lower primary refrigerant charge and because they facilitate use of flammable or toxic refrigerants by isolating them from the sales area /Ari02/.

Other designs, including “distributed systems” and hybrid systems constituted by direct and indirect system concepts have been developed and are presented in Section 4.3.3.

## 4.3 Data on Outlets and Stand-Alone Equipment

The structure of commercial refrigeration consists of: food specialists and groceries where stand-alone systems and condensing units are mostly found, and supermarkets and hypermarkets (large supermarkets) with centralised refrigerating systems as the main system, but also using stand-alone and condensing unit equipment.

Statistics are not available for all types of equipment. For vending machines, data on sales are available from several sources for nearly all developed countries and the main Article 5 countries. For condensing units and stand-alone equipment, data are scarce. , Statistics compiled by governmental agencies are available for nearly all countries on the numbers of supermarkets. Studies also can be prepared to analyse trends in sizes of supermarkets and to evaluate additional applications for refrigerating systems, such as in gas stations and railway stations.

### 4.3.1 Supermarkets and Hypermarkets

A number of leading U.S. and European companies are expanding world-wide and the design in developing countries is similar to the original design. The sales areas are similar and so the refrigerant capacity, nevertheless, the refrigerant choice will depend on the local regulations.

The installed base[3] of supermarkets and hypermarkets (Table 4.1) by country or region has been taken from /Clo06/. Contradictory data may be found for the same country coming from different sources (company associations, state data, etc.).

***Table 4-1 – Number of supermarkets and hypermarkets outlets in 2003 /Clo06/***

| 2003 | Supermarkets | Hypermarkets |
|---|---|---|
| USA | 33 841 | 3 568 |
| Brazil | 15 100 | 232 |
| Australia | 1 822 | 2 |
| China | 288 000 | 311 |
| Japan | 15 181 | 1 457 |
| Russia | 1 118 | 31 |
| India | 500 | 0 |
| Europe 25 | 58 752 | 6 236 |
| Other Europe | 10 503 | 429 |
| Other America | 7 344 | 773 |
| Other Asia and Oceania | 26 599 | 1 791 |
| Africa | 3 274 | 95 |
| **TOTAL** | **462 034** | **14 925** |

To deduce the refrigerant charge from the number of supermarkets, the first step is to verify the average sales area depending on the country. As shown in Figure 4-1, sales area may vary significantly from one country to the other. Based on the food sales area, the refrigerating capacity at the two levels of temperatures and then the refrigerant charge can be derived /Clo06/.

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[3] The installed base is the number of all equipment regardless of their vintage (representing systems installed in supermarkets and hypermarkets).

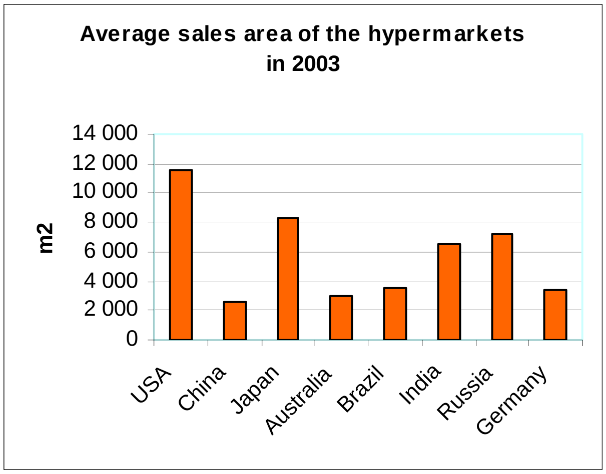

***Figure 4-1 – Average sales area in hypermarkets and supermarkets by country /Clo06/.***

### 4.3.2 Evaluation of the Installed Base of Stand-Alone Equipment and Condensing Units

For vending machines, statistics from suppliers are available for OECD countries and for the main Article 5 countries. For other countries, calculations have been made based on the GDP of the countries. When comparing these numbers of vending machines to the ones in 2001 /UNEP03/, the growth has been of more than 25%.

***Table 4-2 Estimate of the number of vending machines - 2003 /Clo06/.***

| | |
|---|---:|
| EU25 | 967 000 |
| Other Europe + Russia | 156 000 |
| Western Asia + Middle east (including India) | 560 000 |
| Eastern and South Asia (including China) | 1 850 000 |
| Japan | 3 930 000 |
| USA | 10 800 000 |
| Oceania | 60 000 |
| Africa | 20 000 |
| South and Latin America | 160 000 |
| Total | 18 503 000 |

Different from Table 4-2, where data are partially based on available statistics coming from OEMs or distributors, data shown in Table 4-3 for condensing units and stand-alone equipment come from calculations of the refrigerating capacities installed in food specialists, convenience stores, gas stations, etc. So the uncertainties are significantly larger compared to the data presented in Tables 4-1 and 4-2. Additional analysis is needed to consolidate these numbers.

***Table 4-3 Estimate of the number of condensing units and stand-alone equipment – in use – in 2003 /Clo06/***

| | Condensing units | Hermetic groups in stand-alone equipment |
|---|---|---|
| EU25 | 6 820 000 | 6 950 000 |
| Other Europe + Russia | 970 000 | 854 000 |
| Western Asia + Middle East (including India) | 4 820 000 | 3 960 000 |
| Eastern and South Asia (including China) | 7 852 000 | 8 600 000 |
| Japan | 2 430 000 | 2 670 000 |
| USA | 4 520 000 | 5 620 000 |
| Oceania | 660 000 | 752 000 |
| Africa | 151 000 | 250 000 |
| South and Latin America | 862 000 | 1 250 600 |
| Total | 29 085 000 | 30 906 600 |

## 4.4 Refrigerant Options for New Equipment

Refrigerant choices for new equipment are different depending on the national or regional regulations, the refrigerant quantity, the refrigerating capacity and the temperature. The use of flammable or toxic refrigerants may be limited or forbidden by safety standards or regulations.

### 4.4.1 Stand-Alone Equipment

The majority of stand-alone equipment (see below the different types) is based upon HFC technology. Some well-established beverage companies and ice-cream manufacturers committed themselves in 2004 to eliminate HFC use in their equipment /Coc04/. Use of HCs and $CO_2$ is growing in several applications.

Most of the stand-alone equipment used in commercial installations, hotels, and bars, (such as wine-coolers, professional kitchen refrigerators and freezers, and hotel mini-bars) is based on the same technology as domestic refrigerators and freezers, for which technical options are addressed in Chapter 3. Other stand-alone equipment, even if based on the same technology, is used only for commercial purposes: ice cream cabinets, water coolers. Plug-in display cabinets, ice machines, and vending machines are specifically designed for commercial use.

*Ice cream Freezers*
Ice cream freezers with glass lids can be found in a large number of supermarkets and convenience stores. Most of them have been installed by ice-cream suppliers.

The standard choice of refrigerant is R-404A or HFC -134a. However, HC cabinets have been available since 2000, and HC technology is gaining market share. More than 100,000 HC ice cream freezers have been installed by one global company. Another one has chosen $CO_2$ as the refrigerant and has just begun to commercialise them in 2006.

In most ice cream freezers with HCs, HC-290 (propane) is used. Where domestic freezers are used as commercial cabinets, isobutane may be used. It is the main option for global companies for the renewal of their ice cream freezers.

*Water Fountains*

A great number of 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 standard refrigerant. The typical HFC-134a charge is about 40 g. Some companies have developed models using HC-600a (isobutane).

*Ice Making Machines*

A great number of ice machines are installed in restaurants and bars, and usually use HFC-134a.

*Vending Machines*

The cooling capacity of vending machines is significant (typically 600 W) to achieve the necessary rapid cooling of cans. HFC-134a is the standard refrigerant in vending machines. Vending machines using HC-290 have been commercialised as of 2004 in Japan, and recently equipment using HC-600a has been introduced. So far about 3,000 units using HCs have been installed by the end of 2005 in Japan. Most soft-drink vending machines are purchased by large suppliers of soft drinks.

$CO_2$ as a refrigerant has been chosen by one global company and so far about 4,000 single-door coolers and vending machines using $CO_2$ have been installed since 2005 (1,000 have been employed during the 2006 Olympic Winter Games), mostly in Europe. This new $CO_2$ system is installed inside a plug-in/pull-out cassette. Tests by DTI (Denmark) on $CO_2$ cassettes, have shown energy efficiency better than or equal to, up-to-date HFC-134a technology for outdoor temperature below 32 °C.

Stirling system prototypes (a not-in-kind technology using helium as a working fluid) have been thoroughly tested and have shown favourable energy efficiency in the same range as an up-to-date HFC-134a machine /IPCC05/.

*Glass-Door Coolers*

Glass-door bottle coolers can be found in several places like supermarkets, convenience stores, 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. As indicated above global companies have introduced $CO_2$ systems for those 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 even if they are significantly less efficient.

The energy balance has to be made on the store itself because the release of heat 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 than usual ones. So far, R-404A refrigerant is the standard choice, and the charge per unit varies from 220 to 300 g.

### 4.4.2 Condensing Unit Systems

Condensing units are found in many convenience stores and food speciality shops for cooling a small cold room and one or more display cases. The cooling capacity varies from 5 to 20 kW and the majority of condensing units are working at evaporating temperatures varying between –10 and –15°C. Several small racks of condensing units (up to 20) installed side-by-side can be found in small machinery rooms in larger food stores. The use of several small condensing units is less energy efficient by far than a well-designed small-centralised system, but condensing units are chosen for initial or investment cost reasons, ease of installation and are available ready-to-install in large supply companies. Cost driven designs have the same consequences as do condensing units and plug-in display cabinets; the system is significantly less efficient compared to a small centralised system. A significant path forward in designing a commercial refrigeration system could be the development of life cycle cost analysis of the equipment including energy consumption and maintenance costs.

For condensing units, HCFC-22, is still the most used refrigerant in the U.S. and in all Article 5 countries. 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 the refrigerant are cheaper compared with HFC-134a units of the same cooling capacity.

### 4.4.3 Full Supermarket Systems

The concept of full supermarket systems was introduced in the IPCC report /IPCC05/ to cover the variety of designs now found in supermarkets.
The size of centralised systems can vary from refrigerating capacities of about 20 kW to more than 1 MW. The refrigerant charge is related to the refrigerating capacity and store layout. For large supermarkets, the refrigerant charge varies from 800 kg to 2 tonnes.
In order to lower the refrigerant charge, and limit the impact of emissions related to ruptures of tubes (which is an occurrence with a significant impact on the average emission of the installed base of supermarkets) a number of technical solutions have been developed including mainly, indirect systems and distributed systems. A review of possible system solutions is provided by Arias and Lundqvist /Ari01/.

For large supermarkets, the most common configuration is the centralised systems where all the compressor racks are installed in a single machinery room. This configuration requires several kilometres of piping containing refrigerant in the liquid phase from the machinery room to the sales area and in the vapour phase from the sales area back to the machinery room.

*Distributed Systems*

A technical alternative, called distributed systems, has been studied and designed as of 2000. The concept is to install the compressors close to the display cases either inside or very close to the sales area. In a decentralised system, usually condensers are water-cooled and fitted with the compressor(s) in a soundproof box. The water for condensers is usually supplied from roof-mounted dry coolers. The refrigerant charge can be reduced by up to 75%.

Energy savings can be made due to the reduction of piping length, but the compressors are smaller and the energy efficiency is usually lower. Moreover, an additional difference of temperature is created when using water-cooled condensers that are releasing their heat through the use of air dry coolers. The complexity of the comparison between the baseline (centralised system) and the distributed system is aggravated when changing the refrigerant (HFCs, HCs, or $CO_2$ compared to R-22 or R-502), so wide variation of performance can be found in the technical literature. To date, the introduction of distributed systems is significantly lower than expected.

*Indirect Systems*

Contrary to distributed systems, indirect systems are beginning to take a small market share of new installations, especially in Europe. The main advantage is a 75 to 85% reduction of refrigerant charge compared to direct systems.

Depending on the country, HFCs, R-717 (ammonia), HCs (HC-290 or HC-1270), and $CO_2$ are used as primary refrigerants in the refrigerating system installed in the machinery room and/or outside /IPCC05, RAC01/. Due to high latent heat of vaporisation and low liquid density, the charge with ammonia can be 10% of the usual HFC refrigerant charge /Pre01/. The same applies to HC refrigerant with charge typically 10% of the direct system HFC reference charge. For safety reasons, the refrigerant is distributed among several independent circuits to limit the refrigerant charge of each circuit /IPCC05/.

Many indirect systems have been designed using R-404A as refrigerant in the machinery room. With the reduction of the charge, the reduction of the environmental impact is significant. 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 used in indirect systems need special attention, especially at low temperatures where pumping power may be excessive, and the pumps have to be carefully chosen in order to avoid significant additional energy consumption.

For indirect systems, $CO_2$ and an ice-slurry can both be used as the heat transfer fluid. The use of $CO_2$ as the heat transfer fluid is mainly done for low-temperature display cases and cold rooms. Ice-slurry technology is less mature and is mainly used for medium-temperature applications. Until now, the slurry is used for thermal storage in a centralised tank. Ice slurry circulation to display cases is not yet a commercialised option, but pilot installations exist and research is underway.

*Hybrid Systems*

Hybrids between direct and indirect systems are being offered by European installers. $CO_2$ is used as a refrigerant in the low-temperature stage with an evaporating temperature around –35 °C and a condensing temperature at –12 °C keeping the tubing and the components under the 2.5 MPa pressure threshold of the current technologies. The condensation of this $CO_2$ low-temperature stage rejects its heat through the heat transfer fluid to the medium-temperature stage. So the heat of the $CO_2$ system is delivered at the medium-temperature stage and then released outdoor by the medium-temperature vapour compression system. This concept has been employed 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 tonnes to less than 250 kg. About 50 systems are running with R-404A in large supermarkets using this hybrid technology /IPCC05/. In many Northern European countries, various designs of $CO_2$ systems have been installed in supermarkets /Gir02/: hybrid systems, indirect systems, and also two-stage cascade systems using $CO_2$ in both stages.

*Centralised Direct Systems*

HCFC-22 is the refrigerant most used in supermarkets and hypermarkets in the U.S., in Russia, and almost all Article 5 countries. The adoption of R-404A began in the U.S. in 2000. In Japan, HCFC-22 can still be used even if a voluntary policy initiated by OEMs has led to most of new equipment using HFCs. In Japan, R-407C is the leading choice for medium temperature applications, which is the dominant application of commercial refrigeration due to the large consumption of fresh and raw food. R-404A is used for all low-temperature applications in Japan. In China, HCFC-22, and to a lesser extent HFC-134a, are the most used refrigerants with R-404A showing a rapid growth. Only limited amounts of CFC-12 and R-502 are in use /IPCC05/.

HCFC-22 is the dominant option for all Article 5 countries because of the Montreal Protocol and national regulations. Another important fact that has to be underlined is that the cost of HCFC-22 compressors available on market is attractive compared to new compressors developed for HFCs.

In Europe, due to the 2037/2000 regulation banning HCFC-22 as of 2000, the use of R-404A in centralised systems is the major choice for low and medium temperature ranges. Operation with POE lubricants is reliable and R-404A is now a well-established technology. Due to the lower critical temperature of R-404A (72°C) compared to R-502 (80.7°C) or HCFC-22 (86.5°C), high condensing temperatures significantly limit energy efficiency of R-404A systems. In hot climates, additional sub-cooling of R-404A is a cost- and energy-efficient strategy that can be used to overcome this limitation /Bax03a and Bax03b/.

HFC-134a is also used for small cooling capacities at medium temperatures.
Direct systems with $CO_2$ as refrigerant in a trans-critical or sub-critical cycle, depending on the ambient temperature, have been introduced in several European 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 30 systems have been installed in Europe during the last three years /Gir04, Haa05/.

## 4.5 Options for Existing Equipment

CFCs (CFC-12 and R-502) are mainly used in Article 5 countries and are needed for servicing all types of commercial refrigerating systems. HCFCs are used both for new equipment (in all countries except those in Europe) /EU00/. In some European countries, HCFC-22 is also prohibited for servicing, but the EU regulatory ban of virgin HCFC-22 for servicing purposes does not come into force until January 2010.

For refrigerating systems which have a long lifetime (up to 15 years and more), intermediate HFC-blends as R-413A are used for retrofit of CFC-12 medium temperature systems, and R-417A or R-422B for retrofit of R-502 and even HCFC-22 low-temperature systems. Those intermediate blends have taken some market share in Europe.

### 4.5.1 Stand-Alone Equipment and Condensing Units

Three options are available depending on projected remaining lifetime and costs:
- disposal of the old equipment and purchase of a new one using a non-ODS refrigerant,
- repair and recharge with the same refrigerant, and
- repair and charge with a low-ODP or zero-ODP refrigerant.

The conversion from CFC-12 to HFC-134a involves several steps, including the change of mineral oil to POE lubricant, the adjustment of the superheat in case of thermostatic expansion valve, and the replacement of the filter dryer. These procedures are now well established but still significant training is necessary in many Article 5 countries to avoid unnecessary repair after retrofit.

### 4.5.2 Full Supermarket Systems

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

*R-502 Retrofit*
Due to lubricant 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 is at least as good with these blends as with R-502, and no major problem or breakdown has been recorded. It is a straightforward and reliable option.

*HCFC-22 Retrofit*
It is technically feasible to change from HCFC-22 to R-404A or R-407C. It is a cost-decision based on the remaining value of the refrigerating system. The lubricant has to be changed and the refrigerating system has to be flushed. These technical issues are established from CFC-12 to HFC-134a retrofit experience and described in /UNEP03/. With this kind of retrofit, associated energy efficiency losses are in the range of 5 to 10% due to the difference in the thermodynamic properties of the replacement refrigerants compared to HCFC-22.

New HFC blends (R-417A or R-422B) have been developed to permit retrofit from HCFC-22 to HFCs without change of the lubricant type, but attention must be paid to possible refrigerating capacity losses /Spa02/.

## 4.6 Refrigerant Banks and Emissions

Refrigerant banks[4] and emissions data are taken from /Clo06/ based on a survey of commercial installations, and data on the refrigerating capacities and refrigerant charges of the different types of refrigerating systems.

### 4.6.1 Refrigerant Banks in Commercial Refrigeration

From 1990 to 2003, the bank of CFCs (Table 4-4) has increased from 98,000 to 162,500 tonnes in Article 5 countries, and decreased from 71,000 to 8,700 tonnes in non-Article 5 countries.

The dominant bank (see Table 4-5) is the HCFC-22 one in Article 5 countries as well as in non Article 5 countries and has reached more than 240,000 tonnes in 2003, 60% being in Article 5 countries. Its growth is expected to continue for a number of years due to the extensive use of HCFC-22 in commercial refrigeration in Article 5 countries.

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[4] A refrigerant bank consists of all the refrigerant charges in all equipment regardless of the vintage of the equipment.

***Table 4-4  CFC bank in metric tonnes***

| | Commercial refrigeration | |
|---|---|---|
| **Year** | **Article 5 countries** | **Non article 5 countries** |
| **1990** | 98 046 | 70 863 |
| **1991** | 101 152 | 70 658 |
| **1992** | 105 011 | 70 145 |
| **1993** | 109 743 | 69 367 |
| **1994** | 115 468 | 67 134 |
| **1995** | 122 336 | 61 611 |
| **1996** | 130 777 | 53 575 |
| **1997** | 139 167 | 44 437 |
| **1998** | 145 883 | 35 936 |
| **1999** | 151 423 | 27 025 |
| **2000** | 156 492 | 19 620 |
| **2001** | 160 469 | 13 795 |
| **2002** | 162 525 | 10 065 |
| **2003** | 162 534 | 8 761 |

***Table 4-5  HCFC bank in metric tonnes***

| | Commercial refrigeration | |
|---|---|---|
| **Year** | **Article 5 countries** | **Non article 5 countries** |
| **1990** | 37 669 | 33 483 |
| **1991** | 39 496 | 34 918 |
| **1992** | 41 939 | 36 828 |
| **1993** | 45 130 | 39 285 |
| **1994** | 49 287 | 43 257 |
| **1995** | 54 742 | 50 568 |
| **1996** | 61 854 | 60 336 |
| **1997** | 68 245 | 71 210 |
| **1998** | 74 414 | 80 327 |
| **1999** | 83 019 | 89 552 |
| **2000** | 98 127 | 93 315 |
| **2001** | 111 899 | 94 782 |
| **2002** | 129 201 | 94 828 |
| **2003** | 148 631 | 92 280 |

***Table 4-6  HFC bank in metric tonnes***

| | Commercial refrigeration | |
|---|---|---|
| **Year** | **Article 5 countries** | **Non article 5 countries** |
| **1990** | 0 | 0 |
| **1991** | 0 | 0 |
| **1992** | 0 | 0 |
| **1993** | 0 | 17 |
| **1994** | 19 | 297 |
| **1995** | 63 | 863 |
| **1996** | 132 | 1 744 |
| **1997** | 235 | 3 071 |
| **1998** | 625 | 5 058 |
| **1999** | 1 338 | 8 417 |
| **2000** | 2 363 | 15 914 |
| **2001** | 3 609 | 25 253 |
| **2002** | 5 295 | 34 138 |
| **2003** | 7 553 | 42 229 |

The HFC bank (Table 4-6) is increasing rapidly and has reached 50,000 tonnes in 2003. It is dominated by the EU due to the strict HCFC phase-out dates set out in its ODS regulation. The HFC bank represents about 20% of the current HCFC bank in 2003.

### 4.6.2 Refrigerant Emissions

Emissions from commercial refrigerating equipment are very different depending on the type of equipment. Stand-alone equipment with a fully welded circuit can show emission patterns as low as domestic refrigerators. Nevertheless, when repair occurs or when stand-alone equipment is retrofitted, the emission pattern can be totally different. Overall, the larger the refrigerant charge, the larger the average emission rate. For other types of equipment (condensing units and centralised systems), based on analysis of refrigerant purchase orders /Clo97/, it appears that nearly 70% of the average emission rate of a large number of stores is related to ruptures leading to a complete or partial release of the refrigerant charge. This dominant pattern has to be confirmed on a follow up of several years and leads to a high average annual emission rate, in the range of 30% for large supermarkets (hypermarkets) and in the range of 20% for medium size supermarkets. A number of studies have been carried out in the USA /Biv04/ and in

Europe /Bir00/ that show different patterns depending on the company policy and on technical choices.

In order to evaluate the global emissions, the key element is to derive the banks of the different refrigerants used in all commercial refrigeration applications. In many European countries emission rates have decreased from 35% to 20% in hypermarkets, and from 25 to 18% in supermarkets. A recent annualised emission rate analysis of 1700 supermarkets in Europe and in the USA showed a very wide range, between 3 and 22%, with an average value of 18% /IPCC05/. The 2003 heat wave in Europe led to significant releases of refrigerants due unintended opening of pressure-relief valves. Some Article 5 countries have lowered their average emission rates and improved the recovery efficiency through programs funded by the Multilateral Fund /UNEP05/.

***Table 4-7 – CFC emissions in metric tonnes***

| | Commercial refrigeration | |
|---|---|---|
| **Year** | **Article 5 countries** | **Non article 5 countries** |
| **1990** | 23 950 | 16 974 |
| **1991** | 24 597 | 17 175 |
| **1992** | 25 420 | 17 016 |
| **1993** | 26 550 | 16 893 |
| **1994** | 28 050 | 16 653 |
| **1995** | 30 046 | 15 800 |
| **1996** | 32 836 | 14 666 |
| **1997** | 35 736 | 12 618 |
| **1998** | 37 469 | 10 127 |
| **1999** | 38 986 | 7 945 |
| **2000** | 40 558 | 5 609 |
| **2001** | 41 240 | 3 918 |
| **2002** | 42 168 | 2 447 |
| **2003** | 42 499 | 1 919 |

***Table 4-8 HCFC emissions in metric tonnes***

| | Commercial refrigeration | |
|---|---|---|
| **Year** | **Article 5 countries** | **Non article 5 countries** |
| **1990** | 12 041 | 9 778 |
| **1991** | 12 616 | 10 258 |
| **1992** | 13 377 | 10 745 |
| **1993** | 14 425 | 11 386 |
| **1994** | 15 856 | 12 537 |
| **1995** | 17 793 | 14 564 |
| **1996** | 20 435 | 17 428 |
| **1997** | 23 101 | 20 702 |
| **1998** | 25 353 | 23 576 |
| **1999** | 28 220 | 26 586 |
| **2000** | 33 711 | 28 131 |
| **2001** | 37 976 | 29 589 |
| **2002** | 43 508 | 29 655 |
| **2003** | 49 208 | 28 930 |

The refrigerant emissions of CFCs, HCFCs, and HFCs were respectively 44,000, 78,000, and 10,000 tonnes in 2003 (see Tables 4-7, 4-8, and 4-9). They are proportional to the size of their respective refrigerant banks.

***Table 4-9 HFC emissions in metric tonnes***

| | Commercial refrigeration | |
|---|---|---|
| **Year** | **Article 5 countries** | **Non article 5 countries** |
| **1990** | 0 | 0 |
| **1991** | 0 | 0 |
| **1992** | 0 | 0 |
| **1993** | 0 | 5 |
| **1994** | 2 | 31 |
| **1995** | 5 | 76 |
| **1996** | 12 | 162 |
| **1997** | 27 | 349 |
| **1998** | 70 | 648 |
| **1999** | 130 | 1 250 |
| **2000** | 203 | 2 252 |
| **2001** | 285 | 4 520 |
| **2002** | 413 | 7 053 |
| **2003** | 596 | 9 333 |

The impact of CFC, HCFC and HFC emissions on stratospheric ozone and climate change is well known. Limitation of emissions by better containment and systematic recovery of refrigerant for re-use is a justified policy allowing use of the refrigerant for a longer operating time of refrigerating equipment.

## 4.7 Article 5 Country Aspects

*Cost Issues for New Systems*
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 release all heat inside the sales area and either the air-conditioning system has to be designed to absorb this additional heat 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 products at the right temperature. Moreover, the overall energy efficiency of supermarkets using plug-in cabinets is low, because the energy efficiency of small compressors is lower than for medium and large size compressors. This difference can be verified by systematic study of compressor performance in manufacturer catalogues. The technical reasons are related to both lower energy efficiency of small electric motors and the relative higher impact of mechanical friction on small capacity compressors.

What is described here for stand-alone equipment is also valid for condensing units when those units are replacing larger compressors. As indicated in Section 4.5.2, some supermarkets in Article 5 countries use several condensing units in parallel to cool display cabinets. So instead of having a rack of 3 to 4 compressors, a rack of 20 or more condensing units can be found. This inefficient solution is chosen due to investment cost reasons and to the availability of condensing units everywhere in the world. Moreover these condensing units are produced in large series in Article 5 countries, avoiding the import of large size compressors. The energy losses due to the use of condensing units are up to 30 to 50% compared to the usual efficiency of large size compressors.

*Retrofit and Servicing in Article 5 Countries*
Retrofit of commercial refrigeration equipment is of particular interest in Article 5 counties in order to save cost. To make reliable retrofits, significant training of servicing technicians is necessary. For many servicing companies, the knowledge and equipment are not always available in the countries where they are most needed. Retrofits require the change of lubricant and need more technical precautions. The filter-dryers have to be carefully chosen and more importantly the availability of the new POE lubricants as well as the new filter-dryers has to be verified. In Article 5 countries, many servicing companies still lack of adequate tooling: recovery equipment, connecting hoses, recovery cylinders, dry vacuum pump, and a precise scale. All this equipment is necessary in order to realise proper recovery, evacuation, oil flushing, change of oil, and careful charge of the new refrigerant.

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# 5 Industrial refrigeration

## 5.1 Introduction

The industrial sector of the refrigeration market, including large scale heat pumps as well as refrigerating plants, is characterised by heat loads in the range of 10 kW to 10 MW, typically at evaporating temperatures from –50$^{o}$C to +20$^{o}$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. There is also some cross-over with the air-conditioning sector, where a few buildings are served by custom-designed central chilling systems which have more in common with industrial systems than the typical standardised air-conditioning market. The increased use of ammonia chillers in large buildings has extended this overlap, however as this equipment becomes more standardised it will fall more readily into the air-conditioning sector. Specialist systems in the leisure industry, such as ice rinks, indoor ski-slopes and ice-covered climbing walls are other examples of an industrial refrigeration niche within the building construction market. The industrial sector generally does not include mass-produced or batch-produced packaged equipment, such as bottle coolers, display cases and walk-in freezers which are covered by chapter 4 of this report, nor does it cover larger standard equipment such as packaged water chillers which are examined in chapter 9. Food processing (including brewing, maltings, distilling, dairy produce and soft drinks industries), storage and distribution account for the majority of industrial refrigeration applications, with the balance being found in the chemical, petrochemical and pharmaceutical industries (collectively known as “Process Industries”).

Heat rejection from industrial refrigeration systems has traditionally been achieved with evaporative cooling systems such as evaporative condensers or cooling towers. Recent increases in utility charges for water and the cost of water treatment coupled with increased incidence of Legionnaires’ Disease have encouraged the use of air-cooled condensers, particularly where there is a perceived threat to business continuity in the event of a local outbreak of Legionnaires’ Disease causing a temporary local ban on all evaporative systems, even if they have been correctly maintained and are free of Legionella bacteria. Air-cooled condensers reduce the efficiency of the refrigerating system, require more space for the installation and tend to operate at higher noise levels than evaporative equipment. Recent developments to address the disadvantages of air-cooled condensers include temperature-controlled water sparge systems and Hybrid Cooling Systems, which combines air-cooled heat exchanger technology with water spray or wetting of heat exchanger surfaces. The economic breakpoint for choosing “wet” cooling instead of “dry” cooling was understood to be at about 100 kW heat rejection 20 years ago. Recently this has increased to about 500 kW, and air-cooled systems of several MW capacity are now not uncommon.

In countries not covered by Article 5 of the Montreal Protocol (non-Article 5 countries) where CFCs have already been phased out and HCFCs are severely restricted, the majority of industrial refrigeration systems use R-717 as the refrigerant. In the United States and Canada R-717 systems were commonplace throughout the twentieth century, although HCFC-22 gained limited acceptance from 1970 onwards. In Europe the use of HCFC-22 and R-502 was much more common, and R-717 became much less common in the 1970s and 1980s, particularly in the United Kingdom, Germany, the Netherlands and France. When the restrictions on CFCs were introduced in the mid-1980s the UK and German markets moved relatively easily back to R-717, but in other European countries this change was hampered by restrictive regulations on its use.

In countries covered by Article 5 of the Montreal Protocol (Article 5 countries), where national regulations still permit the use of CFCs and HCFCs they are preferred to R-717. In general refrigerating systems are smaller and less well maintained than in the non-Article 5 countries, leading to a fear of R-717 on grounds of safety. CFC-12 and HCFC-22 are the most commonly used, and azeotropic blends such as R-502 tend not to be used as much as they were in Europe in the mid 1980s.

## 5.2 Applications

Refrigeration is often used to extend the shelf-life of foodstuffs, but it can also control the rate of reactions (for example in brewing, malting or chemical plants) or it may prepare the product for processing (for example chilling of meat or fish prior to cutting). In some cases, such as ice cream or margarine manufacturing, the method of refrigerating the product is an essential part of the production process. Most industrial applications use evaporating refrigerant in “direct” systems, usually in a pumped recirculation system. At higher temperature conditions glycol or brine solutions may be circulated to the process, so that the primary refrigeration circuit can be contained within a machinery room. For lower temperature applications (operating below –15$^o$C) the viscosity of the secondary fluid usually makes the pumping cost of these indirect systems excessive. Considerations that would tend to predicate a direct system include emphasis on low capital cost and emphasis on operating efficiency. Where charge reduction is a priority, for example to ameliorate the effects of a large refrigerant loss for reasons of public safety or product protection, secondary systems are more common.

### 5.2.1 Food Processing

The global annual chilled food market has been estimated to be about 350 million tonnes per year and this is estimated to be growing at 7% per annum. Most refrigeration in chilled food factories is used in air temperature control to ensure product life is not impaired during processing. Where there is a large fresh air input to a processing area the majority of the heat load may be in refrigerating the ambient air influx in summertime. The same applies to fruit and vegetable storage facilities where the build-up of off-gases from the product must be controlled in order to inhibit premature ripening. Significant heat loads will also be found in chillers for cooling cooked product immediately after the cooking process. Again the main objective is to ensure product quality and long life. Refrigeration equipment is also used in the production of ice in tube, plate or flake form.

In most cases ammonia is used as refrigerant in larger ice systems, although R-22 was previously popular.

There has been a significant increase over the last 15 years in the amount of prepared foods in the chilled market, including sandwiches, salads, fruit salad and cooked meats. There has also been a rapid expansion in the variety of chilled produce on offer. It was estimated in 1999 that 50% of chilled foods purchased was of a type that did not exist ten years earlier /Bil99/.

The freezing process is generally defined by achieving a product core temperature of –18°C, although this value is not particularly critical /Bog99/. Fresh meat and fish are sometimes frozen for transportation from the abattoir or port and then thawed for processing, either into meat cuts or in value-added presentations such as ready meals. Prepared meat, either as packaged cuts or as ready meals, is packaged for sale prior to freezing, whereas hamburgers, sausages or pies are more likely to be frozen prior to packaging. The type of freezing process depends on the size, shape and packaging of the meat: thin items like hamburgers and fries can be frozen on a belt in a tunnel or spiral freezer but boxes of meat cuts will either be palletised and blast-frozen or processed in boxes in large plate freezers.

Global consumption of frozen food is estimated to be about 40 million tonnes per year. In the decade from 1990 to 2000 consumption increased by 50%, and it is still rising/ADE06/, although the rate of increase has been slower since 1997.

Spiral, tunnel and blast freezers are usually operated with an evaporating temperature of about –40°C, giving a saturation temperature at the compressor suction of –42°C. Smaller freezers, with a capacity of 50 kW or less, operate with HCFCs in Article 5 countries and North America, and HFCs in Europe. In the range 50 kW to 200 kW ammonia may be used instead, and for larger freezers ammonia is preferred due to improved energy efficiency and reduced leakage. A recent trend observed in Europe, Japan, Australia and the USA has been the use of R-744 (carbon dioxide) for freezers, offering several advantages. Due to the high suction pressures at low temperature it is possible to run R-744 freezers economically at lower temperatures, typically evaporating at –50°C. Such systems have been reported from 50 kW up to several MW capacity, with the smaller units cascaded with R-404A and the larger ones cascaded with R-717 /Pea00/. In plate freezers the benefit of R-744 is even greater because high heat transfer rates can be achieved at lower recirculation rates and so the pressure drop in flexible hoses from the plates is greatly reduced.

Secondary fluids such as calcium chloride (“brine”) and ethylene glycol are commonly used in chill systems although propylene glycol is often preferred to ethylene in food production and distribution plants because it is less toxic and is classified as “food-safe”. This is unfortunate because the pumping cost is significantly higher, particularly as the viscosity increases at lower temperatures. Other food-safe fluids have been introduced in the last ten years, including potassium formate, potassium acetate and betaïne. These offer the benefits of being food safe and requiring less pumping power than glycols at low temperature, but the potassium salts are highly corrosive to zinc and copper, so they have not been widely adopted in low temperature systems.

### 5.2.2 Cold Storage

The industrial sector for cold storage covers temperature controlled chambers ranging from –30°C to +15°C. The total volume of refrigerated storage in the world is estimated to be 300,000,000 $m^3$ /IIR02/. The chamber volume could be as small as 100 $m^3$, rising to facilities with chambers of 100,000 $m^3$ or more. Small rooms have a ceiling height of 4 – 5 m, whereas in larger chambers, the height may be up to 12 m, limited by the reach of a fork truck for placing pallets in racked storage. Smaller rooms are often served by stand-alone systems using CFC, HCFC or HFC in commercial condensing units, but in food production facilities they may also form a side load on a large industrial freezer plant. In small cold stores the heat load is dominated by air and moisture ingress from the doors, and the load could be as high as 50 $W/m^3$. As the chamber size increases the effect of air ingress is reduced, and a typical large facility has a load of about 12 $W/m^3$. In the last ten years several low temperature "high-bay" facilities have been constructed in Europe. These are typically fully racked with automatic pallet handling systems, and offer reduced construction and operating costs. The store may be up to 40 m high, although 30 m is more common as the racking structure must be capable of carrying the load. The air ingress load for these facilities is very low giving a heat load of about 7 $W/m^3$. Operation is very efficient because the heat load is low and the need for defrosting is reduced significantly, typically to one or two defrosts per week, compared with up to three per day for a low temperature distribution warehouse. In chillled stores there is often greater activity, particularly in distribution centres where product is marshalled for shipment to supermarkets. Here the heat load may be as high as 30 $W/m^3$ even in a large store, depending on the level of activity and the amount of automated equipment used.

### 5.2.2 Process Refrigeration

The process industries include chemical production plants, petrochemical sites, pharmaceutical plants and the oil and gas industries. Refrigeration is primarily used for temperature control of heat transfer fluids. At high temperatures water is most commonly used, and brine or glycol can be used for medium temperature applications, however for very low temperatures, and where there is a risk of reaction with process fluids in the event of a leak, other fluids may be used. The most common are diethylbenzene and polydimethylsiloxane. Often the fluid is also used for heating the process, and may be required to operate across a temperature range from –80°C to +200°C. R-744 has also been proposed as a cooling fluid in this sector and has been used in a chlorine production plant where the violent reaction between chlorine and ammonia precluded the use of a direct ammonia system. However R-744 is not suitable as a heating medium. R-507A and R-410A have also been used for chlorine liquefaction /Meu02/, /Sch03/.

Refrigeration is also used in process industries for the production of ice for use in chemical reactions. This is usually in the form of flakes or tubular pieces which can be automatically harvested, stored and transported. The ice is usually added to reactor vessels to control the rate of reaction, so large quantities are required over a short time period. The ice plants are typically far larger than those found in the food industry, and usually use ammonia as the refrigerant. Flake ice is also used in very large quantities for concrete cooling on large civil engineering projects, where it is added to the concrete batch during mixing to avoid overheating and maintain high quality.

### 5.2.3 Liquefaction of Gases

The vapour compression process is used down to temperatures of –170°C for the liquefaction of gases like carbon dioxide, chlorine, hydrocarbons and liquid natural gases. Liquefaction of cryogenic gases like air (nitrogen, oxygen, argon), hydrogen and helium is achieved by cooling and drying the gas with vapour compression using R-717 or a fluorocarbon. The dry gas is compressed in several stages to about 10 MPa, with intercooling, and then expanded back to atmospheric pressure. Liquefaction is achieved by the temperature drop caused by expansion, but a refrigeration plant is necessary for the dehumidification and intercooling processes prior to the expansion.

### 5.2.4 Industrial Heat Pumps and Heat Recovery

Large industrial heat pumps, which today are a proven, reliable and energy saving technology, use waste heat from other processes or the environment and consequently reduce the demand for fossil fuels for heating, cooling and dehumidification in industrial applications. They may also be used for district heating systems, reducing energy consumption in residential and commercial buildings. The vast majority of heat pumps currently in operation are electrically driven closed cycle vapour compression type systems similar to the systems used for industrial refrigeration.

Industrial heat pumps are used for heating process streams, heat recovery and hot water or steam production. They are often an integral part of industrial processes, such as drying, evaporative concentration and distillation. The majority of industrial heat pumps operate in the chemical industry and food processing industries. Heat pumps are also used for drying products like ceramics, timber and textiles. Energy efficiency and quality of the products, gained by better temperature control of the drying process, make heat pump driers very competitive compared to conventional driers, though they often have less annual operating hours than other industrial heat pumps.

Industrial heat pumps are generally large in thermal capacity ranging from about 100 kW to several MWs, and the systems are usually custom designed. Evaporation temperatures are generally higher than with residential and commercial/institutional applications and condensation temperatures are typically in the 80°C to 120°C range.

Systems driven by gas engines, or absorption cycle heat pumps which are directly fired or employ waste heat, have found niche markets. The type of heat pump applied depends heavily on the process, the heat source and the operating temperatures. The most common types of industrial heat pumps on the market are:

- Mechanical (closed) vapour compression heat pumps
- Mechanical (open) vapour recompression (MVR)
- Absorption heat pumps
- Heat transformers

Mechanical (closed) vapour compression heat pumps: Industrial heat pumps have traditionally used CFCs, HCFCs, or R-717 as the working fluid. Hydrocarbons have also a small niche market, in the petrochemical industry. HFC-134a, R-404A and R-407C are identified as the most used retrofit refrigerants for smaller units previously charged with CFC-12, R-502 and HCFC-22 although in all three cases the lower critical temperature of the replacement restricts the range of application and makes the units rather less efficient. HCFC-22 is still used as one of the main refrigerants in small heat pumps. Most manufacturers in non-Article 5 countries have introduced HFC alternatives, primarily HFC-134a and R-404A to replace their HCFC heat pump models. For heat pumps working with condensing temperatures up to 80°C, HFC-134a is the preferred refrigerant, especially large capacity units. R-717 with reciprocating compressors rated for 4,000 kPa discharge pressure is applied in medium and large capacity heat pumps, especially in Scandinavian countries.

Refrigerant charges in industrial closed cycle heat pumps range from 0.1 to 2.5 kg per kW thermal output, with an estimated average roughly the same as for residential and commercial/institutional heat pumps, i.e. 1.0 and 0.5 kg/kW for units produced before and after 1994 respectively.

In Europe the total installed capacity for large industrial heat pumps for hot water distribution systems is approximately 1200 MW. New systems are realised with HFC-134a and the charge is 0.6 kg HFC-134a / kW heating capacity. This figure results in a total of 684 tonnes of HFC-134a in this type of heat pump /Bai02/.

Mechanical (open) vapour recompression: MVR systems, also known as open or semi-open heat pumps, are extensively used in industrial processes for evaporation and distillation. Most systems operate with water vapour as the process fluid. In the chemical industry other process vapours are used in MVRs (e.g. ethanol, methanol, propane). These systems often require oil-free compressors, and hence they are limited in their application.

Absorption heat pumps: are in most cases driven by steam or industrial waste heat, and are mostly used in countries with thermal power based electricity production and high electricity prices. Absorption heat pumps are still only to a small extent installed in industrial applications. In Germany, Sweden and Denmark a number of units are installed in refuse incineration plants to recover heat from the flue gas cleaning process and supply heat to district heating networks. Most absorption heat pumps use water and lithium bromide as the working pair, and are able to deliver heat up to 100ºC. Industrial absorption heat pumps are, for economic reasons, mainly used in large sizes (MW).

Absorption heat pumps with a typical primary energy ratio (PER) in the range of 1.2 to 1.5 have higher system energy efficiency than vapour compression systems driven by electricity produced in conventional power plants. Research is concentrating on the development of systems with high efficiency, high temperature lifts, high output temperatures, a wider range of application and lower cost. This includes the development of double-lift, double-effect and triple-effect units, generator/absorber heat exchanger systems (GAX) and new working fluids.

Heat transformers: produce high-temperature heat from medium-temperature industrial waste heat and operate on a similar process to absorption heat pumps. Current systems have a maximum delivery temperature and temperature lift of 145-150°C and 50K, respectively. Heat transformers use water and lithium bromide as the working pair. They typically achieve PERs in the range 0.45 to 0.48. Only a few systems are in operation world wide, the majority of them in Japan.

## 5.3 Refrigerant Options for New Equipment

Where new equipment is being constructed, whether for green-field projects or the refurbishment of existing buildings, the designer has a wide range of choice of refrigerant. The decision is usually based on capital cost, but other considerations include operating cost, maintenance cost, the likelihood of refrigerant leakage, health and safety considerations and in specific cases the ease of installation. These issues are explained in each of the following paragraphs.

### 5.3.1 R-717 (ammonia)

R-717 has been used as a refrigerant for industrial processes since 1872 and is the preferred choice for large installations in most parts of the world. It is acutely toxic in relatively small concentrations, but has a distinctive, pungent odour which is evident at levels well below the dangerous concentration, so the incidence of fatality and serious injury in R-717 systems is extremely low. It is flammable in relatively high concentrations, so specific safety measures must be included for industrial systems, but in practice R-717 combustion is not a common concern. The products of combustion are nitrogen and water, so the chance of safety complications in the event of a major building fire are very low. In the United States and Canada ammonia has remained the preferred refrigerant for the food and process industries over the last 50 years, and installations are typically large, with R-717 charges ranging from 5 tonnes to 100 tonnes. The industry in the United States and Canada is well regulated and although small R-717 releases are frequently reported, the incidence of fatality or serious injury is relatively low. For example the United States Chemical Safety Board (CSB) reports that R-717 incidents account for 11% of all reported chemical releases in the USA, with on average one every five days, but there were only four fatalities in the ten year period from 1994 to 2004 /Smi06/. This compares with over 800 deaths from lightning strikes in the USA during the same period. In Europe R-717 has been widely adopted for industrial refrigeration in UK and Germany but is more tightly regulated in France, Belgium, the Netherlands and Italy, and it is consequently less common. It is the most common alternative to HFCs for larger systems in Scandinavia, mainly as a result of restrictions and taxation on greenhouse gases. R-717 is less widely used in Article 5 countries where it was superseded by CFCs from 1970 onwards, and more recently the CFCs have been replaced by HCFCs in smaller systems. It is likely that ammonia will be the preferred replacement for these systems when HCFCs are phased out in these countries, but there will be a need for appropriate legislation and training of contractors and end users to achieve this shift.

In Europe a blend of R-717 and HE-E170 (dimethyl ether) has been used in some applications to improve the lubricant return in small sized direct expansion chillers. It has also been suggested as a refrigerant for high temperature heat pumps as it would permit slightly higher condensing temperatures to be achieved in current equipment designs. This fluid is sometimes denoted "R723", but it has not been submitted for inclusion in ASHRAE34 or ISO817. If classified, it would probably be assigned to safety group B3, which would limit its application, and it would not be allocated a refrigerant number in the 700 range.

### 5.3.2 HCFC-22

HCFC-22 was introduced in the 1950s as a safer alternative to R-717 in industrial systems and it was widely adopted in a range of systems. By the mid 1980s it was the most common refrigerant in industrial systems in Europe, and was beginning to gain popularity in North America. However the American market did not make a significant switch to HCFC-22 and the Europeans were generally quick to switch back to R-717 once the extent of the controls imposed on ozone depleting substances became clear. HCFC-22 is not permitted for use in new installations in Europe, where it is regulated by the Control of Ozone Depleting Substances Regulations. It has not yet been prohibited in North America, but the majority of new installations are using HFCs as the ban on HCFCs will be implemented in 2010. In the Article 5 countries HCFC-22 is preferred to HFCs because it is generally cheaper and more efficient, and the restrictions on its use are not due to be implemented for several years.

### 5.3.3 HFCs

HFCs were introduced as replacements for CFCs in the late 1980s, but they have not in general been accepted for industrial systems. The capital cost of the refrigerant inventory and the cost of lubricants are unacceptably high for large industrial systems, and site experience suggests that refrigerant leakage rates from the smaller systems installed with these refrigerants would be unacceptable. An exception is in large centrifugal chillers where HFC-134a is common, although these units are not usual in industrial systems. In smaller cold stores and freezers R-404A and R-507A have been used in commercial-style units, typically with semi-hermetic compressors and condensing units. Although it has excellent low temperature properties, R-410A has not been used much in industrial systems, perhaps as a result of the relatively high price of refrigerant. For an industrial refrigeration system the cost of the refrigerant charge will be about 5-10% of the total cost of the system. The financial risk associated with the loss of the charge is unacceptably high for contractors and end-users.

### 5.3.4 R-744 (carbon dioxide)

In situations where the use of a direct R-717 system is not possible, or the consequence of leakage is not acceptable then R-744 has been used in conjunction with the R-717 plant to reduce the R-717 charge and the consequence of leakage. R-744 was first used as a refrigerant in 1867, and it became very popular towards the end of the nineteenth century, particularly for marine refrigeration where it was preferred to R-717 on grounds of safety. It fell out of favour in the middle of the twentieth century when refrigeration systems switched from river water and atmospheric condensers to evaporative and air cooled condensers running at higher discharge pressures. This made R-744 very inefficient relative to R-717.

R-744 has found favour again at the end of the twentieth century as an alternative to ammonia on safety grounds and HFCs on cost and operability grounds. It is particularly well suited to low temperature freezer systems, where the high operating pressure results in very small compressors and pipe sizes making equipment economic to install and maintain. The evaporator performance of plate freezers on R-744 is significantly better than with any other refrigerant, making it the preferred solution for plants of that type. R-744 has also been successfully used in cold stores and chill stores, although the benefits are less well defined. In comparison with direct R-717 systems it has been reported that an R-744 plant is about 5% cheaper to install and almost exactly the same operating cost /Chr06/. In another study in comparison with R-717/glycol systems for chill stores the R-744 option was about 1% cheaper to install than the glycol system, but 15% cheaper to operate /Pea03/. Comparison is difficult in these cases because it depends on the specification adopted for each system. In the cases mentioned here the first used electric defrost and hence was cheaper to install but more expensive to operate, and the second used hot gas defrost, so was more expensive to install but cheaper to operate. If a secondary system is being contemplated on grounds of reduced R-717 charge then R-744 will offer a cost effective alternative to glycol.

There are now systems installed with R-744 as refrigerant in niche applications at higher temperatures. One example is the cooling of blade server computers in data centres, where R-744 is a safe alternative to water in high heat load applications and air cooling is not sufficient /Hut05/.

### 5.3.5 Water

Chillers using water compression have been reported occasionally over the last ten years, often in association with industrial projects, as the size of the equipment is a major impediment to its use for building services applications. Typical capacities are 1 MW to 6 MW. The industrial projects have been very specialised and the technology does not seem to be spreading to more general use in the food or process markets. These systems can be adapted to produce ice slurry as a heat transfer medium, but they are not capable of running at the lower temperatures required for most industrial applications.

### 5.3.6 Absorption/Compression Cycle

“Ammonia absorption refrigeration” is receiving more attention as energy prices continue to rise, but in general these plants are only economic where there is a plentiful supply of waste heat. It is possible to achieve temperatures as low as $-60^{o}C$ with a coefficient of performance of about 0.4, and at higher temperatures this rises to about 0.8 when evaporating at $0^{o}C$. Capital cost of this equipment is high, and operational reliability is dependent on the availability of the heat source, which may be intermittent in some applications. Lithium bromide absorption systems and all adsorption systems are not suitable for operation below $0^{o}C$ as they use water as the refrigerant.

## 5.4 Retrofit Options for Existing Systems

Significant development of replacements for CFC and HCFC refrigerants has been achieved over the last twenty years. In addition to these fluorocarbon replacements a few cases have been reported where HCFC-22 was replaced by R-717 or R-744 but these projects require a project-specific feasibility assessment of materials compatibility, system design pressure and equipment suitability, so they are not appropriate in the majority of cases.

For CFC-12 systems it is possible to retrofit with HFC-134a provided the lubricant can be changed to a polyol ester type. Seals and o-rings may also require replacement. Where replacement with HFC-134a is not possible, for example in centrifugal compressors without changing the impeller and other parts, a blend with equivalent molecular weight, such as R-423A, may be used. CFC-12 was not common for industrial systems, so is not discussed further here. Drop in service replacements for R-502 were also produced, but these plants have now almost all been superseded, either by new HFC equipment or by new ammonia plants.

There is no single component replacement for HCFC-22, as the HFC equivalent, HFC-125 has a much lower critical temperature ($t_{crit,HFC-125} = 66^{o}C$ compared with $t_{crit,HFC-22} = 96^{o}C$). This means that it is significantly less efficient, even in evaporative cooled systems. For retrofit applications lubricant compatibility and temperature glide are major concerns and the blends used as substitutes for HCFC-22 in new equipment are not really suitable. A wide range of blends containing some hydrocarbon, usually propane or butane, is available. The hydrocarbon content is usually restricted to ensure A1 classification, but even a few percent can significantly improve the oil management in these systems. Care must be taken to ensure that operating pressures are compatible with the original equipment design, and that the plant capacity is not excessively adversely affected. Increased capacity can also be a problem: in some cases the combination of higher capacity with lower coefficient of performance can result in significant increases in current drawn by the compressor motor. Most of the retrofit blends for HCFC-22 have a significant temperature glide, and so are not well suited to use in industrial systems using flooded evaporators. This has severely restricted the adoption of retrofit of HCFC-22 in the industrial market, with many end users opting to retain their existing plant for as long as possible and then replacing it with new equipment.

## 5.5 Service Requirements

Except in Europe, where CFCs have been phased out, CFC service demands have gone down due to improved routines, better leak tightness and better organised arrangements for CFC recycling. However, considerable amounts of CFCs are still required for service. CFC prices have risen very considerably, making improved maintenance and sound conservation practices economic.

To meet service needs after CFC phase out, facilities and procedures for refrigerant recycling (and destruction) have been established in most countries. Equipment for refrigerant recovery and purification has been on the market for several years.

In the past, the major proportion of refrigerant consumption (60-80%) concerned replenishment after leakage and release during service and repair. According to a survey conducted by SINTEF in 1991, covering CFC and HCFC systems in the Norwegian fish industry, on average 15% of the charge had to be replenished each year due to emissions /SIN91/. With reference to the experience from Sweden, annual emissions of 8% of the charge have been assumed for existing systems (CFC and HCFC) in forecasting demands beyond 2000 and 6% for new systems (HCFC and HFC).

It is technically possible to manage without HCFCs in new industrial systems as demonstrated in Europe since 2000. The reasons for continued use of HCFCs in other countries are cost and energy efficiency. Furthermore, contractors and end users are reluctant to change since HCFC technology is well known. Concern over the long-term future of HFCs has also been identified as a barrier to changeover /Mar96/, /Eur01/.

Lower price, better efficiency and greater margins with respect to failure, make HCFCs and CFCs attractive compared to HFCs in many Article 5 countries. In comparison to R-717, differences in initial costs may be even more significant than in industrialised countries, since systems are generally smaller in size. Since cost is a limiting factor in CFC phase out, availability of HCFCs may reduce the CFC problem in these countries, while lack of HCFCs may prolong dependency of CFCs.

There is no "ideal" refrigerant to replace HCFC-22 in existing systems with flooded evaporators. Technically, R-404A or R-507A could be used but at the expense of a significant increase in energy consumption, and with some risk of poorer oil recovery. For these reasons, HCFCs will be required for service throughout system lifetimes.

As a conclusion, HCFCs will be in demand for systems in Article 5 countries in the short to mid-term and for service purposes in all regions. Provided that current CFC practices with respect to refrigerant conservation are transferred to HCFCs, only small amounts of virgin refrigerant should be required for future service.

## 5.6 Available Data on Consumption

Since information on the number of large size refrigeration systems, amounts of refrigerant per system and other specific technical data is virtually impossible to obtain, given estimates on emissions have to be characterised as "qualified guesses". Emissions depends upon installation losses, leakage rate during operation, irregular events such as pipe fractures, servicing losses including recovery loss and end of life loss during reinstallation/reconstruction.

As a world wide average, current CFC and HCFC annual emission rates have previously been estimated to be in the range of 10-12% of the charge /TOC02/. In /Bir03/ current CFC and HCFC annual emission rates are estimated to 7-10% in industrial refrigeration systems as an average for Germany. In /Sch04/ a complete survey for the refrigeration sector has been presented for Germany, for the Industrial Refrigeration sector emission rates of less than 8 % per year are documented. These values are not supported by figures given by Clodic et al /ADE06/, reporting global emission rates of 24% (CFCs), 16% (HCFC-22) and 10% (HFCs) in this sector for 2003. In this study the provided emission rates, including ammonia, are based on production figures published by FAO for some food products, excluding several other sectors of industrial refrigeration. The refrigerant banks in non-Article 5 and Article 5 countries for the section of the industrial sector covered by Clodic et al are shown in figures 5.1 to 5.3 for CFCs, HCFCs and HFCs respectively. The annual emissions on the same basis are shown in figures 5.4 to 5.6. Based on this data the emission rates have been extrapolated to the whole sector of Industrial Refrigeration.

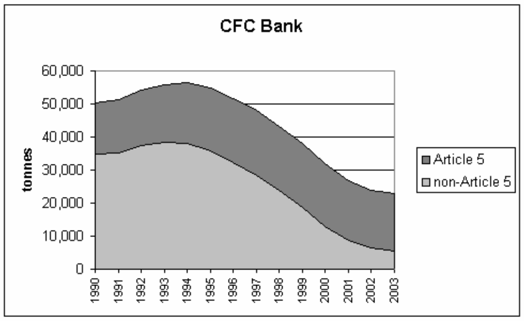

*Figure 5-1 CFC bank*

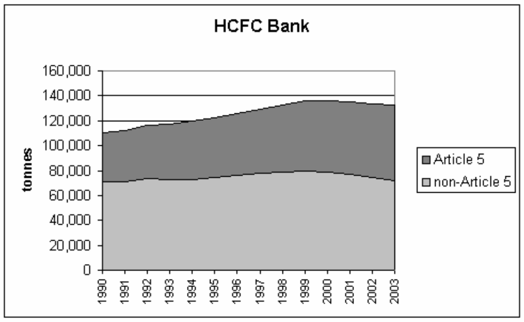

*Figure 5-2 HCFC bank*

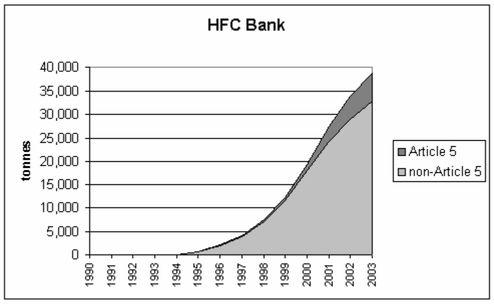

*Figure 5-3 HFC bank*

In general it can be observed that the bank of HCFCs is relatively stable in both the Article 5 and the non-Article 5 countries over the last five years whereas CFCs are generally being substituted by HFCs in non-Article 5 countries and to a lesser extent in Article 5 countries. The Clodic study also shows an average growth in the total global bank of CFCs, HCFCs and HFCs of 1.44% per annum over the period 1990 – 2003.

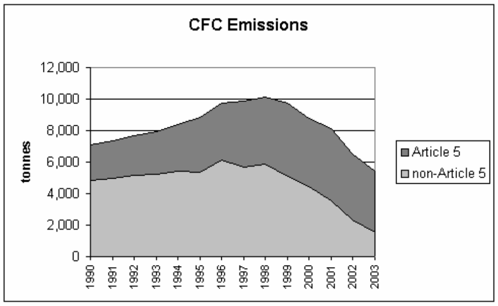

*Figure 5-5 CFC emissions*

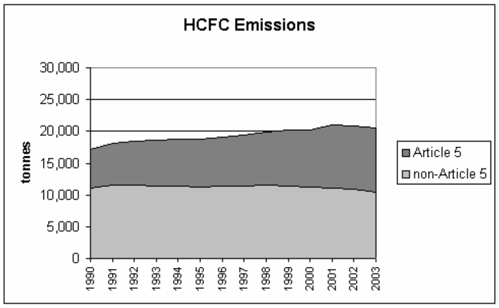

*Figure 5-6 HCFC emissions*

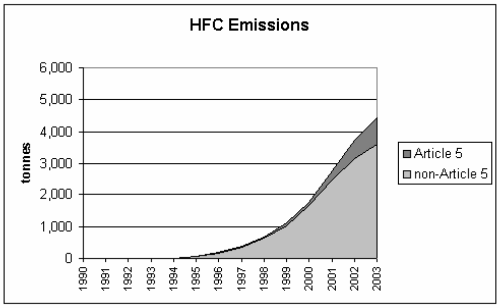

*Figure 5-7 HFC emissions*

The pattern of substitution of CFC with HFC and stability in HCFC figures is repeated in the emissions trends. Correlation of the bank and emissions figures for the latest year in figures 5-1 – 5-6 gives emission rate figures for non-Article 5 countries and Article 5 countries as shown in Table 5-1.

***Table 5-1 2003 emission rates of fluorocarbon refrigerant in the industrial sector***

| | Non-Article 5 countries | Article 5 countries |
|---|---|---|
| CFC | 27.7% | 22.4% |
| HCFC | 14.4% | 16.8% |
| HFC | 11.0% | 13.7% |

There are several possible reasons for the patterns observed in the table. CFC leakage may be higher in non-Article 5 countries than in Article 5 countries because the equipment is on average older. It is therefore probably more prone to leakage through wear and tear, and is less likely to be designed for low charge. There may also be a tendency for CFC replacement to be completed earlier by more responsible users, so the average condition of the remaining CFC equipment is poorer and hence the average leakage rate increases. Over the period 1990-2001 the aggregate emission rate for CFCs rose from 14.1% to 30.3%, whereas the aggregate rate for HCFCs has remained constant, staying in the range 15.5% +/- 0.7%. More recently the CFC emission rate has been falling again, and is estimated to be 18% for 2006. It should be noted that there is also a higher margin of error in the CFC emission rate for non-Article 5 countries and the HFC emission rate for Article 5 countries because the bank is so small.

Based on the references and common market knowledge HFCs and other fluorocarbons consumption and banks have been estimated for the industrial refrigeration sector as a whole. In this approach food processing and cold storage are assumed to account for 75% of the combined emissions, and process refrigeration for the remaining 25%.

The proportion of global food production which is refrigerated has previously been estimated to be 350 Mtonnes per year /Mat90/, /IIR02/. With the assumption of 4% annual growth rate in non-Article 5 countries and 7% in Article 5 countries the refrigerated food production for 2006 is estimated to be 760 Mtonnes and the annual consumption of refrigerants has been calculated with the values given in /TOC02/, /Sch04/. For non-Article 5 countries it is assumed that a lower growth of consumption occurred for HCFCs (108% compared to 2002), with a strong increase of consumption of HFCs (232% compared to 2002 when there was very low total consumption) and a clear reduction in CFCs consumption (85% compared to 2002). This assumption results in a growth rate in total consumption in non-Article 5 countries of 17% over the last 4 years. For Article 5 countries the assumption of 36% growth rate over the last 4 years has been taken, with a smaller increase of consumption for CFCs (115% compared to 2002), a larger increase of consumption for HCFCs (142% compared to 2002) and the market introduction of HFCs. These estimations resulted in the values given in table 5.2 which shows a total increase in fluorocarbon consumption of 25% over the four year period. In the same period the total bank of fluorocarbons has increased by 20%, principally caused by growth of the HCFC bank.

***Table 5-2 Estimated refrigerant consumption, emission and bank in tonnes per year for industrial refrigeration, food processing and cold storage (data from /TOC02/, IPCC and assumption for 2006 review)***

| | **CFCs (CFC-12 and R-502)** | | **HCFC-22** | | **HFCs** | |
|---|---|---|---|---|---|---|
| **Cooling Capacity** | 25-1000 kW | | 25 kW-30 MW | | 25-1000 kW | |
| | 2002 | 2006 | 2002 | 2006 | 2002 | 2006 |
| **Consumption, t/yr** | 12700 | 11000 | 25900 | 31000 | 4500 | 12000 |
| **Bank** | 113000 | 95000 | 155000 | 212000 | 9000 | 25500 |
| **Emission, t/yr** | 30500 | 17100 | 23250 | 31800 | 900 | 3315 |
| **Emissions, % yr** | 27 | 18 | 15 | 15 | 10 | 13 |

Based on these figures a forecast for the demand of halocarbon refrigerants has been calculated with identical growth rates.

***Table 5-3 Forecast of demand of halocarbon refrigerants for industrial refrigeration systems, cold storage and food processing***

| Refrigerant | 2006 | 2009 |
|---|---|---|
| CFCs, t/yr | 11000 | 6000 |
| HCFCs t/yr | 31000 | 29000 |
| HFCs, t/yr | 12000 | 28700 |
| Total consumption | 54000 | 63700 |

This projection shows an increase in fluorocarbon consumption over the next three years of 18%, despite reductions in CFC and HCFC consumption.

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# 6 Transport Refrigeration

## 6.1 Introduction

Transport Refrigeration includes transport of chilled or frozen products by reefer ships, intermodal refrigerated containers, refrigerated railcars and road transport including trailers, diesel trucks and small trucks and vans.

It also includes use of refrigeration and air conditioning on merchant ships above 300 gross tonnes, and air conditioning in rail cars.

The continuously operating, mechanically or electrically driven vapour compression cycle is the technology used predominantly in transport refrigeration. Refrigerants such as CFC, HCFC, HFC, R717 or R744 are utilised for this technology. Continuously operating heat driven sorption systems could be used for specific installations independently /Cub97/ /Wan03/ /Gar03/, or in combination with a vapour compression cycle /Sor05/, but have only found very limited application so far /Bau06/.

A number of refrigeration systems are based on using discontinuous processes. Open systems use refrigerants like solid or liquid R-744, ice or liquid nitrogen as a low temperature heat sink to remove heat in transport. The refrigerant is being completely emitted and lost after use /Vie03/. Closed systems reuse the same substance, e.g. eutectic plates /Cub97/ or ice slurry, which is recharged at a central cooling unit /Pau99/.

Technical requirements for transport refrigeration units are more severe than for many other applications of refrigeration. The equipment has to operate over a wide range of ambient temperatures and under extremely variable weather conditions (sun radiation, rain…); it also has to be able to carry any one of a wide range of cargoes with differing temperature requirements, and it must be robust and reliable in the often severe transport environment /IPPC05/.

All transport refrigeration systems have to be compact and lightweight, being built to be very robust and sturdy to withstand movement and acceleration during transportation. Despite these efforts, leaks within the refrigeration system occur because of vibrations, sudden shocks etc. /IPPC05/. It is imperative that spare parts and refrigerant are available along transport routes. In particular open discontinuous systems completely depend on the supply of refrigerant in the required thermo-physical state. While this requirement is easy to meet in the case of road transport for short distances, all long distance transport systems have to be designed to fulfil that need as well /Bau06/.

Transport systems have to ensure safety in varying conditions and environments. The likeliness of leaks or ruptures is also greater than with stationary systems because of a higher risk of collisions with other objects. Ensuring safe operation with all working fluids is particularly essential in the case of ships, for example, where space is restricted and evacuation is difficult or impossible /SCA01/. Safety is either inherent in the fluids or is ensured through a number of technical measures /Ste99/.

## 6.2 Applications

According to a recent study /Kui05/, transport refrigeration still accounted for 0.8 % of all ODS emissions in 2002, while transport refrigeration equipment contained just 0.5 % of the world refrigerant bank. This indicates that leakage rates of transport refrigeration equipment are still higher than industry average. Since the working environment in all sub-sections of transport refrigeration is under rough conditions, emissions on average are higher than in other areas. To reduce leakages, better quality systems are now on the market, meaning higher costs to the user, but also better conditions for the goods transported.

Rough conditions bring about shorter life cycles so that the typical life span of many transport refrigeration systems is lower than for stationary refrigeration and air conditioning equipment. This is the reason that the transport refrigeration sector has already shifted more towards HFCs than other industry sectors.

The market share of HFCs which went into transport refrigeration systems was 2 % of all HFCs used in 2002, the market share of CFCs was 0.5 % and the share of HCFCs was 0.3%. All over the world, including Article 5 - countries, new transport refrigeration systems are commissioned with HFC refrigerants, thus continuously decreasing the bank of ODS containing equipment in this sector.

Since the 2002 Assessment, CFCs have not been used for new equipment in developed countries and a big proportion of CFC-containing equipment has disappeared. There are few remaining CFC-containing systems in the developed world today and they will not last longer than two to five years, thereby being replaced before 2010.

The shift to HFCs as single fluids or blends in containers, railcars and road transport proceeded, while use of HCFC-22 further decreased.

There have been few developments in natural refrigerants, although European Legislation has gone ahead to start focussing on HFCs in high emission applications like automotive A/C (MAC).

Transport on container vessels has shown an enormous rise with a 50 %-increase in the number of units since 2002, so that intermodal refrigerated containers now make up 80 % of the capacity for refrigerated transport at sea. As they can also be used for non-refrigerated transport, they carry approx. 55 % of the total volume of refrigerated transport at sea /Bau06/.

Transport on reefer ships has decreased slightly, while there have been virtually no new reefer ships produced in the last few years. The number of reefer ships using HCFC-22 for cooling has decreased significantly and HFCs are predominantly used in new equipment.

All sectors of transport cooling have added satisfactory alternatives to CFCs and HCFCs to their refrigerant portfolio, and they are readily available now.

### 6.2.1 Reefer Ships

The conventional reefer fleet shows a negative growth rate since 1994, while the container fleet expanded at an even higher rate than anticipated. There are approx. 1250 reefer ships larger than 10,000 cb.ft. in operation today, with an average size of 267,000 cb.ft./Bau06/ Within the last four years just a handful of new reefer ships have been built, while 10 to 20 million cb.ft. have been scrapped per year, leaving a total reefer fleet capacity of 330 million cb.ft../Hoc05/. No more than 500 ships larger than 250,000 cb.ft. account for 140 million cb.ft. capacity /Bau06/.

Almost 90 % of all reefer ships still use HCFC-22. As virtually all ships that have been scrapped recently have been built in the 1970s with HCFC-22 systems and charges of 1 to 5 tonnes, the HCFC-22 bank has been reduced to 3000 t.

About 10 % of all reefer ship refrigeration systems run on HFCs such as HFC-134a (mainly), R-404A and R-407C or R-410A, mostly in indirect systems where 500 kg to 1000 kg refrigerant charges are applied. Some HFC-23 is used in freezer applications. The HFC bank therefore contains approx. 100 t.

Most systems employ the vapour compression cycle. Some sorption systems are employed, using waste heat from the ship’s engine as driving power, thus reducing energy consumption /Cub97/ /Wan03/ /Han99/.

Since 1993 there has been an increase in R717 systems in new vessels. In 1993, five big ships using ammonia refrigerating systems were built in Denmark. More ammonia systems followed in Japan and Korea. In Spain two hybrid reefer/container ships with ammonia in their central refrigeration system were built in 2005. /Bau06/

Generally there has been a trend towards hybrid ships carrying refrigerated cargo, containers and cars or lorries rather than pure reefers /Hoc05/.

There has also been an increase in the use of indirect systems, inevitably when using R-717, but also reducing charges of other primary refrigerants.

Emissions are still high for older systems and are estimated to 20 % per year whereas 5-10 % per year can be achieved using indirect systems with a reduced initial charge.

Leak detectors are used increasingly to prevent leakages and ensure system reliability, but have not spread throughout the industry yet /Bau06/.

### 6.2.2 Refrigeration and Air Conditioning on Merchant Marine, Naval and Fishing Vessels

This sector is very non-uniform as it consists of branches as different as fishing and cruise-shipping. Depending on the part of industry that companies are involved in, they convey extremely diverse perceptions. This has resulted in enormous discrepancies between different data origins. The results displayed here can only represent these discrepancies.

Approximately 64,000 ships (>300 G/T) sail in this category today. Nearly all of them have refrigeration systems for their provision rooms and air conditioning. 70 to 80 % of the fleet still use HCFC-22 as refrigerant, the rest are HFCs and some R-717 and R-717/R-744 cascade systems on fishing vessels /Nie03/. There are also some remaining CFC-based systems.

About 45000 ships still use HCFC-22. There are about 6000 HFC-134a, 16000 R-507 or R-404A, 1200 R-407C and roughly 450 R-410A systems and, in addition, approximately 1000 ammonia systems in use.

Estimates for refrigerant banks (depending on source of data) vary from a few thousand up to 14000 t HCFC-22, 200 to 600 t HFC-134a, 800 to 1300 t R507/R404 and about 100 t R-410A.

CFC in use bank has been reduced to 50 t by retrofits and mainly by scrapping of old ships.

1000 to 2000 new ships are delivered annually. HFC-134a, R-404A and R-507 are established in the market and readily available, while R-410A is gaining market share slowly. R-407C is not well established in the market because its suitability is limited to medium and high temperature applications.

Estimated leakage rates vary between 1 % and 100 % annually depending on the data source. Concerning this discrepancy several factors have to be regarded.

Firstly system manufacturers confidently state that their systems are designed for leak rates of 0.5 % for the life of the unit. It is agreed in the industry that extremely low leakage rates can be achieved, even in the rough environment of sea borne transport, if appropriate equipment is used, maintained and controlled by trained personnel.

However, appropriate equipment and proper maintenance are not always employed where local, cheap designs and semi-skilled crewmembers with little technical knowledge are low priced alternatives, because cost control is a major factor in merchant shipping. This is especially true for equipment which is considered non-essential, as is often the case for air-conditioning or refrigeration.

There also seems to be a lack of awareness in parts of the industry where no concern is given to leakage rates, as is described in the following example: “According to the Netherlands environmental inspectorate, refrigeration and freezer units in Dutch merchant and fishing vessels are leaking relatively large amounts of fluorocarbon gases. The inspectorate found annual losses of 50 % in merchant ships and 80 % in fishing vessels. In some cases, the entire contents of a vessel’s cooling plant had leaked to atmosphere, sometimes as often as six times per year /Bau06/.” There are similar reports from other countries.

Dutch regulation stipulates that the “target percentage for both land and sea emissions is 1 % at most.” It is easy to see, that a yearly emission rate of 600 % in one ship results in an average leakage rate of 61 % for ten ships, even if the other nine achieve 1 %.

As the STEK licensing system for trained personnel and maintenance companies has been remarkably successful in Dutch land-based refrigeration equipment, it is expected that measures will be taken to transfer this success to Dutch seafaring vessels. One important step on the way to this success is to transfer responsibility for adequate service and maintenance to operating companies /EPE05/ /Hoo04/.

There are also regulations introduced on an international level through IMO (International Marine Organisation of the UN)., as laid out in Marpol Annex VI, on national level through Flag State Authorities(like SWEDAC, EPA 608, STEK and others) and, last but not least, through Classification Societies like DnV, LRS, GL and others. Also the EU is working on a European Regulation, which would be applicable to all EU flagged ships (i.e. all ships that are registered in the EU) and all ships that sail in European waters /Bau06/.

Some suppliers of Marine Refrigerants are very proactive in keeping their international customer base up-dated about the handling of refrigerants (including rules and regulations). A leading service company has therefore introduced a Refrigerant Handling Guide /Uni03/ and is implementing a system that allows importation of commonly used Ozone Depleting Substances like CFCs, HCFCs and Halons for final treatment in an approved and environmentally sound manner. The system is called Enviro Return Management (ERM) and will be implemented on a global basis. There is already an EU approved solution for selected major ports within the EU in place /Bau06/.

There is a clear drop in HFC refrigerant consumption in the cruise industry due to increased maintenance activities as a consequence of more stringent environmental rules applied in the US (EPA 608). There is also a strong increase in sales of refrigerant recovery equipment as well as an increasing demand for refrigeration system inspections and repairs. Change over solutions for HCFC-22 to ozone friendly HFCs are implemented to encourage operating companies to prepare for the future /Bau06/.

Decommissioning of old (naval) ships in Article 5 countries like Bangladesh, China and India has to be focused on as most of these ships contain several tons of HCFC-22.

In addition to the references indicated above, text of this section has been based on /Bau06/, /Nie03/, /Uni03/ and /Pal03/.

### 6.2.3 Intermodal Refrigerated Containers

As predicted in 2002, the rate of container fleet increase has been enormous and charter rates are likely to continue rising /Hoc04/, so that the fleet will continue to grow.

The number of units in operation in 2005 is approximately 750,000, equivalent to 1,270,000 TEU. TEU “Twenty foot Equivalent Unit” refers to a unit of volume corresponding to a twenty foot ISO container, which used to be the standard container. But today 40 foot containers of the “HighCube” type dominate the market for new reefer containers. Their size surpasses two TEU and therefore the increase in container traffic exceeds the increase in the number of units at the present time. All new containers use HFC.

There are no more than 18,000 containers of the porthole type in operation now and no new porthole containers are built.

A growing share of refrigerated containers today are fitted with new-generation systems (i.e. scroll compressors /Wil03/) offering many advantages including reliability, leak-proofness, weight, size and noise emissions. Current technology features reduced refrigerant charges and emissions and therefore helps to decrease their impact on the environment.

There are approximately 3,300 containers left that operate with CFC-12 and approximately 10,000 that operate with transitional (HCFC) blends, which makes a CFC bank of less than 100 t. Remaining CFC-containing units will reach their end of lifetime before the end of 2007.

There are still about 50,000 units using HCFC-22, but no new HCFC-22 systems are built. About 700,000 units use HFC-134a with a small proportion of R-404A. The refrigerant bank therefore consists of an estimated 250 t of HCFC-22, 3500 t of HFC-134a, 200 t of R-404A, and no more than 100 t of CFC.

About 200 new container ships and 160,000 TEU new refrigerated containers were built annually during the last few years. 140,000 of them employ HFC-134a systems, up to 20,000 employ R-404A systems.

When applying an estimated average emission rate of 15 % of the refrigerant bank, emissions of approximately 40 t of HCFC-22, 500 t of HFC-134a, 30 t of R-404A and 10 t of CFC-12 result /Bau06/.

Use of nonfluorocarbon alternatives has been considered in the container industry, but has not been pursued because of concerns about cost, flammability and/or toxicity of the alternatives /Bau06/.

### 6.2.4 Road Transport (Trailers, Diesel Trucks, Small Trucks)

According to /WBC04/ road freight volume amounted to $16 \cdot 10^{12}$ t·km [5] world-wide in 2005 while growth rates of 2.5 %/a are expected until 2030. About a tenth of the world transport volume is carried out in Europe while roughly 3% of European road transport is refrigerated, resulting in approx. $50 \cdot 10^{9}$ t·km of refrigerated road transport in Europe. This task is completed by a fleet of about 650,000 refrigerated vehicles, which operate mainly on R-404A.

The refrigerant bank for road transport in Europe consists of 60 t HCFC-22 (with an average remaining equipment life span of 5 years), 200 t HFC-134a, 2800 t R-404A, 100 t R-410A and about 50 t CFC in some Eastern European countries. In Western Europe CFC has completely disappeared from road transport equipment.

Leakage rates are 25 % on average, which means that up to 775 t of HFC refrigerant per annum are being emitted by refrigerated transport in Europe. CFC and HCFC emissions are likely to be higher than 25 %, estimated at 40 t of ODS emissions.

A recent study /Clo05/ used a correlation between the tonnage of refrigerated and frozen food and the number of refrigerated vehicles and found the world fleet for refrigerated road transport to be approximately 4 million vehicles in 2003. These are estimated to contain a refrigerant bank of 4000 t CFCs, 4000 t HCFC-22 (pure or as a mixture) and 14000 t HFCs, with R-404A being predominantly used, approximately 15 % HFC-134a and 2 % R-410A.

Emissions can be as high as 40 % for direct drive systems (mostly used with HFC-134a). For Diesel drive systems the rate is about 25 % and below 10 % for electrically driven R-410A units.

Therefore emissions of at least 1000 t CFC, 1000 t HCFC, 800 t HFC-134a, 3000 t R-404A and 30 t R-410A yearly can be assumed to occur in this sector of transport refrigeration.

Excellent refrigerant properties make hydrocarbons like R-290 and R-600a promising candidates for refrigerated transport. There have been developments in Australia, Germany and other European countries testing with HC-290 (Propane) which is commercially available. Because of the flammability of hydrocarbons, these systems require a leak detector in the trailer and special driver training to ensure safe operation. Technically this solution could be adopted world wide in small and medium size systems, in particular in compact systems. However, existing regulations concerning transport safety, which partially exclude hydrocarbons, would have to be adapted, and this could cause delay /Bau06/.

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[5] t·km = tonne·kilometer, to account for distances covered

There have been a few developments in the use of R744 in refrigerated transport. In Germany a R-744 – prototype delivery vehicle has been tested since September 2002 /Son04/. An Italian system uses eutectic plates, including throttling valve and evaporator on the vehicle. An R-744 -condensing-unit is connected to the vehicle by flat-face couplings when it is parked in the warehouse, to freeze the eutectic material /Mic05/. Tests of this system have been successfully completed and six prototype trucks are in the field at present, regularly operated by the customers for their ice cream and frozen food deliveries, in the same way as other trucks. About 20 trucks, made in a more industrialised way, are scheduled for next year. The results obtained in the field test confirm until now the expectancies /Bau06/. A system using expansion of R-744 in an open evaporator is available and used by approximately 100 vehicles in Scandinavia /Bau06 and The06/.

Application of the air cycle has been proposed for road transport, but high energy consumption seems to put off potential users. Recent investigations did, however, show favourable part load characteristics, /Spe04/ /Spe05/ which could enable the air-cycle system to “match overall fuel consumption of an equivalent vapour cycle refrigeration unit, while delivering the benefit of a completely refrigerant free system” /Spe05/.

SLA (synthetic liquid air) technology has proven to be too expensive when combined with a mechanical system as well as being unconvincing because of its poor energy efficiency.

The same applies to liquid nitrogen ($N_2$), which is used in less than 5000 units.

Cascade systems for diesel trucks, combining a heat driven adsorption system and a vapour compression cycle are still under development. Condensing temperatures of 20 °C for the vapour compression unit are available. This is an ideal condition to run a subcritical R744-vapour compression cycle in second stage /Sor05/.

Figures for this sector have been extracted from /Pal01/, /ECM05/, /Bau06/, /Sch04/.

### 6.2.5 Refrigerated Railcars

Refrigerated railway transport is used in North America, Europe, Asia, Australia and New Zealand. For traffic within the countries of the European Union and Turkey, the operation of refrigerated railcars is mainly handled by one company. Out of their 835 wagons in 2002, 285 were mechanically refrigerated /ICF02/; the remaining only insulated and, when needed, cooled with discontinuous methods. Solid R744 as well as ice have been used in discontinuous emissive systems until today. Alternatively, mechanically driven refrigeration systems have been used and are today the prime choice because of the typically long duration of trips, making refilling of the emitted refrigerant in open cycles a challenge both for logistics as well as cost. /Bau06/

Since 2002 the refrigerated boxcar fleet in the US, having a total size of approximately 8000 units /RTW01/, is undergoing a partial replacement process where both old mechanical as well as R744 discontinuous systems are replaced by new, mechanically driven systems /RTW01/ /CTI04/. There are presently no other activities for renewal of refrigerated railway systems known /Bau06/.

The lifetime of newer rail refrigeration systems, which are often easily replaceable units originally developed for road transport and only adapted for rail use, is believed to be 8 to 10 years with a running time of 1000 to 1200 h annually /RTW01/ and a refrigerant charge of approximately 7.5 kg/system, as per road trailer units /Val99/. Older units developed specifically for rail use and fully integrated with the railcar itself are expected to operate for the whole lifetime of the railcar, i.e. typically 40 years, and have a refrigerant charge of approximately 15 kg /UNEP02/. Therefore no more than 200 t of refrigerants of all kinds are used in this sector. Since operating conditions (shock, vibration, acceleration) in rail use are more demanding than in road transport, the annual leakage rate may be assumed to be at least similar to the leakage rate experienced in road transport /Bau06/.

As containers and trailers on a flat rail car dominate the fleet today, there is a decrease of refrigerated railcars remaining in service /Bau06/.

Most of the CFC-containing units have been retired, converted or overhauled in the developed world.

## 6.3 Refrigerant Options for New Equipment

The prognosis of 2002, that vapour compression will stay the main means of cooling in all sections of world wide transport, has proven true up to now. There are still very few units running on absorption processes, air or liquid gas.

HFC-134a and R-404A/R-507 have been implemented in many cases. Use of R-410A will advance further.

There are some hopeful developments, such as the testing of natural refrigerants, use of secondary refrigerants and implementing improved components to reduce refrigerant charges in vapour compression cycles.

Hydrocarbon (HC) refrigeration systems are commercially available for road transport in Europe. It is assumed that changes to hydrocarbons would be limited at first to a national level and to road transport. The flammability of hydrocarbons will require additional safety measures, thus increasing system costs and probably also insurance rates in the beginning. Use of HCs in containers might also require changes in the transporting ships /Bau06/.

Ammonia (R-717) as refrigerant has been increasingly used recently in marine refrigeration equipment in Europe and Japan. Applications include its use for reefer ships /Ste99/, as proposed refrigerant for sorption ice machines /Gar03/, and for fishing vessels both as single refrigerant /UNEP02/ /Ber95/ as well as in combination with R744 /Nie03/.

The applicability has been sufficiently proven. Major issues about using ammonia as refrigerant are its high volumetric capacity, making it suitable only for large refrigeration plants, as well as its toxicity and its flammability. Both risk potentials are moderate and can technically be handled, but require certain design considerations as well as the presence of additional safety equipment on board /Bau06/. Carbon dioxide ($CO_2$ or R744) as refrigerant in mechanically driven vapour compression systems might be used as a sub-critical refrigerant (critical point at 31 °C) with a condensing temperature well below the critical point, in cascade systems or in applications where low temperature cooling means are available. Alternatively, it can be used as a near-critical or, more likely, super-critical working fluid. The sub-critical use often offers significant advantages in terms of efficiency and costs in comparison to other refrigerants. Super-critical uses require a much higher pressure resistance of the equipment than is usual today and they are, at high ambient temperatures, energetically often less favourable than other refrigerants in the same temperature range. At low ambient temperatures, i.e., below 25°C, R744 shows good energy efficiency.

Consequently, for low temperature uses combinations of ammonia and carbon dioxide have been developed and are built into ships in Europe. A comparison shows that the efficiency for –40 °C evaporation and 25 °C condensing temperature is 17 % higher than that of a 2-stage HCFC-22 system (25% improvement at –50 °C/25 °C) /Nie03/. The advantage of the use of R744 in such applications is that the necessary components – in particular the compressor – are commercially available or require only minor modifications, while consuming less space than other solutions /Bau06/.

## 6.4 Refrigerant Options for Existing Equipment

There are not very many CFC-applications left and interim solutions like R-401A/B or R-409A can still be used for equipment which is near the end of its lifetime.

However, in Europe the phasing out of refrigerants and blends containing HCFC-22 is well on its way and from 2010 it will be prohibited to use HCFC-22 pure or in blends for retrofits. Therefore systems that have more than five years of operational service remaining could be retrofitted with a range of HFC retrofit refrigerants like R-407D, R-417A or R-413A. R-413A is non-flammable in air at atmospheric pressure and normal temperatures /Dup06/, but is classed as an A2 refrigerant by ASHRAE because the blend could become flammable under certain leakage scenarios /Bau06/.

Efforts have to be increased in order to reduce leakage during lifetime and decommissioning. Very low values can be achieved with the right combination of good practice, legislation and incentives.

## 6.5 Banks and Emissions Data

The following table shows the refrigerant bank per sector and the refrigerant emissions in these sectors of transport refrigeration for the year 2003.

| | Refrigerant bank in tons | | | | | Refrigerant emissions in tons | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total | HCFC-22 | HFC | R717 | CFC | Total | HCFC-22 | HFC | R717 | CFC |
| Reefer ships | 3120 | 3000 | 100 | 20 | 0 | 618 | 600 | 15 | 3 | 0 |
| Merchant marine, naval, fishing | 12070 | 10000 | 2000 | 20 | 50 | 2919 | 2500 | 400 | 4 | 15 |
| Containers | 4050 | 250 | 3700 | 0 | 100 | 608 | 38 | 555 | 0 | 15 |
| Road | 22000 | 4000 | 14000 | 0 | 4000 | 5780 | 1000 | 3780 | 0 | 1000 |
| Rail | 200 | 20 | 60 | 0 | 120 | 50 | 5 | 15 | 0 | 30 |
| Total transport | 41440 | 17270 | 19860 | 40 | 4270 | 9975 | 4143 | 4765 | 7 | 1060 |

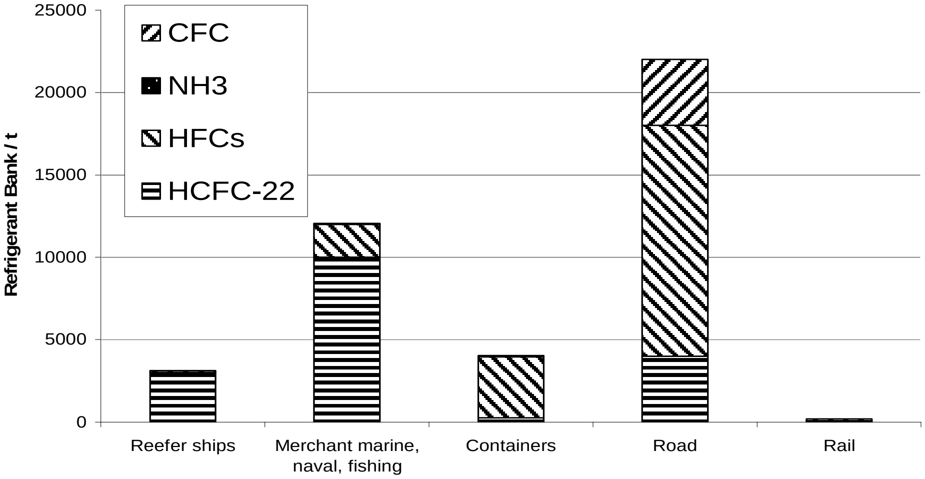

*Figure 6.1. Total Refrigerant Bank in Transport Refrigeration world wide (41 440 t)*

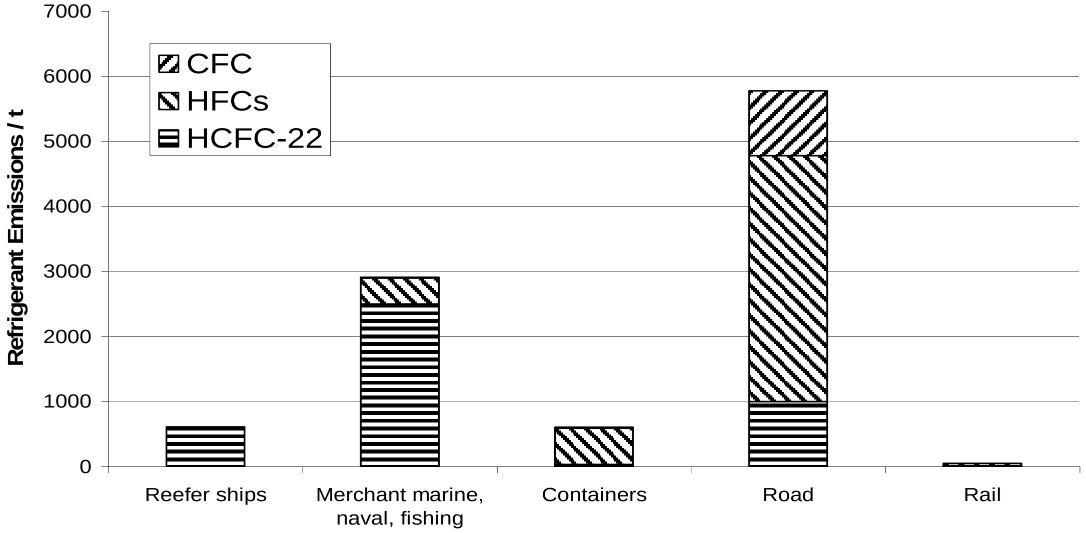

*Figure 6.2. Total Refrigerant Emissions in Transport Refrigeration world wide (9 975 t)*

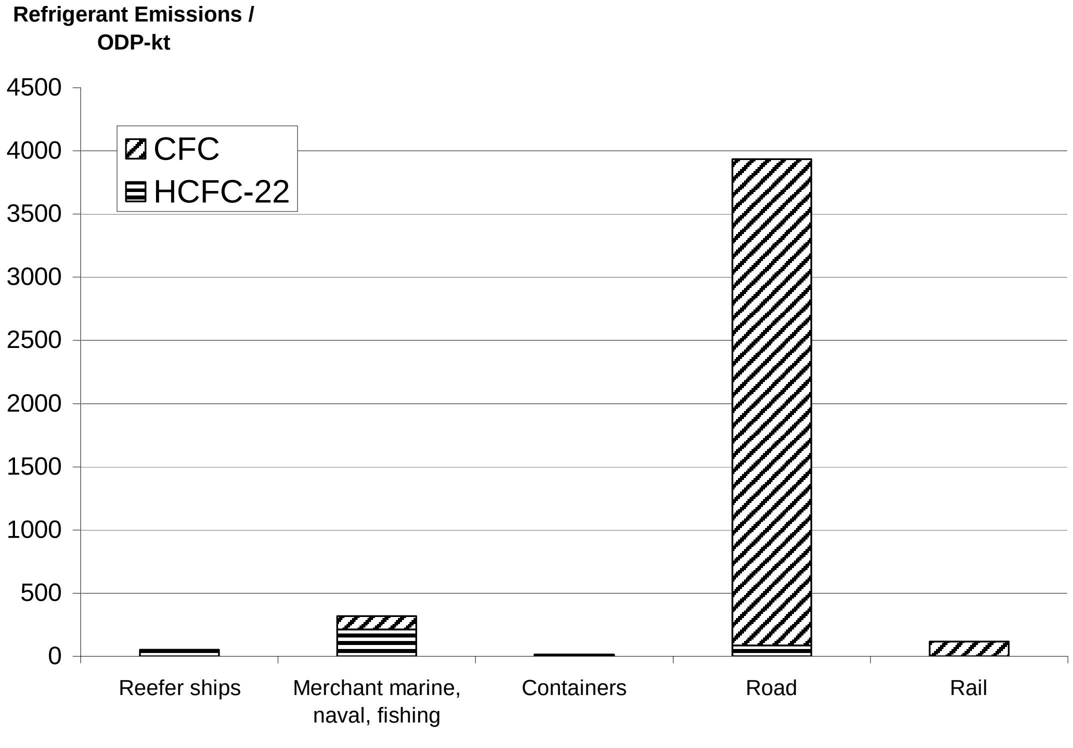

*Figure 6.3. Total ODP-rated Refrigerant Emissions in Transport Refrigeration world wide (4.45 Mio ODP-t)*

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# 7 Air Conditioners and Heat Pumps

## 7.1 Introduction

On a global basis, air conditioners and 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 35kW). In the remainder of this chapter the term air conditioning will be used to apply to both air conditioners and heat pumps that directly heat air. This broad category is sometimes referred to as air-cooled or unitary equipment /ASH05/. 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 420 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 in the condensation process. In the process, the condensing vapour transfers heat to the air.

In 2004, an estimated 3148 GW (cooling) of air-cooled air conditioners and heat pumps were operating world-wide. Refrigerant charge quantities vary proportional to capacity. These 3148 GW (cooling) of installed capacity represent an installed bank of approximately 887,000 metric-tonnes of HCFC-22.

Nearly all air-cooled air conditioners and heat pumps manufactured prior to 2000 used HCFC-22 as their working fluid. There are no publicly available statistics which delineates the percentage of air-cooled air conditioners and heat pumps being manufactured with non-ODS refrigerants. However, many Non-Article 5 countries have been transitioning to non-ODP alternates ahead of the Montreal Protocol commitment dates. Therefore, the projection model used to generate many of the estimates presented in this section indicates that approximately 94% of the installed unit population currently uses HCFC-22 as the refrigerant and approximately 16% of the units produced globally in 2004 used non-ODP refrigerants. Approximately 5% of the refrigerant used in the production of these products in 2004 was non-ODP refrigerant.

## 7.2 Applications

Air-cooled air conditioners and heat pumps 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). In each of these categories, the term “air conditioner” includes heat pumps that directly cool or heat 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, RAC
- Through-the Wall Air Conditioner
- Portable Air Conditioner [6]
- 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, recent data suggests that duct-free, split type room air conditioners are being selected more frequently as the first comfort air conditioning option in many countries—resulting in a global decline in the growth in demand for window mounted and through-the-wall air conditioners.

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 include a compressor/heat exchanger 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. There is generally one fan-coil unit for each conditioned room.

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[6] 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.

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. 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 air conditioners have average HCFC-22 charge levels of approximately 0.25 to 0.30 kg per kW of cooling capacity. Non-ducted split air conditioners can be applied to commercial buildings, schools, apartments and free-standing residences.

Single Packaged Vertical Units, SPVU, are another category of single packed duct-free units. SPVU systems are air conditioners which have their major components arranged vertically. This equipment is designed for exterior mounting on, adjacent to, or through an outside wall to provide cooling or heating for a single space. A common application is to provide heating or cooling to mobile or temporary structures.

Another sub-category of non-ducted air conditioning systems is Variable Refrigerant Flow, VRF, systems. These systems are designed to provide air conditioning to multiple spaces using a single outdoor unit and multiple indoor units. 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 consists of a number of indoor air handling units connected to a single outdoor air conditioning unit. The outdoor air conditioning unit can adjust the total amount of 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. Some of the modulation methodologies used are: multiple compressors, variable speed compressors (inverter driven) or various compressor-unloading schemes.

VRF systems typically use hermetic rotary or scroll compressors. VRF systems have capacities ranging from 10 kW to over 130kW. Since the VRF outdoor unit is connected to each of the individual indoor units by refrigerant piping, these systems tend to have higher refrigerant charge levels per kW of cooling than one-on-one non-ducted systems. Typical refrigerant charge levels for VRF systems are 0.50 – 0.70 kg/kW of cooling. Because these systems may use long runs of interconnecting refrigerant tubing, assuring leak tightness of the interconnecting tubing is a critical factor for maintaining the efficiency and reducing the environmental impact of these systems.

### 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 increases. In the United States, the minimum efficiency of residential air conditioners that can be sold was increased 30 percent in January 2006. 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/.

### 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 must be 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).

## 7.3 Current Use

Estimates of the installed base (number of units) and refrigerant inventory were made using a computer model which predicts the number units and refrigerant in the installed population using, production data and product longevity models Annex A, /Kel97/, /Kel04/, /Clo04/.

### 7.3.1 Small Self-Contained Air Conditioners

On a world-wide basis, an estimated 15.2 million window-mounted[7] and through-the-wall (packaged terminal) air conditioners were sold in 2004, each one containing an average of 0.75 kg of HCFC-22.

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[7] 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.

With service lives over 10 years, it is estimated that more than 115 million window-mounted and through-the-wall air conditioners remain in operation globally (Table 7-1). The total 2004 global bank of HCFC-22 in the installed population of window-mounted and through-the-wall air conditioners (including portable air conditioners) has been estimated to be 81,000 metric-tonnes.

During this assessment period, there has been a significant shift toward the use of non-ducted split residential air conditioners as the entry-level air conditioning system. This trend can be observed in Table 7-2 which shows that the annual production of window-mounted and through-the-wall air conditioners increased modestly from 1999 to 2004 while the annual production of non-ducted split residential and commercial air conditioners increased dramatically during the same period.

The majority of this growth has occurred in the Article 5 countries of Asia. The high growth rates in these countries are understandable since the markets in these countries are in their infancy while the markets in the non-Article 5 countries are more mature and have reached relatively stable equipment populations.

***Table 7-1 Estimated 2004 Unit Population and HCFC-22 Banks***

| Product Category | Estimated Population Operating Units (2004)[8] | Estimated HCFC-22 Bank[9] (metric-tonnes) |
|---|---|---|
| Window-mounted and Through-the Wall (Packaged Terminal) Air Conditioners | 115 million | 81,000 |
| Non-ducted or Duct-free Split Residential and Commercial Air Conditioners | 259 million | 305,000 |
| Ducted, Split Residential Air conditioners and Heat Pumps | 83 million | 273,000 |
| Ducted Commercial Split and Packaged Air Conditioners | 21 million | 228,000 |
| Total | 478 million | 887,000 |

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[8] Unit population includes units manufactured with non-ODS refrigerants.
[9] HCFC-22 Inventory does not include non-ODS refrigerants.

*Table 7-2 Comparison of Units Manufactured 1999 and 2004*

| Product Category | Units Manufactured 2004 | Units Manufactured 1999 | Increase 2004 versus 1999 |
|---|---|---|---|
| Window-mounted and Through-the Wall (Packaged Terminal) Air Conditioners | 15.2 million | 12.9 million | 18 % |
| Non-ducted or duct-free Split Residential and Commercial Air Conditioners | 39.2 million | 19.6 million | 100 % |
| Ducted, Split Residential Air conditioner | 6.9 million | 6.0 million | 15.0 % |
| Ducted Commercial Split and Packaged Air Conditioners | 1.7 million | 1.7 million | 0 %[10] |
| Total | 63.0 million | 40.2 million | 57% |

Source: /ARI04/, /JAR04/

### 7.3.2 Non-ducted Split Air Conditioners

An estimated 259 million non-ducted split air conditioners were operating world-wide in 2004. Approximately 7.7% of these used non-ODP refrigerants. Non-ducted split air conditioners, ranging in capacity from 2.0 kW to 20 kW (average size of 3.8kW), have gained greatest acceptance outside of the United States and Canada due to different construction methods and a preponderance of hydronic or non-central heating systems in these areas.

The average charge per kW increases as the operating efficiency of these systems increases. The total inventory of HCFC-22 in the installed population of duct-free split systems world-wide in 2004 has been estimated to be 305,000 metric-tonnes.

### 7.3.3. Ducted, Split Residential Air Conditioners

An estimated 83 million ducted, split residential air conditioner were in service world-wide in 2004. 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 273,000 metric-tonnes.

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[10] The low growth-rate reflects the impact of the economic downturn on the Commercial market between 1999 and 2004.

Approximately 9% of ducted, split residential air conditioners manufactured globally in 2004 utilised non-ODS refrigerants. Approximately 2.6 million of the installed population of 83 million ducted, split residential air conditioners were manufactured with non-ODP refrigerants.

### 7.3.4 Ducted Commercial Split and Packaged Air conditioner

An estimated 21 million air-cooled ducted commercial split and packaged air conditioners and heat pumps were operating world-wide in 2004. Ducted commercial air conditioners and heat pumps range in capacity from about 5 kW to as large as 420 kW). The estimated total world-wide bank of HCFC-22 in the installed base of these systems in 2004 has been estimated to be 228,000 metric-tonnes. Approximately 647,000 of these 21 million air-cooled ducted commercial units were manufactured with non-ODP refrigerants.

### 7.3.5 Summary

Common attributes of these equipment categories have been their nearly universal use of HCFC-22 as a working fluid. On a mass basis in 2004, HCFC-22 accounted for 95% of the refrigerant bank for these product categories. Table 7-1 summarises the total estimated bank of HCFC-22 used in these product categories.

Since the last assessment, there has been an increase in the number of new products in these categories, which utilise non-ODS refrigerants. In North America, there has been a modest shift to non-ODS refrigerants (less than 8% of new production) while in Europe and Japan there has been a nearly complete shift to the use of non-ODS refrigerants - predominately HFC blends. The majority of Article 5 countries are still utilising HCFC-22 to produce these categories of products for their domestic markets.

## 7.4 Refrigerant Options for New Equipment

A survey of current product offerings indicates that the majority of non-HCFC products available for the product categories covered in this section are using HFC blends as the refrigerant with a small number of units using hydrocarbon refrigerants (portable and small split system air conditioning units).

While HFC-134a and R-744 ($CO_2$) are technically feasible options, there has been very limited commercialisation of air-cooled air conditioning products using HFC-134a or R-744.

Of the pure component refrigerants investigated, only HFC-134a, R-744 and HC-290 are still considered viable single component refrigerant options. Following is a summary of the most viable HCFC-22 replacement candidates for air-conditioners.

### 7.4.1 Single Component HFC Refrigerants

Several single component HFC refrigerants have been investigated as replacements for the CFCs and HCFCs currently used in air-cooled air conditioners. However, HFC-134a is the only single component HFC that has seen any commercial application 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, and re-sized compressor motors.

While HFC-134a is a potential HCFC-22 replacement in air-cooled applications, it has not seen broad use because manufacturers have been able to develop 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 chiller and mobile air conditioning applications (Chapters 9 and 10 respectively). It therefore appears that HFC-134a will see very limited application in air-cooled air conditioning applications.

### 7.4.2 HFC Blends

A number of HFC blends have emerged as replacements for HCFC-22 in air conditioning applications. 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-410A and R-407C.

#### *7.4.2.1 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/. It has been reported that the deviation from HCFC-22, under retrofit conditions, increases above these nominal values as the outdoor ambient increases /Dev05ii/.

There are currently R-407C air conditioning products widely available in Europe, Japan and other parts of Asia. R-407C has also seen some limited usage in the United States and Canada, 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 where the transition was moving faster than the design of new equipment tailored for HFC-410A (Europe and Japan).

R-407C may also be an attractive alternative for large capacity (greater than 50 kW) unitary products that would require extensive design modification and high capital equipment investments to be converted to a higher-pressure refrigerant such as R-410A.

In Europe, R-407C has been used as the dominant replacement for HCFC-22 in air-cooled air conditioning applications. In Japan, R-407C has been used primarily in the larger capacity duct-free and multi-split products and VRF systems. However, many of these products are now beginning to transition from R-407C to R-410A to obtain improved serviceability (lower glide) and higher efficiencies, resulting in size and cost reductions.

#### *7.4.2.2 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 points are approximately 10°C lower than HCFC-22, resulting in condensing pressures up to 4000 kPa.

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 8% of the US Ducted Residential Market in 2004 used R-410A as the refrigerant. After 1 January 2010, air conditioners sold in the US Ducted Residential market will predominately utilise R-410A as the HCFC-22 replacement.

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 heavier wall compressor shells, pressure vessels (accumulators, receivers, filter driers etc.), heat exchangers and refrigerant tubing.

#### *7.4.2.3 Lubricants for R-407C and R-410A Systems*

The naphthenic mineral-oil-based and alkyl benzene lubricants commonly used in HCFC-22 systems are not miscible with HFC refrigerants. Considerable research has been conducted to determine the optimum lubricant combinations for HFC systems. Several approaches have been pursued by the industry:

1. Polyolester (POE) Lubricants (Synthetic),
2. Polyvinylether Lubricants (PVE) (Synthetic),
3. Polyalphaolefin Lubricants (PAO) (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 after extensive material compatibility and reliability testing.

### *7.4.2.4 R-417A and Other Service Blends*

R-417A refrigerant combines two HFC refrigerants with a small amount of HC-600 (butane) refrigerant. R-417A is a zeotropic blend having a glide similar to R-407C /Bit04/. The HC-600 is added to the blend to enable this refrigerant to utilise standard naphthenic mineral-oil-based and alkyl benzene lubricants. This refrigerant has primarily been promoted as a *drop-in* and *retrofit* refrigerant for HCFC-22 in air conditioning and refrigeration applications. Published data for air conditioning and heat pump applications suggests this refrigerant exhibits approximately a 12% lower COP and 20% lower capacity than HCFC-22 when used as service fluid in systems originally designed to use HCFC-22 /Spa04/, /DuP05/. Other similar blends have been proposed as potential service refrigerants including R-419A and R-422B.

### 7.4.3 Hydrocarbon Refrigerants

There have been a number of performance comparisons made between HC-290, propane, and HCFC-22 /Col00/, /Dev05i/, /ART01/. The results of these comparisons suggest that the HC-290 systems have 2-9% higher efficiency than the HCFC-22 baseline systems during drop-in and soft optimised unit performance comparisons excluding indirect systems.

Compared to HFCs, hydrocarbon refrigerants offer reduced charge levels (approximately 0.10 - 0.15kg/kW of cooling capacity /Col99/), miscibility with mineral oils (synthetic lubricants are not required), reduced compressor discharge temperatures, and improved heat transfer due to favourable thermo-physical properties.

The factors that work against application of the hydrocarbon refrigerants in air conditioning systems are the safety concerns, handling, installation practices and field service skills and practices.

European and international standards generally limit the use of hydrocarbon refrigerants to applications having refrigerant charge levels below 1 kg. In systems with charge levels below 150g the design requirements necessary to meet current and future safety requirements can generally be applied cost effectively /Sic99/.

When designing new air conditioning systems with HC-290 or other flammable refrigerants, the designer should be sure to comply with all applicable safety standards and regulations, as there can be significant regional differences in codes and standards. Service practices will also need to be modified to avoid exposing service technicians to the additional risks associated with working with 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 will still be a need to require recovery during servicing and at the end of the product’s life to protect those servicing or recycling the product.

The ultimate decision on whether hydrocarbon refrigerants are practical in air-cooled air conditioning products will be determined by whether the added costs of safety mitigation technologies result in a product more costly than can be developed using other non-ODP substances.

*Lubricants for Hydrocarbon Systems*

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

### 7.4.4 Carbon Dioxide (R-744)

Carbon dioxide (R-744) offers a number of desirable properties as a refrigerant: readily available, low-toxicity, low GWP and low cost. R-744 systems are also likely to be very compact; though not necessarily lower cost than HCFC-22 systems /Nek01/. These desirable characteristics are offset by the fact that R-744 air conditioning systems can have low operating efficiencies and very high operating pressures. The refrigerant R-744 cycle differs from the conventional vapour compression cycle in that the condenser is replaced with a gas cooler since the R-744 will not condense at the typical air conditioning operating temperatures, which are above the critical point of R-744. Typical gas cooler operating pressures for R-744 systems will be as high as 14,000 kPa /Ibr03/.

The literature has a significant amount of conflicting data on the performance of R-744 air conditioning systems. Some of these data shows a significant loss of efficiency with R-744 when compared to HCFC-22, while other papers suggest equal or better performance.

Another indicator of current state of the art is the fact that commercially available air-cooled R-744 air conditioners have not been introduced into the market. A significant barrier to the commercialisation of R-744-based air conditioners continues to be the limited availability of compatible components such as compressors, heat exchangers and refrigerant controls. However, a number of compressor manufacturers have presented papers in journals and conferences indicating active development programs on R-744 compressors.

The efficiency of R-744 systems can be improved through optimised system designs, the use of refrigerant expanders, various inter-cycle heat exchangers, and cross-counter-flow heat exchangers, which take advantage of the favourable thermo physical properties of R-744.

Considering the current state of the art and limited commercial availability of R-744 components, R-744 is not expected to play a significant role in the replacement of HCFC-22 in non-mobile air conditioning applications for many years.

*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 beginning to develop as more researchers conduct studies of R-744 compressors /Hub02/, /Li00ii/, /You03/. Some of the lubricants being considered for R-744 systems are POEs, PAO, and naphthenic mineral oil or alkyl benzene lubricants /You03/, /See06/. None of the current literature identifies a perfect lubricant for R-744 systems. However, the literature is optimistic that suitable lubricants will be developed and successfully applied to R-744 refrigeration systems. The optimal lubricant will most likely be different for different applications and categories of compressors.

### 7.4.5 Alternative Refrigeration Cycles

In the past assessments, a number of potential new technologies were presented as options that could have a positive impact on the phase-out of ODS. Some of the technologies presented in prior assessments were: absorption, desiccant cooling systems, Stirling systems, thermoelectric and number of other systems. However, a search of the literature published since the prior assessment has continued to confirm that 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 theoretically feasible, it is unlikely that they will significantly penetrate these markets in the next decade. Alternate cycle technologies will therefore have a minimal impact on the HCFC-22 phase-out in both Non-Article 5 and Article 5 countries.

In addition to the new technologies mentioned above, mature proven technologies can also provide non-ODP options for some regions and applications in Article 5 countries. For example, *Evaporative Cooling* technology could provide a very low cost and energy efficient alternative to vapour compression refrigeration in both Non-Article 5 and Article 5 countries having hot arid climates /ASH03/.

### 7.4.6 Summary

Considering the options presented in Section 7.5, the current trends indicate that HFC blends are the most likely near-term refrigerants to replace HCFC-22 in air-cooled systems during the next 10 to 15 years. Air-cooled air conditioning equipment using HFC refrigerants is already commercially available in most non-Article 5 regions of the world. Commercial availability of systems using HFC refrigerants is also occurring in some Article 5 countries; primarily for export.

Hydrocarbon refrigerants may be suitable replacements for HCFC-22 in some categories of products--particularly very low charge level applications. There are international and some regional standards that permit the use of hydrocarbon refrigerants at very low charge levels. However, the designer must ensure that local codes or national standards do not pre-empt the international and regional standards.

The role of hydrocarbon refrigerants may ultimately be determined by the costs necessary to mitigate all safety concerns. If hydrocarbon systems could be developed as safe and efficient as their HFC counterparts, the ultimate decision on their commercial viability would be driven by economic factors, consumer acceptance, and safety codes and standards.

There is a significant amount of research being conducted on R-744 systems. This research is being focused on component development, modelling tools and breadboard system designs. However, this research has been primarily focused on mobile air-conditioning, refrigeration and water-heating applications. Development of R-744 air-cooled air conditioning systems lags behind HC and HFC technologies by many years.

## 7.5 Refrigerant 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* 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. In Non-Article 5 countries, unit replacement is more common because the costs associated with performing a major repair 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 field repair replaces the refrigerant without changing the lubricant used in the original equipment. Refrigerants meeting these requirements are sometimes referred to as *Service Fluids or Refrigerants*. 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. Retrofit field repair can be substantially more costly than *service* or *drop-in* repairs or even unit replacement.

### 7.5.1 Drop-in Refrigerants

A *drop-in* refrigerant should require either no system modifications or only minor system modifications and as a minimum should result in reliable performance with the existing naphthenic mineral oil or alkyl benzene synthetic oil lubricant used in the original equipment and should provide substantially the same performance as the original refrigerant.

A number of service refrigerants have been suggested as potential drop-in refrigerants. Their performance in drop-in applications has not been well documented so further study is needed to validate their suitability as drop-in replacements for HCFC-22.

### 7.5.2 Retrofit Refrigerants

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.

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.

### 7.5.3 Anticipated Market Impact of *drop-in* and *Retrofit* 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* 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 *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 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. Commercialisation of suitable retrofit refrigerants should continue because they will provide high value to Article 5 countries.

### 7.5.4 Hydrocarbons as *drop-in* Refrigerants

It has been reported that HC-290, HC-1270 and HC-290/HC-170 blends have been used as *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. In many cases, the costs of meeting safety standards and codes-of-practice have been found to be too costly to justify a retrofit to a hydrocarbon refrigerant.

## 7.6 HCFC Usage, Banks and Emissions

For more than 60 years, HCFC-22 has been the most widely used refrigerant for air-cooled air conditioners. Significant progress has been made in developing qualified substitutes for HCFC-22. However, significant quantities of HCFC-22 will be required to service new and existing equipment through at least 2020 to 2030. All projections in the section were made using the model described in Annex A.

Four factors must be considered when estimating future HCFC-22 requirements:

1. Anticipated demand in the world market for air-cooled air conditioning equipment,
2. Impact of recycling and destruction on the available supplies of HCFC-22,
3. Implementation rate of HFC refrigerants and other technologies into air cooled air conditioning equipment and,
4. Changes in system design and servicing practices, which will reduce the refrigerant charge quantities and refrigerant make-up requirements for air-cooled air conditioning equipment.

This Section presents HCFC-22 usage forecasts based on a likely conversion scenario. The projection of future HCFC-22 demand was predicted using a life-mortgaging model. This projection model has been significantly enhanced since the 2002 Assessment. The model does a more detailed analysis of Article 5 country usage and separately analyses the usage for the Chinese domestic market. The model requires the establishment of assumptions for a number of key parameters.

1. Market historical production rates
2. Market Growth Rates
3. Unit Life Estimates
4. Leak Rate Estimates for each product category
5. Projected rates of conversion to non-ODS refrigerants
6. Estimated re-claim, destruction and recycling rates.

In attempting to project HCFC-22 usage for the period 2004 through 2015, the assumptions were selected to evaluate the “most likely” scenario. Annex A to this chapter lists the detailed assumptions used for the analysis.

Table 7-3, 7-4, and 7-5 present the predicted HCFC-22 Demand, Bank and Emissions for the period 2004- 2015.

***Table 7-3 HCFC-22 Global Requirements 2004-2015 (Air Conditioning)***

| | New HCFC-22 Requirements (Tonnes) | | |
|---|---|---|---|
| Year | Non-Article 5 | Article 5 | Total |
| 2003 | 166,039 | 99,017 | 265,056 |
| 2004 | 161,864 | 108,398 | 270,262 |
| 2005 | 153,798 | 117,955 | 271,753 |
| 2010 | 73,692 | 165,306 | 238,998 |
| 2015 | 32,362 | 212,221 | 244,583 |

In 2004, roughly 231,000 metric-tonnes (Table 7-3) of HCFC-22 were used globally to manufacture and service the air-cooled air conditioners and heat pumps covered in this section. Nearly 60% of this HCFC-22 was used to service the installed population of air conditioners and heat pumps. The high servicing requirement can be attributed to two factors, the large installed population of air-cooled air conditioning products (see Table 7-1) and servicing practices, which include very little usage of recycled refrigerant. Table 7-4 shows the projected HCFC-22 Refrigerant Bank for air conditioning products.

***Table 7-4 HCFC-22 Bank 2004-2015 (Air Conditioning)***

| | HCFC-22 Bank (Tonnes) | | |
|---|---|---|---|
| Year | Non-Article 5 | Article 5 | Total |
| 2003 | 619,668 | 222,169 | 841,838 |
| 2004 | 632,794 | 254,417 | 887,211 |
| 2005 | 641,251 | 289,206 | 930,458 |
| 2010 | 575,975 | 492,509 | 1,068,485 |
| 2015 | 375,902 | 722,017 | 1,097,919 |

***Table 7-5 HCFC-22 Emissions 2004-2015 (Air Conditioning)***

| | HCFC-22 Emissions (Tonnes) | | |
|---|---|---|---|
| Year | Non-Article 5 | Article 5 | Total |
| 2003 | 115,013 | 46,981 | 161,994 |
| 2004 | 111,964 | 51,002 | 162,966 |
| 2005 | 108,496 | 55,408 | 163,904 |
| 2010 | 82,877 | 82,385 | 165,262 |
| 2015 | 50,044 | 110,781 | 160,825 |

Table 7-6 shows the projected new HFC requirements, emissions and bank for Non-

Article 5 countries for the period 2004 through 2015. The analysis assumes that all usage of HFCs in Article 5 countries is for export and not for domestic use. The analysis assumed that all non-ODP designs use HFCs in order to simplify the analysis. If a mix of HFCs, HCs and R-744 were used the HFC demand would obviously be reduced from the levels shown in Table 7-6. However, the usage of hydrocarbon refrigerants is expected to be limited to low charge level applications (< 1 kg) and R-744 is not expected to capture an appreciable market share within this segment in the near future. Therefore, hydrocarbon and R-744 refrigerants will probably have minimal impact on the HFC demand for non-Article 5 countries since most will have phased out HCFC-22 by 2010, with the remaining phasing out HCFC-22 in new products by 2015.

Hydrocarbons and R-744 may have an increased impact on the phase-out of HCFC-22 in Article 5 countries since the additional time for phase-out will enable hydrocarbon and R-744 technologies to further mature prior to the phase-out dates required by the Montreal Protocol.

***Table 7-6 Non-Article 5 HFC Emissions, Bank and New Requirements (2004-2015)***

| Year | Emissions (Tonnes) | Bank (Tonnes) | Requirements For New HFC (Tonnes) |
|---|---:|---:|---:|
| 2003 | 3,253 | 28,459 | 16,762 |
| 2004 | 4,836 | 43,543 | 24,306 |
| 2005 | 6,749 | 62,102 | 30,756 |
| 2010 | 32,561 | 314,848 | 128,268 |
| 2015 | 74,075 | 723,465 | 189,395 |

## 7.7 Article 5 Country Considerations

Historically, the first air conditioning products to enter Article 5 countries were large water or air-cooled chillers, intended for industrial or institutional use. Window room air conditioners air conditioners for residential use were typically the first residential and light commercial air cooled air conditioners utilised in developing markets. Most air-cooled air conditioners and heat pumps will utilise HCFC refrigerants, if they are purchased prior to the phase-out date for HCFCs. The primary technical concerns of the Article 5 countries are, adequate supplies of HCFCs to service existing equipment and equipment manufactured before the HCFC Phase-out date dictated by the Montreal Protocol, adequate supplies of alternative refrigerants, and concerns over their cost and safety aspects.

The average life expectancy of most air-cooled air conditioning equipment is approximately 15 to 20 years. The Article 5 country concern over the availability of HCFCs to service existing equipment can be handled by allowing a sufficient service tail or through an accelerated phase-out of HCFCs in the fastest growing Article 5 country markets. In the fastest growing markets, a phase-out more aggressive than dictated by the Protocol may be necessary to keep usage below the Protocol caps.

The previous sections of this chapter provide an overview of the alternative refrigerants and technologies, which are applicable to products in both non-Article 5 and Article 5 countries. Commercialised products using HFC refrigerants are available in most non-Article 5 countries. Products that utilise HC refrigerants are available to a limited extent in some product categories e.g. portable air conditioners. The widespread availability of these technologies in non-Article 5 countries should provide some optimism that the technologies will be cost effective and readily available in Article 5 countries within the next decade. In addition, some Article 5 countries will be exporting products to non-Article 5 countries and will need to have access to non-ODP technologies.

Co-operative research programs, workshops and technical conferences provide a broad spectrum of technical information which addresses the cost, safety and performance issues associated with the transition to non-ODP refrigerants. The published information from these conferences and programs is a valuable resource of technical information that should assist researchers and designers in Article 5 countries. In addition, component, product and refrigerant manufactures are also excellent sources of technical information on the application of non-ODS technologies.

As the state of development progresses the alternative refrigerants and technologies available today in non-Article 5 countries should become readily available in most Article 5 countries.

Article 5 countries face specific equipment issues with respect to the containment and conservation of refrigerants. Since the manufacturing process is approaching a global standard, those developing countries manufacturing large quantities of air conditioning equipment are using processes that are nearly the same as those used in non-Article 5 countries. Also, since many of Article 5 countries are or will be importers and not manufacturers of air-conditioning equipment, the specific issues faced by these countries are mostly related to servicing, training of technicians, and regulation of refrigerants. Important points are:

- Technician training and awareness are essential to the success of refrigerant conservation, where preventive maintenance procedures have not been routine in the past;
- Article 5 countries could devote resources to developing a reclamation infrastructure, with the necessary refrigerant recovery and reclaiming network, or emphasise on-site refrigerant recycling. The Multilateral Fund of the Montreal Protocol supports this practice;
- In many Article 5 countries, preventive maintenance of air-conditioning and refrigeration equipment has been rare. Conservation approaches, which rely heavily on regular maintenance, could be successfully implemented if countries were to provide incentives to encourage routine scheduled maintenance /UNEP05/.

## 7.8 References

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## 7.9 Annex A

A significant amount of information and assumptions are needed to run the refrigerant usage model. The key input parameters are:

1. Historical Shipment data (15 Year Minimum)
2. Average capacity (kW) and refrigerant charge (kg/kW)
3. Future shipment estimates by region or estimated market average growth rates
4. Projected HCFC to HFC Transition Rates by Montreal Protocol Country Category
5. Estimated Leak Rates
6. Estimated product life for each product category
7. Estimated Utilization of Refrigerant Recovery
8. Estimated Unit Manufacturing Refrigerant Losses

The following tables summarize the key assumptions used in the Unitary Refrigerant Usage Model.

***Table A-1 Key Assumptions by Product Type***

| Product Category | Assumed Leak Rate **(%)** | Assumed Product Life (Years) | Average Charge (kg) | Average Unit Capacity (kW) |
|---|---|---|---|---|
| Small Self Contained Air Conditioners | 2 | 10 | 0.75 | 2.7 |
| Non-ducted (or duct-free) Split Residential and Commercial Air Conditioners | 5 | 15 | 1.28 | 4.8 |
| Ducted, Split Residential Air Conditioners | 5 | 20 | 3.40 | 10.9 |
| Ducted Commercial Split and Packaged Air Conditioner | 5 | 20 | 11.35 | 35 |

The model uses actual shipment statistics for historical years. For future years the model relies on future estimates of the market size or projects the future market size using forecasted market growth rates for each product category by geographic location. Table A-3 shows the market growth rate assumptions used in the model.

### *A-2 Historical Shipment Data (000)*

| Product Category | | 1985 (000) | 1990 (000) | 1995 (000) | 2000 (000) | 2005 (000) |
|---|---|---|---|---|---|---|
| Ducted RES | Non-Article 5 | 2,625 | 3,292 | 4,403 | 5,684 | 6,495 |
| | Article 5 | 201 | 78 | 174 | 247 | 439 |
| | Total | 2,826 | 3,370 | 4,577 | 5,931 | 6,934 |
| DFS | Non-Article 5 | 3,441 | 6,962 | 9,361 | 10,989 | 12,968 |
| | Article 5 | 291 | 779 | 4,530 | 12,678 | 25,667 |
| | Total | 3,732 | 7,741 | 13,891 | 23,667 | 38,635 |
| SSAC | Non-Article 5 | 3,536 | 5,162 | 5,265 | 7,673 | 8,927 |
| | Article 5 | 2,513 | 3,213 | 4,898 | 5,886 | 6,159 |
| | Total | 6,049 | 8,375 | 10,163 | 13,559 | 15,086 |
| Ducted Commercial | Non-Article 5 | 912 | 1,173 | 1,187 | 1,492 | 1,489 |
| | Article 5 | 150 | 63 | 351 | 230 | 289 |
| | Total | 1,062 | 1,236 | 1,538 | 1,722 | 1,778 |

### *A-3 Market growth assumptions (Compounded Annual Growth Rate, %)*

| Product Category | | 2005-2010 | 2010- 2015 |
|---|---|---|---|
| Ducted RES | Non-Article 5 | 3.2 | 2.9 |
| | Article 5 | 8,8 | 8.3 |
| DFS | Non-Article 5 | 4.4 | 3.2 |
| | Article 5 | 10.6 | 7.6 |
| SSAC | Non-Article 5 | 2.5 | -3.9 |
| | Article 5 | 7.5 | 7.9 |
| Commercial | Non-Article 5 | 2.0 | 2.0 |
| | Article 5 | 2.2 | 2.0 |

# 8 Water-Heating Heat Pumps (WHHP)

This section describes equipment and refrigerants for heating water with heat pumps[11]. These heat pumps also may be called Heat Pump Water Heaters (HPWH) in the literature.

## 8.1 Role of Heat Pumps for Water Heating

Heat pumps are used to heat water for space heating (comfort) and for domestic hot water (DHW). Energy consumption for space heating is being reduced by better building insulation, so the energy share for DHW production is continuously increasing. Thus, combined production of space heating and DHW is of increasing interest in a number of countries.

## 8.2 Types of Heat Pumps

### 8.2.1 Vapour Compression Heat Pumps

Most heat pumps work on the principle of the vapour-compression cycle. Heating-only space-heating heat pumps are manufactured in all sizes ranging from 1 kW heating capacity for single room units, to 50-1000 kW for commercial/institutional/industrial applications, and tens of MW for district heating plants. Most small to medium capacity heat pumps in buildings are standardised factory-made units. Large heat pump installations usually are custom-made and are assembled at the site. Chapter 5 of this report presents information on these large heat pumps used, for example, in district heating plants.

Heat sources include outdoor, exhaust, and ventilation air, sea and lake water, sewage water, ground water, earth, industrial wastewater, and process waste heat. Air-source and ground-coupled heat pumps dominate the market. The use of ground water from wells as a heat source is discouraged by many countries or jurisdictions for environmental reasons (ground subsidence, higher-value uses for well water). In countries with cold climates such as northern Europe, some heat pumps are used for heating only. In countries with warmer climates, heat pumps serving hydronic systems with fan coils provide heat in the winter and cooling in the summer. Heat pumps having dual functions, heating water and cooling air simultaneously, also are available.

Domestic hot water heat pumps have become popular recently in countries such as Japan where night-time electricity rates are much lower than daytime rates. European countries have been installing DHW heat pumps for a number of years.

The heat pumps for comfort heating have capacities up to 25 kW. Supply temperatures are $35^{o}$ - $45^{o}$C for comfort heat in new construction and $55^{o}$ - $65^{o}$ C when the heat pump replaces a boiler. Regulations in a number of European countries require domestic water

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[11] Heat pumps that heat air are included in Chapter 7, Stationary Air Conditioners

heaters to produce supply temperatures of 60° to 65° C. Even higher temperatures are attained by some Japanese heat pumps.

Integrated heat pumps can provide some combinations of ventilation, space heating, domestic hot water heating, cooling, and dehumidification. The solutions vary depending upon the climate and building design in different countries and regions /IEA05b/.

### 8.2.2 Absorption Heat Pumps

Absorption heat pumps for hot water space heating are mostly gas-fired and commonly provide cooling simultaneously with heating. Most of the systems use water and lithium bromide as the working pair. They can achieve about 100° C output temperature.

An updated family of absorption machines is available in the European market using an ammonia-water cycle powered by natural gas or LPG. The absorption machines produce hot water for winter heating with much higher efficiency than that of a condensing boiler, and also cold water for summer air conditioning. They are suitable for small/medium size heating and cooling plants which are built up from modular units to produce 17 kW to 87.5 kW of cooling power and 35 kW to 130 kW of heating power. These absorption heat pumps are used in residential and light commercial applications (hotels and offices). Versions available include air-to-water reversible; air-to-water heating only; water-to-water heating and cooling, or heating only; and ground-to-water for heating. The units can operate in the winter down to -20° C, and in the summer up to 45° C. Hot water is produced up to 60° C, and chilled water down to 5° C. Electricity requirements for ancillary power are about 20% those of an equivalent size electric compressor-driven unit /IEA06, JAR06d/.

## 8.3 WHHP Market Characteristics

### 8.3.1 Comfort Heating Applications

Comfort heating dominates heat pump markets in Europe, - mostly with hydronic systems using outside air or the ground as the heat source. Systems are becoming available that provide both floor panel heating and fan coil heating or cooling /JAR06c/. There is increasing use of heat pumps that recover a portion of the heat in exhaust air to heat incoming air in balanced ventilation systems. This reduces the thermal load compared to having to heat the incoming air with primary fuel or electricity.

Air-to-water heat pumps in southern European countries generally are employed with fan-coil units for residential and light commercial use. Hot water delivery temperatures are in the $45^0$ to $55^0$ C range. For hydronic circuits employing radiators, the delivery temperatures are 55° to 75° C. Typical capacities are 10-30 kW.

Excluding heat recovery heat pumps, in 2004 over 84,000 heating-only WHHP were sold in northern Europe (Sweden, Germany, France, Switzerland, and Austria). The categories included here are air/water, water/water, brine/water, DX/water, or direct condensation

/EHP05/. In this context, “brine” means an antifreeze solution such as 25% methanol in water.

New German regulations require all boilers installed before 1978 to be replaced before the end of 2006. As “drop-in” replacements, heat pumps must provide water at $70^o$ C or higher using refrigerants such as propane, R-717, and R-744 ($CO_2$) /JAR05d/.

Heat pumps for combined comfort heating and domestic hot water heating are used in some European countries. Most of the combined systems on the market alternate between space and water heating, but units simultaneously serving both uses are being introduced /IEA04/.

Circulation pumps in hydronic systems can use up to 15% of the electrical energy in a European household. Thus, an effort is under way to develop more efficient circulating pumps. /IEA05a/.

In the mild climate zones of China and Japan, air source heat pumps are used for heating and cooling of residential and commercial buildings with fan coil units. The current market size is about 40,000 units per year, mostly with reciprocating or screw compressors /Yos05/. Commercial size heat pumps up to 700 or 1000 kW capacity are used for retrofit, replacing old chillers and boilers to vacate machine room space and eliminate cooling towers /JAR02b/.

In Japan, water-to-water heat pumps are used extensively in district heating and cooling systems with heat sources such as sea water, river water, and sewage water. Heat recovery systems with water storage for simultaneous heating and cooling in winter are a common practice for large buildings and district systems. Surface water is used as a heat source for heat pumps for district heating and cooling plants in China and South Korea /Yos05/.

The estimated share of the market for air source WHHP heat pumps, as part of the category “small tonnage liquid chillers” (under 250 kW), is 30% in Europe, 20% in China, but much less in the U.S. /JAR05i/.

### 8.3.2 Domestic Hot Water Heating Applications

Germany and Austria have been installing dedicated domestic hot water heat pumps for a number of years /IEA04/

In the residential sector in Japan, tap water heating is mostly done with gas or oil fired heaters today. Energy consumption for tap water heating comprises about 1/3 of total residential energy consumption /Yos05/. In an effort to reduce this energy consumption, the government provides subsidies to introduce high efficiency R-744 water heaters. A system producing $80\text{-}90^o$ C hot water has a COP of 3.0 to 4.0, which is 3-4 times that of an electric water heater.

The first heat pump water heater using R-744 was commercialised in 2001. Now Japanese electric companies use the trademarked brand name "ECO CUTE" for DHW heat pumps using R-744 as the refrigerant. 330,000 R-744 heat pump water heaters are expected to be sold in 2006 /JAR06c/. Typical capacity ranges are 4.5 to 6.0 kW. The penetration of R-744 water heaters is planned by the government to reach 5.2. million units by 2010 /JAR05g/.

New units with multiple functions provide DHW, floor heating, and bathroom heating/ventilation/drying. Heat pumps with higher capacity (23 kW with scroll compressors) heat water instantaneously so only a very small hot water tank is needed /JAR05b, JAR06b, JAR06c/.

The demand for heat pump water heaters using HFC refrigerant, which do not benefit from the government subsidy, also has increased as all-electric homes become more common.

The R-744 units also are of interest to Europeans because they can be operated even when the outside temperature is –20$^{o}$ C /JAR06b/.

## 8.4 Refrigerant Choices for WHHP

In the past, the most common refrigerants for vapour-compression heat pumps have been CFC-12, R-502, HCFC-22, and R-500. In non-Article 5 countries, HCFC-22 still is used in heat pumps, but manufacturers have begun to introduce models using HFC alternatives (HFC-134a, R-410A, R-407C, R-404A), R-744, or hydrocarbons to replace their HCFC-22 models.

In Japan as described above, R-744 is used in domestic hot water heating heat pumps in the residential market. For large water heaters for commercial use, R-410A is employed because R-744 compressors with capacities above 50 kW are not available /JAR04c/.

## 8.5 Inventories of WHHP Equipment and Refrigerant in Service

Data on the installed base of water-heating heat pumps are not readily available for most countries. In particular, data needed to estimate the bank of various refrigerants that are in use in these heat pumps do not seem to exist. Sales of these heat pumps were small around the world prior to 1995, but have increased steadily since that time. The installed base of ground-source heat pumps was estimated to be about 110,000 units in 1998 /IEA99/. The proportion of these units that are used for hydronic heating (typically floor heating) is not specified in the reference but is believed to be high.

The Swedish Energy Agency estimates that over 300,000 heat pumps are in operation there, a small portion of which are "air-to-air" /IEA03/.

More than 90,000 heat pump heating systems were installed in Germany by the end of 2004. Most were water-heating heat pumps /IEA05a/.

By the end of 2004, more than 200,000 water-heating heat pumps had been installed in Japan for comfort heating and domestic hot water applications.

## 8.6 Options for New WHHP Equipment

### 8.6.1 Vapour-compression WHHP Systems with Fluorocarbon Refrigerants

HCFC-22 still is used as one of the main refrigerants in heat pumps, but this refrigerant has been phased out in some countries that elected to phase-out ahead of the schedule set by the Montreal Protocol. Manufacturers have begun to introduce models using HFC alternatives (HFC-134a, R-407C, R-404A, R-410A), hydrocarbons, or R-744 to replace their HCFC-22 models. It is likely that R-407C will serve primarily as a transition refrigerant for heat pumps originally designed for HCFC-22. As new-generation heat pump products are developed, they are likely to employ HFC-134a, R-410A, hydrocarbons, or R-744 as refrigerants.

### 8.6.2 Vapour-compression WHHP cycle with non-HFC refrigerants

*Hydrocarbons*

In most applications HC-290 will yield about the same or slightly higher energy efficiency (e.g., 5-10% higher) as HCFC-22. The performance advantage with HC-290 increases in heat pumps at lower ambient temperatures. When designing new heat pump systems with propane or other flammable refrigerants, adequate safety precautions must be taken to ensure safe operation and maintenance. Several standards that regulate the use of hydrocarbons in heat pumps exist or are being developed in Europe, Australia, and New Zealand. An example is European Standard EN 378 /EN00/. Typical safety measures include proper placement and/or gas-tight enclosure of the heat pump, application of low-charge system design, fail-safe ventilation systems, and gas detector alarm activating systems. An alternative is outdoor installation /ART01/. Guidelines for the use of hydrocarbon refrigerants in static refrigeration and air conditioning systems have been produced /EN00, IR01/. Maximum refrigerant charge sizes for systems located within occupied spaces are 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 5 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 /EN00/.

Several northern European manufacturers are using propane (HC-290) or propylene (HC-1270) as refrigerants in small residential and commercial water-to-water and air-to-water heat pumps. The hydrocarbon circuit is located outdoors using ambient air, earth, or ground water sources, and is connected to hydronic floor heating systems /IEA02/.

*Carbon Dioxide (R-744)*

The transcritical R-744 cycle exhibits a significant temperature glide on the high temperature side. “Glide” is a change in refrigerant temperature at constant pressure during evaporation in a direct expansion (DX) heat exchanger. Such a glide can be of benefit in a counter-flow heat exchanger. Heat pumps generating water temperatures of $90^0$ C have been developed in Japan for home use, although water temperatures of $70^o$ to $80^o$ C are more common. Typical heating capacities are 4.5 kW. Operation at this capacity can be provided by typical units down to - $20^o$ C outside air temperature /JAR06b/. The COP achieved by R-744 water heating heat pumps is 4.0 or slightly higher for “mild climates”. This COP also is attained by R-410A heat pumps, but the highest water temperature available is about $80^o$ C /JAR04b/.

*Ammonia (R-717)*

R-717 has been applied in medium-size and large capacity heat pumps, mainly in Scandinavia, Germany, Switzerland, and the Netherlands /IEA93a, IEA94, Kru93, IEA98/.

Application considerations with R-717 are more complex than for many other refrigerants because R-717 is a strong irritant gas that is slightly toxic, corrosive to skin and other membranes, and flammable. Recommended practice /ISO93, ASH04a/ limits the use of large R-717 systems in public buildings to those systems which utilise a secondary heat transfer fluid, confining the R-717 to the machine room where alarms, venting devices, and scrubbers can enhance safety. Guidelines are available for safe design and application of R-717 systems /IEA98, ANS99, EN00, ASH04a/.

## 8.7 Options for Existing WHHP Equipment

The retrofit options which exist for each heat pump are dependent upon the specific refrigerant for which the heat pump 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 ASHRAE-STD-15 or equivalent other national or international standards such as ISO/DIS 5149. It is also recommended that the manufacturers of the equipment be consulted in any retrofit program.

### 8.7.1 CFC-12 and R-500 Alternatives for WHHP

**HFC-134a** is a retrofit candidate for replacing CFC-12 in heat pumps. Mineral oil in the system must be replaced with polyolester lubricant. Proper cleaning of the heat pump system is crucial because residual mineral oil and moisture may create sludge deposits and serious operating problems. Standardised cleaning methods have been developed and a number of small, medium, and large capacity heat pumps have been retrofitted successfully. Experience shows that capacities and COPs are generally higher after a retrofit from CFC-12 to HFC-134a because of the service and cleaning that the system undergoes during a well-done retrofit.

**HCFC/HFC blends** were developed as a near-term retrofit for CFC-12. These blends can use both mineral oil and alkylbenzene lubricants, which make the cleaning process less critical than for a conversion to HFC-134a. Manufacturers in most cases recommend alkylbenzene to ensure adequate lubrication and oil return to the compressor. The HCFC blends are near-azeotropic so only minor system modifications are needed. Common ternary blends are R-401A, R-401B, and R-409A. Volumetric refrigeration capacity and theoretical energy efficiency are about the same as for CFC-12, but the blends have a temperature glide of $2^o$-$4^o$ K. "Glide" is a change in refrigerant temperature at constant pressure during evaporation or condensation which is found in non-azeotropic refrigerant mixtures.

**Hydrocarbons** have been suggested as retrofits for CFC-12. Retrofits from CFC-12 to hydrocarbons are more likely to be to an HC-290/600a blend than HC-290 because the blend better matches the characteristics of CFC-12. Hydrocarbons are compatible with mineral oil lubricants and materials commonly used in refrigeration equipment so retrofits do not require a lubricant change. Due to flammability, retrofit to hydrocarbons may be limited by local ordinances and safety codes. It is necessary to ensure that all retrofits conform to relevant safety standards as discussed above in Section 8.6.2.

### 8.7.2 R-502 Alternatives for WHHP

**HFC blends** for retrofitting heat pumps using R-502 have been available since 1993. The retrofitting procedure for HFC blends is similar to HFC-134a retrofitting with a change of lubricant from mineral oil to polyolester lubricant. The most frequently used retrofit blend in heat pumps is R-404A, a near-azeotrope with a negligible temperature glide and a volumetric heating capacity that is similar to that of R-502. R-404A may result in an increase in specific energy consumption giving COPs about 5% to 10% lower than R-502 depending on system design and operating temperatures.

**HCFC-22 and HCFC blends** can use either mineral oil or alkylbenzene as a lubricant which makes the cleaning process less critical than for HFC-134a. The volumetric capacity of HCFC-22 is slightly higher than that of R-502 and the system pressures are lower. Thus, it is not necessary to replace the compressor when retrofitting from R-502 to HCFC-22 and only minor system modifications are needed. However, discharge temperatures are higher with HCFC-22 than for R-502 for the same hot water delivery temperatures. At high temperature lifts this may cause operational problems.

A number of HCFC blends were developed as near-term replacements for R-502. Common near-azeotropic blends are R-402A, R-402B, and R-408A. The retrofit procedure is simple and inexpensive.

**Hydrocarbons** such as R-290, a blend of R-290/R-170, and R-1270 are possible retrofit candidates for R-502 in heat pumps. The volumetric refrigeration capacity of propane is almost the same as for R-502 so compressors of similar design and displacement can be used, although modifications for safety may be required.

Retrofitting R-502 heat pumps to use hydrocarbon refrigerants may lead to substantial expense to incorporate safety features in the equipment and modify the machinery room to meet the safety standards imposed for flammable refrigerants. Section 8.6.2 discussed the safety standards that apply to such conversions.

### 8.7.3 HCFC-22 Alternatives for WHHP

**R-407C** is the most common HFC blend used for replacing HCFC-22 in heat pumps. R-407C has a large temperature glide ($5^o$-$7^o$ C) which may lead to liquid slugging in the compressor when a thermostatic expansion valve is used. The saturation pressure and volumetric cooling capacity are about the same as for HCFC-22. The discharge temperatures are lower with R-407C than with HCFC –22, as is the COP of systems after retrofitting. R-407C has retrofitting procedures similar to HFC-134a which include a change of lubricant from mineral oil to polyolester lubricant.

**Hydrocarbons** R-290, a blend of R-290/170, and R-1270 are possible retrofit candidates for HCFC-22. The volumetric refrigerating capacity of propane is nearly the same as that of HCFC-22 so compressors of similar design and displacement can be used, although modifications for safety may be required. The maximum achievable condensing temperature when using standard 25-bar equipment increases from about $61^0$C to $68^0$C. Hydrocarbons are compatible with mineral oil and the materials commonly used in refrigeration equipment. Section 8.6.2 discussed the safety issues that arise in a conversion from HCFC-22 (and R-502) to a hydrocarbon refrigerant. Heat pumps in Germany have been converted successfully to propane /HPC93c/.

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# 9 Chillers

## 9.1 Role of Chillers

Comfort air conditioning in large commercial buildings and building complexes (including hotels, offices, hospitals, and universities) is commonly provided by water chillers coupled with chilled water distribution and air handling and distribution systems. Chillers also are used for process cooling in industrial applications. Chillers cool water or a water/antifreeze mixture that is pumped through a heat exchanger in an air handler or fan-coil unit for cooling and dehumidifying the air.

## 9.2 Types of Chillers

Two types of water chillers are available: vapour-compression and absorption chillers.

### 9.2.1 Vapour-Compression Chillers

The principal components of a vapour-compression chiller are a compressor driven by an electric motor (or less commonly an engine or turbine), a liquid cooler (evaporator), a condenser, a refrigerant, a refrigerant expansion device, and a control unit. The refrigerating circuit in chillers usually is factory sealed and tested; no connection between refrigerant-containing parts is required on site by the installer. Leaks during installation and use are minimised accordingly. An exception is for very large units, for which the compressors and heat exchangers are separated for shipping due to their large sizes.

Vapour-compression chillers are identified by the type of compressor they employ. They are classified as centrifugal (turbo) compressors 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: water-cooled, air-cooled, and evaporatively-cooled.

Water-cooled chillers generally employ cooling towers for heat rejection from the system. Air-cooled chillers are equipped with refrigerant-to-air finned-tube condenser coils and fans to reject heat to the atmosphere. Evaporatively-cooled chillers are similar to water-cooled except that the cooling tower is integrated into the unit and the heat from the refrigerant is rejected directly to the air through a closed-loop cooling tower. A condenser water system is not required. Water-cooled systems can be more efficient under many operating conditions due to lower condensing temperatures, resulting from the fact that wet bulb temperatures of the air are almost always lower than dry bulb temperatures.

Recently-improved part-load efficiency of air-cooled chillers causes them, in some instances, to be more efficient than water-cooled chillers on an annualised basis. The selection of water-cooled, air-cooled, or evaporatively-cooled chillers for a particular application varies with regional conditions, owner preferences, and project budget.

### 9.2.2 Absorption Chillers

The energy source for absorption chillers is heat provided by steam, hot water, or a fuel burner. In absorption chillers the compressor and motor of the vapour-compression cycle are replaced by two heat exchangers (a generator and an absorber) and a solution pump. The refrigerant in these systems commonly is water and the absorbent usually is lithium bromide, though lithium chloride also was common in the past and is still used infrequently. Small absorption chillers may use an alternative fluid pair, such as ammonia as the refrigerant and water as the absorbent.

Absorption chillers are identified by the number of heat input levels they employ (i.e., single-, double-, or triple effect), and whether they are direct-fired with a burning fuel or use steam or hot water as the heat energy source.

Single-effect absorption applications are limited typically to sites that can utilise waste heat in the form of hot water or steam as the energy source or where boilers must be run year-round such as in hospitals. Other sites include co-generation systems where waste engine heat or steam is available. Double-effect machines can be driven by hot water or steam or can be direct-fired. Triple-effect machines have been developed /JAR06b/.

Double-effect absorption chillers can have primary-energy-based efficiencies that approach 60 to 65% of those of vapour-compression systems. For example, double-effect absorption chillers can have a cooling coefficient of performance (COP)[12] of up to 1.5 based on source energy input. Electrical vapour-compression systems 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 which are predominant.

Table 9-1 lists the cooling capacity range offered by single units of each type of chiller (many applications use multiple chillers).

***Table 9-1 Chiller Capacity Ranges***

| **Chiller Type** | **Capacity Range (kW)** |
|---|---|
| Scroll and reciprocating water-cooled | 7 - 1,600 |
| Screw water-cooled | 140 - 2,275 |
| Positive displacement air-cooled | 35 - 1760 |
| Centrifugal water-cooled | 210 - 30,000 |
| Centrifugal air-cooled | 420 - 1,150 |
| Absorption | Less than 90, and 140 - 17,500 |

Centrifugal chillers were the most common type of chillers above 700 kW capacity for many years. Reciprocating compressors were used in smaller chillers. Beginning in the mid-1980s, screw compressors became available as alternatives to reciprocating

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[12] COP for chillers is the ratio of cooling capacity (kW) divided by energy input (kW).

compressors in the range from 140 to 700 kW and as alternatives to centrifugal compressors up to about 2275 kW. Scroll compressors were introduced about the same time and have been used as alternatives to reciprocating compressors in the range from 7 to over 90 kW per compressor. Scroll compressors are used in chillers up to 1200 kW with 1 to 12 compressors per unit with multiple refrigerant circuits /JAR04e/. Centrifugal compressors with capacities of 210-380 kW recently entered the market as alternatives to screw compressors for water-cooled and air-cooled chiller applications. Features such as direct-variable-high-speed electronic drives and oil-free operation have been introduced with these smaller centrifugal compressors /JAR05i/.

## 9.3 Measures of Chiller Efficiency or Energy Use

One of the key criteria used in describing chillers is the COP. Other efficiency parameters are kW/ton (electrical power consumption in relation to cooling capacity) and EER or Btu/Wh (cooling capacity related to power consumption).

Each type of chiller and refrigerant combination has a best-in-class COP level that can be purchased. This COP level tends to increase as time passes and products are improved. The chillers with the best COPs tend to be higher in cost because they employ larger heat exchangers and other special features. In the absence of minimum efficiency standards, many purchasers choose to buy lower-cost, lower-COP chillers.

Full-load COP is commonly used as a simple measure of chiller efficiency. The COP establishes peak demand which influences both overall power supply costs and the electricity demand costs paid by users.

As recognition grew of the dominant contribution of the energy consumption of chillers to their global warming impact, more attention began to be paid to the energy efficiency of chillers at their more common operating conditions. Manufacturers developed means such as variable-speed compressor drives, advanced controls, and efficient compressor unloading methods to optimise chiller efficiency under a wide range of conditions. In the USA, ARI developed an additional performance measure for chillers called the Integrated Part Load Value (IPLV) described in ARI Standard 550/590 /ARI03/. The IPLV metric is based on weighting the COP at four operating conditions by the percent of time assumed to be spent at each of four load fractions (25, 50, 75, and 100%) by an individual chiller. The IPLV metric gives credit for chiller energy-reducing features, which are becoming commonly-used, but are not reflected in the full-load COP. A similar part-load parameter, ESEER, has been developed in Europe by Eurovent for performance certification. Details are given in CEN TS 14825. China implemented an IPLV standard in 2005 (GB 50189-2005). Japan also is developing a method, which may include multiple chillers.

Different views exist about whether full-load or IPLV ratings offer the better indicator of typical seasonal energy use.

## 9.4 Trends in Chiller Energy Efficiency

Energy efficiency is the primary environmental consideration for chillers. While refrigerants each have a Global Warming Potential (GWP) relative to $CO_2$ (see Chapter 2, Refrigerants), refrigerants do not 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 $CO_2$ emitted in the combustion of fossil fuels generating the electricity to drive them. High annualised chiller efficiencies reduce global warming proportionally.

Today's average 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. 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. Replacement chillers integrated with building retrofits can pay for themselves in as little as two or three years, with a typical return on investment of 20 to 35% in locations with high seasonal cooling loads and/or high electricity prices. Generally, the added cost of the highest efficiency chillers is paid back through energy savings alone. Today's state of the art building automation systems further reduce operating and maintenance costs by monitoring and controlling everyday building operations and by notifying managers of small problems before they become costly problems.

World Bank-ICF /ICF03/ data indicate that the average full-load large water-cooled chiller COPs in Article 5 countries vary from 5.0 to 5.5. This most likely is due to the slower replacement of older CFC chillers in Article 5 countries. Replacing these chillers could reduce energy consumption since new chillers could be more energy efficient.

## 9.5 Refrigerant Choices for Chillers

### 9.5.1 Positive Displacement Chillers

**Screw chillers** generally employed HCFC-22 as the refrigerant when they were first produced in the mid-1980s. In the last several years, HFC-134a chillers have been introduced by a number of manufacturers. The trend has been to replace HCFC-22 product offerings with HFC-134a products when manufacturers introduce new product lines.

Screw chillers using a higher pressure refrigerant, R-410A, also have been introduced recently, largely in Europe. Screw chillers using ammonia as the refrigerant are available from some manufacturers. They are found primarily in northern European countries. The numbers produced are small compared to chillers employing HCFC-22 or HFCs.

Air-cooled and water-cooled screw chillers below 700 kW commonly employ evaporators with refrigerant flowing inside the tubes and chilled water on the shell side.

These are called direct-expansion (DX) evaporators. Chillers with capacities above 700 kW generally employ flooded evaporators with the refrigerant on the shell side. Flooded evaporators generally require larger refrigerant charges than DX evaporators, as shown in Table 9-2 below, but permit higher efficiencies due to closer approach temperatures. Sprayed and falling film evaporators also are used. These types of evaporators typically require less refrigerant charge in the system than flooded evaporators.

Manufacturers are employing variable speed drive devices with screw chillers. The application of variable speed lowers annualised energy consumption, but can decrease full-load efficiency due to drive losses. The benefits of screw compression (efficient part load operation and lack of surge limits present in centrifugal compressors) are combined with the benefits of variable speed drives (efficient part loading and simpler compressor design) to yield lower seasonal energy consumption in water cooled systems for any of the refrigerants above.

**Scroll chillers** are produced in both water-cooled and air-cooled versions using DX evaporators. Refrigerants offered include HCFC-22, HFC-134a, R-410A, and R-407C. R-407C has been used as a transition refrigerant, especially in countries where HCFC-22 has been phased out by regulations in advance of the Montreal Protocol deadlines. R-407C continues to be offered in chillers from a number of manufacturers. New scroll chiller products are using R-410A,

For capacities below 150 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.

**Reciprocating chillers** are produced in both water-cooled and air-cooled versions using DX evaporators. Air-cooled versions have increased market share in recent years. Most of the volume increase is moving to scroll and screw compressors. Reciprocating chiller markets are decreasing.

Prior to the advent of the Montreal Protocol, some of the smaller reciprocating chillers (under 100 kW) were offered with CFC-12 as the refrigerant. Most of the smaller chillers, and nearly all the larger chillers, employed HCFC-22 as the refrigerant. After the advent of the Montreal Protocol, new reciprocating chillers employed HCFC-22, R-407C, and to a small extent HFC-134a R-290 (propane) or R-1270 (propylene). Some water-cooled reciprocating chillers were manufactured with ammonia as the refrigerant, but the number of these units is very small compared to the number of chillers employing fluorocarbon refrigerants. As with scroll chillers, the use of brazed-plate heat exchangers reduces system volume and system charge.

The Table 9-2 below shows approximate charge levels for positive displacement chillers of each type with several refrigerants. (This table does not apply to systems with remote condensers.)

*Table 9-2 Positive displacement chiller refrigerants and average charge levels*

*Note: Charge levels vary over a range of values for each refrigerant and type of chiller depending on capacity levels, target energy efficiency levels, and variations in system design from one manufacturer to another.*

| Refrigerant and Chiller Type | Evaporator Type | kg/kW |
|---|---|---|
| HCFC-22 and HFC -134a screw and scroll chillers | DX | 0.27 |
| R-410A and R-407C scroll chillers | DX | 0.27 |
| HCFC-22 and HFC-134a screw chillers | Flooded | 0.35 |
| HCFC-22 reciprocating chillers | DX | 0.26 |
| R-717 (ammonia) screw or reciprocating chillers (1) | DX | 0.04-0.20 |
| R-717 (ammonia) screw or reciprocating chillers(1) | Flooded | 0.20-0.25 |
| Hydrocarbons | DX | 0.14 |

(1) Charge levels per unit of capacity for R-717 chillers tend to decrease with capacity and are lowest for plate-type heat exchangers rather than with tube-in-shell. Charge levels of 0.10 kg/kW are typical for overfed plate evaporators. Overfed systems pump excess liquid through the evaporator, separate vapour from the liquid at the evaporator discharge, and recirculate it to the evaporator inlet.

### 9.5.2 Centrifugal Chillers

Centrifugal chillers are manufactured in the United States, Asia, and Europe. Prior to 1993, these chillers were offered with CFC-11, CFC-113, CFC-12, CFC-114, R-500, and HCFC-22 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 refrigerants containing CFCs (such as R-500) essentially ended in 1993 in developed countries. Centrifugal chillers using HCFC-22 rarely were produced after the late 1990s.

The primary refrigerant alternative for CFC-11 is HCFC-123, and for CFC-12 and R-500 is HFC-134a. These refrigerants began to be used in centrifugal chillers in 1993 and continue to be used in 2006 in new production chillers.

Table 9-3 shows the range of cooling capacities offered for centrifugal chillers with each of these refrigerants.

*Table 9-3 Centrifugal Chiller Refrigerants*

| Refrigerant | Capacity Range (kW) |
|---|---|
| CFC-11 | 350 – 10,000 |
| CFC-12 | 700 – 11,000 |
| R-500 | 3,500 - 5,000 |
| HCFC-22 | 2,500 - 35,000 |
| HCFC-123 | 700 - 15,000 |
| HFC-134a | 210 - 30,000 |
| HFC-245fa | 2,600-9,200 |

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. New naval chillers primarily use HFC-134a but no manufacturer has introduced new chillers using HFC-236fa.

## 9.6 Inventories of Chiller Equipment and Refrigerant in Service – Centrifugal Chillers

Table 9-4 shows the centrifugal chiller population in a number of countries. This table provides estimates of the refrigerant bank in these chillers, assuming an average cooling capacity of 1400 kW in most cases and approximate values for the refrigerant charge for each refrigerant. The refrigerant charge for a given cooling capacity may vary with the efficiency level of the chiller. For any given refrigerant, higher efficiency levels often are associated with larger heat exchangers and, therefore, larger amounts of charge.

*Table 9-4 Centrifugal chiller population and refrigerant inventory*

| Country or Region | Refrigerant | Avg. Capacity (kW) | Avg. Charge Level (kg/kW) | No. Units | Refrigerant Bank (tonnes) | Source of Unit Nos. |
|---|---|---|---|---|---|---|
| **USA** | CFC-11 | 1400 | 0.28 | 33,300 | 13,050 | /ARI05/ |
| **USA** | HCFC-123<br>HFC-134a | 1400<br>1400 | 0.23<br>0.36 | 28,350<br>28,350 | 9130<br>14,300 | /JAR05a/ with 50% split |
| **Canada** | CFC-11 | 1400 | 0.28 | 3377 | 1324 | /HRA06/ |
| **Canada** | HCFC-123<br>HFC-134a | 1400<br>1400 | 0.23<br>0.36 | 637<br>637 | 205<br>320 | /HRA03/ with 50% split |
| **Japan** | CFC-11<br>HCFC-123 and HFC-134a | 1100<br>1600 | 0.40<br>0.40 | 7,000<br>6700 | 3,080<br>4290 | /JAR05a/ |

| | | | | | | |
|---|---|---|---|---|---|---|
| **India** | CFC-11 | 1450 | 0.28 | 1100 | 447 | /UNE04/ |
| **China** | CFC-11<br>CFC-12<br>HCFC-22<br>HCFC-123<br>HFC-134a | 65% of total are 1400-2450, rest are 2800-3500: 2450 avg. | 0.28<br>0.36<br>0.36<br>0.23<br>0.36 | 3700<br>338<br>550<br>3200<br>3250 | 2540<br>300<br>485<br>1800<br>2870 | /UNE04/<br>/DIG04/ |
| **Brazil** | CFC-11<br>CFC-12 | 1350<br>1450 | 0.28<br>0.36 | 420<br>280 | 160<br>145 | /UNE04/ |
| **17 Developing Countries** | CFC-11<br>CFC-12 | | Avg. unit charge = 364 kg | 11,700 | 4000 | /UNE04/ |

Source for charge levels: /AFE97/; for HFC-134a, /ADL02/

In the USA, the U.S. Environmental Protection Agency estimates that in 2005 there were 165,000 chillers (including centrifugal chillers) employing HCFC-22 as their refrigerant. The number of HCFC-22 chillers still in operation is projected to be 130,000 in 2010, 80,000 in 2015, and 17,000 in 2020 as the use of this refrigerant is phased out. /ICF05/

## 9.7 World Market Characteristics

### 9.7.1 Overview

Data on the market for chillers comes from several sources. ARI compiles statistics for several types of chillers in the USA for both domestic and export markets. The Japan Air-Conditioning, Heating, and Refrigeration News (JARN) provides statistics for Japan and estimates for other countries and regions.

The Japan Air-Conditioning, Heating, and Refrigeration News /JAR04e/ estimates that:

- Among the four major air conditioning markets for water-cooled screw and centrifugal chillers larger than 250 kW, the U.S. and Chinese markets each account for 40%, while Europe and Japan account for about 10% each
- The market for large absorption chillers is highly concentrated in Japan, China, and Korea with the U.S. and Europe as the remaining significant markets.
- The world market for smaller chillers (with hermetic reciprocating, scroll, and screw compressors) is much larger in numbers than for the other chiller types. The majority are in Europe and Asia.

Table 9-5 summarises the market for chillers in 2001. It shows that air-cooled chillers represent nearly 75% of the number of units in the positive displacement category. Chillers larger than 100kW are dominant in the Americas, the Middle East, and Southern Asia while smaller air-cooled chillers and chiller heat pumps are more common in East Asia and Europe for residential and light commercial use.

*Table 9-5 World chiller sales in the year 2001 (number of units)*

| Chiller Type | North and South America | Mideast, S. Asia, Africa | East Asia and Oceania | Europe | World Total |
|---|---|---|---|---|---|
| Pos. Displ. | 16,728 | 11,707 | 66,166 | 77,599 | 172,200 |
| Air cooled | 12,700 | 7,749 | 43,714 | 61,933 | 126,096 |
| Water cooled | 4,028 | 3,958 | 22,542 | 15,666 | 46,104 |
| <100 kW | 2,721 | 1,678 | 48,444 | 58,624 | 111,467 |
| >100 kW | 14,007 | 10,029 | 17,722 | 18,975 | 60,733 |
| Centrifugal | 5,153 | 413 | 2,679 | 664 | 8,908 |
| Absorption >350 kW | 261 | 289 | 5,461 | 528 | 6,539 |
| Total chillers | 22,142 | 12,409 | 74,306 | 78,791 | 187,648 |

Source: /JAR02b/

According to BSRIA's "World AC Study", the estimated size of the world centrifugal chiller market in 2004 was approximately 8500 units, including 3500 in the U.S., 1500 in China, 550 in Europe, 400 in South Korea and Japan, and 300 in the Taiwan region /JAR05h/. Details about chiller sales in Europe are given in Table 9-6.

*Table 9-6 Chiller Sales Statistics for Europe in 2005. /Eur05/*

**1 - Rotary, reciprocating, scroll, screw, open, hermetic, semi-hermetic centrifugal with capacity per compressor below 500 kW**

***Number of units sold***

| Cooling capacity range in kW | Water cooled | Condenserless | Air-cooled non ducted | Air-cooled ducted | Heat pumps (reverse cycle) non ducted | Heat pumps (reverse cycle) ducted | Total |
|---|---|---|---|---|---|---|---|
| < 17,5 | 2027 | 182 | 9243 | 463 | 9083 | 394 | 21392 |
| 17,5 - 50 | 1248 | 541 | 6908 | 1192 | 4492 | 426 | 14807 |
| 51 - 100 | 709 | 517 | 3872 | 761 | 1707 | 256 | 7822 |
| 101 - 200 | 941 | 456 | 3509 | 499 | 1201 | 127 | 6733 |
| 201 - 350 | 835 | 299 | 2784 | 209 | 618 | 21 | 4766 |
| 351 - 500 | 523 | 137 | 1462 | 43 | 126 | 2 | 2293 |
| 501 - 700 | 548 | 51 | 1331 | 46 | 73 | 4 | 2053 |
| 700 - 900 | 255 | 13 | 644 | 4 | 14 | 1 | 931 |
| > 901 | 572 | 9 | 738 | 6 | 2 | 2 | 1329 |
| **Total** | 7658 | 2205 | 30491 | 3223 | 17316 | 1233 | 62126 |

*Cooling capacities are at nominal Eurovent conditions for air conditioning application*

***Refrigerant used - all applications as given above***

***(not incl centrifugal and absorption chillers)***

| | R410A | R407C | HFC-134a | HFC (other) | R-717 (ammonia) | Hydrocarbon |
|---|---|---|---|---|---|---|
| **Number of units** | **6223** | **45746** | **8424** | **522** | **36** | **167** |

**Unit total is slightly lower in this table because some companies did not provide refrigerant information.**

### 2 - Centrifugal chillers - hermetic - open type

| Cooling capacity range in kW | Water + air cooled |
|---|---|
| < 1500 | **54** |
| > 1501 | **241** |
| **Total** | **295** |

*Cooling capacities are at nominal Eurovent conditions for air conditioning application*

### 3 - Absorption chillers, water and air-cooled, all type of solutions, all applications

| Cooling capacity range in kW | Single effect (water or steam) | Double effect (water or steam) | Direct gas fired |
|---|---|---|---|
| < 100 | **4** | **0** | **0** |
| 101 - 500 | **10** | **0** | **26** |
| 501 - 1000 | **19** | **1** | **2** |
| > 1001 | **47** | **0** | **1** |
| **Total** | **80** | **1** | **29** |

*Cooling capacities are at nominal Eurovent conditions for air conditioning application*

### 9.7.2 Some Developments in the Market

In some countries a portion of the commercial air conditioning market appears to be moving away from small chillers toward ductless single-package air conditioners or ducted unitary systems for lower installation cost /JAR02b/ and increased flexibility of floor-by-floor large building systems. Also, the market is shifting from water-cooled to air-cooled chillers and, as of 2005 in the USA, the air-cooled market became larger than the water-cooled market in total kW of capacity shipped.

In Italy, hydronic cooling systems (smaller capacity air-cooled chillers or air source heat pumps) are widely used. More than 25,000 air cooled chillers less than 17 kW in capacity were produced in 2004. They are combined with fan coil units as low as 10 kW capacity for residential and light commercial buildings. Passive cooling with chilled beams is an increasing market. Variable Refrigerant Flow (VRF) systems are becoming a competitor to hydronic cooling. (VRF systems employ multiple indoor units supplied with refrigerant by a single outdoor unit, and are available in cooling-only and heat pump versions.) France also has a market for small, self-contained packaged chiller units. Of the 13,000 chillers sold in France in 2004, one third was rated at 17.5 kW or less. The increasing popularity of passive cooling, particularly underfloor coil systems which combine heating and cooling using the chiller as a heat pump, contributed to this market /JAR05i/. Passive cooling (chilled beams or underfloor coil systems) can be used only in regions where humidity is sufficiently low that condensation does not occur on the cooled surfaces.

In northern Europe, larger chillers of the scroll or screw types are widely used with air handling units and fan coil units in commercial buildings /JAR04e/.

Thermal energy storage, in the form of low temperature chilled water or ice, is employed in Japan where power utilities promote the use of overnight electricity by giving large discounts – down to 25 to 40% of the daytime rate – for operating electrically-driven chillers overnight /JAR04e/. Lower night-time temperatures allow chillers to operate more efficiently than during the day, reducing energy consumption. Less chiller capacity may be required, reducing capital costs. Daytime peaks of power consumption are reduced, forestalling the need to build new power plants /JAR04c/. If cooling is needed for an extended period, such as 16-24 hours/day, the required chiller capacity will be increased if an energy storage system is used. This also is true where there is little temperature difference between day and night as in some maritime climates. It is estimated that there are 20,000 thermal storage systems in Japan and growing demand for ice thermal storage in South Korea and China with an estimated 1000 systems installed /Yos05a/.

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

### 9.7.3 Absorption Chiller Market Characteristics

Absorption chillers are manufactured primarily in Japan, China, and South Korea. A smaller quantity of absorption chillers is manufactured in North America. Absorption chiller energy use can be compared to electrical chiller energy use by calculations based on primary energy.

Absorption systems 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 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.

Single-effect absorption applications typically are limited to sites that can utilise waste heat in the form of hot water or steam as the energy source. Such sites include co-generation systems where waste engine heat or steam is available. Double-effect absorption chillers, driven by steam or hot water or directly fired by fossil fuels, began to be produced in large numbers in Asia (primarily in Japan) for the regional market during the 1980s. Double-effect chillers began to be produced in North America shortly afterward, commonly through licensing from the Asian manufacturers. Small single-effect gas-fired absorption chillers with capacities below 90 kW are produced in Europe and North America using ammonia and water as refrigerant and absorbent, respectively. /JAR06c/

Asia today has the largest demand for water/lithium bromide absorption systems with an estimated share of more than 90% of the gross world market of 10,000 units. /Yos05b/

China is the world’s largest absorption chiller market (approximately 4000 units in 2004). /JAR05f/. Demand for gas-fired absorption chillers and chiller-heaters (absorption chillers also producing hot water) is growing because of electrical power shortages and availability of natural gas from China’s western provinces.

In Japan, gas cooling system development and commercialisation are strongly subsidised by gas companies to promote gas consumption during the summer season /JAR04e/. Japan is the second-largest absorption chiller market after China, shipping an estimated 1700 units above 350 kW in 2004 and about 1000 units below 350 kW. About 50% are used for replacements and 50% for new installations /JAR05h/. Direct-fired units represent 90% of the absorption chiller market in Japan and South Korea. In Japan, the energy sources are 60% gas, 30% oil, and 10% steam or hot water /JAR04e/.

In South Korea the demand for absorption chillers in 2003 dropped below 1000 units after reaching 1500-2000 units per year in the mid 1990’s /JAR04d/.

Use of water-LiBr absorption chillers in trigeneration systems has been implemented in some countries. Trigeneration is the concept of deriving three different forms of energy from the primary energy source, namely, heating, cooling and power generation. This is also 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

Absorption chillers are inherently larger and more expensive than vapour-compression chillers and so have had only limited success in the western market. A key factor in the economic viability of absorption is the penalty on electric vapour-compression chillers imposed by electricity demand/connection charges, which are common in several countries for commercial and industrial customers.

### 9.7.4 Situations in Specific Countries or Regions

**China**

Market conditions in China are of special interest because of the recent rapid development of its internal market, chiller manufacturing capabilities, and export potential. The centrifugal chiller population in China is included in Table 9-4. Significant growth began in the 1990's. Most centrifugals before 1995 were imported. Increasing numbers of chillers were produced in China after 1995 by factories using U.S. designs, primarily using HCFC-123 (30%) and HFC-134a (70%) /ICF03/

For the total of all types of chillers, China is now the largest market in the world with sales of 34,000 units in 2001 and growth of over 8.5%/year. The main market is East China with a growing replacement market. Over half of all chiller sales are now reversible heat pumps that can provide cooling and heating. Screw and scroll chiller sales, mostly using HCFC-22, are rising as their technology becomes more familiar to the major design institutes. China has a major residential market for chillers with fan coil units /BSR01/.

**India**

In 2005, 2249 /JAR05i/ chillers for comfort conditioning were manufactured in India including 782 reciprocating chillers, 807 scroll chillers, 301 screw chillers, and 334 absorption chillers. 1500 chillers were manufactured for industrial process applications. These primarily were reciprocating chillers. In addition, about 1000 chillers were imported, including 964 screw chillers and 79 centrifugal chillers /JAR05i/. Inventory estimates for centrifugal chillers and refrigerants appear in Section 9.6.

**Southeast Asia** /JAR01/

The chiller market size has been estimated in Hong Kong, Malaysia, Thailand, Singapore, Indonesia, and the Philippines. The market for reciprocating and screw chillers in most of these countries is on the order of several hundred units. Centrifugal chiller demand is between several tens of units and a few hundred units per year.

**Latin America** /JAR05i/

The chiller market in Latin America is very small with Brazil being the most important market. The total market size for centrifugal chillers is 240 to 250 units and for absorption chillers 70 to 80 units. Chillers using reciprocating compressors are still the most common, accounting for just over 50% of the market in terms of volume. Scroll and screw chillers are beginning to increase market share. Chillers using these positive displacement compressors account for 3200 to 3300 units with around 6% expansion every year.

## 9.8 Options for New Chiller Equipment

The selection of alternative refrigerants to replace CFCs required a balance among thermophysical properties, chemical and thermal stability, global environment issues of stratospheric ozone depletion and global warming, local safety issues such as toxicity and flammability, performance, and cost /Cal97/. Even within the single issue of global warming, there is a need to account for the direct effects of refrigerant releases to the atmosphere and the energy-related (*indirect*) effect. The indirect effect stems from the emission of carbon dioxide and other greenhouse gases during generation of power to operate the chillers. The energy-related effect depends on the system efficiency, hours of operation, fuel mix, and transmission losses. For chillers, the energy-related effect dominates over the direct effect. The interplay of the refrigerant release and energy-related effect is captured in combined measures such as Total Equivalent Warming Impact (TEWI) or Life-Cycle Climate Performance (LCCP). These measures are discussed in a number of references /Cal93a, Cal93b, Cal99, Fis91, Kui00, and San97/.

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% are reported for measured centrifugal chillers /Cal99, Cal02/.

### 9.8.1 Options for New Positive Displacement Compressor Chillers

#### *9.8.1.1 HCFC-22*

Due to its low ozone depletion potential (ODP), HCFC-22 was viewed as a part of the solution to the problems posed by phase-out of CFC-12 and other CFCs. However, the Copenhagen amendments to the Montreal Protocol called for the phase-down of HCFCs starting in 2004 in developed countries leading to phase-out for new equipment in 2020. Limited production is allowed for service use until 2030. Installed refrigerants, stocked inventories, and amounts recovered from retired equipment may be used to service existing equipment indefinitely where national rules permit. There is a freeze in HCFC production in developing countries starting in 2016 with complete cessation in 2040. The phase-out of individual HCFCs is being managed differently in various countries. A number of European countries mandated the phase-out of HCFC-22 beginning in 2001. The USA also accelerated the phase-out of HCFC-22. Beginning January 1, 2010 no production or importing of HCFC-22 will be permitted for use in new equipment.

The planned HCFC-22 phase-out led to intense activity to find and characterise appropriate alternates. The refrigerants that were found to be most promising for positive displacement chillers, in terms of their ability to satisfy the performance and safety criteria, were HFC-134a and HFC blends. For systems with flooded evaporators, common in chillers larger than 700 kW, HFC-134a generally was chosen as a successor to HCFC-22. Blends considered for use in flooded evaporators are those which are azeotropes or near-azeotropes such as R-410A which has a much higher pressure than HCFC-22. The higher pressure level requires substantial redesign of system components to meet pressure safety codes. R-410A allows a reduction in refrigerant charge for a given cooling capacity and offers improved heat exchanger performance.

#### *9.8.1.2 HFC-134a*

HFC-134a is used in positive displacement water chillers as a replacement for CFC-12 and a successor to HCFC-22. The volumetric flow characteristics of HFC-134a are similar to those for CFC-12, so the compressor and component sizes are similar. Thus, chiller costs were not affected significantly by the change from CFC-12 to HFC-134a. HFC-134a requires larger compressor displacement than HCFC-22 for the same cooling capacity. However, HFC-134a compressor development has progressed to the point that HFC-134a screw chiller costs are fully competitive with HCFC-22 screw chiller costs.

The direct global warming effect of HFC-134a is about 13% of that of CFC-12. The theoretical cycle efficiency is about 2% lower than for CFC-12. However, the heat transfer characteristics of HFC-134a and chiller design advances often offset the lower cycle efficiency. Thus, the TEWI due to HFC-134a in new equipment is less than that of CFC-12 in older equipment. The direct global warming effect of HFC-134a is about 79% of that of HCFC-22. The cycle efficiency is similar for the two refrigerants.

HFC-134a chillers are being marketed with flooded evaporators and economiser sub-cooling for better COP and reduced volumetric flow rate (i.e., reduced compressor size). Increases in compressor efficiency and cycle improvements are being implemented to improve the performance of HFC-134a chillers.

#### *9.8.1.3 R-407C*

Zeotropic mixtures offer the greatest flexibility in blending refrigerants to approximate the physical and thermodynamic properties of HCFC-22, particularly the general trend of the pressure/temperature relationships. The zeotropic mixture R-407C is being used as a replacement for HCFC-22 in direct expansion (DX) systems primarily in Europe and Asia. However, unfavourable changes in heat transfer necessitate larger, more expensive heat exchangers to maintain performance.

In DX evaporators some of this difficulty is offset by using the glide characteristic of R-407C to advantage in counter-flow heat exchange in brazed-plate or single-pass DX evaporators. “Glide” in these heat exchangers is a change in refrigerant temperature at constant pressure during evaporation. The glide also can be accommodated in the traditional cross-flow air-side heat exchangers of air-cooled chillers.

R-407C with its appreciable temperature glide (4-5 K) is not suitable for use in flooded evaporators that predominate in larger chillers. A flooded evaporator is essentially isothermal and isobaric, so the "glide" tendency is exhibited as a composition change between the liquid and vapour phases in the evaporator. These tube-in-shell evaporators keep the refrigerant on the shell side so that the water can be confined to the inside of the tubes, thus facilitating periodic cleaning of the water tubes to eliminate efficiency-destroying mineral build-up.

R-407C has served as a transition refrigerant in certain countries. It has allowed manufacturers in Europe and Asia to offer chillers with an HFC refrigerant instead of HCFC-22 by making modest changes in their products. R-407C continues to be offered in chillers from a number of manufacturers. Others are moving to the use of R-410A and HFC-134a in new-generation chiller designs.

#### *9.8.1.4 Other HFC based refrigerant blends: R-404A, R-410A, R-507A, other HFC blends, HFC-32*

Azeotropic and near-azeotropic mixtures such as R-404A, R-507A, and R-410A have been considered as possible HCFC-22 replacements in other applications. However, no non-flammable azeotrope has been found that matches both the pressure-temperature relationships of HCFC-22 and other selection criteria. Blends of HFC-32 and HFC-125 (e.g., R-410A) have COPs similar to HCFC-22 in a DX system, but at a significantly higher pressure. Substantial product redesign and retooling, with associated major financial investments, are required to use R-410A in chillers. These investments are being made and R-410A is displacing the use of R-407C in smaller chillers (less than 350 kW capacity). Benefits offered by R-410A include refrigerant charge reduction of as much as 40% compared to HCFC-22 systems and improved heat transfer characteristics which allow heat exchanger sizes to be reduced. The use of R-410A is paced in part by the availability of new compressors with the capability to handle the high pressure levels of R-410A.

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 significant performance benefits compared to R-407C or R-410A. Their market penetration 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, and the reluctance of chiller manufacturers to warrant their equipment with refrigerants they have not tested thoroughly (a costly process).

The refrigerant HFC-32 is used as a component in blends such as R-410A. It has been proposed for use as a refrigerant by itself (and in azeotropes with n-butane and isobutane) because it has a comparatively low GWP and good energy efficiency in the vapour-compression cycle. Disadvantages include operating pressure levels higher than for HCFC-22 and flammability. It is classed as an A2 refrigerant under ASHRAE Standard 34 /ASH04b/. Systems using HFC-32 have not been commercialised yet.

#### *9.8.1.5. Carbon dioxide (R-744) in the transcritical cycle*

R-744 is being advocated for a wide range of potential applications using a transcritical cycle. In this cycle the pressure from the compressor discharge to the expansion device inlet is maintained above the critical pressure of R-744 (7.38 MPa or 72 bar at 31°C), compared to HCFC-22 which has a condensing pressure of 1.2 MPa or 12 bar at 30°C. R-744 has poor efficiency as a refrigerant in most chiller applications /ASH01/. Switching to R-744 from the fluorocarbons used as refrigerants today would increase total global warming.

There has been no commercial application of R-744 in chillers, to date but it has been proposed /Pea06/. The high pressure is a particular challenge for larger compressors due to the need for safety margins that are a significant multiple of the design working pressure. These safety margins are specified in pressure vessel codes applicable in the countries where the chiller is manufactured and where it is placed in service.

#### *9.8.1.6. Ammonia (R-717)*

Chillers using R-717 as the refrigerant are available in the capacity range from 200 to 2000 kW with a few larger. Application considerations with R-717 are more complex than for many other refrigerants because R-717 is a strong irritant gas that is slightly toxic, corrosive to skin and other membranes, and flammable. Recommended practice /ISO93, ASH04a/ limits the use of large R-717 systems in public buildings to those systems that utilise a secondary heat transfer fluid (intrinsic to chillers), confining the R-717 to the machine room where alarms, venting devices, and scrubbers can enhance safety. Guidelines are available for safe design and application of R-717 systems /IEA98, IOR02, ASH04a/. Modern, compact factory-built units contain the R-717 much more effectively than old ammonia plants. However, the potential for serious consequences in the event of a major leak limits their applications.

Wider acceptance of ammonia requires that public officials accept the use of R-717 systems and the associated risks under emergency conditions such as building fires or earthquakes, either of which might rupture refrigerant piping and pressure vessels. Most important is the establishment of building codes that are acceptable to the safety officials (e.g. fire marshals) and those concerned with costs (e.g., architects).

The chemical reactivity of R-717 with copper in the presence of water prevents its use in hermetic compressor systems with copper-wound motors. Although motors with aluminium motor windings are commercially available now, there is a potential loss of energy efficiency with the change in material due to the higher electrical resistivity of aluminium compared to that of copper.

#### *9.8.1.7 Hydrocarbons*

Hydrocarbon refrigerants have a long history of application in industrial chillers in petrochemical plants. They were not used in chillers for comfort air conditioning before 1997 due to reservations about systems safety. European manufacturers now offer a range of hydrocarbon chillers. Unit sales of hydrocarbon chillers are about 100 to 150 annually, primarily in northern Europe. This is a small number compared to the market for more than 62,000 HCFC and HFC chillers in Europe (Table 9-6). The applications have been mostly office buildings, process cooling, and supermarkets.

One might be able to achieve efficiency increases in systems optimised for hydrocarbons, for example by somewhat greater than 5% using R-290 (propane) instead of HCFC-22. Efficiency comparisons for HCFC, HFC, and HC systems in the literature sometimes show substantial differences, but they do not always represent rigorous comparisons /ART01/. The cost of HC chillers is higher than that of HCFC or HFC equivalents, partly due to the fact that safety concerns with hydrocarbon chillers make the market small.

A problem with hydrocarbons is their flammability which deters consideration for use in many applications. Safety measures for use of hydrocarbons in chillers include proper placement and/or gas-tight enclosure of the chiller, application of low-charge system design, fail-safe ventilation systems, and gas detector alarm activating systems. An alternative is outdoor installation /ART01/. Guidelines for the use of hydrocarbon refrigerants in static refrigeration and air conditioning systems have been produced /EN00, IR01/. Maximum refrigerant charge sizes for systems located within occupied spaces are 1.5 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 5 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 /EN00/.

### 9.8.2 Options for New Centrifugal Compressor 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.

The traditional centrifugal chiller refrigerants were CFC-11, CFC-12, HCFC-22, and R-500. CFC-113 was used in a limited number of chillers produced years ago. CFC-114 was used in some commercial chillers, especially heat recovery chillers, but found wide use in naval surface vessels and submarines. Production of CFCs was phased out in developed countries by the end of 1995 in response to the Montreal Protocol.

CFC-11 and CFC-12 have been replaced by HCFC-123 and HFC-134a, respectively.

#### *9.8.2.1 HCFC-123*

HCFC-123 is the most efficient refrigerant for water chillers other than CFC-11 and HCFC-141b, both of which have significantly higher ODP and higher GWP. Its similar properties permitted HCFC-123 to replace CFC-11 in new and existing chillers without extensive modifications of equipment. There was no other replacement with these characteristics, so HCFC-123 was critical to the transition away from CFCs in the centrifugal chiller sector. HCFC-123 refrigerant is offered in new centrifugal water chillers from approximately 700 to 15,000 kW. HCFC-123 has a very low overall impact on the environment because of its low ODP, very low GWP, very short atmospheric lifetime, very low emissions in current chiller designs, and highest theoretical cycle efficiency of all current options /Cal00, Cal06a, Cal06b/.

Published studies /Cal97, Cal99/ have shown that use of HCFC-123 in chillers would have imperceptible impact on stratospheric ozone while offering significant advantages in theoretical efficiency, thereby lowering greenhouse gas emissions from associated energy use /Cal06a/.

HCFC-123 production is slated for phase-out by 2030 in developed countries and 2040 in Article 5 countries. Installed, recovered, and stocked quantities of HCFC-123 may be used indefinitely. Use of HCFC-123 in new equipment will end in most developed countries by 2020 and already has stopped in Europe

#### *9.8.2.2 HFC-134a*

HFC-134a refrigerant is used in centrifugal chillers from approximately 350 to 30,000 kW capacity. HFC-134a systems operate at higher pressure than HCFC-123 systems and must meet pressure vessel code requirements. Pressures are above atmospheric throughout the system, so purge units and pressurising devices typically are not used. HFC-134a has a zero ODP and a GWP lower than that of CFC-11, CFC-12, or HCFC-22. Design features of current HFC-134a centrifugal chillers achieve very low refrigerant emission rates.

#### *9.8.2.3 HCFC-22*

HCFC-22 has been used in centrifugal chillers in capacities up to 35,000 kW. Manufacturers found it relatively easy to convert their centrifugal compressor and chiller product lines to switch from HCFC-22 to HFC-134a. Centrifugal chillers have long operating lives, so purchasers of HCFC-22 chillers have tended to change their specifications to call for HFC-134a. As a result, the production of centrifugal chillers using HCFC-22 ended before 2000.

#### *9.8.2.4. Other refrigerants*

Several refrigerant blends are offered for use in centrifugal chillers designed for HCFC-22 or CFC-12.

In addition to these blends, HFC-245fa can be used as a centrifugal chiller refrigerant. HFC-245fa is a chemical developed for use in appliance insulation foam blowing. It went into commercial production in 2003. HFC-245fa has operating pressures higher than for HCFC-123 and CFC-11 but lower than for HFC-134a. Its use requires redesign of compressors to match its properties, a common requirement for this type of compressor. In addition, the heat exchangers in an HFC-245fa chiller must be designed to meet pressure vessel codes, unlike those for CFC-11 and HCFC-123. One manufacturer offers HFC-245fa chillers above 2800 kW /JAR06b/.

It is difficult for a new refrigerant such as HFC-245fa or one of the blends to become accepted as a widely-used centrifugal chiller refrigerant. Such refrigerants must be available on a world-wide basis, must be assured to be available for the life of the equipment, and must pass manufacturers' tests to assure equipment reliability. The design of centrifugal chillers for new refrigerants and the cost of testing to assure reliability is difficult for manufacturers to justify unless present alternatives no longer are acceptable.

#### *9.8.2.5. 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 differing boiling points (NBP) of the mixture constituents in flooded evaporators result in a composition change between the liquid and vapour phases in the refrigerant on the shell side of the evaporator. The composition change results in poor performance of the chiller. (The differing boiling points in DX evaporators result in a temperature glide rather than composition changes as explained in Section 9.8.1.3.).

Hydrocarbon refrigerants are used 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. Hydrocarbon refrigerants have not been used in centrifugal chillers for air conditioning due to concerns about system safety with large charges of flammable refrigerants.

R-717 is not a suitable refrigerant for centrifugal chillers because of its low molecular mass which requires a large number of compressor stages to produce the pressure rise ("head") required for the R-717 chiller cycle.

### 9.8.3 Alternative Technologies

#### *9.8.3.1. Absorption chillers*

Heat-activated absorption water chillers are a viable alternative to the vapour-compression cycle for some installations. Absorption chillers have been described in Sections 9.2.2 and 9.7.3.

#### *9.8.3.2. Water as a refrigerant for chillers*

Water is a very low-pressure refrigerant, with a condensing pressure of 4.2 kPa (0.61 psia) at 30°C and a suction pressure of 1.6 kPa (0.23 psia) at 9°C. Traditionally, water has been used in specialty applications with steam aspirators, rarely with vapour compressors. The low pressures and very high volumetric flow rates required in water vapour-compression systems require compressor designs that are uncommon in the air conditioning field.

The few applications for water as a refrigerant use it to chill water or produce an ice slurry by direct evaporation from a pool of water. These systems carry a cost premium of more than 50% above conventional systems. The higher costs are inherent and are associated with the large physical size of water vapour chillers and the complexity of their compressor technology.

Recent studies indicate that there are no known compressor designs or cycle configurations of any cost that will enable water vapour-compression cycles to reach efficiencies comparable to existing technology /ART00, ART04/.

## 9.9 Options for Existing Chiller Equipment

No substitute refrigerant can be used as a "drop-in" for CFCs. After CFC production for domestic consumption ceased in developed countries, the functions performed by CFC chillers had to be supported in one of the following ways:

> **Retain/Contain**: continued operation with CFCs in conjunction with containment procedures and equipment to reduce emissions, using refrigerant which has been stockpiled or is available after being recovered from other units converted to non-CFCs or retired.
>
> **Retrofit**: modification to allow operation with alternative refrigerants (HFCs or HCFCs [availability depends on national regulations]).
>
> **Replace**: early retirement/replacement with new chillers, most likely using HFC or HCFC refrigerants due to installation restrictions but possibly using ammonia or HC vapour-compression or absorption if the circumstances permit.

The retrofit options, which exist for each chiller, are dependent upon 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 ASHRAE Standard 15 or equivalent other national or international standards such as ISO/DIS 5149. It is also recommended that the manufacturers of the equipment be consulted in any retrofit program.

### 9.9.1 Positive Displacement Chillers

A positive displacement compressor inherently can be applied to handle a number of different refrigerants and cycle 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 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.

#### *9.9.1.1 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. 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.

#### *9.9.1.2. R-407C, R-417A, HFC-134a, 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.

For equipment using HCFC-22 in DX evaporators, zeotropic and azeotropic mixtures of HFCs have been developed.  The comments in Section 9.8.1.3 concerning new equipment explain the problems with zeotropic blends, such as R-407C, which cause their use as an alternative in many HCFC-22 chillers to be accompanied by losses in capacity and energy efficiency.

Alternative retrofit refrigerants for HCFC-22 primarily are R-407C or 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.

Several blends including R-417A have been proposed as replacements for HCFC-22. R-417A has a temperature glide of 4-5 K. Laboratory test results of chillers using this refrigerant have not been found.

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.

Hydrocarbon refrigerants are not appropriate for retrofitting CFC or HCFC chillers. Substantial expense would be incurred to incorporate safety features in the equipment and modify the machinery room to meet the safety standards imposed for flammable refrigerants.

#### *9.9.1.3. R-404A or R-507A as replacements for HCFC-22*

Refrigerant blends R-404A and R-507A were developed as replacements for R-502, a blend that contains a CFC. The new blends have been successful as R-502 replacements for commercial and industrial refrigeration. 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.

### 9.9.2 Centrifugal Chillers

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. 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.

A survey of chiller manufacturers, conducted by the Air-Conditioning and Refrigeration Institute (ARI) revealed that by the end of 2004 approximately 33,300 of the estimated 80,000 CFC chillers in service in the early 1990s still use CFCs. Some estimates suggest a higher initial inventory of 92,000-94,000 chillers, implying a higher number of CFC units still in use. During 2004, there were 2735 chiller replacements and 176 conversions to non-CFC refrigerants to bring the year-end total to 46,703 chillers (58 %) that no longer use CFCs. The prediction for future conversions is given in Table 9-7.

***Table 9-7 CFC Chiller Conversions and Replacements /ARI05/***

| | Conversions | Replacements | Total | Remainder |
|---|---|---|---|---|
| Prior to 1/1/05 | 9,060 | 37,643 | 46,703 | 33,297 |
| 1/05 to 1/1/06 | 155 | 2,674 | 49,532 | 30,468 |
| 1/06 to 1/1/07 | 130 | 2,860 | 52,522 | 27,478 |
| 1/07 to 1/1/08 | 108 | 3,002 | 55,632 | 24,368 |

Table 9-7 shows that 38% of the original 80,000 U.S. CFC centrifugal chillers still employed CFCs at the end of 2005.

In Canada, 267 CFC chillers were converted or replaced in 2005, bringing the total number of converted or replaced chillers to 2,109 out of a total 1995 stock of 5,486 chillers /HRA06/. In Japan there are about 7000 CFC chillers still in operation /JAR06a/.

The conversion (retrofit) option is no longer viable for most existing CFC chillers. Most of the chillers that still have reasonable operating life remaining and relatively good energy efficiency already have been converted to non-CFC refrigerants. Thus, the replacement option is best for the remaining CFC centrifugal chillers. Manufacturers offer HCFC and HFC chillers with significantly improved energy efficiency compared to most CFC chillers in service. The savings in energy costs often justify the complete replacement of an aging CFC chiller with a new HCFC or HFC chiller.

#### *9.9.2.1 HCFC-123 for CFC-11 in centrifugal chillers*

HCFC-123 became available in 1989 to retrofit existing CFC-11 chillers. It has different solvent properties than CFC-11. Some non-metallic materials and hermetic motors have to be replaced with materials and motors that are compatible with HCFC-123. Change-out of the compressor to a higher capacity model may be necessary. In most cases, a proper conversion of a CFC-11 chiller to HCFC-123 will result in an acceptably small reduction in capacity and negligible reduction in efficiency.

#### *9.9.2.2. HFC-134a for CFC-12 and R-500 in centrifugal chillers*

HFC-134a became available in 1989 to retrofit existing CFC-12 and R-500 chillers. Its use requires about 15% higher impeller tip speeds than CFC-12, so compressor replacement or at least impeller modification probably will be necessary. In some cases, the heat exchangers may be able to be re-tubed to reduce head pressure. In either case, an engineered conversion is necessary to minimise loss of capacity and efficiency.

The mineral oils used with CFC-12 are not miscible with HFC-134a. Polyolester oils are used instead and compatibility problems have been understood and overcome. However, residual mineral oil concentrations in HFC-134a systems should be reduced to less than 3% even with POE oils, or else heat exchanger performance will be reduced. Most desiccants commonly used in CFC-12 systems (e.g., activated alumina) are not compatible with HFC-134a.

#### *9.9.2.3. Other candidates to replace CFC-12 in centrifugal chillers*

Several refrigerants have been suggested as drop-in replacements for CFC-12 in centrifugal chillers, but they have not been demonstrated to be satisfactory in that application. One is R-416A, a blend that has a small temperature glide (2-3 K). It is expected that this temperature glide, and its demonstrated reduced cycle performance when used for automotive air conditioning, will cause its performance to be lower than that of CFC-12 originally used in the chiller. Laboratory test results for chillers with R-416A have not been reported.

Another refrigerant said to be a drop-in replacement for CFC-12 is R-423a, a mixture of HFC-134a and HFC-227ea. It is offered by one refrigerant manufacturer now and is said to be a near-azeotrope (1 K temperature glide). Laboratory test results in a calorimeter with a reciprocating compressor yielded a COP practically identical to that with CFC-12, but evaporator capacity with R-423a was lowered by 11% at $0^{o}$C evaporating temperature and $55^{o}$C condensing temperature. Field tests in a two-stage air-cooled centrifugal chiller converted from CFC-12 exhibited results similar to the laboratory results within measurement accuracy /Pea99/.

#### *9.9.2.4. Candidates to replace HCFC-22 in centrifugal chillers*

Centrifugal compressors are designed for specific refrigerants. Unless the properties of the retrofit refrigerant are very close to those of the refrigerant for which the compressor was designed, the compressor must be modified or replaced in a retrofit situation. Zeotropic refrigerant blends are unacceptable in the flooded evaporators of centrifugal chillers. For these reasons, there are no simple conversions of HCFC-22 centrifugal chillers to use HFC refrigerants or blends. The primary alternatives are to replace the chiller or to convert the system to use HFC-134a, replacing the compressor with one providing a higher flow rate. The manufacturer of the system could play an active part in the conversion to assure success.

#### *9.9.2.5. Other refrigerant possibilities for centrifugal chillers*

HFC-236fa has been used as a retrofit refrigerant to replace CFC-114 in naval chillers. Operating pressures are higher than those with CFC-114. Energy efficiency considerations, equipment modification needs, and materials compatibility issues must be addressed in these conversions.

#### *9.9.2.6 Not-in-Kind Chiller Replacements – Absorption*

A factor that 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.

## 9.10 Refrigerant Banks and Emissions for Chillers

Table 9-8 presents estimates of the trends for banks of refrigerants contained in chillers through 2003.

***Table 9-8 Trends in refrigerant banks contained in chillers (tonnes) /Clo06/***

**CFC Bank**

| Year | Article 5 Countries | Non Article 5 Countries |
|---|---|---|
| **1991** | 58,039 | 115,796 |
| **1993** | 58,195 | 116,644 |
| **1995** | 55,747 | 112,402 |
| **1997** | 52,937 | 101,873 |
| **1999** | 49,612 | 85,071 |
| **2001** | 46,639 | 71,221 |
| **2003** | 43,618 | 63,664 |

**HCFC Bank**

| Year | Article 5 Countries | Non Article 5 Countries |
|---|---|---|
| **1991** | 21,795 | 49,183 |
| **1993** | 22,986 | 51,848 |
| **1995** | 24,297 | 61,662 |
| **1997** | 25,711 | 73,782 |
| **1999** | 26,256 | 81,321 |
| **2001** | 27,137 | 85,201 |
| **2003** | 26,943 | 85,326 |

**HFC Bank**

| Year | Article 5 Countries | Non Article 5 Countries |
|---|---|---|
| **1991** | 76 | 1,356 |
| **1993** | 575 | 2,756 |
| **1995** | 1,383 | 10,630 |
| **1997** | 2,614 | 23,112 |
| **1999** | 4,617 | 35,698 |
| **2001** | 7,703 | 46,909 |
| **2003** | 11,744 | 53,781 |

Estimates of trends in emissions from chillers through 2003 are shown in Table 9-9.

***Table 9-9  Trends in refrigerant emissions from chillers in 2003 (tonnes) /Clo06/***

**CFC Emissions**

| Year | Article 5 Countries | Non Article 5 Countries |
|---|---|---|
| **1991** | 9,313 | 12,614 |
| **1993** | 9,353 | 12,599 |
| **1995** | 9,103 | 11,981 |
| **1997** | 8,819 | 11,147 |
| **1999** | 8,446 | 9,542 |
| **2001** | 8,411 | 7,620 |
| **2003** | 8,002 | 6,629 |

**HCFC Emissions**

| Year | Article 5 Countries | Non Article 5 Countries |
|---|---|---|
| **1991** | 3,697 | 7,439 |
| **1993** | 3,841 | 7,469 |
| **1995** | 3,999 | 7,796 |
| **1997** | 4,153 | 7,986 |
| **1999** | 4,161 | 8,027 |
| **2001** | 4,060 | 7,785 |
| **2003** | 3,981 | 7,407 |

**HFC Emissions**

| Year | Article 5 Countries | Non Article 5 Countries |
|---|---|---|
| **1991** | 11 | 194 |
| **1993** | 75 | 319 |
| **1995** | 163 | 965 |
| **1997** | 312 | 1,674 |
| **1999** | 531 | 2,557 |
| **2001** | 694 | 3,656 |
| **2003** | 1,034 | 4,140 |

## 9.11 Future Needs for CFCs and HCFCs for Chillers

One way to assess future needs for CFCs and HCFCs is to consider estimates of emissions that are expected to occur. The IPCC fostered the development of these estimates using three possible scenarios for conditions in the year 2015. The most pessimistic scenario is “Business as Usual” (BAU). In this scenario, the usual practices affecting emission rates are kept unchanged through 2015. Recovery efficiency is assumed not to increase. Nevertheless, regulations related to refrigerant phase-out are considered in the case of refrigerant replacements. According to /Pal04/, CFC emissions in the Stationary A/C sector are forecast to be 6640 tonnes during the year 2015. Here, Stationary A/C includes the class of equipment described in Chapter 7 of this TOC report as well as chillers. It is reasonable to assume that most CFC emissions in this sector would be from chillers and not unitary equipment.

For HCFC emissions in 2015, the BAU estimate is 123,000 tonnes /Pal04/. HCFC-22 is the most common refrigerant used in unitary equipment. The bank of HCFC-123 or HCFC-22 contained in chillers is very small compared to the bank of HCFC-22 in unitary equipment, and emission rates for chillers are comparable to, or smaller than, those of unitary systems. Thus, only a small part of the 123,000 tonnes represents emissions from chillers.

In a report prepared for the U.S. Environmental Protection Agency, ICF forecasts a demand for HCFC-22 for servicing equipment to be 66,300 tonnes in 2010 and 49,600 tonnes in 2015 for the USA. Chiller servicing needs account for 27% of the demand in 2010 and 29% in 2015. In 2010, 29% of the HCFC-22 is projected to come from recovered refrigerant (recycled or reclaimed). In 2015, 61% of the HCFC-22 is projected to come from recovered refrigerant. /ICF05/

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# 10 Vehicle Air Conditioning

## 10.1 Introduction

Vehicles (cars, trucks, buses, and railcars) built before the mid-1990's mainly used CFC-12 as the refrigerant. Since then, in accord with the Montreal Protocol, new vehicles with A/C have been equipped with HFC-134a, a zero ODP chemical, as the refrigerant. As a result, especially due to the early phase out in India, China, and other developing countries with car manufacturing industries, HFC-134a has now replaced CFC-12 as the globally accepted mobile A/C (MAC) refrigerant and the industry is busy expanding global production to meet the increasing demand.

HFC-134a is considered a potent greenhouse gas and, due to concerns about its emission from MAC systems, the European Union has finalised legislation to ban the use of HFC-134a in new type vehicles from 2011 and from all new vehicles from 2017. In addition, they have limited replacement refrigerants to those with a global warming potential (GWP) to a maximum of 150, and placed interim emission limits on new HFC-134a systems until the ban is completed. As a result, vehicle makers and their suppliers are focussing attention on reducing refrigerant leakage, improving system energy efficiency, and developing replacement refrigerants.

### 10.1.1 Special Comments on Bus and Rail Air Conditioning

Bus and railcar air conditioning systems have in common that they usually use fin-and-tube heat exchangers and reciprocating compressors. In railcars often also screw compressors are installed. A lot of bus and railcar air conditioning technology is shared with commercial air conditioning and refrigeration. The compressors in buses usually are open-type compressors driven by the bus engine whereas in railcars mostly semi-hermetic compressors are employed. Directly driven open compressors can be capacity controlled by switching cylinders on and off while semi-hermetic compressors usually have variable speed capacity control.

Since the mid-1990's new bus air conditioning systems increasingly use HFC-134a as the refrigerant but HCFC-22 is still in use as well.

For railcars, HFC-134a and R-407C have gained market shares of 15-25 % and 2-3 %, respectively, in Europe and North America. For newly built equipment, these HFCs are used in railcars in many countries (e.g. 50 % of new railcars in US, where the other 50% are still mostly HCFC-22 /Bau06/).

Awareness of system leak tightness has grown within the bus and railcar industry, so that annual emissions of 15 % or less can be achieved implementing regular service, maintenance and controls and using today's technology in systems which contain smaller initial refrigerant charges as system efficiencies have improved /Bau06/.

In Germany, high speed trains (approx. 500 railcars) use air cycle systems for their air conditioning. Furthermore, demonstrator units are operated in the UK. Due to the physical characteristics of air, energy consumption in these systems is higher than that in a vapour compression cycle. However, these systems easily allow regenerative heat recovery for cooling and for heating. Therefore annual energy consumption ranks in the same range as for the HFC-134a-equipped system. Besides ecological characteristics – zero ozone depleting potential and no direct greenhouse impact – the low amount of system components brings reduced maintenance and leakage and improved system reliability that have led to the decision to apply the air cycle /Bau06/.

## 10.2 Options for Future Vehicle Air Conditioning Systems

### 10.2.1 Improved HFC-134a Systems

The SAE, International, is, under the auspices of the Mobile Air Conditioning Climate Protection Partnership, co-ordinating an industry-government co-operative research program known as SAE I-MAC (Improved Mobile Air Conditioning) to reduce HFC-134a emissions and improve A/C system efficiency /IMAC06/. Among the 28 participants are the world’s major carmakers, A/C system and component suppliers, and refrigerant suppliers .

Targeted improvements include a 50% reduction in refrigerant emissions (the emissions refer to controllable losses as well as to losses due to service) and a 30% reduction in energy use. Current regulatory policies world-wide ignore the fuel consumption of AC system operation. The technical potential for reducing AC system fuel consumption could be up to 30 to 40%, depending on option chosen and climate, and could lead to avoidance globally of 40 million tonnes per year of $CO_2$. The I-MAC consortium consists of four teams working on emission reduction, energy reduction, vehicle solar thermal load reduction, and improved service procedures. Each team has identified and measured improvements that can be applied industry-wide from original system design to field service. The consortium is on track to achieve its targeted improvements /IMAC06/, which are intended to significantly improve the climate performance of HFC-134a systems. This work is scheduled to conclude by mid-2007.

The results of the I-MAC effort are being drafted into SAE standards and recommended practices by the SAE Interior Climate Control Standards Committee to provide a pattern for global adoption. MAC systems incorporating the identified emission reduction improvements can now be certified in the U.S. by the SAE to meet the SAE J2727 low refrigerant emission standard, for which the state of California (USA) intends to reward with emission credits to offset pending vehicle greenhouse gas emission reduction requirements (Cal06). Similar certification for improved energy efficiency is expected following adoption of draft SAE energy efficiency standards.

Improved HFC-134a systems offer low leakage rate, and higher energy efficiency. Moreover further emission reductions may be obtained by full professional service with recovery and recycling, and systematic end of life (EOL) recovery enabled by refrigerant management policies resulting from national regulations and incentives.

The SAE I-MAC program provides a model for other industries to follow for assessing their impact on the environment, and for developing effective ways to minimise that impact.

### 10.2.2 Carbon Dioxide Systems

In the timeframe 1998-2006, the leading potential replacement refrigerant in Europe has been carbon dioxide (also known as R-744). Almost all global vehicle manufacturers and suppliers are currently working on such systems and many have already demonstrated prototype cars. Carbon dioxide has been shown to be comparable to HFC-134a with respect to cooling performance and fuel use in MAC systems and qualifies for use in the EU under the current impending regulation (The EU GWP limit of 150 was imposed to set an environmental standard and to allow the use of low GWP refrigerants).

Prototype systems have been built for bus air conditioning based on a low-cost design using carbon dioxide as refrigerant /Son02/. More than 4000 running hours on-the-road accumulated by these prototypes indicate that R-744 systems are technically and economically feasible for bus air conditioning. Similar R-744 activities are also known for railcar air conditioning systems /Kai06/.

R-744 systems have been described in detail in the 2002 RTOC report /UNEP03/ and the 2005 IPCC-TEAP Special Report /IPCC05/. The high pressure of the R-744 systems makes it necessary to mitigate the risk of rupture which could lead to burst hazard. As a result, R-744 systems require completely redesigned components using new manufacturing processes to withstand the high operating pressures, as well as additional components and controls to allow operation at, or near, optimum energy efficiency. Both capital costs and consumer costs (especially for A/C-only systems) are expected to be significant, at least for the first generation of serial production. A significant concern is the need to establish a new infrastructure to service these systems. R-744 has the advantage that it may also be useful in a heat pump system (a sophisticated reversible A/C system), allowing both heating and cooling of the vehicle. R-744 is classified as an A1 refrigerant (ISO 817). However, although the Threshold Limit Value (TLV) is five times higher for carbon dioxide than for most HFCs (5,000ppm compared with 1,000ppm), the Immediate Danger to Life Value (IDLV) is a relatively low (40,000ppm compared with 150,000ppm). This means, leakage of R-744 into the passenger cabin creates risks of impairment, so care must be taken to prevent an unrecognised build-up of dangerous levels of R-744 in the passenger compartment. The US EPA has studied the potential use of R-744 as refrigerant under the US Clean Air Act’s Significant New Alternatives Policy (SNAP) Program. Their findings have been that risk mitigation will be necessary for this refrigerant if used in direct expansion systems. It is believed that engineering solutions (secondary loop, refrigerant discharge devices, sensors, gas monitors, etc.) are available that can significantly mitigate safety concerns. The EU has not yet established safety standards for the use of R-744 as a MAC refrigerant.

To date, no announcements have been made regarding commercial implementation of R-744 MAC systems. Technical and commercial hurdles exist (leakage, leak detection, materials selection, lines & fittings materials, component technology selection, cost, etc.) that require resolution. The German VDA /Mag04/ is active in developing MAC system specifications.

### 10.2.3 HFC-152a Systems

The use of HFC-152a was proposed in 2001 and has been publicly demonstrated in several prototype vehicles. HFC-152a has been shown to be comparable to HFC-134a with respect to cooling performance and fuel use in MAC systems and qualifies for use in the EU under the afore-mentioned regulation. HFC-152a systems have been described in detail in the 2002 RTOC report /UNEP03/ and the 2005 IPCC-TEAP Special Report /IPCC05/. Due to the low fuel use, the carbon-equivalent emissions of HFC-152a in a direct expansion system could be offset by its fuel savings. If used in a secondary loop system, its fuel consumption is expected to similar to that of the current HFC-134a system. With the exception of a safety system, HFC-152a systems use the same components as HFC-134a systems, allowing flexible manufacturing and/or a low cost transition from HFC-134a.

Classified as an A2 refrigerant (ISO 817), the only inherent drawback of HFC-152a is its flammability; but there are no technical hurdles that would prevent its use. 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. Their findings have been that risk mitigation will be necessary for this refrigerant if used in direct expansion systems to prevent the build-up of dangerous concentrations of gases in the passenger compartment. It is believed that engineering solutions (secondary loop, refrigerant discharge devices, sensors, gas monitors, etc.) are available that can significantly mitigate safety concerns. The EU has not yet established safety standards for the use of HFC-152a as a MAC refrigerant. It is anticipated that, due to the small refrigerant amount needed, combined with the mentioned safety engineering, its use will result in a commercially acceptable MAC system. To date, no announcements have been made regarding commercial implementation of HFC-152a MAC systems.

Additionally, it should be noted that the current production capacity of HFC-152a would need to be substantially increased to accommodate its use in MAC systems, which may require 1-2 years lead time for the chemical industry to respond. The existing service infrastructure would need to be enhanced with new/modified equipment and technician training to safely handle this refrigerant.

### 10.2.4 Adoption of R-744 and HFC-152a

Both R-744 and HFC-152a have GWPs below the 150 threshold and adoption of either would be of equivalent environmental benefit /IPCC05/. The decision of which refrigerant to choose would have to be made based on other considerations, such as energy usage, cost, heat pump capability, safety, and servicing.

### 10.2.5 New Alternative Refrigerant Candidates

Following finalisation of the EU F-gas directive for MACs, several chemical companies (others probably will follow) have each announced a new refrigerant blend to replace HFC-134a in Europe. One is an azeotropic blend of $CF_3I$ and 1,1,1,2-tetrafluoropropene. Two other formulations have not been publicly released. Chemicals with a low GWP tend to be more reactive; this lack of stability can result in unwanted chemical reactions in the lower atmosphere (e.g., smog), in the A/C system (e.g., material incompatibility), and in the human body (e.g., toxicity). These new chemicals, as well as their break-down products, must be fully assessed for acceptability (especially safety and energy use).

The role of very short-lived substances (containing Cl, Br, and I) in stratospheric ozone depletion is now believed to be of greater importance than previously assessed. This suggests that significant anthropogenic production of such substances could enhance ozone depletion. New analyses suggest upper-limit Ozone Depletion Potentials for $CF_3I$ of 0.018 for tropical emissions and 0.011 for mid-latitude emissions. The previous assessment had an upper limit of 0.008 /UNEP06/.

In August 2006, due to safety and cost issues of R-744 and R-152a, German carmakers collectively asked for, and formally organised, a co-operative effort to collectively assess the new candidates with a focus on selecting a replacement for HFC-134a by mid-2007. The SAE and Japanese Automobile Manufacturers Association are assisting this effort. Working groups have been formed to assess the toxicity, safety risk, environmental acceptability including ODP, performance, energy use, and materials compatibility of these refrigerants and their respective lubricants with typical A/C system components.

Since so little is known to date about the blends, their components, and their break-down products, it is not clear whether systems using these blends will need safety systems similar to those necessary for R-744 and HFC-152a.

Time is truly of the essence as decisions must be made by mid-2007 as to the acceptable replacement(s) for HFC-134a in order to produce vehicles that meet the 2011 European requirement.

Other refrigerants, such as hydrocarbons (HC’s) or blends of hydrocarbons, have been investigated but have not received support from car manufacturers as a possible alternative technology due to safety concerns.

Other refrigeration technologies exist and have been tested, such as sorption systems and air cycles, but (with the exception of the mentioned German railcar system) none is seen as sufficiently energy efficient to replace vapour compression technology.

## 10.3 Refrigerant Options for Existing Systems

Vehicles originally built with CFC-12 systems are at least 10 years old, so most are nearing the end of their useful life. Options for existing systems that are still operating and using CFC-12 include continuing to use CFC-12 as long as it is available or retrofitting the system to enable the use of HFC-134a. SAE, International has published standards for retrofitting from CFC-12 to HFC-134a /UNEP04/.

## 10.4 Banks and Emissions

### 10.4.1 Passenger Vehicles

The complete picture of CFC, HCFC and HFC usage in the MAC sector is given in Tables 10-1 through 10-3, showing annual estimates for the bank, market and emissions of each refrigerant class used in the sector.

The decrease of the bank of CFC-12 in the MAC sector is steady due to the relative short lifetime of vehicles. The bank has decreased from about 245,000 tonnes in 1993 to about 55,000 tonnes in 2003 /Clo05/.

Because no more CFC-12 is being produced, the amount of CFC-12 in the bank intended for use in MACs defines the maximum of the total emissions expected. Although not done in this report, annual global emissions for MAC systems could be estimated by extrapolating the rate of disappearance of the bank.

### 10.4.2 Buses and Trains

Based on the data given in /Sch04/ and /Sch05/ it can be estimated that there exist more than 300,000 buses and coaches in Europe. It is assumed that about 66% of those are air conditioned. The average refrigerant charge of a bus or coach air conditioning system is about 10 kg of HFC-134a with an annual leakage rate estimated to be about 1 kg per bus or coach air conditioner /Sch05/, i.e., about 10% of the total charge. Corresponding data for the whole world is not available.

For railcars it is estimated that 100,000 systems operate world-wide containing a refrigerant pool of roughly 2000 t where more than 50% still consists of HCFC-22, accounting for emissions of at least 200 t/a. There are some systems still operating on CFC-12 and transitional blends.

Remaining CFC and HCFC-containing equipment will reach the end of its lifespan within an average of five years /Bau06/.

***Table 10-1 CFC Bank, Market and Emissions in the MAC sector, 1990-2003***

|  | CFC Bank |  | CFC Market |  | CFC Emissions |  |
|---|---|---|---|---|---|---|
|  | metric tonnes |  | metric tonnes |  | metric tonnes |  |
| YEAR |  |  |  |  |  |  |
|  | Article 5 | Non-Article 5 | Article 5 | Non article 5 | Article 5 | Non-Article 5 |
|  | Countries | Countries | Countries | Countries | Countries | Countries |
| **1,990** | 26,478 | 202,423 | 8719 | 74169 | 9,891 | 73,854 |
| **1,991** | 27,225 | 209,810 | 9534 | 89561 | 10,420 | 81,517 |
| **1,992** | 27,947 | 216,426 | 9939 | 75870 | 10,911 | 75,392 |
| **1,993** | 28,445 | 214,953 | 10214 | 58804 | 11,269 | 68,335 |
| **1,994** | 28,457 | 207,073 | 10000 | 77368 | 11,601 | 73,658 |
| **1,995** | 28,106 | 192,637 | 9648 | 57148 | 11,688 | 67,229 |
| **1,996** | 27,482 | 174,772 | 9476 | 39775 | 11,392 | 57,892 |
| **1,997** | 26,772 | 154,113 | 10140 | 52924 | 11,041 | 60,282 |
| **1,998** | 25,986 | 128,797 | 10356 | 27973 | 10,830 | 51,362 |
| **1,999** | 25,549 | 102,141 | 10590 | 25048 | 10,259 | 44,724 |
| **2,000** | 26,394 | 76,997 | 11375 | 30229 | 9,461 | 39,408 |
| **2,001** | 26,333 | 57,723 | 10920 | 13027 | 7,953 | 27,812 |
| **2,002** | 26,144 | 41,207 | 10598 | 9382 | 7,718 | 21,521 |
| **2,003** | 25,750 | 28,834 | 11729 | 7975 | 7,883 | 16,183 |

***Table 10-2 HCFC Bank, Market and Emissions in the MAC sector, 1990-2003***

|  | HCFC Bank |  | HCFC Market |  | HCFC Emissions |  |
|---|---|---|---|---|---|---|
|  | metric tonnes |  | metric tonnes |  | metric tonnes |  |
| YEAR | Mobile AC |  | Mobile AC |  | Mobile AC |  |
|  | Article 5 | Non-Article 5 | Article 5 | Non-Article 5 | Article 5 | Non-Article 5 |
|  | Countries | Countries | Countries | Countries | Countries | Countries |
| **1,990** | 1,303 | 3,893 | 512 | 3723 | 743 | 3,254 |
| **1,991** | 1,393 | 4,312 | 584 | 3977 | 819 | 3,354 |
| **1,992** | 1,509 | 4,743 | 667 | 3638 | 904 | 3,449 |
| **1,993** | 1,656 | 5,187 | 782 | 4213 | 1,011 | 3,584 |
| **1,994** | 1,841 | 5,715 | 904 | 4017 | 1,142 | 3,725 |
| **1,995** | 2,018 | 6,388 | 983 | 4205 | 1,261 | 3,816 |
| **1,996** | 2,228 | 7,062 | 1089 | 4202 | 1,384 | 3,809 |
| **1,997** | 2,490 | 7,764 | 1242 | 4796 | 1,540 | 4,092 |
| **1,998** | 2,815 | 8,469 | 1434 | 5405 | 1,740 | 4,459 |
| **1,999** | 3,191 | 9,137 | 1645 | 6094 | 1,973 | 4,850 |
| **2,000** | 3,600 | 9,605 | 1853 | 6242 | 2,234 | 5,170 |
| **2,001** | 3,764 | 9,785 | 1018 | 5027 | 1,632 | 5,084 |
| **2,002** | 4,240 | 9,916 | 1150 | 4692 | 1,829 | 5,095 |
| **2,003** | 4,754 | 9,960 | 1266 | 4513 | 2,034 | 4,999 |

*Table 10-3 HFC Bank, Market and Emissions in the MAC sector, 1990-2003*

| | HFC Bank | | HFC Market | | HFC Emissions | |
|---|---|---|---|---|---|---|
| | metric tonnes | | metric tonnes | | metric tonnes | |
| YEAR | | | | | | |
| | Article 5 Countries | Non-Article 5 Countries | Article 5 Countries | Non-Article 5 Countries | Article 5 Countries | Non-Article 5 Countries |
| **1,990** | 0 | 0 | 0 | 123 | 0 | 122 |
| **1,991** | 0 | 0 | 0 | 197 | 0 | 130 |
| **1,992** | 0 | 855 | 0 | 1142 | 0 | 333 |
| **1,993** | 0 | 9,764 | 0 | 7855 | 0 | 1,965 |
| **1,994** | 0 | 25,423 | 0 | 14313 | 0 | 4,465 |
| **1,995** | 0 | 47,904 | 0 | 23841 | 0 | 8,805 |
| **1,996** | 6,255 | 67,866 | 4195 | 28008 | 1,741 | 12,323 |
| **1,997** | 9,348 | 95,855 | 5494 | 37773 | 2,757 | 18,277 |
| **1,998** | 13,272 | 128,892 | 7168 | 48934 | 4,290 | 24,633 |
| **1,999** | 17,518 | 163,142 | 8556 | 52812 | 5,812 | 30,551 |
| **2,000** | 21,777 | 196,903 | 8557 | 49783 | 7,476 | 34,423 |
| **2,001** | 25,787 | 221,225 | 11887 | 62851 | 8,793 | 41,853 |
| **2,002** | 32,458 | 245,449 | 14705 | 65211 | 10,283 | 47,123 |
| **2,003** | 40,391 | 264,967 | 16671 | 53379 | 11,619 | 47,592 |

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# 11 Refrigerant Conservation

## 11.1 Introduction

Refrigerant conservation is an effort to extend the life span of refrigeration and air-conditioning equipment by establishing efforts to recover, recycle, and reuse refrigerants or properly dispose of stockpiled quantities.  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.  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., ARI Standard 700-2004 and SAE J1991).  Whereas, destruction involves Protocol approved technologies (typically thermal incineration) that effectively destroy ODS to an established destruction removal efficiency.

Conservation efforts should be placed on refrigerant recovery at the point of installation and continue throughout service and 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.  This may be accomplished by 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 and end-of-life, established market for the resale and reuse of used refrigerants, and providing for the destruction of stockpiled or banked refrigerants.

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 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 handle refrigeration conservation 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. 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 could 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, chloride, 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/. 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. 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.

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 limit the practical usage of recovery equipment on the majority of refrigeration or air-conditioning equipment that contain up to 5 kg of refrigerant. 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 ARI Standards for certifying. Adoption of such standards as a part of common service procedures could 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. The level of training for service of domestic refrigeration differs from that for centrifugal chillers, for example and the types of refrigerants also differ between different end-uses.

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 France, companies have to be registered to prove that their staff is certified for handling refrigerant, according to the type of system they service. There again, certified companies alone will be allowed to buy refrigerants.

In Japan, obligations of recovery operators are specified by 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 refrigerants 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 for 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/.

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.

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 CFCs.

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 tonnes 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.

Reclaimed refrigerant can be used in any system without threatening it, as contamination can lead to system failure. 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 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 and service equipment fittings to prevent inadvertent mixing. Hoses will 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

Destruction plants exist in Europe, Japan and North America.  There are no identified plants available in low consuming Article 5 or CEIT countries, which may lead to the need for transportation of hazardous wastes.  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 /DES92/.

Belgium, Brazil, Finland, Japan and Switzerland possess the rotary kiln incineration technology to destroy CFCs, halon, and HCFCs. 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 phase-out programs, commercial opportunities for destruction may become available. Australia, United States, and Japan currently have the capacity to destroy recovered ODS.

## 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 (five years for a hermetically sealed system and three years for other systems); the refrigerant quantity may be lost by leakage during this period without significantly affecting the operational efficiency of the system the refrigerant used, and the maximum operating pressures and temperatures in 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. 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 has to 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 feasibility 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 escalating tax on refrigerant makes conservation 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

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.

To the greatest possible extent, standards should be performance based rather than technology based to encourage innovation. 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 reuse 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.

In 2000, a study done for Uruguay observed that the local price of CFC-12 interferes negatively with recycling and recovery project development and results.

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. In Article 5 countries where CFC prices are so low that people use them to replace HFCs (especially in car air conditioning), tax on CFC purchases may be useful.

### 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.

In the Decree of December 7, 1992, /FD92/ the French government made the recovery of CFCs, HCFCs, and HFCs mandatory for equipment greater than a two kilogram (2 kg) charge. The decree mandates that recovery be performed by experienced operators and registered companies. This decree, updated in 1998, makes an annual leak tightness inspection mandatory except for domestic appliances and automotive air-conditioning. It also specifies the sensitivity requirements of detection equipment. The decree is being updated in order to meet the new 2037/2000 regulation, which will mandate the recovery of all types of refrigerant regardless of the equipment charge.

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 mixtures of refrigerant,, 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.

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 natural 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.

## 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*

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 Phase-out 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 Phase-out 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 Eastern Europe

Several Eastern European countries, including Slovenia and Russia, have been successful in implementing new refrigerant recovery programs. Recovery procedures and distribution of refrigerant recovery units have been mandated. A large number of service technicians have also been trained to efficiently service refrigerant equipment and minimise environmental damage. However, financing continues to be a problem, as there is no state support for recovery programs. In addition, illegal importing from Yugoslavian states has become a source of concern.

Romania ratified the Vienna Convention and the Montreal Protocol with the London Amendment in 1993, the Copenhagen Amendment in 2000, the Montreal Amendment in

2001, and the Beijing Amendment in 2005. In March 2005, a national CFC phase-out plan was approved by the 45th Meeting of the Executive Committee, to be implemented jointly by UNIDO and Sweden. The RMP for Romania started in 1999 and was completed in 2002 with UNIDO as Implementing Agency. The RMP established a National Certification System for service technicians, a National Training Center to promote available ODS alternatives and a National Recovery and Recycling Network. Through this program, 550 service technicians were trained and certified, with 350 service shops around the country given recovery units. Wholesale companies and equipment suppliers, at different locations in the country, became the location of 7 recycling centres. Training courses for service technicians focused mainly on the techniques of refrigerant recovery and on the appropriate use of recovery equipment. Additional training activities are being developed, with funds from servicing companies, outside the RMP framework by ICPIAF and also the Technical University of Civil Engineering in Bucharest. The process of modernisation, liberalisation and privatisation in Romania is playing a more important role in the phase-out of ODS than price differentials. Due to the high cost of recycling compared to the price of new refrigerants the transition will be much more difficult for small service workshops. In Romania, no specific measures to change relative price relations are applied, and no subsidies for alternatives or special environment taxes on controlled substances have been introduced.

### 11.9.5 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.

### 11.9.6 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 relatively low price of CFC refrigerants.* CFCs are not scheduled to be phased out until 2010 in most Article 5 countries; thus, they remain relatively inexpensive in most such countries. In fact, CFC refrigerants are reportedly less expensive than ever in some Article 5 countries. 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.

- *Absence of 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 needs to 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 I: Recent Global Production and Consumption of Fluorochemicals

In a section in the 2002 report data were provided on global production and consumption of CFCs during the period 1986-2000, during 1989-2000 for HCFCs and during 1990-2000 for HFC-134a. Data sources included those assembled from chemical manufacture sources as overseen by the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS) and their independent accountant, Grant Thornton. These CFC, HCFC and HFC data are from participating companies headquartered in developed countries. CFC and HCFC data were used as contained in the report Production and Consumption of Ozone Depleting Substances under the Montreal Protocol 1986-2000, April, 2002 /Pro02/ and in UNEP/OzL.Pro/14/3, dated 18 October, 2002. The accuracy of HFC data from AFEAS is excellent as virtually all HFC-134a production takes place in contributing companies. It should be recognised that this is the only global source of such data as there is no jurisdiction for reporting of HFCs.

However, it is felt that the analysis of these data deserves a broader audience than the one that will take note of this RTOC Assessment Report. UNEP reported data on production and consumption, as well as a comparison with AFEAS data, and a discussion on differences between emissions determined via bottom up methods and via atmospheric measurements can be found in the Task Force Report on Emissions Discrepancies, which has been published by UNEP, October 2006, and can be found on UNEP's website (unep.org/ozone).

## Annex II: Glossary

| | |
|---|---|
| A/C | Air Conditioning |
| AFEAS | Alternative Fluorocarbon Environmental Acceptability Study |
| Article 5 | Article 5 in the Montreal Protocol defines “developing countries”, whose consumption of controlled substances is not allowed to exceed 0.3 kg per capita |
| Blend | A mixture of two or more pure (refrigerant) fluids:<br>azeotropic: with a behaviour as pure fluids<br>near azeotropic: similar to azeotropic blends (small temperature glide)<br>non-azeotropic: blends with a considerable temperature glide during evaporation/condensation |
| CEIT | Country with Economy In Transition |
| CFC | Chlorofluorocarbon |
| COP | Coefficient of Performance |
| Drop-In | Use of a different refrigerant without modifying the equipment including the lubricant; it may imply changing desiccants or similar devices |
| DX | Direct Expansion |
| GWP | Global Warming Potential (relative to $CO_2$ with a GWP of 1); GWP can be given for different time horizons, i.e. 20, 100, 500 years |
| Halocarbon | Hydrocarbons ((un-)saturated, cyclic) with one or several of the hydrogen atoms replaced by chlorine (Cl), fluorine (F), bromine (Br) or Iodine (I); fully halogenated compounds are in most cases CFCs |
| Halon | Fire extinguishant |
| HC | Hydrocarbon |
| HCFC | Hydrochlorofluorocarbon |
| HFC | Hydrofluorocarbon |

| | |
|---|---|
| HTF | Heat Transfer Fluid, also called “secondary refrigerant”. Fluid mainly in liquid phase circulating to provide cold out of a machinery room. |
| HVAC | Heating, Ventilation and Air Conditioning |
| LCCP | Life Cycle Climate Performance |
| Lifetime | Period after which a chemical has been absorbed/decomposed in the atmosphere by 1/e |
| Long-term | Alternatives considered to be long-term are expected those of which the use will pertain during several decades, they can be considered intergenerational |
| Mid-term | Alternatives for the mid-term, which use can be considered to pertain for one to two decades |
| ODP | Ozone Depletion Potential |
| ODS | Ozone Depleting Substance |
| OEM | Original Equipment Manufacturer |
| PAC | Packaged Air Conditioner |
| PFC | Perfluorocarbon |
| RAC | Room Air Conditioner |
| R A/C | Refrigeration and Air Conditioning |
| reclaim | processing refrigerant to meet new product specifications, which involves processing “off-site” |
| recovery | extracting refrigerant from equipment during service or disposal in any condition |
| recycling | the reduction of contaminants in recovered substances by basic cleaning processes |
| refrigerant | a chemical that is applied in equipment to provide the cooling effect by the use of its phase change characteristics, usually transferring heat from a “cold” source to a “hot” sink |
| retrofit | adaptation of refrigeration equipment to make it suitable for the (reliable) use of alternative refrigerants |
| TEAP | Technology and Economic Assessment Panel |

| | |
|---|---|
| TEWI | Total Equivalent Warming Impact (this combines the global warming effect associated with energy consumption ($CO_2$ emissions) and the direct global warming effect (GWP) of a chemical if emitted) |
| TOC | Technical Options Committee |
| VOC | Volatile Organic Compound |

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