MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

2002 REPORT OF THE
REFRIGERATION, AIR CONDITIONING AND HEAT PUMPS
TECHNICAL OPTIONS COMMITTEE

2002 Assessment

Montreal Protocol
On Substances that Deplete the Ozone Layer

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Abstract Executive Summary of the 2002 TOC Refrigeration, Air Conditioning and Heat Pumps Assessment Report

Current status

In the last decade, the refrigeration, air conditioning and heat pump industry made tremendous technical progress and complied with the Montreal Protocol through phasing out CFCs and, in several applications, HCFCs as well. The mobile air conditioning and the domestic refrigeration industries have shifted rapidly from CFC-12 to non-ODS refrigerants. Other applications, such as chillers and commercial refrigeration, have shifted from CFCs to HCFCs and HFCs or other fluids.

The requirement to phase out CFCs and eventually other ODS, along with considerations to reduce global warming impacts, has spurred unprecedented transitions. Differences in timing and in choosing options between countries have been influenced by regional and national regulations. The primary solutions for new equipment are summarised below by application:

- *domestic refrigeration*: HFC-134a and isobutane (HC-600a),
- *commercial refrigeration*: HCFC-22 and mainly R-404A in supermarket systems, HCs in some self-contained units as well as in a few indirect systems and, to a small extent, carbon dioxide (R-744),
- *industrial refrigeration*: ammonia (R-717), HCFCs, HFCs and to some extent carbon dioxide for low temperature,
- *transport refrigeration*: HFCs for the majority of applications,
- *stationary air conditioning equipment*: HCFC-22 (in about 90% of the equipment), with the remainder using the currently produced HFCs and HFC blends and, to a lesser extent, HCs,
- *chillers*: HCFCs (primarily HCFC-22 in small and HCFC-123 in centrifugal chillers), HFCs (primarily HFC-134a and, in smaller equipment, also blends) and much less commonly ammonia and HCs,
- *heat pump water heaters*: HCFC-22, HFC-134a, propane (HC-290), R-410A and, to some extent, carbon dioxide,
- *mobile air conditioning*: HFC-134a for virtually all new vehicles (being the global choice).

The above solutions are also being applied in Article 5(1) countries, where in several sectors the conversion is not complete, however, the number of conversions is steadily increasing. There still is a certain amount of new equipment manufactured with CFCs, also in domestic, but particularly in commercial and transport refrigeration.

What is left to be achieved

Worldwide, a significant amount of installed refrigeration equipment still uses CFCs and HCFCs. As a consequence, service demand for CFCs and HCFCs remains high. The refrigerant demand for these service needs is best minimised by preventive service, containment, retrofit, recovery and recycling. Recovery at decommissioning or scrapping of equipment, not only in the case of refrigerators, is an important topic, which receives increasing attention now that the non-Article 5(1) ODS consumption has been restricted to essential uses. The first step in addressing the refrigerant conservation topics cited above is through training of installers and service technicians, together with certification and regulations. Countries where programs have been successful have had comprehensive regulations requiring recovery and recycling.

The way forward

Current developments concentrate on increasing use of HFCs as well the non-fluorocarbon options mentioned above in most sectors, with emphasis on optimising system efficiency (COP) and reducing emissions of high-GWP refrigerants. A high degree of containment, in fact, applies to all future refrigerant applications, either for decreasing climate impact or for safety reasons. Additional research and development is ongoing all over the world (i) to enhance the development status and the quality of the equipment using the current alternatives and, (ii) to investigate the potential of other long term in-kind and not-in-kind solutions, seeking both lower environmental impact including higher energy efficiency and improved safety characteristics.

Executive Summaries of all Chapters

Refrigerants

This chapter summarises data for refrigerants and specifically those addressed in other sections. 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 refrigerants") for air-conditioning, heat pump and refrigeration systems.

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
- molecular mass
- normal boiling point (NBP)
- critical temperature (T_c)
- critical pressure (P_c)
- occupational exposure limits
- lower flammability limit (LFL)
- heat of combustion (HOC)
- safety classification
- atmospheric lifetime (τ_{atm})
- ozone depletion potential (ODP)
- global warming potential (GWP)
- control status

The summary tables also add new blends introduced since the 1998 assessment report. The new chapter clarifies the significance of between *modelled*, *semi-empirical*, *time-dependent* and *regulatory* bases for Ozone Depletion Potentials (ODPs) and tabulates comparative *modelled* and *regulatory* values for controlled, single-compound refrigerants. The updated chapter adds guidance for ODPs and GWPs for regulatory reporting.

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.

Status of Refrigerant Data

The status of data for the thermophysical properties of refrigerants, which include both thermodynamic properties (such as density, pressure, enthalpy, entropy and heat capacity) and transport properties (such as viscosity and thermal conductivity), is generally good and excellent for the most common alternative HFCs. 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). Concerted research on the refrigerant-lubricant mixtures is in the early stages. It is complicated by the great variety of lubricants in use and by the often highly proprietary nature of the chemical structure 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

The 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.

Heat Transfer Fluids (“Secondary Refrigerants”) for Indirect Systems

The expanded update adds information on heat transfer fluids (HTFs) — also referred to as *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 constrains 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:

- Glycol solutions
- Salt solutions
- Synthetic oils
- Hydrofluoroethers

The use of phase-change fluids in indirect systems is becoming more popular due to favourable thermal and transport properties leading toward energetic 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. With the benefit of much greater heat capacities, and generally improved heat transfer coefficient associated with change of phase, they offer systems potential benefits from lower flow rates and pumping costs, smaller pipe sizes and heat exchangers.

Domestic Refrigeration

The transition from CFC refrigerants in new equipment is complete in non-Article 5(1) countries and is accelerating in Article 5(1) countries. The 15 to 25 year typical life span for domestic refrigerators results in older product manufactured using CFC-12 refrigerant still comprising the majority of units in the installed base. This in-turn significantly retards the rate of reduction in the demand for CFC-12 refrigerant in the servicing sector.

HC-600a and HFC-134a continue to be the dominant alternative refrigerant candidates to replace CFC-12 in new domestic refrigeration equipment. Both of these have demonstrated mass production capability for safe, efficient, reliable and economic use. In practice, similar product efficiencies result from the use of either refrigerant. Independent studies have concluded that other design parameters introduce more efficiency variation opportunities than is presented by the refrigerant choice. Comprehensive refrigerant selection criteria include safety, environmental, functional and performance requirements. A grossly simplified summary of relative considerations for these two refrigerants is:

- HC-600a is compatible with historically accepted mineral oils as a lubricant. Designs must take care to properly deal with the flammable nature of the refrigerant.
- HFC-134a uses moisture-sensitive polyolester oils. Manufacturing processes must take care to properly maintain low moisture levels. Long-term reliability requires more careful avoidance of contaminants during production or servicing compared to previous CFC-12 based designs.

No significant new technology options are expected to emerge which will significantly alter options for conversion to ozone-safe refrigerants in the remaining Article 5(1) countries still using CFC-12 in new equipment. All required technologies are mature and readily available; availability and prioritisation of capital resources are dictating conversion timing. Current technology designs typically use less than one-half the electrical energy required by the units they replace. This reliable performance is provided without resorting to higher cost or more complex designs. Anticipated enhancements with leading edge technologies will provide further incremental improvements in unit performance and/or energy efficiency. In some cases this efficiency will be provided at the cost of increased complexity or reduced tolerance to abnormal conditions. Government regulations and voluntary agreements on energy efficiency and labelling programs have demonstrated effectiveness in modifying product offerings in several countries.

Commercial Refrigeration

Commercial refrigeration types of equipment are very different in term of size, mainly depending on the country and the kind of shops. Commercial refrigeration equipment consists of 3 main different system types.

- *Stand-alone equipment* includes integrated display cases, ice machines, vending machines, and an array of small equipment installed in stores or public areas in developed countries as well as in many Article 5(1) countries. It is estimated that there are 44.7 million units in this category world-wide. Refrigerant charges range between 0.2 and 1 kg. HFC-134a is the usual refrigerant replacing CFC-12. HCs (HC-600a and HC-290) are now being used in some European countries. Beverage and ice cream vending machines are estimated at 14.7 million units. Several large food and beverage companies have indicated that they will refrain from using HFCs within a few years where suitable alternatives are available. HFC-134a is clearly the dominant option at present.
- *Condensing units* are typically installed in specialised shops. The refrigerant charge varies between 1 and 5 kg, and the estimated global number is on the order of 32.5 million. The refrigerant of choice depends on the temperature range required. Both HFC-134a and the HFC blend R-404A are the preferred options for medium temperatures, and R-404A for low temperatures. Due to safety concerns, HCs are not a common option for the charge amount normally present in condensing units.
- *Centralised systems* are installed in super- and hyper-markets. The estimated number of supermarkets where a wide range of refrigerating capacities is installed is estimated as 340,000; this number includes 18,000 hyper-markets, i.e., very large supermarkets. In centralised systems, the refrigerant charge varies from 100 kg up to 2,000 kg. The refrigerating system is installed in a machinery room and the refrigerant circulates between this machinery room and the display cases installed in the sales area. The choice of refrigerants largely depends on national regulations.
- CFC-12 is still being used in Article 5(1) countries, but new supermarkets in these countries use the same refrigerant as is used in non-Article 5(1) countries. HCFC-22 is still widely used in the United States, but R-404A is gaining market share in the USA. In Europe, the use of HCFC-22 in new equipment has been banned since 1 January 2001. R-404A is the preferred choice there. In Japan CFC-12 has been replaced by HFC-134a and sometimes by R-407C.
- In Europe, indirect systems are receiving more and more attention in order to limit the refrigerant charge (whatever the type of refrigerant) or to allow the use of ammonia or hydrocarbons. CO_2 is being evaluated as a heat transfer fluid or as a low temperature refrigerant. Several hundred of indirect systems have been installed in the last four years, especially in Northern Europe.
- The energy consumption of both direct and indirect systems is being evaluated. However, the reference base varies widely as there are many variables such as the size of sales areas, the type of display cases (with or without doors), the control system, and the climatic zones, etc. Particularly at the medium temperature level, well-designed indirect

systems may show equal or even slightly better energy consumption compared to the usual, centralised direct systems.

- It should be mentioned that indirect systems need a more complex and a more expensive design. The initial costs are higher, whereas currently the operating costs and the maintenance costs are still being evaluated. For large store companies, the initial costs still form the main driver; it is for this reason that centralised direct expansion systems form the most common technology for supermarkets.

Large Size Refrigeration (Industrial, Cold Storage and Food Processing)

The applications covered in this chapter are industrial refrigeration, cold storage, food processing and large industrial heat pumps. The major concern for the systems, which are described in this chapter, is the reduction of energy consumption. The systems are mainly custom made and often erected on site. As a refrigerant, ammonia (NH_3) is used in approximately 75-85% of the current installations followed by HCFC-22, CFCs and HFCs.

Industrial Refrigeration covers a wide range of cooling and freezing applications, including chemical and pharmaceutical industries, petrochemical, oil and gas industries, metallurgical industry, plastic moulding, civil engineering, sports and leisure facilities, industrial ice making, air liquefaction and others.

Food Processing is one of the fastest developing industries in the world. Food processing covers a wide range of cooling and freezing applications, including the processing and storage of meat, fish, cheese, beer, eggs, fruits and vegetables. Refrigeration is used to preserve food from harvest, catch or slaughter, through processing, transport, storage and distribution to retail sales and markets.

Cold Storage is related to both raw materials and finished products in a food processing factory. Modern cold storage warehousing typically consist of a one level building with elevated loading banks for the rational handling of full pallets.

In 2000, the world-wide consumption of frozen food was 30 million tonnes. The United States accounts for more than half of this, with more than 63 kg per capita. The average figure for the European Union (EU) is 25 kg and for Japan 16 kg. Chilled foods form 10 -15 times the frozen product quantity. Total quantity of temperature controlled products is estimated at 350 million tonnes (1995), where the annual growth is estimated as 5%.

Most systems use NH_3 with a tendency emerging to reduce the charge through indirect systems using brines or cascade systems using refrigerants. Beside traditional brines “ice slurries” have been introduced as a new option (in breweries first). It is expected that the market share will increase for such systems where a reduction of refrigerant charge is required. At low temperatures (below –40 to –45 °C) a clear global trend can be observed towards cascade systems, where CO_2 is used in the low temperature stage of the system. Particularly in Europe, large cascade systems with cooling capacities of several MW have been built utilising NH_3/CO_2 cascade systems. For new systems no CFCs or HCFCs have been used. In applications, where, for various reasons, NH_3 cannot be utilised, HFCs are used.

The retrofit of industrial refrigeration plants is difficult due to the fact that these are custom-made installations. Most existing systems that use CFCs and HCFC-22 are still in operation, although in some special cases end-users have already converted HCFC-22 systems to operate on CO_2 or NH_3.

In Article 5(1) countries the use of NH_3 is not so common as in the developed countries, but there is a significant number of –mostly old- systems still in operation. Systems based on HCFC-22 have been installed there more often, with CFC units to a much lesser extent.

Transport Refrigeration

Transport refrigeration includes refrigeration in ships, fishing vessels, containers, road transport equipment and railcars. For transport air conditioning only merchant ships and railcars are covered.

Most systems which still used CFCs in 1998 have been retrofitted or scrapped and the remaining uses are concentrated on old refrigerated containers and trucks with a short remaining operational lifetime, yet the existing CFC fleet remains still significant.

In ships, most existing systems use HCFC-22, though R-407C and R-404A/R-507 are options already used today in Europe for new systems. For the future, R-410A is expected to play an important role.

On merchant ships most systems use HCFC-22, and CFC use is reducing significantly since 1998. R-404A/R-507 is dominating new systems, and fishing fleets and naval vessels form a significant part of this sector.

Out of the about 550,000 refrigerated containers fleet, only a small portion still uses CFC-12, and some may be in use beyond the year 2003. They could be retrofitted with an interim solution to cope with their remaining lifetime. For new units HFC-134a and R-404A predominate the market. Beside, some development of carbon dioxide based units has started.

There are about 1,200,000 refrigerated road vehicles in use. Half of these still use CFC-12 or R-502. Current production uses HFC-134a, R-404A, or HCFC-22 (to a lesser extent) and some units with R-410A are available. Research and tests of hydrocarbon, solar and cryogenic systems with liquid air or liquid carbon dioxide are in progress.

Numbers of refrigerated railcars and swap-bodies remain relatively small.

Railcar air conditioning is moving from HCFC-22 with relatively high leakage rates to R-134a or R-407C, which require specific attention for system containment. Railcar air conditioning exhibits increasing market penetration.

Generally, HFCs offer today the preferred future options for new systems, though there is development work on alternatives including hydrocarbons, ammonia, air cycle and CO_2.

HFC and HC retrofit options exist for systems in use. Application of some of these could be restricted by local legislation in some countries.

There is a need to concentrate on containment, training and efficiency issues, and to accept the imminent restrictions on HCFC use in some countries.

Air Conditioning & Heat Pumps (Refrigerant-To-Air)

Globally, air-cooled air conditioners (including heat pumps) comprise a vast majority of the air conditioning market. Air-cooled air conditioners fall into four categories: window-mounted, non-ducted split residential and commercial, ducted split residential, and ducted commercial air conditioners. Nearly all air-cooled air conditioners manufactured prior to 2000 used HCFC-22 as a working fluid.

It is estimated that 131 million window-mounted and through-the-wall air conditioners are in operation globally—containing an installed HCFC-22 bank of approximately 85,000 tonnes. During this assessment period, there has been a significant shift away from the use of window-mounted air conditioners to non-ducted split residential air conditioners as the entry-level air conditioning product in Article 5(1) countries--particularly in Asia. An estimated 158 million non-ducted or duct-free Split air conditioners are installed worldwide—containing a refrigerant bank of 199,000 tonnes. An estimated 60 million ducted split residential air conditioners are currently in service worldwide. The total estimated inventory of HCFC-22 in the installed population of ducted systems has been estimated to be 164,000 tonnes. Approximately 19 million air-cooled Ducted Commercial Split and Packaged air conditioners and heat pumps are installed worldwide containing and estimated refrigerant bank of 101,000 tonnes.

Since the last assessment, the primary non-ODS refrigerants used in these products have been R-407C, R-410A and to a lesser extent HC-290. A significant shift to non-ODS alternatives has been observed in Europe and Japan. A shift of approximately 5% has been observed in the US. In the remainder of the world there has been minimal conversion to non-ODS alternatives in air conditioning applications. A rough estimate would indicate that globally 85 to 90% of the air-cooled air conditioners and heat pumps currently produced globally still use HCFC-22 as the refrigerant. HFC refrigerants and hydrocarbon refrigerants, to a lesser extent, will have the greatest impact on the industry transition for the next 10-15 years.

The primary retrofit refrigerant is the zeotropic blend, R-407C. Hydrocarbon refrigerants are viewed as unlikely retrofit options because of high cost and complexity of safely retrofitting existing HCFC-22 systems.

Demand for HCFC-22 may continue to increase until approximately 2005 and gradually decline as developed countries expand their usage of non-ODS alternatives to meet regional and Montreal Protocol phase-out dates.

Most of the technology required to phase-out ODS substances in Article 5(1) countries has been developed and is slowly being transferred to the Article 5(1) countries. As the penetration of these technologies increases, costs will fall, resulting in increased conversion to non-ODS refrigerants in the Article 5(1) countries.

Chillers and Heat-Pump Water Heaters

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.

Heat pump water heaters are reversible chillers capable of drawing heat from an air or water source and using it for service (sometimes indicated as sanitary) supply or for hydronic heating systems employing convectors, fan coils, or other heat exchangers.

New Equipment since 1998

In, general, the types of available equipment have not changed since 1998, but there have been subtle changes in the relative importance of various refrigerants. CFCs are decreasing in importance as the older machines are phased out in the developed countries and are being replaced largely by HCFCs and HFCs. There is some growth of machinery using non-ODS refrigerants, primarily ammonia, hydrocarbons in small machines, and CO_2 in some heat pump water heaters. In chillers employing positive displacement compressors, reciprocating compressors are being displaced by screw compressors (above 140 kW) or scroll compressors (below 140kW).

Options to Replace Current Systems

The technological options available to the systems designer or machine purchaser have not changed substantially since 1998. The most significant changes have been:

1. Increases in efficiency,
2. Elimination of production of HCFC-22 centrifugal machines,
3. Migration from HCFC-22 towards HFCs in screw and large scroll chillers,
4. Softening of the absorption chiller market,
5. Growing chiller industry in some Article 5(1) countries (especially China and Korea),
6. Decreased optimism for the prospects for CO_2 except in water-heating applications, and
7. Less optimism for the commercial viability of new low pressure refrigerants R-236fa and R-245fa.

Market Characteristics

The market for centrifugal and large screw chillers is divided among the USA (40%), Asia (25%-30%), and smaller percentages in Europe and the Middle East. The market for smaller positive displacement chillers is much larger in numbers and in market revenues world-wide than for the other chiller types. The market for absorption chillers is concentrated in Japan, China, and Korea. The market for heat-pump water heaters is growing and is found primarily in Western Europe and Japan.

Article 5(1) Countries / Technology Transfer

Chillers are technologically sophisticated machines. In Article 5(1) countries, they are normally first seen in large hotels, resorts, well-funded industries, commercial buildings, and hospitals. As the economy grows, so does the use of chillers.

Some Article 5(1) countries have developed domestic production capacity for chillers, largely as a result of joint venture technology transfer. This is perhaps most noticeable in China, but also in India and some Latin American countries. The joint venture partner companies are typically Japanese, Korean, or American.

Vehicle Air Conditioning

Vehicles (cars, trucks, and buses) built before the mid-1990's 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, 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.

HFC-134a is considered a potent greenhouse gas and, due to concerns about emissions of HFC-134a from MAC systems, vehicle makers and their suppliers are reducing their system leakage and improving energy efficiency, and are searching for a replacement refrigerant. In the timeframe 1998-2002, the leading potential replacement refrigerant has been carbon dioxide (R-744) for which many global vehicle manufacturers and suppliers have demonstrated prototype cars. Recently, the use of HFC-152a (with a global warming potential less than one-tenth that of HFC-134a) has been proposed and publicly demonstrated in two prototype car systems.

On-site recycling of refrigerant at service shops has been proven to be quite effective for HFC-134a systems; a full 60% of the original charge can be recycled and reused during service. Combining this with service frequency scenarios allows an estimation of the current and future refrigerant emissions from MAC systems. Such emission estimates can be useful when calculating the cost benefit analysis of proposed changes.

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(1) 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 must establish economic assessments that make owners of systems take conservation efforts or enforce government requirements by means of financial or other penalties. Article 5(1) 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 should 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 Protocol was open for signature during one year; 21 more countries signed it during this period, including 9 developing countries. The Montreal Protocol entered into force on January 1, 1989. This international environmental agreement originally limited production of specified CFCs to 50% 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% of the 1991 world production of CFCs and halons.

Shortly after the 1987 Protocol was negotiated, new scientific evidence conclusively linked CFCs to 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 assessment reports, and agreed to Protocol adjustments requiring more stringent controls on the CFCs and halons 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 an Interim Multilateral Fund (the magnitude of which would depend on the fact whether China and/or India would accede to the Protocol).

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(1) 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 (IV/13), for decisions by the Parties in their 1995 Meeting.

At the 7th Meeting in Vienna (November 1995) the Parties focused on the progress made in phasing out ozone depleting chemicals, and 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 HCFCs for the Article 5(1) countries was agreed upon (a freeze by the year 2016 and a phase-out by the year 2040).

Article 5(1) 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; they also requested a new study for the replenishment of the Multilateral Fund.

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.

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 three Assessment Panels to update their 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 to the Protocol in 2003.".* Together with the Science and Environmental Effects Assessment reports, the 2002 TEAP assessment report -together with the 2002 TOC assessment reports- forms the direct response to the above-mentioned decision.

The present status (early 2003) is that the Montreal Protocol has been ratified by 184 countries, Parties to the Protocol (the Vienna Convention has been ratified by 185 countries, Equatorial Guinea has only ratified the Convention). The London Amendment has been ratified by 164 Parties and the Copenhagen Amendment by 145 Parties. The Montreal Amendment has been ratified by 91 countries, and the Beijing Amendment has been ratified by 47 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 Meeting of the Parties 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(1) 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:

(1) **Aerosols, Sterilants, and Miscellaneous Uses** Technical Options Committee
(2) **Rigid and Flexible Foams** Technical Options Committee
(3) **Halons** Technical Options Committee

(4) **Methyl Bromide** Technical Options Committee
(5) **Refrigeration, A/C and Heat Pumps** Technical Options Committee
(6) **Solvents, Coatings and Adhesives** Technical Options Committee.

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

The Parties in Copenhagen took a number of decisions, which concern the work of the Technology and Economic Assessment Panel and its Committees. A decision (IV/13) on "Progress" requested the TEAP and its TOCs to annually report on progress in the development of technology and chemical substitutes. This decision was re-evaluated and restated in the meeting in Vienna, in 1995 (VII/34). As a result, progress reports have been conceived annually by the TEAP and its Committees; they were submitted to the Parties in the years 1993 – 2002 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 1993-2002 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.” Parties to the UNFCCC (Buenos Aires) and to the Montreal Protocol took mirror decisions in 1998, in Buenos Aires and Cairo, on the use of HFCs, the interaction between the Montreal and the Kyoto Protocol, etc. 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 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, 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). It asks for a joint undertaking by the IPCC and TEAP in order to prepare a 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 and the three TEAP co-chairs) oversees the study. The Steering committee started its work in November 2002. It is expected that many members of the 2002 TOC Refrigeration will be part of the membership for the drafting group of this IPCC/TEAP Report.

The 2002 Technical and Economic Assessment study has been carried out by the Technology and Economic Assessment Panel and its six Technical Options Committees. The six Committees consisted of more than 200 experts from a large number of countries (for a list see the annex to the Technology and Economic Assessment Panel Report 2002).

The 2002 Technical Options Committees consist of several members of the 1994 and 1998 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(1) 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 and http://www.teap.org)

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 also forms part of the UNEP review pursuant to Article 6 of the Montreal Protocol.

It is part of the 2002 assessment work of the Technology and Economic Assessment Panel (requested by the Parties in Beijing (XI/17)). 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 2002, as well as the overall Synthesis Report by the three Assessment Panels.

The Technical Options Report on Refrigeration, A/C and Heat Pumps 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, and an annex, which gives historic data for refrigerant production and consumption. The structure of the report was chosen more or less similar to the structure of the 1998 Technical Options Committee Assessment Report.

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

Brazil	Japan	Thailand
France	Kenya	Tunisia
Germany	Netherlands	Uganda
	Norway	
Hungary	Poland	United Kingdom
India	Russian Federation	United States
Indonesia	Slovakia	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 who did the larger part of the drafting and the co-ordination. The 2002 Technical Options Committee included 39 representatives from African, Asian, European, Latin and North American governments, universities and companies, as well as independent experts (see Table 1-3). These representatives have been acting as Reporting Members; as resource persons the Technical Options Committee Refrigeration, AC and Heat Pumps also has 22 Consulting Members.

Affiliations of the Reporting Committee members are listed in Table 1-5 (39 organisations were involved in the drafting of the report). The names and contact details are given as an appendix to this Technical Options Committee Assessment Report.

Several drafts of the report were made, reviewed by the separate chapters and discussed in six Options Committee meetings (preliminary draft mid 2000, draft end 2000, draft March 2001, draft September 2001, peer review draft July/September 2002 and final report December 2002). A preliminary committee meeting was held in W-Lafayette, Purdue University, July 2000. Drafting and reviewing meetings were held in Hungary (Budapest), April 2001, Germany (Hannover), October 2001, USA (W-Lafayette, Purdue), July 2002 and France (Paris), December 2002.

As stated, the structure of the Refrigeration Technical Options Committee Report is more or less similar to the Assessment Report of the Refrigeration Technical Options Committee in 1998, except for the fact that the report does not contain separate chapters on industrial refrigeration and cold storage. With technology proceeding rapidly, the report is not a simple update of the 1998 report, but all options described in 1998 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 beginning of October and 20 November 2002 (see Table 1-4 for the organisations involved). All peer review comments were dealt with by the Technical Options Committee (on a case-by-case basis) in plenary during its meeting in Paris, December 2002. The Technical Options Committee greatly acknowledges the voluntary support given by the peer review institutions.

Table 1-4 *Organisations involved in the peer review of the UNEP TOC Refrigeration Report*

ARI	*Air Conditioning and Refrigeration Institute*
BIR	*British Institute of Refrigeration*
CCSEE	*Brazilian Manufacturers*
DKV	*German Refrigeration Society*
Greenchill Aus	*Greenchill Australia*
IIR	*International Institute of Refrigeration*
ISHRAE	*Indian Society of Heating, Refrigeration and AC Engineers*
JRAIA	*Japanese Refrigeration and Air Conditioning Industry Association*
U of Illinois	*U of Illinois, Refrigeration Department (Pedrag Hrnjak)*

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

ARI, Air Conditioning and Refrigeration Institute	U.S.A.
Atofina	France
Axima Refrigeration	Germany
Bandung Institute of Technology	Indonesia
Braunschweig University	Germany
Calm (Consultant)	U.S.A.
Calor Gas Limited	UK
Carrier Corporation	U.S.A.
CPPI Projects, ODS Phase-out	Russia
Daikin Industries Ltd.	Japan
Dehon Service SA	France
Delphi Automotive Systems	U.S.A.
Ecole des Mines Paris	France
FKW Hannover	Germany
General Electric, Appliance Division	U.S.A.
Hickman (Consultant)	U.S.A.
Honeywell International	U.S.A.
Hungarian Refrigeration and AC Association	Hungary
IEA Heat Pump Centre	Netherlands
Indian Inst. Technology IIT New Delhi	India
Inst. Fluid Flow Machinery Gdansk	Poland
Karlsruhe University	Germany
Makerere University, Kampala	Uganda
Matsushita Electric Ind. Corporation Ltd.	Japan
Maua Institute of Technology	Brazil
Ministry of Fisheries, Hanoi	Vietnam
Ministry of Industrial Development	Kenya
Multibrás SA Eletrodomésticos	Brazil
Nat. Chemical Laboratory Pune	India
Re/genT Co	Netherlands
Siccon Consultancy (Sicars)	Germany
SINTEF Energy Research, Trondheim	Norway
Slovak Union for Cooling and AC Technology	Slovakia
Sofrifac, Tunis	Tunisia
Sun Test Engineering	U.S.A.
Technical University Eindhoven	Netherlands
Thai Compressor Manufacturing Co. Ltd.	Thailand
The Trane Company	U.S.A.
U.S. Environmental Protection Agency	U.S.A.

1.4 Refrigeration, Air Conditioning and Heat Pumps

1.4.1 General Remarks

Refrigeration, air conditioning and heat pump applications represent the sector which is the largest consumer of refrigerant chemicals; 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 be between 10-20%.

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) industrial 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 (performance);
- temperature ranges;
- pressures and 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 TOC Refrigeration, A/C and Heat Pumps 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 Long Term Options and Energy Efficiency

CFC production has been phased out in the developed countries, and the CFC phase-out is underway in the developing countries. In both developed and developing countries, HCFCs and HFCs have 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(1) 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 TOC Refrigeration assessment report). The larger part of the centrifugal chillers in the world (the majority being on CFC-11) has so far not been retrofitted from CFCs to substitutes. 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 EU) 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.

One should state here that it is not the changing refrigerant options that form 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 long term, there remain, in fact, only five important different refrigerant options for the vapour compression cycle in all refrigeration and A/C sectors, listed alphabetically:

1. ammonia (R-717);
2. carbon dioxide (R-744);
3. hydrocarbons and blends (HCs, e.g. HC-290, HC-600, HC-600a etc.);
4. hydrofluorocarbons (HFCs, HFC-blends with 400 and 500 number designation);
5. 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, 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 options above are in different stages of development or commercialisation; HFCs are widely applied in many sectors, ammonia and hydrocarbons enjoy growth in sectors where they can be easily accommodated, and for certain applications, CO_2 equipment is under development and the first demonstration components have reached the market. Water is used and may see some increase in use in limited applications. Work is being done by several committees in developing standards to permit the application of new refrigerants, and it is the intent of companies to reach world-wide accepted limits in those different standards.

Similarly, energy efficiency research is partly spurred by the role of energy production in carbon dioxide emissions. Options for energy efficient operation of equipment form an important issue in each of the chapters of this 2002 TOC Refrigeration 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, 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). It asks for a joint undertaking by the IPCC and TEAP in order to prepare a report on “Safeguarding the climate system and protecting the ozone layer; issues related to HFCs and PFCs”. A Steering Committee, consisting of six members (three IPCC and the three TEAP co-chairs) oversees the study. The Steering committee started its work in November 2002. Next to members from other TOCs, it is expected that many members of the 2002 TOC Refrigeration will be part of the membership for the drafting group of this IPCC/TEAP Report.

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, in particular with the dependence or independence of each of these sectors on HCFCs and the introduction of non-ODP options now and/or in the near future. Chapter 9 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 and hydrocarbons will have. Chapter 10 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 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 sections. 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 refrigerants") for air-conditioning, heat pump, and refrigeration systems. 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 summary tables also add new blends introduced since the 1998 assessment report.

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

The table in Annex IV (located at the end of this report) 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 data in this table were extracted from a summary by Calm and Hourahan /Cal01b/ and the ARTI Refrigerant Database /Cal01a/; 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 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 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 /Lem02/ 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 /ASH01a and ASH02a/
- chemical formula, in accordance with the IUPAC convention /IUP79/ or, for blends, the blend composition in accordance with ASHRAE Standard 34 /ASH01a and ASH02a/
- molecular mass
- 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
- critical pressure (P_c) in kPa or, for blends, the calculated pseudo-critical pressure
- 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 measure

- lower flammability limit (LFL) in % concentration ambient air, determined in accordance with ASHRAE Standard 34 /ASH01a and ASH02a/. The LFLs indicated for blends are for the nominal formulations and do not reflect potential fractionation, which is considered in safety classifications.
- heat of combustion (HOC) in MJ/kg calculated assuming complete reaction to the most stable products in their vapour state (for example C, N, and S react to CO_2, N_2, and SO_3, respectively; F and Cl form HF and HCl if there is sufficient H in the molecule or F_2 and Cl_2 otherwise; and excess H is converted to H_2O): This conservative definition is used for refrigerant safety classifications /ASH01a/, but typical heat releases will be lower depending on the refrigerant and combustion conditions. Negative values indicate endothermic reactions while positive values indicate exothermic reactions
- safety classification, if assigned, in accordance with ASHRAE Standard 34 /ASH01a and ASH02a/ or pending addenda thereto: Some of the classifications are followed by lower case letters, which indicate:

  d signifies that the project committee responsible for ASHRAE Standard 34, SSPC 34, has recommended *deletion* of the classification, but final approval and/or publication is still pending ("d" alone indicates that a prior classification was deleted and that the refrigerant no longer has a safety classification).

  p indicates that the classification was 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
- atmospheric lifetime (τ_{atm}) in years: Note that τ_{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 R-11 based on the values adopted in the *Scientific Assessment* /WMO99/ or, for blends, the mass-weighted averages /Cal01a,b/ based on the IUPAC atomic weights /Cop97/ 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 Assessment /IPC01/ or, for blends, the mass-weighted average based on the IUPAC atomic weights /Cop97/ of the component GWPs
- 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

2.2.1 Ozone Depletion Potentials

The ODPs indicated in the Table are *modelled* values, the most indicative of environmental impacts. There are other ODP indices, among them *semi-empirical*, *time-dependent*, and *regulatory* variations /Cal01b/. Semi-empirical ODPs are calculated values that incorporate adjustments for observed atmospheric measurements. This approach is conceptually more accurate, but the data needed are difficult to measure precisely. Time-dependent ODPs use chemicals other than R-11 as the reference to emphasise impacts for other, typically shorter, timeframes. Normalising values to short-lived compounds accentuates near-term impacts, but discounts long-term effects. Time-dependent ODPs are not cited often, particularly since the release of ozone-depleting substances already has peaked and recovery of the stratospheric ozone layer is underway. Regulatory ODPs generally are old data used to set phase-out steps, determine compliance with the Montreal Protocol, and allocate production quotas in national regulations. Because of the political and competitive complexities in changing consumption targets and production allocations, these values commonly are left unchanged even when newer scientific findings improve the quantification precision. The ODP values listed in the annexes to the Montreal Protocol, for example, have not been updated since 1987 for chlorofluorocarbons (CFCs) and 1992 for hydrochlorofluorocarbons (HCFCs). A note in the Protocol indicates that the values "are estimates based on existing knowledge and will be reviewed and revised periodically," but that has not happened yet /UNE00/. Table 2-1 contrasts modelled (the most indicative of environmental impacts) and regulatory (as used in the Montreal Protocol, but generally based on old data) ODPs.

Table 2-1 *Modelled and Regulatory ODPs for BFC, CFC, and HCFC Refrigerants*

	ODP	
refrigerant	Modelled	regulatory
11	1.000	1.0
12	0.820	1.0
12B1	5.100	3.0
13	1.000	1.0
13B1	12.000	10.0
21	0.010	0.04
22	0.034	0.055
113	0.900	0.8
114	0.850	1.0
115	0.400	0.6
123	0.012	0.02
124	0.026	0.022
142b	0.043	0.065

2.2.2 ODP and GWP Data for Regulatory Reporting

The data presented in the Table in Annex IV 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 and many national regulations pursuant to it use older, adopted values. Similarly, emission reporting pursuant to the Kyoto Protocol are based on data from the 1995 IPCC assessment /IPC96/ rather than the updated 2001 assessment /IPC01/.

THE ODP AND GWP DATA IN THE TABLE IN ANNEX IV SHOULD NOT BE USED FOR REGULATORY REPORTING THAT REQUIRES USE OF SPECIFIED (TYPICALLY OLDER) DATA ADOPTED IN THE CONTROLLING REGULATIONS. Table 2-1 provides the "regulatory" ODPs for the Montreal Protocol. Table 1 of the 1998 TOC assessment provides the GWPs from the 1995 IPCC Assessment including derived values calculated for blends /UNE98/.

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 (R-32, R-125, and R-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 R-290 (propane), R-600 (n-butane), and R-600a (isobutane) are good, but they are not known as well as is commonly assumed and not as well as for the HFCs. Observed inconsistencies should be resolved. A review of the current models should be carried out in light of 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, ammonia, and CO_2. McLinden et al. /McL98b/ and Lemmon and McLinden /Lem01/ provide a summary of the available data for blends. An International Standards Organization working group (ISO TC86/SC8/WG7) presently is working towards an international standard for the thermodynamic properties of ten single-compound refrigerants and four blends; the standard is expected to be complete in late 2002 or 2003. Assael et al. /Ass99/ and McLinden et al. /McL00/ provide references to transport property data for 31 and 14 refrigerants, respectively.

The data situation for the less-common fluids is more variable. There is interest in the ethers and particularly the hydrofluoroethers (R-E series refrigerants as in, for example, R-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 in the early stages. 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 R-22 or R-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 insure reliability.

Citing representative problem areas and development needs, ammonia is not compatible with most types of electrical wiring insulation, converting polyester compounds to amides. 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. Aluminium 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/.

As reported by Kruse and Tiedemann /Kru97/, the thermal stability of R-170 (ethane), R-290 (propane), R-600a (isobutane), and R-1270 (propylene) in the presence of lubricants is being investigated. The tolerable amount of impurities in hydrocarbons based on performance and materials compatibility also is being studied. Sealed tube tests containing R-290 and R-600a with various oils, materials, and air show negligible degradation /San96/.

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 Mechanical Refrigeration* /ASH01b/, which is the basis of many national and international standards and regulations, provide guidance on vessel requirements, pressure relief devices, and testing.

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

Safety data and resulting recommendations for refrigerant concentration limits and occupational exposure limits generally are available for fluorochemical refrigerants /Cal00, Cal01a, and Cal01b/. 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.

Efforts are underway to develop recommended refrigerant concentration limits for unplanned exposures and to improve flammability test methods and data /ASH00c and ASH00d/.

2.4 Status and Research Needs for Heat Transfer Fluids (“Secondary Refrigerants”) for Indirect Systems

Heat transfer fluids (HTFs) — also referred to as *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:

- Glycol solutions (e.g., propylene glycol, ethylene glycol)
- Salt solutions (e.g., calcium chloride, sodium chloride, potassium formate, potassium acetate, calcium carbonate)
- Synthetic oils (e.g., dimethylsiloxanes)
- Hydrofluoroethers (e.g. R-E4-49 (methoxy-nonafluorobutane), R-E5-69mccc (1-

(ethoxy)-1,1,2,2,3,3,4,4,4-nonafluorobutane))

The following fluids also are used, but not commonly because of their flammability.

- Alcohol solutions (e.g., ethanol, methanol, propanol)
- Aliphatic Hydrocarbon (e.g., pentanes, hexanes)
- Aromatic hydrocarbons (e.g., benzyltoluenes)

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

The use of phase-change fluids in indirect systems is becoming more popular due to favourable thermal and transport properties leading toward energetic 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. With the benefit of much greater heat capacities, and generally improved heat transfer coefficient associated with change of phase, they offer systems potential benefits from lower flow rates and pumping costs, smaller pipe sizes and heat exchangers.

The important aspects associated with the 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 brines, are more corrosive than others. In most cases inhibitors are required as well as methods for 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 additive 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 salt mixtures 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: Recent work by Melinder /Mel97/ has characterised the properties of many HTFs in use. Melinder /Mel98/ shows that there is considerable discrepancies between the published data for HTFs, particularly at low temperature. Similar disagreement is found in freezing point measurements, which is important for establishing ice concentrations in slurries.
>
> Properties of phase-change HTFs: There is significant progress on properties for ice slurries using a broad range of different brines, glycols and alcohol solutions (e.g., /Lot00 and Mee00/). There is an Ice Slurry Centre (ISC) based in Denmark that is progressing the majority of work in this field. Significant work is also being done on carbon dioxide, although the earlier section on primary refrigerants should be referred to for property aspects.
>
> Compatibility: The most significant problems encountered by industry are compatibility issues. Generally inhibitors are provided with the product, but these vary between manufacturers and dissemination of information is limited. Since absorbed air is difficult to remove and spillage frequently occur, 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 and freezers are used for food storage in individual dwelling units and in non-commercial areas such as offices throughout the world. More than 80,000,000 units are produced annually. Models available include: *fresh food storage only*, generally maintained at +1 to +5 °C; *frozen food storage only*, generally maintained at -6 to –24 °C; or *products having multiple chambers* maintained at each of these temperatures. Internal storage capacities range from 20 litres to greater than 850 litres. Added features commonly available include multiple access doors, ice-makers, dispensers, various types of defrosting mechanisms and specialty storage chambers with different temperature control points. Life style and food supply infrastructures are strong determinants for consumer selected storage capacities and features. As a consequence, consumer preferences for product configuration vary widely among different global regions. Typical products are totally factory assembled and apply reciprocating compressor mechanisms driven by 50 to 250 watt induction motors integrated within a hermetically sealed refrigeration system. Rotary compressor mechanisms are also used in a small fraction of global production. Polyurethane closed cell foam is typically used for thermal insulation.

Conversion of the historic universal application of CFC-12 refrigerant in these units to ozone-safe alternatives continues to occur in advance of the Montreal Protocol requirements. As reported in 1998 /UNE98/, national transition schedules in remaining Article 5(1) and CEIT countries continue to be influenced by national regulatory initiatives and the availability of capital resources, including those obtained through the Multilateral Fund and the Global Environment Facility (GEF). Notable among interactive regulatory initiatives are efforts to reduce greenhouse gas emissions in compliance with the Kyoto Protocol /Kyo97/. Amongst other drivers, such as energy price and shortage of supply, this leads to energy efficiency regulations to control the secondary effects of greenhouse emissions from power generation and distribution as well as direct product emission prescriptive regulations.

3.2 New Equipment Alternative Refrigerants

HC-600a and HFC-134a continue to be the dominant alternative refrigerant candidates to replace CFC-12 in domestic refrigeration new equipment. Other alternative candidates have regional appeal, primarily driven by availability of suitable compressors or refrigerants. Example regional candidates include mixtures of HC-600a and HFC-152a in Russia[1], mixtures of HC-600a and HC-290 in India, and mixtures of HCFC-22 and HFC-152a in China. With passing of time and expansion of international trade of both domestic refrigerators and their components, new equipment options may be limited to HC-600a and HFC-134a. The use of an HC-600a / HC-290 hydrocarbon blend allows retention of volumetric capacity to avoid capital expense for retooling compressors. This blend may be significantly less energy efficient than either HC-600a or HFC-134a and requires use of charging techniques suitable for use with a blend of two fluids having different boiling points. Applications of HC-600a/HC-290 blends in Europe during the 1990's was an interim step toward a final transition to HC-600a using retooled compressors.

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[1] A 30% HC-600a/ 70% HFC-152a mixture is identified C1. Russia also has commercial capacity for mixtures of HCFC-22/ HCFC-21/ HFC-134a (S10-M2) and HCFC-22/ HCFC-142b/ HCFC-21 (S10). Animal studies with HCFC-21 indicate possible reproductive effects as well as kidney and liver effects. Allowable chronic exposure limits may be as low as 10 ppm .

Both HC-600a and HFC-134a have demonstrated mass production capability for safe, efficient, reliable and economic use. In practice, similar product efficiencies result from the use of either refrigerant. Independent studies have concluded that other design parameters introduce more efficiency variation opportunities than is presented by the refrigerant choice /AFE97, Fis94, Del96, Wen96/. Additional discussion of this topic is included in section 3.3 below.

Refrigerant selection is truly a strategic decision. It is not a short-term tactical option decision. Comprehensive refrigerant selection criteria include safety, environmental, functional and performance requirements. These requirements were discussed in detail in the 1998 report of this committee. Discussions were framed within the context of general refrigerator-freezer construction type – combined refrigerator-freezer, fresh food only, freezer only, manual defrost, cycle defrost, auto-defrost -- and, within a general type, the specific evaporator construction used. These limited design parameters, coupled with an awareness of construction types prevalent in various global regions, provide the reader insight to the underlying reasons for different preferred refrigerant selections in different global regions. Further, considering general differences in climate, consumer lifestyles and living environments provides insight regarding why various global regions historically evolved toward particular construction types.

Design trade studies of these requirements lead to economic trade studies which are unique to regional needs. Commercial realities such as cost, availability of appropriate materials and components, access to technical assistance if needed, and available service support and training infrastructures must be integrated with the technical facts to achieve a comprehensive assessment. Either alternative refrigerant may be the “right answer” for a specific set of conditions. A grossly simplified summary of relative considerations for these two refrigerants is:

- HC-600a uses historically accepted mineral oils. Designs must take care to properly deal with the flammable nature of the refrigerant.
- HFC-134a uses moisture sensitive polyolester oils. Manufacturing processes must take care to properly maintain low moisture levels. Long-term reliability requires more careful avoidance of contaminants compared to previous CFC-12 based production or servicing.

The refrigerant conversion status and pattern of use for new equipment domestic refrigeration is summarised in Table 3-1, *Estimated 1992, 1996 and 2000 World Production of Domestic Refrigerators and Freezers with Corresponding Refrigerant Type*[2].

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[2] 2000 OEM Production Data from Euromonitor database /Eur01/. Refrigerant conversion data estimated from published worldwide refrigerator fleet estimate /Clo02/ and inputs from members of this committee and compressor manufacturers. 1992 and 1996 data from 1995 and 1998 Refrigerants TOC reports respectively /UNE95, UNE98/. 1996 OEM Production volumes were adjusted to be consistent with the Euromonitor database 1996 values to provide internally consistent consumption data for trend analysis.

Table 3.1 Estimated 1992, 1996 and 2000 Production of Domestic Refrigerators and Freezers by Refrigerant Type

Global Region	Year	New Unit Production, MM Units					New Unit Refrigerant Use, Tons				
		CFC12	HFC134a	HC600a	Other(a)	Total	CFC12	HFC134a	HC600a	Other(a)	Total
Western Europe	1992	16.3				16.3	2280				2280
	1996		11.2	6.1		17.3		1220	410		1630
	2000		8.3	11.4		19.7		900	770		1670
Eastern Europe	1992	7.5				7.5	1500				1500
	1996	2.8	3.2			6.0	320	370			690
	2000	1.1	3.4	0.5	0.2	5.2	230	420	40	30	720
North America	1992	11.6				11.6	1750				1750
	1996		12.5			12.5		2290			2290
	2000		13.4			13.4		2460			2460
Central & South America	1992	4.0				4.0	600				600
	1996	8.2				8.2	1280				1280
	2000	1.2	5.4			6.6	200	1200			1400
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	12.5	11.9	5.7	1.6	31.7	2030	1900	570	200	4700
Africa and Mid-East	1992	5.2				5.2	840				840
	1996	3.4	0.7			4.1	590	120			710
	2000	5.0	1.6			6.6	870	270			1140
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	19.8	44.0	17.6	1.8	83.2	3330	7150	1380	230	12090

Footnote: a. HCFC-22 and HFC-152a

This Table clearly demonstrates that conversion from CFC-12 to ozone-safe alternatives is occurring in advance of the Montreal Protocol requirements. By 2000, 76% of new unit production had been converted: 53% to HFC-134a, 21% to HC-600a and 2% all other. This trend has continued since 2000, examples include accelerating conversion in China and India. Another development was the introduction in 2002 of a few domestic Japanese production units containing HC-600a refrigerant rather than the HFC-134a used in the majority of Japanese refrigerators.

3.3 Energy Efficiency Considerations

No significant new technology options are expected to emerge which will significantly alter options for conversion to ozone safe refrigerants in the remaining Article 5(1) countries still using CFC-12 in new equipment. All required technologies are mature and readily available; availability and prioritisation of capital resources are dictating conversion timing. Prioritisation may be influenced by uncertainty introduced from conflicting points of view regarding the interaction of the alternative options with other desired national initiatives, such as reduced greenhouse gas emissions and power grid enhancements. The energy efficiency of domestic refrigeration products directly influences these two alternative initiatives with a national leverage equal to the percentage of generated power consumed by domestic refrigeration products.

Anticipated technology enhancements include incremental improvements in component hardware, modified control and defrost algorithms, and modified refrigeration system configurations. All of these have objectives of improved unit performance and/or energy efficiency. In many cases this efficiency is provided at the cost of increased complexity or reduced tolerance to abnormal conditions. The immediately following text addresses high potential areas to help realise efficiency enhancements.

3.3.1 Compressors:

- Run capacitors and improved efficiency compressor configurations are broadly available with modest product cost penalties.
- Use of lower viscosity oil reduces compressor drag losses but may require improved fabrication process cleanliness and tightened machining tolerances.
- Reduction of losses during the compression process (valves, dampers, etc.) and further reduction of temperature levels inside the compressor (direct or semi-direct suction) will continue to improve compressor efficiencies. Enhancements in conventional electric motor efficiencies will also improve efficiency.
- Increased use of electronically commutated variable speed motors will reduce inertial and cycle losses. Their application will result in higher product cost and more complex control systems.
- Use of high efficiency linear motors with variable capacity to improve run efficiency and reduce cycle losses at the expense of higher product cost and unproven mechanism and lubrication concerns. Linear motor driven compressors are new developments, which have not yet achieved high volume production usage.

3.3.2 Improved Efficiency Evaporator and Condenser Fan Motors:

ECM evaporator and condenser fan motors are available with significant energy efficiency improvements versus the shaded pole motors historically used in these applications. The subset of product configurations using forced convection heat transfer for the evaporator and/or condenser heat exchange can realise significant energy efficiency benefit with associated increased product cost.

3.3.3 Modified Control Technology and Defrost Algorithms:

Application of electronic sensors and controls permits adaptive defrost control versus fixed cycle-time control set for worst case conditions. Automatic defrost model benefits include improved energy efficiency and more precise thermal control at the expense of higher variable cost and design complexity.

3.3.4 Modified Refrigeration System Configurations:

Research continues on efficiency improvements from dual evaporator inter-cooled systems for two-compartment refrigerator-freezers. The Lorenz and Meutzner cycle, possibly the best known of these, requires a zeotropic blend of refrigerants with different boiling points. Efficiency improvement greater than 20% has been reported /Fin97/ but this is still an experimental system. No attempts to commercialise it have been rumoured. It is believed that there are significant challenges in achieving control stability under varying application environment and usage patterns.

3.3.5 Realisable Efficiency Improvements in Article 5(1) and CEIT Countries:

Domestic refrigeration technology has grown tremendously over the 10 to 30 year life span of the units currently in use. Compressor efficiency, heat exchange efficiency, insulation efficiency and construction techniques are example core enhancements. Current technology units, in many circumstances, use less than one-half of the electrical energy required by the units they replace. Proven, reliable equipment can yield significant improvements without resorting to higher cost and more complex designs practising leading edge technologies. Several leading edge technologies are not generally applicable to typical units of interest. For example, modified defrost algorithms are not applicable to manual defrost units. Similarly, modified system configurations are not applicable to single door units.

Successful producers respond to consumer preferences, which are most accurately communicated by consumer purchase decisions. The limited number of high efficiency models in producer offerings suggests that cost savings from reduced energy consumption have not generally been sufficient to justify higher product costs and consequent higher product selling prices. Alternatively, government regulations and voluntary agreements on energy efficiency and labelling programs have demonstrated effectiveness in modifying product offerings in several countries. Energy regulations have taken different forms in various countries, suggesting customisation to address regional needs is important. The Collaborative Labeling and Appliance Standards Program(CLASP) maintains a web site with substantive information including links to various national programs (URL: www.CLASPonline.org). The interested reader is referred to regulating agencies in various global regions for insight regarding regulation drivers, effectiveness and opportunities for improvement.

Multiple options exist to influence consumer demand. Purchase rebate incentives have been effective in altering consumer purchase decisions toward higher efficiency models, but have not always accomplished their intent of reducing the power grid load. When not accompanied by a replaced unit retirement requirement, the replaced unit has frequently stayed in service, thereby increasing the power grid load. The U.S. Congress recently introduced a producer rebate incentive as an alternative technique for promoting improved energy efficiency /HR402/. Details of several examples of rebate incentive programs and their effectiveness are available from power generation and government regulatory and management organisations. Several studies have been conducted assessing *early retirement incentives*. Some proponents advocate these as providing greater leverage than high efficiency model rebates based on assumed modest rebate levels and mandatory replaced unit disposal. A properly constituted administrative process is essential to ensure old appliances are removed from service and the intended energy consumption benefits are realised.

3.3.6 Closed Cell Foam Thermal Insulation:

Closed cell foam insulation technology is vital for improved refrigeratorenergy efficiency. A discussion of available options to CFC–11 was included as an Annex to this chapter in the 1998 report of this committee /UNE98/. Continuing developments have been evolutionary with no significant new alternatives introduced. The Foam Technical Options Committee Report does not address refrigeration insulating foam performance in their 2002 status report. Technological improvements do not justify extended discussion, but brief status comments are included below.

Polyurethane foam insulation is a key contributor to refrigerator cabinet structural integrity. Foam integration within the steel and plastic skinned laminate structure improves cabinet thermal efficiency by minimising thermal losses through avoidance of high conductivity thermal shunts from metal brackets and braces. In addition, the foam provides the basic thermal insulation performance that is vital to energy efficiency. The limited residual use of fibreglass as insulation for refrigerators referenced in the 1998 report of this committed has now ceased.

The 1998 report referenced 5 low conductivity gas options competing to be the selected closed cell foam blowing agent. One of these, HCFC-141b, is being regulated from existence by 2020 by the Montreal Protocol or as early as 2003 in Europe, Japan and the United States. New applications should assess material availability when selecting a blowing agent. There are multiple commercial plants for cyclopentane and HFC-134a. A commercial HFC-245fa plant is operational in the United States. Commercial production of HFC-365mfc will begin in 2003 in France. Table 3-2 shows relative thermal performance for these candidates. Data from the 1998 report of this committee /UNE98/ have been updated to better reflect current understanding and global material variations.

With secondary global warming effects being a significant contributor to global warming for domestic refrigeration products, there is no clear choice on an integrated assessment basis.

Table 3-2 *Blowing Agent Comparisons*[3]

Characteristic	HCFC-141b	HFC-134a	HFC-245fa	HFC-365mfc	Cyclopentane
Ozone Depletion Potential	0.11	0	0	0	0
Global Warming Potential (100 year)	630	1300	820	840	11
Relative Foam Thermal Conductivity Index @ 23.9 C Mean Temperature	100	120 - 123	108-109	102	110 - 113
Relative Refrigerator Energy Use Index	100	108 - 112	100 - 102	Not Available	106 - 110
Relative Foam Aging Rate	Base	Worse	Better	Not Available	Worse
Relative Density Index	100	108 - 110	98 - 100	Not Available	102 - 112

/Alb97, Bro97, Dee98, Doe97, Haw99, Mil01, Zip97/

Environmental impact analyses to date have assumed that all blowing agent contained within polyurethane foam is vented to the atmosphere during useful life or upon disposal of the refrigerator. Investigations of the fugitive nature of CFC-11, HCFC-141b, HFC-134a and HFC-245fa blowing agents during shredding and landfill operations are in progress at Denmark Technical University /Kje01/. Results to date show less than 40% of the blowing agent is released through shredding operations and an additional six weeks of ageing in ambient air. Additional studies are being initiated to assess the retention of the blowing agents in the shredder fluff when buried in a landfill /Kje02/. Previous work by these investigators indicates that, under conditions found in many landfills, much of the blowing agent in foam may be broken down by enzymes and bacteria in the soil and that very little

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[3] Data listed are for commercial grade cyclopentane. The generic term “cyclopentane foam: includes isopentane/cyclopentane blends and may include various other blends such as butane/pentane.

may ever be released to the atmosphere /AHA01/. If initial results are confirmed, alternative assumptions regarding emission of blowing agents to the atmosphere and subsequent GWP impact may be more meaningful.

3.4 Existing Equipment Retrofits and Field Service

Field conversion options and any associated unique field repair issues were thoroughly discussed in the 1998 report of this committee /UNE98/. There have been no significant developments which alter that discussion.

3.4.1 Refrigeration Sealed System Failure Frequencies

The disperse and uncoordinated nature of the service infrastructure for domestic refrigerators and freezers hampers quantification of sealed system failure frequencies. Estimates of these failure rates and their use in estimating service refrigerant demand were discussed in the 1998 report of this committee /UNE98/. Following review, this committee concluded the estimates listed below, expressed as annual percentage of installed base, are still reasonable and should be used to estimate refrigerant demand for service in 2000.

- Non-Article 5(1) countries: 2% to 3% estimate range 2% most likely
- Article 5(1) countries: 5% to 10% estimate range 10% most likely

Rationales offered for the significantly higher failure rates in Article 5(1) countries include: frequent sub-tropic use environment, extended service life, uncertain power service, more aggressive transport conditions; frequently more aggressive humidity-related corrosion, and deficient service technician training resulting in misdiagnosis. Additionally, the premium value of capital goods results in compressors typically being rebuilt versus replaced. This cottage industry rebuilding, with its inherent variable quality, will also contribute to high failure rates. In Non-Article 5(1) countries the rate of sealed system failures is estimated to be a cumulative 1% during the first five years, primarily driven by manufacturing quality defects, and an additional cumulative 1% during the typically remaining 10 to 15 year product life. In Article 5(1) countries these failure rates are estimated to be 3% and 7% respectively /UNE98/.

3.4.2 Service Refrigerant Demand and Availability

Table 3-3 tabulates estimates of refrigerant demand for service. These estimates integrate estimates of the size of the installed base, the failure frequency estimates discussed above, information regarding transition from CFC-12 usage, and committee members’ estimates of the refrigerant usage efficiency during service in the various global regions. The estimates are crude, but believed to be directionally correct. Total service demand is estimated to be approximately one-half of the original equipment production demand. CFC-12 demand represents nearly 90% of the total service demand. This disquieting number is greatly over-stated since it includes non-CFC refrigerants used during retrofit or conversion service procedures in addition to conventional CFC-12 service procedures. Significant residual service demand for CFC-12 following original equipment production phase-out is evident. This results from the large number of refrigerators in the installed base, their long service life, and their significant average failure rate, particularly in Article 5(1) countries. The 1998 report of this committee included detailed discussion of field repair alternatives /UNE98/.

Interested readers are referred to that report or to various regional service organisations for information on the topic.

Table 3.3 Estimated 1992, 1996 and 2000 Domestic Refrigerators and Freezers Service Refrigerant Demand

Global Region	Year	Service Refrigerant Demand, Tons			
		CFC12	HFC134a	HC600a	Total
Western Europe	1992	68			68
	1996	52	10	4	66
	2000	34	14	12	60
Eastern Europe	1992	220			220
	1996	220	13		233
	2000	180	17	4	201
North America	1992	130			130
	1996	110	16		126
	2000	60	60		120
Central & South America	1992	780			780
	1996	1080			1080
	2000	990	20		1010
Asia and Oceania	1992	2390			2390
	1996	2670	190	0.1	2860
	2000	2420	230	130	2780
Africa and Mid-East	1992	870			870
	1996	870	120		990
	2000	800	50		850
World Totals	1992	4458			4458
	1996	5002	349	4	5355
	2000	4484	391	146	5021

Notes: 1. Demand estimates prepared for three primary refrigerants only.
2. Multiple refrigerants compete to substitute for CFC-12 service demand. Market share information is not available. There is a general discussion of alternatives in the body of the text.

Routine CFC-12 service procedures continue to dominate the demand. In Article 5(1) countries, CFC-12 is readily available and likely to be the lowest cost alternative. CFC-12 supply constraints in Non-Article 5(1) countries limit availability. This drives price inflation and costs 50-times historic levels are not uncommon. As a consequence, alternative procedures become cost competitive and reduce the CFC-12 service demand. Popular alternatives include conversion for use of a conventional new equipment refrigerant or retrofitting for use of one of several competing commercial blend refrigerants targeted at after-market service. Professional service technicians should be consulted for benefits and concerns with various alternatives.

3.4.3 Special Field Repair Issues

The potential for multiple refrigerant management introduces new issues to the service sector. The heightened cleanliness dictated by reduced clearances with high efficiency compressors and the refrigerant purity demands introduced by some new refrigerants elevates cleanliness needs to unprecedented levels. Dealing with multiple refrigerants complicates this task. The moisture sensitivity of polyolester oils requires careful control of moisture levels when using HFC-134a refrigerant. The flammable nature of hydrocarbons requires careful control of potential ignition sources when using HC-600a refrigerant. The simple presence of multiple refrigerants in the service sector increases the potential for system charging errors, both amount and type. Most, if not all, after-market refrigerant blends are zeotropes with multiple boiling points. This may dictate the need for liquid charging techniques to avoid refrigerant composition variation from fractionation during charging. Each of these issues is manageable. However, the number of incremental issues complicates service management requirements.

3.5 Unique Domestic Refrigeration Conservation and Containment Concern

3.5.1 Refrigerant Recovery During Service and End-Of-Life Disposal

CFC-12 refrigerant is the refrigerant in a large number of domestic refrigerators and freezers currently in service. Appropriate measures to deal with this legacy issue and the related issues of substitute refrigerants are topics of considerable debate. Factors influencing debates include differences in environmental effects of various refrigerants, complications introduced when dealing with multiple refrigerants, and limited financial benefit versus high cost of recovery and reclamation. The small charge quantities present in domestic refrigeration systems, combined with the geographically disperse service needs, minimises commercial incentives for recovery and recycling.

Equipment and techniques are readily available with active mandatory recovery programs in several countries. Existing refrigerant recovery programs are regulatory driven. Problems are encountered when dealing with multiple refrigerants. Equipment contamination occurs despite having duplicate recovery equipment to avoid cross contamination. When cross contamination occurs, the fluids have negative value; they have no useful purpose and they are difficult to properly dispose of with an associated high disposal cost.

3.5.2 Blowing Agent Recovery During End-Of-Life Disposal

Closed cell insulating foams are never serviced in the field, but similar debates are held concerning proper handling of insulation at end-of-life disposal. CFC-11, for years the accepted standard choice for insulating foam blowing agent, is contained in a large number of existing domestic refrigerators and freezer. Analogous to the CFC-12 refrigerant concerns, appropriate measures to deal with this legacy blowing agent issue and the related issues of substitute blowing agents are topics of considerable debate. Technology for blowing agent recovery is constrained by the blowing agent being contained within very small closed cells and being in solution within polymeric cell walls. Incineration is a practicable disposal method which requires special incineration equipment to withstand corrosive combustion products and effective scrubbing equipment to prevent acid rain pollution.

3.6 Summary Comments

Transition of domestic refrigerators and freezers to use ozone safe alternatives has been completed in Non-Article 5(1) countries. The transition in Article 5(1) countries is proceeding in advance of Montreal Protocol requirements. HC-600a and HFC-134a both have received widespread support as the preferred alternative to replace CFC-12. The large number of units in the installed base and the extended unit life cycle result in significant residual demand for CFC-12 to service the installed base. Experience to date indicates service alternatives have not been generally accepted while CFC-12 is economically available.

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4 Commercial Refrigeration

Commercial Refrigeration is a part of the cold chain, making available for customers frozen and fresh food at the desirable levels of temperatures.

4.1 Introduction

Commercial refrigeration comprises 3 main types of equipment: stand-alone equipment, condensing units and centralised systems.

Stand-Alone Equipment

Stand-alone equipment consists of systems where all the components are integrated: wine coolers, beer machines, ice cream machines, beverage vending machines, and all kind of stand-alone display cases. This equipment is installed in metro and train platforms, small shops, schools, company buildings and their annual growth is significant. Vending machines can be either bought or rented and no special attention is paid to the refrigeration system by the end-user. Companies who install and maintain this equipment have the knowledge on the refrigerant used. Stand-alone equipment, freezers and all kind of small equipment are used intensively in non-Article 5(1) countries and are also installed in many Article 5(1) countries.

Small Commercial Equipment With Condensing Unit

This type of small commercial equipment comprises :
- one (or two) compressor(s), a condenser and a receiver constituting the condensing unit which is located external to the sales area;
- the cooling equipment includes one or more display case(s) in the sales area and/or a small cold room for food conservation.

These condensing units are installed in specialised shops as bakeries, butchers and convenience stores. In a number of small supermarkets (typically cash & carry type), one can find a large number of these condensing units (up to 20) installed side-by-side in a small machinery room. Similarly to stand-alone equipment, condensing units are installed in many Article 5(1) countries.

Centralised Systems

Centralised systems consist of systems with compressors located in a machinery room. Two options are met, direct and indirect systems:

- ***Direct Systems***

Are widespread and simple. The refrigerant circulates from the machinery room to the sales area, where it evaporates in display cases and then returns in vapour phase to the suction port of compressors. Cold rooms are also cooled in the same way. In the machinery room, racks of multiple compressors are installed, each rack is usually associated with an air condenser. Specific racks are dedicated to low temperature and others to medium temperature with common connection for each level of temperature.

- ***Indirect Systems***

Are composed of a primary heat exchanger where a Heat Transfer Fluid (also called secondary refrigerant) is cooled down by the refrigerating system, then pumped towards the display cases where it absorbs heat, and then comes back in the primary heat exchanger. Indirect systems permit:

- to lower the refrigerant charge whatever the refrigerant,
- to use flammable or toxic refrigerants when located in a machinery room separated from the sales area.

Indirect systems receive a lot of attention, especially in Europe because of regulatory constraints on HCFCs and, for some EU countries, on HFCs.

Distributed Systems

These systems could be seen as a 4th technology, and have recently been developed for large and medium size supermarkets in order to limit the refrigerant charge by shortening the refrigerant circuit length and using water condensers. The water condensing circuit rejects heat on a wet or dry cooling tower. Compressors are installed in sound-proof boxes near the display cases, inside or above the sales area. This concept developed 5 years ago, has not taken a significant market share.

Temperature Levels and Refrigerant Choice

For all these systems, two levels of temperature (medium temperature for preservation of fresh food and low temperature for frozen products) may imply the use of different refrigerants. Chilled food is maintained in the range of 1 °C to 14 °C but the evaporating temperature for the equipment varies between –15 °C and –6 °C dependent upon a lot of factors: the type of product, the type of display case (closed or open), the type of system (direct or indirect), the distance between the display cases and the machinery room. Frozen products are kept at different temperatures (from –12 °C to –18 °C) depending on the country. Ice creams are kept at –20 °C. Usual evaporating temperatures are in the range of -35 to –40 °C.

4.2 Data on Systems and Refrigerant Charges

Commercial refrigeration stores are very different, even in neighbouring countries, because of very different consumption habits, regulation of opening hours, leadership of brand names and wealth of people.

A number of leading US and European companies are expanding world wide specially in Eastern European countries such as Poland, Hungary, Czech Republic and in emerging countries such as: Argentina, Brazil, China, Indonesia, Mexico, Taiwan, Thailand and Tunisia. The growth of all types of commercial refrigerating systems in China is one of the most significant developments in the last four years. To take an example, the number of small supermarkets, where the average surface is about 380 m^2, has been multiplied by 6 in the last 4 years in China /Eur01/.

Table 4-1 *Typical surfaces of supermarkets in different countries*

	Brazil	China	France	Japan	USA
Average surface of supermarkets (m^2)	680	510	1500	1120	4000
Average surface of hypermarkets (m^2)	3500	6800	6000	8250	11500

As indicated in Table 4-1, the average surface of supermarkets is significantly different depending on the country. Moreover, the "hypermarket" concept selling food, clothing, and all types of household goods, is expanding world-wide.

Based on a report /Gge02/ and detailed marketing studies /Eur01/, statistics on supermarket numbers, stand-alone equipment, and vending machines have been deeply modified compared to the 1999 TOC report. Table 4-2 shows the impact of the rapid economic growth of China: Chinese supermarkets represent more than 30% of the total global number of supermarkets.

Table 4-2 *Number of supermarkets and hypermarkets /Eur01/ and /Gge02/*

	Number of Supermarkets	Number of Hypermarkets
EU	58 134	5 410
Other Europe	8 954	492
USA	40 203	2 470
Other America	75 441	7 287
China	101 200	100
Japan	14 663	1 603
Other Asia	18 826	620
Africa, Oceania	4 538	39
Total	321 959	18 021

The refrigerant quantities that are charged in supermarket refrigerating systems cannot be derived from the sole number of supermarkets. Additional data are necessary and are not currently available.

Based on the same two reports, the numbers concerning condensing units, all types of stand-alone equipment and vending machines have dramatically changed because of better available data (see Table 4-3).

Table 4-3 *Evaluation of the Number of Commercial Equipment /Eur01/ and /Gge02/*

	Condensing units	Hermetic groups in stand-alone equipment	Vending machines
EU	6 330 500	6 400 700	1 189 000
Other Europe	862 000	754 700	113 900
USA	247 500	217 400	8 807 900
Other America	3 321 300	2 430 600	411 800
China	13 000 000	12 316 600	385 000
Japan	2 216 000	2 470 600	2 954 500
Other Asia	5 750 400	5 750 600	758 200
Africa, Oceania	843 700	831 400	87 000
Total	32 571 400	31 172 600	14 707 300

For small commercial surfaces, China represents about 40% of the total global numbers, except for vending machines. The market growth of vending machines is still very significant, in particular in Europe.

Energy Consumption of Supermarkets

Depending on the supermarket size, the refrigeration equipment energy consumption represents between 35 to 50% of the total energy consumption of the store. This ratio depends on a number of factors, specially lighting, which represents for a number of developed countries the highest energy consumption of use. However, for typical small supermarkets, refrigeration represents between 40 to 50% of the total energy consumption; for small supermarkets it could be up to 65%. The European standard EN 441 is the first attempt to define a reference level of energy consumption. However, its scope is limited to stand-alone equipment, i.e. including the refrigerating equipment in the display case itself. More generally, there is no reference line for energy consumption of commercial centralised refrigerating systems.

Some new high-efficiency commercial supermarkets have been designed in some European countries and in the U.S., using a number of efficient technologies. These references can be seen as prototypes; some of them present energy consumption that is lower by more than “a factor of 5” compared to usual stores /Wor00/. However, investment costs could be higher than 10 times the usual investment costs.

Energy Efficiency of Refrigerating Systems

Energy efficiency of refrigerating systems depends first on the temperature levels and of the global design of the system. A number of measurements performed on site /Clo01/ show:

- COP ranging between 1 and 1.8 for low temperature applications, with evaporating temperature of –40 °C and condensing temperature of +40 °C;
- COP varying between 2.4 and 3.2 for medium temperature applications with evaporating temperature varying between –6 °C and –15 °C and condensing temperature fixed at +40 °C.

The overall energy efficiency of the system depends on a number of parameters: pressure losses related to the circuit length, system control and outside temperature. For a number of global companies, the energy consumption and so the energy efficiency of refrigerating systems has become an important issue, especially in countries where electricity prices are high. The issue of climate change and desire to reduce greenhouse gas emissions, chiefly CO_2, has heightened concerns to increase energy efficiency.

4.3 Refrigerant Options for New Equipment

Refrigerant choices for new equipment are different in Europe, US and Japan.

Since 1 January 2001, the use of HCFC-22 and HCFC-22 blends in new systems in Europe is forbidden by the European regulation 2037/00 /Eur00/ for all types of refrigerating equipment and the use of CFC is forbidden, i.e. no additional CFC shall be added for servicing. If refrigerant is needed, the installation shall be retrofitted in order not to use any CFC. For large capacity systems, R-404A (and R-507A) is the preferred choice for low temperature but also for medium temperature level. HFC-134a is chosen for medium temperature low capacity systems. A number of HCs, ammonia and CO_2 systems of different refrigerating capacities have been installed in various EU countries in the last 5 years.

In Japan, voluntary policy is undertaken by OEMs and more than one third of brand new equipment is charged with HFCs. R-407C is used for medium temperature and R-404A for low temperature.

In the U.S., HCFC-22 is still in use even for new equipment but, more and more R-404A is the refrigerant of choice for supermarkets.

In Russia, HCFC-22 continues to be used in new equipment, but after the CFC-12 phase- out HFC-134a and HCFC-22 blends, as well as R-404A come into use.

4.4 Stand-Alone Equipment and Condensing Unit Systems

The majority of stand-alone equipment is based upon HFC technology. However, some well-established beverage companies and ice cream manufacturers have recently stated (2001) that by 2004 they will no longer use HFCs in their refrigerating systems, provided that alternative refrigerants or technologies (such as Stirling cycle) will be available at acceptable cost. Equipment used by these companies are mainly vending machines, specialised freezers and so-called walk-in coolers, which are glass-door display cabinets.

- HFCs

Display cases for medium temperature and stand-alone equipment are in general designed to work with HFC-134a. For low and medium temperature applications, R-404A (or sometimes R-507A) is the major option for new equipment in developed countries and also in some Article 5(1) countries.

- HCs

Vending machines and small commercial equipment have been developed in the UK, Sweden, Denmark, Germany and Austria, but also in Australia. The above mentioned equipment uses HCs such as HC-600a or HC-290, or HC-based blends. Developments tend to lower the refrigerant charge to follow the limits required by European safety standard EN 378.

- CO_2

CO_2 is evaluated by a European company to develop a stand-alone equipment with direct expansion CO_2 system /Chr99/.

- HCFCs

HCFC-22 is used in some Article 5(1) countries (that manufacture equipment) for condensing units.

4.5 Centralised Systems

The size of centralised systems depends on the refrigerating capacity which can vary from about 20 kW to more than 1 MW. The quantity of refrigerant is related to the refrigerating capacity; depending on the quantity, the refrigerant choice can be quite different.

4.5.1 Direct Systems

- HFCs

The use of R-404A is the major option in Europe in low temperature and in medium range temperature refrigeration systems. The use of POE lubricant has not raised difficult handling, and brand new systems using R-404A show equal easiness of servicing compared to HCFC-22 or R-502 systems. For countries where high condensing temperatures are met (above 50 °C), a new concept with an additional small refrigerating system dedicated to liquid sub-cooling has been developed and is installed in the field. Energy efficiency gains are significant. For medium temperature, HFC-134a is also used. No major problems have been encountered in the field. R-407C has been tested in a number of cases, but is not considered a major option except in Japan where a specific market is raising for medium temperature applications, which are the most usual, due to the large extent of chilled food.

- CO_2

Two types of refrigerating CO_2 systems are on the market:
- direct systems using only CO_2 with a transcritical cycle both for low and medium temperatures /Gir02/
- cascade systems, with CO_2 at the low temperature stage associated with ammonia or other refrigerant (for example R-404A) at the medium temperature stage. Ten of these prototypes have been installed in the field and are under evaluation in different European countries. It shall be underlined that this technology can gain a certain interest because it can also be developed for food industry /Rol99/.

4.5.2 Indirect Systems: HFCs, Ammonia, CO_2 and HCs

Indirect systems have gained considerable attention for a number of supermarket chains, due to the fact that these systems permit to lower the refrigerant charge whatever the refrigerant. Depending on the country, HFCs, ammonia, HCs, and CO_2 are used as refrigerant in the refrigerating system entirely installed in the machinery room and/or outside /Rac01/, /Wor00/. The quantity of HFCs can be reduced by 50 to 75% compared to usual direct systems. The quantity of ammonia can be 1/10 of the usual HFC refrigerant charge, due to thermodynamic properties (latent heat vaporisation and liquid density). For HCs, the refrigerant charge is typically 25% of the HFC direct system charge. Medium temperature and low temperature circuits are independent. Medium temperature technologies are mature whereas for low temperature applications new concepts shall be designed to meet ease of handling and acceptable energy consumption and efficiency.

Medium Temperature Applications

For this level of temperature, the Heat Transfer Fluid used is mainly MPG (MonoPropyleneGlycol), which is still dominant. Potassium acetate and some other type of brines have gained interest. More information on HTF can be found in chapter 2.

Ice slurries may contain up to 20% of ice in weight. The solid/liquid phase change permits the system to run at a quasi-constant temperature. They can be used preferably at medium temperature level and scarcely at low temperature level. Even if a number of studies are still performed in different laboratories, the cost of the primary heat exchanger producing the ice slurry, and also the level of the evaporating temperature needed to produce the ice, make the process always difficult and non-attractive for cost reasons. Some field experiments are ongoing.

Low Temperature Applications

MPG cannot be an option any longer because of very high viscosity and so only potassium acetate, low viscosity brines or CO_2 can be used. Taking into account viscosity constraint and good heat transfer properties, more consideration has been paid to the use of CO_2 as low temperature HTF. Specially when CO_2 is used with evaporating option, the diameter of the tubes is smaller by nearly a factor 5 to 10, and heat transfer efficiency in the display case heat exchanger is much more attractive. The major difficulty for CO_2 handling is to keep it at the level of temperature (typically –12 °C) permitting to use classical technologies, i.e. tubes and heat exchanger designed for maximum operating pressure of 2500 kPa.

Refrigerant Choices

- HFCs

In a number of countries (France, Germany, UK, Brazil), hundreds of indirect refrigeration systems have been installed using HFCs as primary refrigerant (R-404A and R-507A).

- Ammonia and HCs /Pow98/, /Pre01/

In Northern Europe, ammonia or HCs have been used as refrigerants for the same type of indirect systems. HC-1270 (propylene) has been chosen by some European companies because its volumetric refrigerant capacity is nearly identical to the one of HCFC-22, and so permits the use of a compressor designed for HCFC-22. Changes shall be made for the lubricant, generally higher viscosity grade is chosen, due to high solubility of HCs in lubricants. For safety purposes, the refrigerant circuits in the machinery rooms are separated in a number of independent circuits to limit the charge of each system.

- CO_2

CO_2 can be used either as usual Heat Transfer Fluid without phase change or it can evaporate partially in the display case evaporators, then condense in the primary heat exchanger, and so CO_2 is used as a vapour-liquid Heat Transfer Fluid.

Energy Consumption

The evaluation of additional energy consumption related to indirect systems is ongoing. The reference line is complex for direct systems because very different energy efficiencies can be met. The direct field comparisons between direct and indirect systems are difficult. Moreover, the main driver for centralised systems is initial cost and not total cost. Due to the actual design of heat exchangers of display cases, and specially open-type ones, performances of some indirect systems can be equal or even slightly better compared to direct systems. For low temperature level, energy penalty can be substantial depending on the design.

On the other hand, indirect systems, especially for small stores, can show an additional consumption of 10 to 15% compared to usual direct systems. To draw conclusion, it is necessary to create reference lines for energy consumption of centralised systems, making also clear the origin of energy inefficiencies.

It shall be underlined that the initial cost is about 15% higher than usual direct systems. Companies promoting indirect systems insist on ease of servicing, which is not fully demonstrated. Some of the supermarket chains went back from indirect system preference to usual direct systems, mainly for initial cost purposes.

Defrosting Issue

The secondary loop requests special attention for defrosting due to the fact that all the HTF will be heated up from a typical temperature of –15 °C to above 2 or 3 °C. For large-scale supermarkets, the quantity of HTF as MPG or potassium acetate is varying between 1.5 to nearly 4 metric tonnes and so the energy consumption associated with defrosting is significant. An interesting option is to cool down the condenser of the low temperature system by the medium temperature secondary loop. This design also permits to defrost the medium temperature heat exchangers by releasing the heat of the low temperature system. More recently, companies are employing a thermostatically controlled 3-pipe defrosting scheme where the HTF is warmed independently, avoiding the heating up of all the HTF and therefore avoiding large energy losses. For CO_2 electrical defrosting is usual.

4.6 Options for Existing Systems

4.6.1 Stand-Alone Equipment and Condensing Units

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

Until 2010, it is permitted in Article 5(1) countries to use CFC to repair and recharge the equipment not with the same refrigerant but with virgin CFC refrigerant. In any case CFC or HCFC refrigerants will be recovered and, in Europe, regulation 2037/2000 /Eu00/ makes destruction mandatory for CFCs. Refrigerants can be recycled before recharge. When changing from CFC to HCFCs or HFCs in case of retrofit, the lubricant shall also be changed and shall be compatible with the new refrigerant or refrigerant blends.

4.6.2 Centralised Systems

In developed countries, supermarket equipment is partially or totally renewed every 7 or 10 years, depending on countries. In Article 5(1) countries, the lifetime can be longer, typically 15 years.

CFC-12 Retrofit

The conversion from CFC-12 to HFC-134a involves several steps, including change of mineral oil to synthetic oil, the evaluation of the expansion device and adjustment of the superheat in case of thermostatic expansion valve and the replacement of the filter dryer.

R-502 Retrofit

Due to lubricants, retrofits are mainly from R-502 to HCFC-22 based blends. 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 nor breakdown has been recorded. It can be seen as a straightforward and reliable procedure. In some cases, a distinction may have to be made between R-502 retrofit in low temperature systems and medium temperature systems. Based on the refrigerant cost, for medium temperature systems it may be worth using HCFC-22 and changing the expansion valve. This option is not typical.

HCFC-22 Retrofit

It is technically feasible to change from HCFC-22 to R-404A or R-407C. Oil has to be changed and the system has to be flushed. These technical issues are established from CFC-12 to HFC-134a retrofit experience. It is essentially a political decision to make this kind of retrofit due to the cost. Energy efficiency losses associated with this kind of retrofit are typically in the range of 5 to 10%. New designs adapted to R-404A or R-407C must be undertaken. New HFC blends with small amount of HCs (typically 3%) have been developed in order to make easy retrofit from HCFC-22 to HFCs without change of the lubricant type, but attention must be paid on eventual refrigerating capacity losses, and also on oil return effectiveness /Spa02/.

4.7 Refrigerant Containment

The new European regulation 2037/2000 requires annual leak tightness control for CFC and HCFC refrigerating systems with a refrigerant charge of more than 3 kg. The European Climate Change Program (ECCP) recommends in its final conclusion that the EC issues a new directive for HFC use, with a high level of containment, annual leak tightness control and mandatory recovery of HFCs. The refrigerant management in commercial refrigeration will deeply change within the next years in Europe and the annual emission level will be reduced significantly.

The experience of The Netherlands, performed under the STEK organisation, where contractors are certified, has led to significant reduction of the emission level. Even in commercial refrigeration, emissions have been reduced down to 5% in The Netherlands.

Regulation and regulation enforcement play a key role for making refrigerant containment more effective and make changes in servicing habits.

More generally, it is seen as economically feasible to reduce annual emissions from former 30% (referred to initial refrigerant charge) down to 10 to 15%. In Article 5(1) countries, emission level can be much higher than the typical 30% level.

4.8 Article 5(1) Country Aspects

- In the least developed Article 5(1) countries, commercial refrigeration is found in small shops, supermarkets do not exist. Refrigerating equipment can be domestic refrigerators and freezers used for commercial purposes.
- For more developed countries stand-alone equipment or small cold rooms with a condensing unit are the first type of equipment which are easily available on the market. The refrigerants in use in such equipment are either HFC-134a or HCFC-22, sometimes R-404A.
- In Article 5(1) countries such as Brazil, Mexico, Tunisia and Indonesia, a number of global companies are developing supermarkets using basically the same type of technology and refrigerant as they use in developed countries. A supermarket in those countries is certainly not different from another one located in the U.S. or in Europe, in terms of refrigeration systems.
- For new compressors bought for replacement purposes, CFC and HCFC compressors become less available on the international market pushing commercial companies in some Article 5(1) countries, which do not manufacture compressors, to evaluate the interest to shift from CFC or HCFC to HFCs.
- On the contrary, due to the possible use of HCFC-22 for a longer period of time, the second hand HCFC-22 compressors (and some other components) become an attractive business for exports towards Article 5(1) countries with no local compressor production.
- Due to cost issues, the lifetime of equipment is much longer in Article 5(1) countries compared to developed countries and so the repair takes higher importance which makes refrigerant recovery even more necessary than in developed countries. Regulation has to be issued, training programs have to be established and economical incentives have to be found in order to make recovery an efficient and effective activity integrated in the usual servicing procedures (see chapter 10 on containment and recovery).
- The date of phase out of CFCs, especially CFC-12 and in a less important way R-502, will become more and more important in the next few years. So the conservation, through recovery and recycling and the shift to drop-in refrigerants shall be taken into account.

4.9 References

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5 Large Refrigerating Systems (Industrial refrigeration, Cold Storage and Food Processing)

5.1 Introduction

Industrial refrigeration, cold storage, food processing and district heating and cooling are important applications. Large refrigerating systems are commonly used in this sub-sector. The cooling/heating capacity of such units varies from 25 kW to 30 MW or even higher shaft power. These refrigeration systems are based on reciprocating, screw and centrifugal compressors depending on capacity and application. Systems described in this chapter are custom made and often erected on site.

Refrigerants used are preferably single refrigerants, because most of the systems are using flooded type of evaporators. Industrial refrigeration systems are normally located in industrial areas with very limited public access. For this reason ammonia is commonly used in many applications where the hazards of toxicity and flammability are clearly evident, well-defined, well understood and easily handled by competent personnel. Hydrocarbons may be used as an alternative to ammonia within sectors handling flammable fluids such as chemical processing.

There are clear differences how different countries have developed the technology for industrial refrigeration based on national legal regulation. In Europe, the use of HCFC-22 and HCFC-22 blends in new systems is forbidden by the European regulation 2037/00 Eur01 since 1 January 2001 for all type of refrigerating equipment and the use of CFC is forbidden, i.e. no additional CFC shall be added for servicing. HFCs are occasionally used where ammonia or hydrocarbons are not acceptable, however they are often not preferred because specifiers expect regulations limiting the use of greenhouse gases to be introduced in future /Exp02, Sp02/.

The annual consumption of frozen food world-wide is 30 million tonnes per year. The United States accounts for more than half of the consumption, with more than 63 kg per capita. The average figure for the European Union (EU) is 25 kg and for Japan 16 kg. Chilled food is 10 – 15 times the frozen product quantity. The total quantity of temperature controlled products is estimated at 350 million tonnes (1995), and the annual growth is estimated to be 5% /IIR96/. The estimated annual growth rate between 1996 and 2002 in the developed countries amounts to 4% and in developing countries to 7%.

Energy conservation is one of the main strategies to alleviate the environmental problems arising from the ever-increasing global energy demand. Industrial heat pumps utilise renewable and waste heat and consequently reduce the demand for fossil fuels for heating, cooling and dehumidification.

The present section is an updated and combined version of three sections of the earlier Technical Options Report from 1998 /TOR98/, namely Industrial Refrigeration, Cold Storage and Food Processing and Large Heat Pumps. Attempts have been made to update the information on technical options and the data on consumption of refrigerants.

5.2 Applications

Chilling is the process to cool a product to a temperature above the freezing point, **Freezing** is to lower the temperature below the freezing point. The freezing of food products requires product temperatures of –18 °C or lower.

The majority of refrigerating systems for cold storage and food processing are of direct type, with the refrigerant distributed to heat exchangers in the space or apparatus to be refrigerated. Indirect systems with liquid chillers or ice banks are used to a lesser extent, primarily for chilling purposes, such as fruit packaging.

System size varies from cold stores of 50 kW cooling capacity at –25 °C air temperature in Article 5(1) countries to large processing plants requiring several MW of cooling. In the lower capacity range, reciprocating compressors are most frequently used, while screw compressors are common in larger systems, in particular those with NH_3, in single stage economised or two-stage arrangements.

5.2.1 Cold Storage

Cold Storage, with storage temperatures of approximately –25 °C is split into private storage and public cold storage. Private storage is often related to raw materials and finished products in a food processing factory.

In fruit and vegetable cold stores, it is possible to prolong storage life from few months to almost a year if the constituents of cold room atmosphere such as CO_2, O_2 and ethylene are controlled. The most common fruits stored under this condition are apple, pears and vegetables.

The refrigeration in cold and chill stores is generally direct cooling with NH_3 in evaporators placed at high levels in these buildings or in special “penthouses”. Where direct cooling with NH_3 is not acceptable, an indirect system is likely to be used rather than a HCFC-22 system. In a few cases, CO_2 in cascade systems with NH_3 or as secondary refrigerant have been built recently /Axi02/. In Japan, several food storage systems exist with ice slurry produced by NH_3 refrigeration plants.

Electrical defrost is avoided for refrigerants such as NH_3 or CO_2 because it is extremely inefficient in large coolers. Most systems use pumped recirculation of the refrigerant through the evaporators and defrost is achieved by supplying high pressure gas to individual coolers or small groups. In some special cases, where the climate, the evaporator design or the process requirements are suitable, it is possible to defrost evaporators with ambient air or water.

5.2.2 Food Processing

Food Processing is one of the fastest developing industries in the world. Refrigeration for food processing (including the beverage industry) is a subset of industrial refrigeration including: dairy products, ice cream, meat processing, poultry processing, fish processing, abattoirs, fruit & vegetable processing, coffee, cocoa, chocolate & sugar confectionery, grain, bread & flour confectionery and biscuits, vegetable and animal oils and fats, miscellaneous foods, breweries, soft drinks /Mar92/. The major concern of operators is the reliability of the system. Energy efficiency is often given lower priority than capital cost, reliability and cost of maintenance. According to the large variety of products, the chilling or freezing procedure has to be adopted to each product behaviour as far as temperatures, humidity and chilling or freezing rates are concerned.

In Article 5(1) countries most of the food processing industry use HCFC-22 and few still use CFC-12. The use of pumped NH_3 is not common, many systems use flooded systems with gravity fed evaporators.

5.2.3 Industrial Refrigeration

Industrial refrigeration covers a very wide range of cooling and freezing applications, including the chemical and pharmaceutical industries, the petrochemical and the oil and gas industries, the metallurgical industry, plastic moulding, civil engineering, sports and leisure facilities, industrial ice making, air liquefying and other miscellaneous uses. A large portion of the refrigeration applications is used to preserve food from harvest, catch or slaughter, processing, transport, storage and distribution to retail sales and supermarkets.

The majority of industrial refrigeration covers temperatures from +10 °C for chilling and air conditioning, down to –40 °C for food freezing and storage. Recently a tendency for lower product freezing temperatures down to –60 °C has been realised to improve product quality and to increase factory production capability. Lower temperatures are used for some special applications in food preservation and more common for other chemical processes. There are some minor applications for medical use in the range -90 to –130 °C. For lower temperature needs cryogenics gases such as liquid nitrogen and synthetic liquefied air (SLA) are used.

5.2.4 Liquefaction of Gases

The vapour compression process is used for the liquefaction of gases such as CO_2, Cl_2, HC and liquid natural gases down to temperatures of –170 °C. Liquefaction of cryogenic gases such as air (N_2, O_2, Ar, etc.), hydrogen, helium is performed by another technology such as gas processes. In the process of air liquefaction, the cooling and drying of the product (air) often is achieved with vapour compression using NH_3 or HCFC or HFC blend.

5.2.5 Industrial Heat Pumps and Heat Recovery

Another important application of industrial refrigeration is heat pumps for heating and heat recovery. Especially large industrial heat pumps which today are a proven, reliable and energy saving technology, utilise renewable and waste heat and consequently reduce the demand for fossil fuels for heating, cooling and dehumidification industrial applications. 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 of process streams, heat recovery and hot water/steam production. They are often an integrated part of industrial processes, such as drying, evaporative concentration and distillation. The majority of industrial heat pumps operate in the chemical industry, food processing industries and fish farming. Heat pumps are also used for drying of products such as ceramics, timber, textiles and different kind of food. Energy efficiency and quality of the products, gained by better temperature control of the drying process, make heat pump dryers very competitive compared to conventional dryers, 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 up to 80 °C, in some special cases up to 120 °C.

The vast majority of heat pumps currently in operation are electrically driven closed-cycle compression type systems. 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: Traditionally, industrial heat pumps have been using CFCs, HCFCs, and NH_3 as working fluid. Hydrocarbons have also a small niche market, in petrochemical industry. HFC-134a, R-404A and R-407C are identified as the most used retrofit refrigerants for units with CFC-12, R-502 and HCFC-22. HCFC-22 is still used as one of the main refrigerants in heat pumps. Most developed country manufacturers have introduced HFC alternatives to replace their HCFC heat pump models. HFC-134a and R-404A have been on the market for several years. For heat pumps working with higher condensing temperatures up to 80 °C, HFC-134a is the preferred refrigerant, especially large capacity units. NH_3 with 40 bar – compressors is applied in medium/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 /UNE91, Ste98/.

In Europe large industrial heat pumps for hot water distribution systems have capacities of approximately 1200 MW. New Systems are realised with HFC-134a, the charge per kW heating capacities amounts to 0.6 kg of HFC-134a / kW. This figures results in 684 tonnes of HFC-134a in this type of heat pumps /JAR99, Bai02/.

Mechanical (open) vapour recompression: MVR systems, or open (semi-open) heat pumps, are extensively used in industrial processes for evaporation or distillation. Most systems operate with water vapour as the process fluid. In chemical industry other process vapours are used in MVRs (e.g. ethanol, methanol, propane).

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 Sweden and Denmark a number of units are installed in refuse incineration plants to recover heat from the flue gas cleaning process, to supply heat to district heating networks. Most absorption heat pumps use water and lithium bromide as the working pair, and are capable of delivering heat up to 100 ºC. 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: which are producing high-temperature heat from medium-temperature industrial waste heat operate on a similar process as absorption heat pumps. Current systems have a maximum delivery temperature and temperature lift of 145-150 °C and 50 °C, respectively. Also heat transformers use water and lithium bromide as the working pair. Heat transformers 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 /HPC94a/.

5.3 Current Status and Trends

In comparison to the TOC Report 1998, this section describes new technologies and general trends.

CFC systems are still in operation and CFCs are available for servicing, except for the European Union where regulations are in force and servicing with CFCs is forbidden since January 2001 /Eur01/. Globally, many larger industrial CFC systems keep running until their expected time of retirement (year 2010-2015).

Significant amounts of CFCs are still available from stockpiled reserves, recovered fluid and, to some extent, illegal imports. In addition, service demands have gone down significantly due to improved routines and better leak tightness.

In Industrial Refrigeration a clear trend can be observed towards CO_2 as refrigerant at temperatures lower than –45 °C and as brine for higher cooling temperatures /Pir02/. It is likely that cascade CO_2 systems will be used for higher evaporating temperatures, probably up to –30 °C, in the near future. The lower limit of evaporating temperature for CO_2 is –54 °C, owing to the triple point of –56 °C. Comparison to other refrigerants has been done, cost benefits for CO2/NH3 cascade systems with low NH_3 charge have been achieved /Rot02/. Several systems with total cooling capacities of more than 16 MW at different temperatures are already in operation /Koe02/.

Industrial chiller units using water (H_2O) as refrigerant are in operation directly connected to the hydraulic H_2O system /Aqu00, Bur01/. Studies have been investigated on theoretical basis to estimate the potential of H_2O /ARI00/. The potential of H_2O in industrial refrigeration is limited to temperatures of approximately +4 °C. Costs for H_2O systems are twice as high as for conventional units using HFC-134a at the moment.

Ice slurry is proposed as option as secondary fluid to reduce refrigerant charge, especially to reduce NH_3 charge to comply with regulations. Through an additional heat exchanger, ice slurry is produced by evaporating the refrigerant in the vapour cycle and then pumped directly to the consumers. Direct use of ice slurry is known from several cold storage facilities. At least 20 systems are running where ice slurry is used both as thermal storage but also in the distribution system. The types of applications vary from dairies, slaughterhouses, bakeries, breweries to fish processing factories on shore /DTI02/.

5.3.1 Developed Countries

The process of phasing out CFCs in existing systems has moved much slower than previously anticipated. Estimations of banked refrigerants resulted in 70,000 tonnes of CFCs in these systems /TOC98/.

No additional refrigerant options for industrial refrigeration have emerged since 1994/95. Refrigerants for new systems for industrial refrigeration, cold storage and food processing are selected among fluids including NH_3, HFC-134a, R-507, R-404A and R-410A and also hydrocarbons. The use of HCFC-22 as refrigerant in new industrial refrigeration systems is reduced, except in the European Union where HCFC-22 is already forbidden.

NH_3 has further strengthened its position as the leading refrigerant for cold storage and food processing and other industrial applications in many countries, especially in the European countries. A clear trend can be observed in all new systems, i.e., the reduction of the refrigerant charge in the system regardless the refrigerant choice. As a consequence a second clear trend can be observed, the use of CO_2 as brine and refrigerant. The low charge technology for NH_3 has achieved a particularly strong position in Europe and even led to expansion into less traditional use areas for NH_3 such as centralised systems for cooling and/or heating. CO_2 is commercialised in Europe and will enter into the market in the USA and other countries.

In other regions, the halocarbons have more or less kept their dominant market position, even though a growing interest in NH_3 can be observed. HFC use is moderate but expanding, mainly at the expense of HCFC-22. Except in the European Union, HCFC-22 is still the leading halocarbon refrigerant.

Unit systems with hydrocarbons are commercialised, also these with the low charge designs.

5.3.2 Article 5(1) Countries

In most of the Article 5(1) countries including large countries such as India, China, Brazil, etc the food processing industry is still developing. There are food-processing plants of medium to large capacity. The capacity may vary from 50 kW to 1000 kW of cooling. Mostly small capacity plants use CFC-12 as refrigerant while the majority of larger capacity plants are based on either NH_3 or HCFC-22. There are some low temperature plants which use CFC-502, but such plants are smaller in number.

Many Article 5(1) countries have vast coastal area where fishing and its processing is a medium scale industry. There are fish processing and ice-making plants. The fish-processing unit uses CFC-12 as refrigerant while majority of ice-making plants are either based on NH_3

or HCFC-22. Alternative refrigerants such as HCs or HFC- blends have not yet started penetration in this sub-sector due to availability of CFCs, HCFCs and NH_3.

In most of the Article 5(1) countries, the use of HCFC-22 is growing.

NH_3 systems are gaining popularity because of low operation cost. But in some cases the installation cost could be very high. One of the hindrances to the NH_3 system is that there is a very limited training opportunity in NH_3 systems. Most of the technologies are imported from developed countries. Some of the major compressor manufacturers have subsidiary companies in Article 5(1) countries with skilled labour.

5.4 Refrigerant Options for New Equipment

The current situation regarding alternatives for new systems is described as follows:
- NH_3 is technically feasible in all types of systems;
- CO_2 - technology is readily available for low temperature applications, technology for general purposes is commercialised;
- HFC technology is considered to be fully mature (with regard to HFC-134a, R-404A and R-507A);
- system components for R-410A are available;
- hydrocarbons are technically feasible for all types of systems but practical application is restricted by safety codes and national regulations.

Therefore, it is technically possible to build new industrial refrigeration systems without HCFCs.

Most of the manufacturers of refrigeration equipment and refrigerants are from developed countries. These companies often have their subsidiaries in Article 5(1) countries with skilled labour and market for the equipment. The use of HCFC-22 will be the most favourable refrigerant in the Article 5(1) countries. The use of R-502 and CFC-12 in the industrial refrigeration outside Europe is on decline. There are no new equipment imported. The use of NH_3 is peaking slowly in large refrigeration plants such as breweries. Vapour compression is most common, screw compressors are gaining ground in high capacity refrigeration.

5.4.1 Ammonia (NH_3)

Modern refrigeration using NH_3 has improved in quality regarding design, use of low temperature materials, better welding procedures and non-destructive control of the manufacture. Education and understanding of NH_3 is improving the safe operation.

Low charge is another positive development but more important is that these factory-made units or systems represent a new level of quality improvement. These systems are not likely to break or in another way release their charge unless there is a human error or direct physical damage.

Charge reduction has been achieved through the use of plate type heat exchangers or direct expansion tube and shell evaporators. Compared to conventional chillers with pool boiling evaporators, refrigerant charge has been reduced by up to 90%. Low charge NH_3 technology was regarded as being fully mature but strong market penetration has not been realised since its introduction because of price competition to HFC-based units.

5.4.2 HCFC-22

The use of HCFC-22 is declining in food processing, industrial refrigeration and cold storage and heat pump applications in most countries. In Europe, the use of HCFC-22 in new systems is forbidden by regulations. Some of the end users therefore prefer NH_3 and CO_2.

In the Article 5(1) countries, HCFC-22 is an important replacement fluid for CFCs in new industrial systems, where this fluid will be available for service for full system lifetime. There are various reasons for choosing HCFC-22. It is technically well proven, applicable for a wide temperature range, fairly efficient and gives the lowest initial costs (except for large, distributed systems). In addition, NH_3 may not be a candidate for all types of applications, dependent on national regulations.

From a technical point of view, HCFC-22 could replace CFC-12 and CFC-502 in new systems. To replace R-502 for freezing, two-stage compression has to be applied, resulting in improvements in energy efficiency, but at the expense of greatly increased capital cost.

HCFC-22 has become the most common refrigerant to replace CFCs in cold storage and food processing in the USA.

5.4.3 HFCs

HFCs and HFC-blends with azeotropic or near azeotropic behaviour are proven for industrial applications, their penetration into the industrial market has been realised. Today, systems are in operation in industrial refrigeration with HFCs, consumption is increasing mainly at the expense of HCFC-22. However, HFCs tend only to be used in small systems, mainly because of the high costs of the refrigerants.

In Europe, many industrial end users expressed uncertainty regarding the future use of HFCs, especially in response to realised phase out of HFCs by Denmark by 2007 /KK02/. In Denmark since 2001 and Norway from 2003 a TAX-System is already in force (examples (Euro/kg): Denmark HFC-134a: 18, R-404A: 44, Norway HFC-134a: 32, R-404A: 80).

HFC-134a has completely replaced CFC-12 in high capacity centrifugal liquid chillers. Units with HFC-134a as refrigerant are in operation, with medium and large size capacities from 1 MW to 30 MW @ 6/12 °C and in heat pump applications. HFC-134a is used in a growing sector of distributed cold and hot water supply systems, new systems with capacities of 52 MW have been realised recently in Europe (Sweden, France) /Cli02/. HFC-134a is not considered for freezing applications.

As **R-404A and R-507A** are very similar in composition and refrigeration properties, both have become the main HFCs for industrial applications, cold storage and food processing. In spite of minor temperature glides, R-404A and R-507A have proven to be applicable even in flooded systems /Bar96/. Cycle efficiencies (COP) are comparable to R-502 but significantly lower compared to those of NH_3 and HCFC-22, especially at high condensing temperatures. Air-cooled condensers should be avoided as far as possible. To achieve best efficiencies and high cost-effectiveness for systems with R-404A and R-507A the liquid should be sub-cooled. In chill applications it may also be necessary to add significant superheat to the suction gas in order to avoid refrigerant condensation in the oil separator.

R-410A is well suited for industrial applications, COPs are comparable to NH_3 and HCFC-22, slightly higher compared to R-404A, R-507A for evaporation temperatures down to –40 °C. Below –40 °C to the normal boiling point at -51,6 °C, COPs are slightly higher for R-410A compared to other refrigerants. Since R-410A is a so-called high pressure refrigerant, moderate condensing temperature below +35 °C is required for system design pressure of 25 bar. Due to high volumetric capacity (40% above that of HCFC-22), compressor efficiency has been reported to be higher than with HCFC-22 /IEA99/. So far, experiences from realised systems in the industrial sector are limited /Gti02/.

In the future, the high capacity refrigerant R-410A is expected to gain market shares and is one of the leading HFCs as replacement for HCFC-22 for industrial applications with low evaporating temperatures. Compressor size will be less compared to other refrigerants except CO_2, and compressor efficiencies, pressure drop in suction lines and heat transfer efficiency will benefit from high system pressure.

Refrigerants with significant temperature glide such as R-407C has not been used in industrial applications. No reports have been published describing the use of R-407C in industrial applications.

5.4.4 Hydrocarbons (HC)

HC may fit into any temperature range from evaporating temperature down to –170 °C. Historically, their uses as working fluids have been restricted to large refrigeration plants within the oil and gas industry. A certain increase in hydrocarbon consumption, which has been registered, has appeared mainly in these sectors.

Commercialised products used in industrial refrigeration equipment include HC-290, HC-1270 and HC-290/600a blends, although pure substances will be preferred in flooded systems. All of these refrigerants possess vapour pressures very similar to those of HCFC-22 and CFC-502. System performance with regard to system efficiency is comparable to and, in some cases even superior to, that of the halocarbons. Hydrocarbons are soluble with all lubricants and compatible with materials such as metals and elastomers that are traditionally used in refrigeration equipment. Beside safety aspects, standard refrigeration practice as for HCFCs and CFCs can be used without major system detriment to system integrity.

Given the flammability concerns, design considerations as detailed in the relevant safety standards should be adhered to. Additional safety measures should be considered for repairing and servicing. Several national and European standards permit the use of HCs in industrial applications and lay down specific safety requirements.

5.4.5 Carbon Dioxide (CO_2/R-744)

Besides being non-ODP and non-GWP, carbon dioxide (CO_2) offers a number of advantages:

- excellent thermophysical properties, leading to high heat transfer;
- efficient compression and compact system design due to high volumetric capacity;

- non-flammable and low toxicity;
- low system costs at evaporation temperatures below –45 °C (depending on system design).

However there is a lower limit on evaporating temperature of –54 °C, owing to the triple point (the pressure at which CO_2 liquid solidifies). In the industrial sector the transcritical cycle with CO_2 is so far not considered because of high pressure (120 bar) components are not available. However, the use of CO_2 in low stage of cascade systems is growing for industrial refrigeration. CO_2 is also commonly used as a secondary refrigerant. Design requires pressure of 40 bar for secondary refrigerant systems, and 25 bar for CO_2 used as refrigerant. Defrosting is still an open issue, therefore parts of the systems are designed for 40 bar. If hot gas defrost is required it is necessary to design parts of the system for higher pressures, typically 50 bar.

CO_2 technology has been realised for industrial refrigeration and cold storage, both as a conventional refrigerant and as secondary refrigerant.

A comparisons-study for low temperatures has been carried out with typical systems design with cooling capacities of 600 kW @ -54 °C for R-410A, R-507 and NH_3 used as single fluid in two stage systems and for NH_3/CO_2 and HFC-134a/R-410A as refrigerants in high/low stage cascade systems. The volumetric refrigerating capacity of CO_2 is five times higher than HFC-410A and eight times higher than for NH_3 and other refrigerants, consequently reducing the size of most components in the system. The study found the lowest cost for NH_3/CO_2 /Rot01/. In case of using CO_2 as refrigerant the cost break-even point for industrial refrigeration compared to NH_3 and R-410A exists approximately at an evaporating temperature of –40 to –45 °C. Below this temperature lower costs for CO_2/NH_3 cascade systems have been archived. It is expected that costs for screw or reciprocating units, including compressors and oil separation circuit will be further reduced /Rot01/. Efficiency of CO_2 systems in this temperature range is comparable to other refrigerants such as R-410A or NH_3. CO_2 shows strong cost benefits if the system size is increasing, especially in cases where evaporators or heat exchangers are distributed and long piping systems are required. In this application cost benefits have been achieved with total pipe runs of more than 2500 m /Axi02/.

In USA, the first large CO_2 Systems will be realised with cooling capacities of 6 MW in 2002/03. In Europe more than 10 large systems with CO_2 as secondary refrigerant and as refrigerant have been installed since 1998 and are in operation with total cooling capacities of 2.7 MW@ -5 to –10 °C, 2.2 MW@ -25 to –35 °C and 4.1 MW @ -45 °C or lower /Koe02/.

In industrial refrigeration a clear trend can be observed towards CO_2 as refrigerant at temperatures lower than –45 °C and as brine for higher cooling temperatures /PIR02/.

CO_2 as brine is today a reliable technology and well accepted. CO_2 has been used as retrofit refrigerant for HCFC-22 systems (Supermarket, Cold Storage), the market interest is strongly increasing in Europe. At least 2 large systems have been retrofitted from HCFC-22 (1.5 MW @ -45- -55 °C) and from CFC-13B1 (2.4 MW @ -35 °C) to NH_3/CO_2 cascade systems /Geb01, Koe02/.

It is expected that the CO_2 market share will increase. Through cascading with CO_2, the amount of NH_3 may be reduced from several kilograms per kW cooling effect (pump circulation) to 50-200 grams/kW (liquid chillers, water cooled and air cooled/evaporative condensers respectively).

5.4.6 Water

Water can be used as refrigerant for high-temperature industrial heat pumps. It has favourable thermodynamic and environmental properties and is neither flammable nor toxic. For cooling application a detailed thermodynamic study has been carried out by ARI /ARI01/.

Water systems based on centrifugal compressors have been installed in Germany. Eight H_2O industrial process cooling units are running with cooling capacities of 500 kW to 1 MW @ 6/12 °C /Aqu01, Bur01/. Costs for H_2O chillers are at the moment twice as high as for conventional units using HFC-134a.

Water has been applied as a working fluid in open and semi-open MVR systems in industrial evaporation processes. Operating temperatures are in the range 80 °C to 150 °C. The major disadvantages using water as refrigerant are the low volumetric refrigeration capacity and the relatively high pressure ratio, especially at evaporating temperatures below 100 °C.

5.5 New Technologies

5.5.1 CO_2 in the Transcritical Cycle

By utilising the transcritical CO_2-cycle, combined needs for cooling and heating, which are commonly found in industry, could be met in a very efficient way. A CO_2 heat pump may produce hot water with temperatures up to 100 °C without any operational problems, while traditional heat pump systems are often restricted to hot water temperatures lower than 55 °C.

5.5.2 Absorption / Compression Cycle

Absorption / Compression cycle has been developed by combining the features of the vapour-compression and vapour-absorption cycles. About 20 compression-absorption systems --both on laboratory and full-scale-- have been developed and tested successfully so far. Various analytical and experimental studies have shown that the COP of compression-absorption systems is comparable to vapour compression systems. However, this system suffers from an inherent disadvantage of being capital intensive in nature. The technology is still at developmental stage /Fer02/.

5.6 Retrofit Options for Existing Systems

HCFCs and some HFCs are main refrigerant options for retrofitting industrial refrigeration units, cold storage and food processing systems.

Refrigerant blends with significant temperature glide are applicable only with dry expansion, which is common only in the smaller systems. Due to low cost and simple retrofit procedures, 60-70% of retrofits have involved HCFCs, including blends with HCFCs. Since HCFCs contain chlorine, no oil change is required in most cases.

Hydrocarbons may be used but flammability aspects need to be addressed.

CO_2 has been used as refrigerant for existing HCFC-22 systems, the market interest is strongly increasing in Europe.

Two large systems have been retrofitted from HCFC-22 (1.5 MW @ -45- -55 °C) and from CFC-13B1 (2.4 MW @ -35 °C) to NH_3/CO_2 cascade systems /Geb01, Koe02, Gti02/.

In Europe HCFC-124 is no longer allowed in new equipment, therefore HFC-236fa has been tested and commercially used in new equipment such as high temperature crane carbin A/C units in iron melting factories /Mis01/. In addition HFC-227ea is used in new systems. Both refrigerants, HFC-227ea and HFC-236fa have the disadvantage of low volumetric efficiency compared to CFC-114 and HCFC-124, therefore system costs are greater.

The details for the special retrofit options are described in the Technical Options Report 1998 for refrigerants CFC-12, R-502, CFC-13, R-503, R-13B1, HCFC-22, CFC-114, HCFC-124 /TOC98/.

5.7 Service Requirements

As a world wide average, current CFC and HCFC annual emission rates have gone down and may be 7-10% on average in industrial refrigeration systems today /Bir00, Bir02/.

Technical Requirements for HCFC for service:
It will be technically possible to manage without HCFCs in new industrial systems as described in sub-section 5.5. Reasons for continued use of HCFCs are costs and energy efficiency. Furthermore, contractors and end users are reluctant to change since HCFC technology is well known. Also, concern over the long-term future of HFCs has been identified as a barrier to changeover /Mar96, Eur01/.

Lower price, better efficiency and probably greater margins with respect to failure, make HCFCs (and, unfortunately, CFCs) attractive compared to HFCs in many Article 5(1) countries. In comparison to NH_3, 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 the CFC phase-out, availability of HCFCs may reduce the CFC problem in these countries, while lack of HCFCs may prolong dependency of CFCs.

Except in Europe, HCFC-22 is still used in new industrial systems because “all problems are known” and due to the fact that it is competitive with respect to cost and efficiency, the latter relative to currently available HFCs.

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 a possible reduction in system reliability if the oil change is not done sufficiently thoroughly. With respect to HCFC-123, no retrofit option is commercially available. For these reasons, HCFCs have to be available for service throughout system lifetimes.

As a conclusion, HCFCs have to be available especially for systems in Article 5(1) countries in the short to mid-term and for service purposes. Provided that current CFC practices with respect to refrigerant conservation (reduced leakages, extensive recovery and recycling, reference next section) are transferred to HCFCs, only small amounts of virgin refrigerant should be required for future service.

Service:
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 replenishment. CFC prices have risen very considerably, making improved maintenance and sound conservation practices economic. It is estimated that a similar figure also applies for HCFC-22. Emissions from HFC systems are probably even lower, due to more leak-proof designs.

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).

5.8 Available Data on Consumption

Since information on the number of systems, amounts of refrigerant per system and other specific technical data is virtually impossible to obtain, given estimates have to be characterised as "qualified guesses", indicating only very rough orders of magnitude.

5.8.1 Refrigerant Consumption

CFC and HCFC inventory and consumption have been estimated for the entire industrial refrigeration sector as a whole, using a top-down approach. To indicate separate figures for the sectors covered by this chapter, it is assumed that cold storage and food processing accounts for 75%, leaving 25% left for other industrial applications. Compared to the 1998 TOC report /TOC98/ annual growth rates of 10% for China and India, 7% for other Article 5(1) countries and 4% for developed countries have been assumed.

***Table 5-1** Estimated consumption of halocarbon refrigerants for industrial refrigeration systems, cold storage and food processing (2002)*

	Consumption, tonnes/year			Refrigerant inventory, tonnes		
	CFCs	HCFCs	HFCs	CFCs	HCFCs	HFCs
Non-A 5(1) countries	10 000	25000	4600	100000	154000	9300
Article 5(1) countries	2300	2700	0	9500	11100	0
Total	12300	27600	4600	110000	165000	9300

5.8.2 Forecast of Use

***Table 5-2** Forecast of demand of halocarbon refrigerants for industrial refrigeration systems, cold storage and food processing*

	Refrigerant	2002	2005	2008
Non-Article 5(1) countries	CFCs, tonnes	10000	6000	4000
	HCFCs, tonnes	25000	22000	19500
	HFCs, tonnes	4600	14000	23000
	Total, tonnes	39600	42000	46500
Article 5(1) Countries	CFCs, tonnes	2300	2350	2200
	HCFCs, tonnes	2700	3800	4100
	HFCs, tonnes	0	750	1600
	Total, tonnes	5000	6900	7900

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6 Transport Refrigeration

6.1 Introduction

Transport Refrigeration includes transport of refrigerated products with reefer ships, intermodal refrigerated containers, refrigerated railcars, and road transport including trailers, diesel trucks and small trucks.

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

Since the 1998 Assessment, qualitative and quantitative changes have resulted in a global acceptance of HFCs either as single fluids or as blends in containers, railcars and road transport as CFCs ceased to be used for new equipment and as use of HCFCs decreases as well.

Transport of refrigerant cargo on ships shows a modest growth in the last years, but is dominated by Intermodal Refrigerated Containers. Transport with conventional refrigerated ships has decreased and most systems are using HCFC-22 in an ageing fleet.

Most systems on reefer ships, however, continue to use HCFC-22, even though a few systems were introduced 8 years ago with the non-fluorocarbon option ammonia. However, the transport volume of reefer ships has decreased in recent years compared to intermodal refrigerated containers, whose share of the total volume is estimated to reach 60% within the next few years.

6.2 Current Status

Since the working environment in all sub-sections of transport refrigeration is under rough conditions, the emissions on average are higher than in other areas. To reduce leakages, better quality systems are now already on the market, meaning higher costs to the user, but also an increase in quality of the product transported.

Most systems which used CFCs in 1998 have been retrofitted or scrapped to meet environmental legislation, but some intermodal refrigerated containers and trucks older than 10 years will continue to use CFC-12 until they are scrapped in the near future, or retrofitted to a drop-in interim solution. The existing fleet using CFCs is still large. However, the European Regulation 2037/2000 /Eur00/ on ODS, which entered into force in Europe on 1 October 2000, has already had a significant impact on this remaining CFC fleet, which should be retrofitted if operation in the European Union is foreseen. By 2006 it is estimated that the transport section will be CFC free in the developed world.

Since all sub-sectors included in transport refrigeration are very dependent on the refrigerant availability, it has taken a longer time to choose alternatives, which meet the criteria for long term solutions.

6.2.1 Reefer Ships

The conventional reefer fleet capacity shows a moderate growth and will also continue in the future as the cargo with reefer ships represents: 2000 - 28.6 million tonnes, to 2005 – 32.2 million tonnes, to 2010 – 37.4 million tonnes /Dyn02/, while the container fleet continues to expand at a much greater rate than the conventional reefer sector. Today there are nearly 1100 full reefer ships larger than 250,000 cb.ft. in operation with an average size of 280,000 cb.ft.

Current refrigerants in use today are mainly HCFC-22 with vapour compression refrigeration. A few ships operate on CFC-12, but they are old and will be scrapped within a few years.

Approximately 70% of all refrigeration systems on fully reefer ships are direct systems, containing a charge from 3 to 5 tonnes of refrigerant. The annual leakage rate is estimated to be on average 10-15% (550 tonnes) of the initial charge. The high emission rate in the transport section occurs because most refrigeration systems operate under adverse conditions as a natural consequence of vibration, tension, saline and humid air.

Ships with indirect systems using brine as a secondary fluid have a more limited refrigerant charge and lower leakage rates than direct systems, from 500 to 1500 kg. The emission from that category is therefore less than 100 tonnes. Most systems built since 1990 are based on compact brine chillers. Ships on order for delivery within the next few years are supplied with alternatives to HCFC-22 because the European Union has banned HCFC-22 in new installations. To reduce the initial charge and improve the possibility for reduced leakage rate, some producers are considering systems be delivered with indirect systems and a secondary refrigerant.

Alternative fluorocarbon candidates today are R-404A and R-407C, but R-410A is gaining importance in the marine market as a replacement for HCFC-22 in new systems. Because of increased refrigeration capacity of R410A, systems can be made more compact and with a reduced initial refrigerant charge on each ship.

Most classification societies have made it mandatory to have fixed leak detectors installed in marine installations to reduce the emission of refrigerants, to protect the environment and for safety concerns.

Non-fluorocarbon alternative systems with ammonia or CO_2 have a good potential on new ships in the future, if the cost associated with such systems could be competitive with systems made for fluorocarbons. A few ships built in 1993 used ammonia for the first time in many years, and this is only possible for indirect systems with a limited charge in a protected space to meet the safety codes. There are costs related to necessary protective equipment, which preclude its use in smaller systems. Ammonia was introduced to be the refrigerant for reefers in the future, but since the construction of five ships in 1993, shipyards and operators have switched back to HCFC-22 as their preferred refrigerant. Recently refrigerated vessels with ammonia were delivered in Europe. The introduction of R-407C, R-404A and R-410A systems and a competitive price on non-fluorocarbon alternatives with indirect refrigeration will dominate the future of new reefer-ships. HCFC-22 has vanished from new systems in Non-Article 5(1) countries.

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

There are more than 30,000 ships of all types in excess of 300 gross tonnes. They all have refrigeration systems for their provision rooms and air conditioning. 85% of the fleet still use HCFC-22 as a refrigerant, the rest are mainly using HFCs; CFCs are insignificant. In the fishing fleet, ammonia is used in several types of systems.

It is estimated that the installed CFC in use pool has been reduced to 500 tonnes, mainly because of retrofitting to more environmentally accepted refrigerants and scrapping of old ships. Annual emissions may be around 50 tonnes, and have been reduced dramatically since 1998.

The total HCFC pool may be around 20,000 tonnes including the fishing fleet and each country's Navy. The emission rate is high on naval vessels due to the special operating conditions, but it is estimated that the leakage amount has been reduced to 7,000 tonnes annually because of better maintenance and quality of the systems.

In fishing vessels NH_3 is a commonly used refrigerant in many countries, such as Russia and Chile. There is a clear trend towards use of NH_3 in fishing vessels in the Scandinavian countries /Nor00/ as an alternative to HCFC-22 which is now phased out. One of the larger manufacturers of equipment to this sector has recently introduced cascade systems with NH_3 and CO_2 in fishing vessels. CO_2 is used in direct expansion in all the freezing equipment onboard /Chr02/.

Approximately 1000 new ships in all categories are delivered annually. Since HCFC-22 is regulated and will be phased out, HFC-134a, R-404A and R-507 are ship owners' and shipyards' first choice and the requests for these fluids, as well as R-407C for A/C systems, are increasing. These fluids are also available world-wide and may dominate the market until R-410A equipment will be available. Indeed, the European Union regulation prevents from building any new HCFC refrigeration or A/C systems (cooling capacity over 100 kW) since the 1 January 2001.

6.2.3 Intermodal Refrigerated Containers

The rate of container fleet increase will far outstrip that of reefer ships in the transport of refrigerated cargo. For the container operators, reefer slot capacity is relatively easily and cheaply installed, and ships in the current fleet have an average capacity of 136 TEU. TEU "Twenty foot equivalent unit" refers to a unit of volume corresponding to a twenty foot ISO container. As many units are of a volume of 2 TEU, there can be confusion between TEU numbers and actual container numbers.

The number of units in operation today is approximately 550,000 units, a portion of them delivered before 1993, still use CFC-12 as a refrigerant. The refrigeration units contain around 5 kg of refrigerants each.

Average lifetime of a container is estimated to be 15 years and a portion of the units in operation today with CFC-12 are expected to operate to the year 2003 and after. There is therefore still potential to retrofit to more environmentally friendly alternatives. Retrofits will accelerate due to EU regulation on CFCs already in force today.

Units made in recent years use HFC-134a (390,000), R-404A (20,000) and 60,000 units use HCFC-22 /And/. The remaining 80,000 units use CFC-12 or transitional blends. The total pool of refrigerants is estimated to be 400 tonnes of CFC-12 and transitional blends, 2000 tonnes of HFC-134a, 100 tonnes of R-404A, and 300 tonnes of HCFC-22. Production on new ocean going containers is estimated to 50,000 annually, and most of them in the future will use HFC refrigerants. However, there is a potential for non-fluorocarbon refrigerant such as CO_2 with a transcritical vapour compression cycle with internal heat exchange. Containers are being tested out today and these could have a high tonnage in the next five to ten years if the technological aspects meet the requirements of the users. Other non-fluorocarbon refrigerants such as hydrocarbons and ammonia will not be allowed as refrigerants in containers because of their flammability with reference to IMO (International Maritime Organization) legislation.

Most refrigeration compressors for intermodal refrigerated containers on the vapour compression cycle are semi-hermetic or also now increasingly hermetic compressors with air-cooled condensers. Existing systems are therefore dependent on a refrigerant with a relatively high critical temperature to match tropical areas.

Emission rate for annual refrigeration use is estimated to 40 tonnes of CFC-12, 200 tonnes of HFC-134a/R-404A and 30 tonnes of HCFC-22.

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

In this sub-section, mechanically refrigerated vehicles dominate. They are classified as insulated vehicles, refrigerated by a machine. It is estimated that approximately 80% in road transport are within this category. The total world fleet is estimated to around 1,200,000 vehicles, of which about 30% are trailer units, 40% are independent truck units and the total remainder are smaller units driven by the truck engine.

Refrigerants CFC-12 and R-502 have been traditionally used and they still account for around 20% of the total today, making the CFC-12 and R-502 pool 1,200 tonnes. Due to EU regulation on ODS in force, European Union CFC fleet has almost disappeared today. Current production uses HFC-134a (400,000 units), R-404A (450,000 units) and HCFC-22 (150,000 units). These make a pool of 1000 tonnes of HCFC-22, and nearly 3000 tonnes of HFCs.

The final development of HFCs is that a number of units using R-410A are now available.

Due to the onerous operating condition, the after service requirement is 20 to 25% of the pool per year.

There have been developments in Australia, Germany and other European countries testing with R-290 (propane) which is now completed and offered as an off-the-shelf product. With the flammability risk of the product, all safety precautions should be taken care of, inclusion of a refrigerant leak detector within the trailer and adequate training for the drivers. There have been several quantitative risk assessments. Still, due to flammability concerns, regulation in some countries must be taken into account (inherent to the application, i.e.

mobile systems, herein described) that can limit these developments. The European Standard EN 378 (2000) also covers road transport and can be used for safe design of transport refrigeration systems, but does not solve the problem for the manufactures of product liability.

A system using synthetic liquid air (SLA) has been developed, and could be used combined with a mechanical system. This technology has not been taken up to any extent.

The use of cryogenic liquid gas in distribution applications is well established. More than 1,000 vehicles in the UK alone currently run using liquid nitrogen as the only means of refrigeration. This technology has been used since the early 1970s. Since the safety precautions which are necessary when using liquid nitrogen gave it limited use, liquid air has been developed, which has the same power capabilities and overcomes the potential asphyxiation hazard with liquid nitrogen.

Another development presented in early 2002 in Great Britain is using liquid carbon dioxide from a bottle to be expanded driving a fan and evaporated in a heat exchanger to cool the cargo. This technology is offered in Sweden where some 50 trucks are already refrigerated with CO_2 and in Belgium for a one-year trial in four trailers.

6.2.5 Refrigerated Railcars

There were approximately 80,000 refrigerated railcars in use world wide in 1997, of which 60% were in the former Soviet Union. The majority of those units use CFC-12 as refrigerant and with two refrigeration units per railcar, each containing approximately 15 kg of refrigerant, the total pool is 2,400 tonnes. Out of this 1,500 tonnes are CFC-12, while the rest are mainly HFCs. In North America it is estimated that 500 railcars are in service with R-404A, but it is reported that there are no such railcars in production today.

Total annual emission is estimated to 10 tonnes where the majority is CFC-12. In Northern Europe many CFC-12 systems are retrofitted to interim blends, depending on how many years are left of their operational life. No report has been received at this stage about the use of non-fluorocarbon refrigerants systems in railcars.

6.2.6 Air Conditioning in Railcars

More than 75,000 systems are installed, of which at least 50% being in Asia and mainly in Japan (35,000). These systems mainly operate on HCFC-22, with a pool of about 1,500 tonnes and an annual use for maintenance of 300 tonnes.

In Germany the newest high-speed trains (approximately 400 railcars) use air cycle systems for their air conditioning. The energy consumption of the air cycle is higher than of the one of the vapour compression-cycle. This leads to the fact that the total energy consumption for air-conditioning of a railcar including heating and ventilating will be 20% higher for railcars with air cycle systems, compared to HFC-134a equipped systems. In the above-mentioned case, it is mainly maintenance and leakage aspects that have led to the decision to apply the air cycle.

New trains in France and Spain use R-407C and HFC-134a.

6.3 Options

Nearly all systems for transport refrigeration operate under the vapour compression cycle and it is estimated that no other technologies will be preferred in the years to come. On refrigerated ships current refrigerants are mainly HCFC-22, but a tendency to move to non-ozone depleting substances has been noticed lately for new ships (mandatory in EU). Merchant ships and, in particular, air conditioning systems in cruise ships have in the majority of cases moved to HFCs as single fluid (HFC-134a) or as mixtures. Types preferred as mixtures are R-404A, R-407C and R-507 (usable in HCFC-22 type of technology).

However, R-410A will be the leading HCFC-22 long-term replacement fluid in the marine sector. Cruise business shows percentages of 40% R-134a, 50% R-410A, 10% other.

Since the refrigeration capacity is superior to HCFC-22 and also the energy efficiency in some conditions it is an interesting product. The majority of refrigerant manufacturers are able to produce R-410A, hence making it easily available. Since 1995 big chillers have been produced for R-410A.

Since 1994 only four new reefer ships have been produced to use ammonia with indirect brine systems.

Another option for refrigerated ships however is the potential comeback of carbon dioxide (CO_2) as the refrigerant, which was used in more than 50% of all ships as late as the 1960s. It is also tested out in refrigerated containers and might become an important factor of the development in this sector. Still, due to very high operating pressures, work on systems must be pursued.

Hydrocarbons are investigated for several applications within transport refrigeration, but specific attention has to be paid to these refrigerants due to flammability issues. It is unlikely that hydrocarbon will be accepted in larger refrigeration systems, e.g. refrigerated ships.

6.4 Retrofits

Fluids used for transport equipment retrofits include the following:

HCFC-22 is used mainly for merchant ships when converting from CFC-12 in provision and air conditioning plant with open drive compressors. It is also necessary to ensure that the system can cope with the higher pressure of HCFC-22. It is also possible to convert to R-401A/B or R-409A, which have similar pressure and capacity as CFC-12. These are interim solutions because they contain HCFCs, but in most cases they will be allowed taking into account the expected lifetime of systems and the time schedules in regulations for HCFCs in force all over the world.

HFC-134a demands a cleanliness of the system, which might be difficult and/or expensive to obtain on an old system operating with CFC-12. It is therefore not recommended since also the capacity and performance on low temperature does not cope with those of CFC-12. Interim solutions are therefore used when the equipment has few years left of operational service, and it is also a cheaper solution since the HCFCs are near to being true drop-in alternatives.

Longer term solutions to retrofit from CFC-12 are available today and this is the best environmental solution. In transport, sub-sections such as containers and trucks with more than five years left of their operational service will have environmental advantages if they retrofit to R-407D or R-413A. It should be noted that the latter is classed an A2 product by ASHRAE.

Systems with HCFC-22 should not preferably be retrofitted, but maintain their systems to be as leak tight as possible and with increased energy efficiency.

One of the World's major LPG/LPN gas carriers has decided to retrofit their HCFC-22 systems to HC-290 and HC-1270. However, here a crew, who are working with hydrocarbons takes daily care of the safety considerations; furthermore all the equipment required is intrinsically safe. From a thermodynamic term the ships retrofitted so far have shown equivalent performance if one compares HCFC-22 to HC-290.

Remark: When ships are scrapped it is mainly done in Article 5(1) countries. The total of refrigerants available could be useful for local markets, if it is recovered and recycled to acceptable standards.

6.5 Environmental Aspects

Major environmental regulations such as the Montreal Protocol, Clean Air Act and the EU legislation on ODS, will make manufacturers and users choose the best solution, including environmental, safety, energy efficiency, costs and other factors.

The EU 2037/2000 regulation regarding ODS, in force from 1 January 2001, has introduced a ban on the sales and use of CFCs for servicing and maintenance of all refrigeration and air-conditioning equipment within the EU. Also important restrictions apply there on HCFCs.

6.6 Conclusion

Probably options in the transport section will focus on a solution for all sub-sections involved with reference to refrigerants as follows:

- Refrigerants in use should not contain any chlorine, i.e. zero ODP;
- Minimum TEWI for the application consistent with technical, safety and cost considerations;
- Requirements for competence tests and refrigerants handling will become mandatory;
- Annual preventive maintenance highlighting on leakages and energy efficiency of systems should become routinely;
- Update and recording of recycled refrigerants and refrigerant recovery will be mandatory.

The Kyoto Protocol (1997) includes fluorocarbons. However, this Protocol considers a six-gas basket and since HFCs are in the fluorocarbon family, it will be necessary to avoid emissions of fluids with a high global warming potential and to be selective when it comes to energy efficiency of the refrigerants and the system. Alternative refrigerants such as CO_2, ammonia, hydrocarbons and air are evaluated within several sectors.

In most European countries HCFC-22 is not allowed in most of new systems since 1 January 2001. More environmental and efficient fluids are available and can replace HCFC-22 in new systems. Also for maintenance of existing equipment restrictions exist on use and commercial availability for HCFC-22 in the EU.

As mentioned previously the CFCs cannot be commercialised anymore in the European community and their use is strictly restricted (service of existing machines forbidden), resulting in a total phase out of CFCs within a few years to come all over Western Europe.

6.7 References

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7 Air Conditioning & Heat Pumps (Refrigerant-to-Air)

7.1 Introduction

On a global basis, air-cooled air conditioners and 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. 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 equipment /ASHF01/. These systems cool, dehumidify and/or heat everything 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 or screw compressors for units with capacities up to 420 kW. Air in the space to be cooled, or dehumidified, is drawn over a coil containing evaporating refrigerant. Heat transfer occurs between the air and the circulating refrigerant. In heat pumps, the refrigerant circulation is reversible. In the heating mode, air from the conditioned space passes over the same coil that now contains gaseous refrigerant in the process of condensing to a liquid. In the process, the condensing gas transfers heat to the air.

An estimated 2221×10^6 kW (cooling) of air-cooled air conditioners and heat pumps are installed worldwide. Refrigerant charge quantities vary proportional to capacity. Assuming an average charge of 0.25 kg per kW of capacity, those 2221 million kW (cooling) of installed capacity represent an installed bank of approximately 548,000 metric-tonnes (1000 kg) of HCFC-22 in the total world population of the air conditioning equipment covered by this chapter.

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 on the percentage of air-cooled air conditioners and heat pumps being manufactured with non-ODS refrigerants. However, a rough estimate would indicate that globally 85 to 90% of the air-cooled air conditioners and heat pumps currently being produced still use HCFC-22 as the refrigerant.

7.2 Applications

Air-cooled air conditioners and heat pumps generally fall into four distinct categories, based primarily on capacity or application: window-mounted and through-the-wall air conditioners; non-ducted or duct-free split residential and commercial air conditioners; ducted split residential air conditioner; ducted commercial split and packaged air conditioner (commercial air cooled). In each of these categories, the term “air conditioner” is assumed to include both heating-only heat pumps and reversible air conditioners.

7.2.1 Window-mounted and Through-the-Wall Air Conditioners

Window-mounted and through-the-wall Air Conditioners are self-contained units designed to cool a single space—such as a bedroom or small office. Because of their size and relatively low cost, window-mounted air conditioners (used in small shops and offices as well as residences) have often been the first individual comfort mechanical refrigeration cooling products to appear in Article 5(1) countries. Window-mounted, through-the-wall, and portable air conditioners[4] range in capacity from less than 2.0 kW to 10.5 kW (having an average size of 2.7 kW). Window-mounted and through-the-wall Air Conditioners have average refrigerant charges of 0.63 kg/unit. All use hermetic rotary, reciprocating or scroll compressors.

7.2.2 Non-ducted (or duct-free) Split Air Conditioners

In many parts of the world most residential and light commercial air-conditioning is done with non-ducted (or duct-free) 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. Small (less than 7 kW) non-ducted or duct-free split air conditioners with a single indoor fan coil are sometimes categorised as split type room air conditioners.

Non-ducted or duct-free split air conditioners use hermetic rotary, scroll or reciprocating compressors. They have average HCFC-22 charge levels of approximately 0.25 to 0.40 kg per kilowatt of cooling capacity. Non-ducted or duct-free Split air conditioners can be applied to commercial buildings, schools, apartments and free-standing residences.

7.2.3 Ducted Split Residential Air Conditioners

Ducted Split Residential Air Conditioners dominate the North American market 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 a single indoor coil (heat exchanger) installed within the duct system or air handler. Air in the living 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 kg per kilowatt of capacity or 2.7 kg/unit.

7.2.4 Ducted Commercial Split and Packaged Air Conditioner

Ducted Commercial Split and Packaged Air Conditioners are manufactured in two forms. Split System units which must be matched with an indoor air handlers and heat exchanger and Single Packaged units which contain and integral blower and heat exchanger section which is connected to the air distribution system of the commercial structure.

The majority of Ducted Commercial Split and Single 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 cool entire low-rise shopping centres, shops, schools or other moderate size commercial structures.

Large commercial structures such as hospitals, exhibition halls or high-rise structures are generally cooled with liquid chillers (Chapter 8). Other commercial products include indoor

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[4] Portable air conditioners are a special class of room air conditioners that are designed to be rolled from room to room. They exhaust their condenser air through a small flexible conduit, which can be placed in an open window.

packaged units as well as split systems in which an outdoor compressor heat exchanger unit is connected by refrigerant piping to one or more ducted indoor fan coils.

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 /Kel97i/, /DRI01/.

7.3.1 Window-mounted and Through-the-Wall Air Conditioners

On a worldwide basis, an estimated 13.4 million window-mounted[5] and through-the-wall (packaged terminal) air conditioners were sold in 2001; each one containing an average of 0.64 kg of HCFC-22. With service lives of up to 20 years, it is estimated that more than 131 million window-mounted and through-the-wall air conditioners remain in operation. The total 2001 worldwide inventory 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 84,000 metric-tonnes.

During this assessment period, there has been a significant shift toward the use of non-ducted (or duct-free) split residential air conditioners as the entry-level air conditioning product in developing countries—particularly in Asia. This trend can be observed in Table 7-1 which shows that the annual production of Window-mounted and through-the-wall air conditioners increased modestly from 1996 to 2001 while the annual production of non-ducted (or duct-free) split residential and commercial air conditioners increased dramatically during the same between 1996 and 2001.

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

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[5] 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.

Table 7-1 *Comparison of Units Manufactured 1998 and 2001*

Product Category	Units Manufactured 2001	Units Manufactured 1998	Increase 2001 versus 1998
Window-mounted and Through-the Wall (Packaged Terminal) Air Conditioners	13.6 million	12.1 million	12 %
Non-ducted or duct-free Split Residential and Commercial Air Conditioners	24.2 million	16.3 million	48.5 %
Ducted Split Residential Air conditioner	5.9 million	5.7 million	3.6 %
Ducted Commercial Split and Packaged Air Conditioners	1.7 million	1.7 million	0 %[6]

Source: /ARI02/, /Jarn02/, /DRI01/

7.3.2 Non-ducted (or duct-free) Split Air Conditioners

An estimated 158 million non-ducted or duct-free Split air conditioners are installed worldwide. Non-ducted or duct-free Split air conditioners, ranging in capacity from 2.0 kW to 20 kW (average size of 3.8kW), have gained greatest acceptance outside of North America due to different construction methods and a preponderance of hydronic or non-central heating systems in these areas. The average charge per kilowatt increases slightly as the operating efficiency of these systems increases. In 2001 the total inventory of HCFC-22 in the installed population of duct-free split systems world-wide has been estimated to be 199,000 metric-tonnes.

7.3.3 Ducted Split Residential Air Conditioners

An estimated 60 million ducted split residential air conditioners are currently in service worldwide - the majority within North America. The total estimated inventory of HCFC-22 in the installed population of ducted systems (< 17.5 kW) has been estimated to be 164,000 metric-tonnes. Approximately 5% of Ducted Split Residential Air Conditioners manufactured globally in 2001 utilised non-ODS refrigerants.

7.3.4 Ducted Commercial Split and Packaged Air conditioner

An estimated 19 million air-cooled Ducted Commercial Split and Packaged air conditioners and heat pumps are installed worldwide. They range in capacity from about 5 kW to as large as 420 kW (sales weighted size of 23.0 kW). Commercial Ducted Commercial Split and Packaged equipment have an average HCFC-22 charge of about 0.31 kg per kilowatt of capacity or 5.3

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[6] The low growth-rate reflects the impact of the economic downturn on the Commercial market.

kg/unit. The estimated total worldwide inventory of HCFC-22 in these systems has been estimated to be 101,000 metric-tonnes. This estimate does not include commercial water chillers (Chapter 8).

7.3.5 Heat Pumps

The vast majority of heat pumps currently in operation are electrically driven closed-cycle compression type systems. However, systems driven by gas engines are available in some markets. The majority of commercially (on a units produced basis) manufactured heat pumps use HCFC refrigerants. However, there is an increasing trend toward the production of heat pumps with non-ODS refrigerants.

Heating-only heat pumps are used for space heating in residential, commercial/institutional and industrial buildings. Space heating heat pumps in residential and commercial/institutional buildings typically operate between 1,000 to 5,000 hours a year, depending on the climatic conditions, type and purpose of the building.

A majority of heat pumps sold in the North American and Japanese markets are reversible air or water source units. In Northern Europe, heat pumps are mainly sold for heating purposes. In North America, the Southern regions of Europe and Japan heat pumps are sized to provide space cooling.

In North America the primary markets for air source heat pumps are in the Midwest and the South and regions not having access to Natural gas. Heat sources include ambient and ventilation air, water (sea water, lake water, industrial wastewater and ground water), and ground coupled heat exchangers. Air source heat pumps dominate the global market.

Heat pumps are manufactured in all sizes ranging from 1 kW heating capacity for single room units, to 50-1,000 kW for commercial/institutional applications, and tens of MWs for district heating plants. Most of the commercial and institutional heat pumps are water –to-water systems that are covered in Chapter 8. Most small to medium size water to air heat pumps are factory made units.

The most common refrigerant used in Ground and Water source heat pumps has been HCFC-22. However a number of different CFC and HCFC refrigerants have been used in heat pump systems to address the requirements of various unique applications.

Recently heat pump systems are being produced in commercial quantities with a number of non-ODS refrigerants; including R-410A, R-407C and, HFC-134a.

7.3.6 Summary of Unit Population and Refrigerant Inventory

Common attributes of these equipment categories have been their nearly universal use of HCFC-22 as a working fluid. On a mass basis, HCFC-22 accounted for nearly all of the refrigerant fluid used in these product categories. Table 7-2 summarises the total estimated inventory 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 5% of new production) while in Europe and Japan there has been a more significant shift to the use of non-ODS refrigerants - predominately HFC blends. The majority of Article 5(1) countries are still utilising HCFC-22 in these categories of products.

Table 7-2 *Estimated 2001 Unit Population and HCFC-22 Inventories*

Product Category	**Estimated Unit Population (2001)**[7]	**Estimated HCFC-22 Inventory**[8] **(metric-tonnes)**
Window-mounted and Through-the Wall (Packaged Terminal) Air Conditioners	131 million	84,000
Non-ducted or duct-free Split Residential and Commercial Air Conditioners	158 million	199,000
Ducted Split Residential Air conditioners and Heat Pumps	60 million	164,000
Ducted Commercial Split and Packaged Air Conditioners	19 million	101,000
Total	368 million	548,000

7.4 Alternative Refrigerant Options

The equipment designer must consider many factors when designing an air conditioning product with a new refrigerant. These include:

1. Performance
2. Reliability
3. Safety
4. Market Acceptance
5. Environmental Impact

The results of current research programs and recent new product introductions indicate that in addition to single-component refrigerants such as HFC-134a, CO_2 and HC-290, several refrigerant blends have now been commercialised or demonstrated as HCFC-22 replacements. Following is a brief summary of some of the refrigerants being used or proposed as HCFC-22 replacements in air-conditioning (and Heat Pump) systems. Of the pure component refrigerants investigated, only HFC-134a and HC-290 are still considered viable single component refrigerant options.

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[7] Unit population estimates do not include units manufactured with non-ODS refrigerants.

[8] HCFC-22 Inventory does not include non-ODS refrigerants.

7.4.1 Single Component HFC Refrigerants and HFC Blends

Several single component HFC refrigerants have been investigated as replacements for CFCs and HCFCs currently used in air-cooled air conditioners and heat pumps.

7.4.1.1 HFC-134a

HFC-134a is not a *drop-in* replacement for HCFC-22 in air-cooled equipment. To achieve the same capacity, as an HCFC-22 system the compressor displacement must be increased approximately 40% to compensate for the lower density of HFC-134a. The efficiency of such a system has been shown to be approximately 5% less than the HCFC-22 system because of the higher pressure-drop, which is a result of its lower density. It is possible to design air-cooled equipment using HFC-134a that will have the same system efficiency and capacity as HCFC. However, significant equipment redesign is necessary to achieve equivalent efficiency and capacity. These design changes include enlarged heat exchangers and refrigerant tubing, larger volumetric displacement compressors, and re-sized compressor motors.

While HFC-134a is a viable HCFC replacement in air-cooled applications, there have been very few air-cooled air conditioning products commercialised that use HFC-134a refrigerant. This is because manufacturers have been able to develop more commercially viable air-cooled air conditioning systems using other non-ODS refrigerants. It is anticipated that HFC-134a will see some usage in higher capacity (greater than 70 kW) systems.

A number of HFC blends have emerged as replacements for HCFC-22 in air conditioning applications. Various compositions of HFC-32, HFC-125, HFC-134a, and HFC-143a are being manufactured as non-ODS replacements for HCFC-22.

Two of the most widely used HFC blends are R-410A and R-407C /Biv00/.

7.4.1.2 HFC-32/125/134a (R-407C)

R-407C has a temperature glide of 5 to 7 °C, while the saturation temperature and volumetric heating and cooling capacity are about the same as HCFC-22. 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 /Lin00/. Devotta et al. has reported that the deviation from HCFC-22, under retrofit conditions, increases above these nominal values as the outdoor ambient increases /Dev02/.

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

Since R-407C refrigerant requires only modest modifications to existing HCFC-22 systems it has been used as a replacement for HCFC-22 where phase-outs of HCFC-22 are occurring on a schedule faster than dictated by the protocol. It may also be an attractive alternative for large capacity (greater than 52 kW) unitary products that would require extensive design modification and high capital equipment investments to be converted to higher pressure refrigerant such as R-410A.

R-407C has seen broad use in both Europe and Japan. In Europe, R-407C has been used as the dominant replacement for HCFC-22 in air-to-air air conditioning applications. In Japan, R-407C has been used primarily in the larger capacity duct-free and multi-split products.

7.4.1.3 HFC-32/125 (R-410A)

R-410A is a binary blend that can replace HCFC-22. The blend consists of HFC-125 and HFC-32, with the composition 50/50%. This blend has a very low temperature glide (near azeotropic). The normal boiling points are approximately 10 °C lower than HCFC-22, causing condensing pressures rise of up to 14 bar. The volumetric heating capacity is 3-4% higher than for HCFC-22.

R-410A air conditioners (up to 17.5 kW) are currently commercially available in the US, Asia and Europe. A significant portion of the duct-free products sold in Japan use R-410A as the preferred refrigerant. Approximately 5% of the US Ducted Residential Market is using R-410A as the refrigerant. It is likely the US Ducted Residential market will predominately utilise R-410A as the HCFC-22 replacement.

System pressures with this blend are approximately 50% 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, heat exchangers and refrigerant tubing. The low critical temperature of R-410A may require design changes to address operation at ambient temperatures above the critical point. A recent study has shown the capacity of an R-410A system will degrade linearly with the outdoor ambient, but at a faster rate than an equivalent HCFC-22 system. The two systems that were evaluated were nearly equal in capacity at 35 °C. At an outdoor ambient of 55 °C the R-410A system had a 9% lower capacity than HCFC-22 system. A similar trend was observed for the COP /Dom02/. In this same investigation the system was operated in the transcritical region without exhibiting any abnormal behaviour.

7.4.1.4 HFC-125/ HFC-134a/ HC-600 (R-417A)

This refrigerant is somewhat unique in that it combines two HFC refrigerants with a small amount of hydrocarbon refrigerant. The hydrocarbon refrigerant, HC-600 was added to the blend to allow this refrigerant to work with standard mineral oil lubricants. There is very limited performance data (other than the refrigerant producers data) on this refrigerant in the literature. The refrigerant producers data suggests that this refrigerant is a near drop-in replacement for HCFC-22 with moderate capacity and efficiency losses (less than 10%). A study of this refrigerant conducted under low temperature refrigeration conditions (-30 °C) showed a 12% loss in COP and a 24% loss in Capacity when compared to HCFC-22 under the same conditions /Fur00/. Systems, which use this refrigerant, require approximately 5-10% more refrigerant mass than HCFC-22 systems. /Voi00/.

7.4.2 Non-Fluorocarbon Refrigerants

7.4.2.1 Hydrocarbon Refrigerants

There have been a number of performance comparisons made between HC-290 and HCFC-22 /Colb00i/. The results of these comparisons suggest that the HC-290 systems had 8-9% higher efficiency than the HCFC-22 baseline systems during drop-in comparisons (without fire-safety related design changes applied to the HC-290 systems).

Compared to HFCs, hydrocarbon refrigerants offer reduced charge levels (approximately 0.15kg/kW of cooling capacity /Colb99ii/), miscibility with mineral oils (synthetic lubricants are not required), reduced compressor discharge temperatures, and improved heat transfer due to more favourable thermo-physical properties.

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

The use of hydrocarbons in air-cooled air conditioning products having refrigerant charge levels greater than 1 kg has been the focus of significant risk analysis and safety standards development activities. A number of organisations have conducted analytical risk assessments of air conditioners using hydrocarbon refrigerants /Rit96/, /Wolf99/, /Rit02/. Most of these assessments conclude that the risk of fire or explosion is reasonably low and is proportional to the quantity of refrigerant in the system. These studies show a wide range of probabilities of fire or explosion. However, the most significant issue that will confront a manufacturer when considering applying hydrocarbon refrigerants is the determination of an acceptable level of risk and the associated liability.

In addition, a joint working group, IEC/SC 61D & ISO/TC86 SC61D, was established to develop amendments to address flammable refrigerants (to be incorporated in ISO 5149 and Amendment 3 to IEC 60335-2-40 Third Edition –1995: Part 2-40: Particular Requirements for electrical heat pumps, air conditioners and dehumidifiers containing flammable refrigerants) /Colb99i/. The ISO/IEC Joint Working Group has completed its work, and has been dissolved. The recommended changes have not yet been approved for inclusion in the standard.

When designing new heat pump systems with propane, HC-290 or other flammable refrigerants, adequate safety precautions should be taken to ensure safe operation and maintenance. Another factor that will need to be considered with flammable refrigerants will be refrigerant recovery requirements. Even though hydrocarbon refrigerants have minimal global warming impact, there will still be a need to require recovery during servicing and at the end of the product's life in order to protect those servicing or recycling the product. The ultimate decision on whether hydrocarbon refrigerants are practical in air cooled air conditioning products will become a financially based decision.

7.4.2.2 Carbon Dioxide

Carbon dioxide (CO_2) offers a number of desirable properties as a refrigerant: readily available, low-toxicity, low Global Warming Potential and low cost. CO_2 systems are also likely to be very compact /Nek01/.

These are offset by the fact that CO_2 in air conditioning applications has low operating efficiencies and high operating pressures. A cycle analysis of a window-mounted room air conditioner has shown that a CO_2 based system will have a COP 60% lower than an HCFC-22 system /Dev00/. Another barrier to the commercialisation of CO_2-based air conditioners is the limited availability of compatible components such as compressors, heat exchangers and refrigerant controls.

The performance penalty can be reduced through optimised system designs, using refrigerant expanders (not yet available), and cross-counter-flow heat exchangers, which take advantage of the favourable thermo physical properties of CO_2. Operation of the transcritical process introduces the need to control the high-side pressure of the system /Nek01/. Actual system tests of non-optimised air conditioning systems have demonstrated COPs in the range of 2.00 to 3.00 /LiD00/.

7.4.3 Lubricant Requirements

7.4.3.1 HFC Refrigerant Lubricants

The mineral-oil-based 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. Four approaches have been pursued by the industry.

1. Polyolester (POE) Lubricants (Synthetic)
2. Polyvinylether Lubricants (PVE) (Synthetic)
3. Polyalphaolefin Lubricants (PAO) (Synthetic)
4. Hydrolytically stable Polyoester (HSPOE) Lubricants
5. System designs that can utilise non-miscible mineral oil lubricants.

Of these, POE is the most widely used lubricant in HFC refrigerant applications. PVE lubricants have been used as alternative to POEs. There has also been some interest in the use of PAO lubricants as alternatives to POE lubricants. Interest in options 4 and 5 has declined since the last assessment.

7.4.3.2 Hydrocarbon Refrigerant Lubricants

A number of researchers and practical experience with hydrocarbon refrigerators confirm that Hydrocarbon refrigerants can utilise mineral oil based lubricants /Colb99ii/.

7.4.3.3 CO_2 Refrigerant Lubricants

There is very limited quantitative information in the literature studying lubricant requirements for CO_2 compressors. Finding an ideal lubricant for CO_2-based systems is complicated by the fact that at transcritical conditions, CO_2 can be a very effective solvent for all types of hydrocarbon lubricants. However, Li also presented data indicating that mineral-oil-based lubricants are non-miscible with CO_2 /Li00/. The results of this work also raised concerns about the compatibility of CO_2 and POE lubricants. Another study indicates that polyglycols and polyoesters appear to have the required properties to lubricate CO_2 refrigeration systems /Wat98/, /Lee02/, /Li02/. The results of all of these studies provide a high degree of optimism that suitable lubricants will be commercially available by the time CO_2 air conditioning systems are commercialised.

7.4.4 Summary

Of the options presented in section 7.4, the introduction of HFC refrigerants and hydrocarbon refrigerants into the market will have the greatest impact on the industry transition from HCFC-22 during the next 10-15 years. Results so far indicate that HFC blends are the most likely near – term refrigerants to replace HCFC-22 in air-cooled systems. Air-cooled air conditioning equipment using HFC refrigerants is already commercially available in many regions of the world. Widespread commercial availability of systems using HFC refrigerants is occurring in most developed countries and in some Article 5(1) countries.

Hydrocarbon refrigerants may also be suitable replacements for HCFC-22 in some categories of products—particularly low charge level applications; assuming International safety standards are developed to define the specific design and application requirements.

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

7.5 New Technology (Alternative Refrigerant 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 new technologies presented in prior assessments were: absorption, desiccant cooling systems, Stirling Cycle systems, thermoelectric and number of other more exotic systems. However, a search of the literature published since the prior assessments has confirmed that none of these technologies have progressed much closer to commercial viability than they were at the time of the prior assessments. While these alternative cycles are theoretically feasible, it is unlikely that they will significantly penetrate these markets in the next several decades. Alternate cycle technologies will therefore have a minimal impact on the HCFC phase-out.

7.6 Retrofit

Retrofitting is the process of replacing the refrigerant in a previously installed system with a different refrigerant. Retrofitting is an important issue for Article 5(1) countries where systems are usually repaired a number of times to extend their useful life beyond that observed in developed countries. Retrofitting of existing air conditioners may be possible using a number of the refrigerant options currently being investigated as retrofit replacements for HCFC-22.

7.6.1 Retrofit Issues

The suitability of a specific retrofit refrigerant will be determined by its attributes in relation to performance, need for system modifications, and potential impact on system reliability and safety issues. The performance characteristics of any retrofit refrigerant will be a key factor in its suitability for retrofit applications. To be acceptable, a retrofit refrigerant should exhibit similar capacity and efficiency to HCFC-22 (±10%). A retrofit refrigerant should require only minor system modifications and, at a minimum, should not require the replacement of the compressor or system heat exchangers. Retrofit options should only include refrigerants, which provide system reliability similar to HCFC-22 systems. A significant drop in system reliability would be unacceptable.

The reliability of the system with a retrofit refrigerant will be highly dependent on the compatibility of the new refrigerant and lubricant with the entire spectrum of materials used in system. Any incompatibility between the retrofit refrigerant/lubricant and the materials used in the system can result in high failure rates of the retrofit system. Safety will be one of the primary characteristics required of any retrofit refrigerant. Toxicity, flammability, handling requirements and operating pressure differences may rule out or limit many potential retrofit candidates. Considerable research and development is still required to locate a refrigerant capable of meeting all of these requirements.

7.6.2 Potential Candidates

At least one promising retrofit candidate is commercially available. The HFC-32/125/134a zeotropic blend, R-407C, may be an acceptable retrofit refrigerant. Several retrofit field tests have been conducted with promising results. In addition, R-417A refrigerant has been suggested, by the producer, as a potential retrofit refrigerant for HCFC-22 /Voi00/.

7.6.3 Anticipated Market Impact of Retrofit Refrigerants

The need for and market impact of, retrofit refrigerants will largely be determined by the HCFC phase-out schedule and allowed service tail. It is anticipated that retrofit refrigerants will be important for Article 5(1) countries, because of the limited capital available to manufacture new non-ODS systems. An accelerated phase-out of HCFCs would increase the need for retrofit refrigerants. A phase-out schedule with a long service tail could reduce the need for retrofit refrigerants.

Most of the installed population of air conditioners and heat pumps has an average service life of 15 to 20 years. Therefore, a longer service tail would reduce the need for retrofit refrigerants. Commercialisation of suitable retrofit refrigerants should continue because they will provide high value to Article 5(1) countries and those that purchase HCFC-22 air-conditioning products prior to the transition to the new refrigerants.

7.6.4 HC-290 as a Retrofit Refrigerant

It has been reported that HC-290, propane, has been used as a retrofit refrigerant for HCFC-22 in several countries, including Australia and Indonesia. While HC-290 provides nearly equal performance (capacity and efficiency) to HCFC-22, the flammable nature of this refrigerant creates a significant safety concern with this practice. If retrofitting is being considered; all relevant safety standards and codes-of-practice should be strictly adhered to. In most cases the cost of meeting safety standards and codes-of-practice has been found to be too costly to justify. The one exception would be large industrial plants where the economics might justify the necessary expense.

7.7 HCFC Usage Forecast

After more than 60 years of experience, HCFC-22 has generally been accepted as the most viable refrigerant for air-cooled air conditioners and heat pumps. 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 the second decade of the 21st century.

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 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.

Section 7.8 presents HCFC-22 usage forecasts based on three scenarios of conversion. The three scenarios were designed to bracket future HCFC-22 requirements for air-cooled air conditioners and heat pumps.

Worldwide use of HCFC-22 in 2000 was estimated by AFEAS to have been 244,000 metric-tonnes for all types of refrigeration applications.

The projection of future HCFC-22 demand was predicted using a life-mortgaging model. The model requires that assumptions of a number of key parameters.

1. Market Growth Rates
2. Unit Life
3. Leak Rates
4. Rates of Conversion to Non-ODS Refrigerants
5. Re-claim and Recycling Rates.

The various assumptions used by the model are described in the Annex to this chapter.

Table 7-3 presents the predicted HCFC-22 demand for the period 2005-2015.

Table 7-3 *HCFC-22 requirements (2000-2015)*

Year	**Total HCFC-22 Requirement (metric-tonnes)**			**Amount from Reclamation (metric-tonnes)**			**New HCFC-22 Required (metric-tonnes)**		
	Pessimistic	Most Likely	Optimistic	Pessimistic	Most Likely	Optimistic	Pessimistic	Most Likely	Optimistic
2000	111,543	109,270	105,838	1,759	2,344	2,577	109,785	106,926	103,262
2005	129,576	115,325	99,303	5,788	7,650	8,317	123,788	107,674	90,986
2010	111,818	89,823	67,700	11,231	14,362	15,005	100,587	75,461	52,695
2015	95,551	70,307	44,349	16,222	19,535	18,961	79,329	50,772	29,688

In 2000 roughly 110,000 metric-tonnes of HCFC-22 were used globally to manufacture and service the air-cooled air conditioners and heat pumps covered in this section.

Approximately 50% of these 110,000 metric-tonnes of HCFC-22 were used to service the installed population of air conditioners and heat pumps. Of the total, 62,000 metric-tonnes of HCFC-22 were used in new equipment--leaving the remainder to service existing products. The high servicing requirement can be attributed to two factors: the large installed population of air cooled air conditioning products (see Table 7-2) and servicing practices, which include limited reclamation.

In attempting to project HCFC-22 usage for the period 2000 through 2015 the various assumptions were adjusted to create three scenarios: pessimistic, most likely and optimistic cases. The Annex to this chapter shows the detailed assumptions for each case.

Comparison of the impact of each of these cases demonstrates the impressive impact that an early phase-in of HFC or HC alternatives will have on the demand for HCFC-22. The scenarios do not assume a specific HFC or HC compound nor do they assume that HFC and HC are the only compounds, which could replace HCFC-22 in these applications. The only assumption is that some environmentally safe refrigerant will replace HCFC-22. The following table shows the three HCFC-22 replacement scenarios assumed for this analysis.

The following table shows the amount of HCFC refrigerant required to support the growing needs of Article 5(1) countries for each of the three scenarios.

Table 7-4 *HCFC-22 Requirements for Article 5(1) Countries (2000-2015)*

Year	**Total HCFC-22 Requirement (metric-tonnes)**		
	Pessimistic	Most Likely	Optimistic
2000	25,102	23,681	22,260
2005	41,699	36,463	31,228
2010	60,024	47,610	35,196
2015	74,677	52,183	29,688

Several conclusions can be drawn from these data. The ***Most Likely*** HCFC-22 predicted usage in this assessment is tracking higher than the ***Pessimistic*** estimate from the 1998 TOC Report. This large shift in the projected requirements is being driven by the dramatic market growth for window room air conditioners and duct-free product in the developing markets of Asia.

If the analysis were carried forward to the 2030 timeframe it is likely that the demand for HCFC-22 will peak and then begin to decrease after 2015. The peak after 2015 could be a significant concern if the level exceeds the developing country cap at 2015 levels. Improved models will be needed to determine if the 2015 cap will result in sufficient HCFC-22 to service the needs of the Article 5(1) countries.

7.8 Article 5(1) Country Considerations

Historically, the first air conditioning products to enter Article 5(1) countries are large water or air-cooled chillers, intended for industrial or institutional use, and window room air conditioners. These products will probably utilise HCFCs as the refrigerant of choice if they are purchased prior to the phase-out date for HCFCs. The primary technical concerns of the Article 5(1) countries are: adequate supplies of HCFCs to service existing equipment and equipment manufactured before the HCFC phase-out date dictated by the protocol, adequate supplies of alternative substances and technologies and concerns over the cost and safety of the alternative refrigerants and technologies.

The average life expectancy of most air-cooled air conditioning equipment is approximately 15 years. The Article 5(1) 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 developing country markets.

The previous sections of this chapter provide an overview of the alternative refrigerants and technologies, which are applicable to products in both developed and developing countries. Commercialised products using most many of these refrigerants are available in most developed countries. The widespread availability of these technologies in developed countries should provide some optimism that the technologies will be cost effective and readily available in Article 5(1) countries within the next decade.

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 should be a valuable resource of technical information that that should assist researchers and designers in Article 5(1) countries. In addition, product and refrigerant manufactures are a source on technical information on the application of the non-ODS technologies.

As the state of development progresses the alternative refrigerants and technologies available today in developed countries should become readily available in most developed countries.

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Annex to Chapter 7

The following tables summarise the assumptions used to develop the HCFC-22 usage forecast.

Table 7A-1 *Assumptions for OEM refrigerant usage in new products (Developed Countries)*

Year	**Pessimistic**		**Most Likely**		**Optimistic**	
	HCFC-22 %	Alternates %	HCFC-22 %	Alternates %	HCFC-22 %	Alternates %
1994	100	0	100	0	100	0
2000	99.6	0.4	98.2	1.8	94.9	5.1
2005	89.2	10.8	75.9	24.1	60.3	39.7
2010	30.2	69.8	27.3	72.7	13.8	86.2
2015	17.4	82.6	14.8	85.2	4.5	95.5

Table 7A-2 *Recycled Refrigerant Assumptions (worldwide average)*

Year	**Worldwide Recycling Rate (%)**
1994 – 2000	20
2001 – 2005	35
2006 – 2010	50
2011 – 2015	60

The analysis assumes a reasonably aggressive refrigerant reclamation effort by the world community. The assumptions on the percentage of refrigerant reclaimed during servicing and unit decommissioning are shown in Table 7A-2.

The analysis predicts current and future populations of air cooled air conditioning products by using yearly unit shipment data (1964-2001) and assumed market growth rates to predict unit production for subsequent years. The product market growth rate assumptions are shown in Table 7A-3.

Table 7A-3 *Average Market Growth-Rate by Product Category (1997-2015)*

Product Category	**Assumed Annual World Market Growth Rate (%/Year)**
Window Room Air Conditioners	4.7
Duct-Free Packaged and Split Systems	7.0
Ducted Systems	3.7
Commercial Systems	3.0

Once the annual production quantities were combined with assumptions of average product life (Gaussian distribution) they were used to predict the size of the current and future unit population. The amount of refrigerant in the unit population was calculated using the average charge quantities presented in section 7.2.

Table 7A-4 *Product life assumptions*

Product Category	**Average Life (years)**
Room Air Conditioners	15
Duct-Free Packaged and Split Systems	15
Ducted Systems	15
Commercial Systems	15

The product life assumptions are shown in Table 7A-4. The Average Life is the average life of a given product type. A Weibull distribution was used to determine the units that fail during each year of the analysis. Using these assumptions the model was able to predict the number of units of each category operating each year and the amount of refrigerant contained in the entire installed population. In addition the model utilised the three HCFC-22 replacement scenarios to predict total annual HCFC-22 requirements, amount of HCFC-22 obtained through reclamation and the net requirement for new HCFC-22.

8 Chillers

8.1 Introduction

8.1.1 Role of Water Chillers in Air Conditioning

Comfort air conditioning in commercial buildings commonly is provided either by unitary air conditioners (addressed in Chapter 7) or by water chillers coupled with an air handling and distribution system. Unitary air conditioners cool and dehumidify by having the air pass directly over a coil containing an evaporating refrigerant. Chillers cool water or a water/antifreeze mixture (often referred to as a "brine"), which is then pumped through a heat exchanger in an air handler or fan-coil unit for cooling and dehumidifying.

8.1.2 Types of Water Chillers

Water chillers using the vapour-compression cycle are manufactured in capacities from approximately 7.0 kW to over 30,000 kW. Two generic types of compressors are used: positive displacement and dynamic (also referred to as turbo), which includes both axial and the much more common centrifugal types. Positive displacement scroll and reciprocating compressors are typically used from 7.0 kW up to 1600 kW. Positive displacement screw compressors are used from 140 kW to 6000 kW. Centrifugal compressors are used from 350 kW to over 30,000 kW. Absorption chillers are available as alternatives to electrical chillers in the range from less than 175 kW to 17,500 kW.

Water chillers are offered in both air- and water-cooled versions up through about 1500 kW in single units. Water-cooled systems are customary in larger capacities because air-cooled units become too large for convenient shipment as factory-assembled systems.

8.1.3 Measures of Chiller Efficiency

Full-load coefficient of performance (COP) was accepted for many years as a simple measure of chiller efficiency. Beginning in 1990 interest has grown in an additional measure called Integrated Part Load Value (IPLV). The IPLV metric is a weighted average of a chiller's efficiency over four operating conditions dominantly reflecting part-load energy consumption. The accepted method for determining IPLV for a chiller is given in Air-Conditioning and Refrigeration Institute (ARI) Standard 550/590 /ARI98/. In some markets purchasers of new chillers are beginning to use IPLV as an important factor in equipment selection and evaluation of first-cost vs. operating cost tradeoffs. Efficiency measures in this chapter are given in terms of full-load COP values.

8.1.4 World Market Characteristics

There are no comprehensive statistics on the world market for chillers. ARI compiles statistics for several types of chillers in the USA for both the domestic and export markets. The Japan Air-Conditioning, Heating, and Refrigeration News (JARN) compiles similar statistics for Japan and estimates for other countries and/or regions.

JARN /JAR01/ estimates that:

- The market for centrifugal and large screw chillers is divided between 40% in the USA and Canada, 25-30% in Asia, and smaller percentages in Europe, the Middle East, and elsewhere.
- The market for large absorption chillers is concentrated in Japan, China, and Korea with the USA and Europe as the remaining significant markets.
- The world market for smaller, positive displacement chillers (with hermetic reciprocating, screw, and scroll compressors) is much larger in quantities than for the other chiller types.

8.1.4.1 U.S. Market Characteristics

ARI /ARI01/ reports that the U.S. domestic market for water-cooled centrifugal and screw chillers under 1400 kW was 2500-2700 chillers per year. U.S. exports of such chillers were 1200-1300 chillers per year. In this range, screw compressors are increasing their market share and HFC-134a is replacing HCFC-22. For chillers above 1400 kW, the U.S. domestic market was 1800-2200 chillers per year with 1200-1600 units exported, primarily centrifugal chillers employing HCFC-123 or HFC-134a.

The market for absorption chillers in the USA primarily entails units of 350 kW or larger. Most use water/lithium bromide as working fluids. In the 1998-2000 period the domestic market declined from 276 units to 179 units /ARI01/. Exports were about two thirds of this number. Roughly half of the units were double-effect (steam or direct-fired) and half were single-effect (steam or hot-water heated). Exports mostly were single-effect chillers.

An estimated 4000-6000 small absorption chillers, using ammonia/water as refrigerant/absorbent, are sold for residential and light commercial air conditioning.

Smaller chillers employ scroll, screw, or reciprocating compressors. In the 1998-2000 period the domestic U.S. market for air-cooled chillers grew from about 8500 to more than 10,000 chillers /ARI01/. The domestic water-cooled chiller market was about 1500 chillers, and remote condensing units (with compressor and evaporator located indoors, connected by refrigerant lines to an outdoor air-cooled condenser) were about 650 units. Exports mostly were air-cooled chillers at about 3000 chillers/year /ARI01/. In the domestic market, about 20% of the air-cooled chillers are below 175 kW, 35% between 175 kW and 350 kW, and 30% between 350 kW and 700 kW. The remaining 15% are larger units. Most of these positive displacement chillers still employ HCFC-22, but HFC-134a, R-407C, and -- to a limited extent so far -- R-410A are being introduced.

8.1.4.2 Asian Market Characteristics /JAR00, JAR01, JAR02/

Absorption chillers are favoured in a number of Asian markets. The market for absorption chillers larger than 350 kW is of the order of 8600 units per year, with 30% in Japan, 35% in China, and 20% in Korea /JARN01, JARN02/.

Japan manufactures about 3250 large (over 175 kW) absorption chillers as well as 1600 absorption chillers smaller than 175 kW each year. About 300 centrifugal chillers are produced per year. Of these, 40% use HCFC-123 and the remainder use HFC-134a. In addition, over 100 centrifugal chillers were imported in 2000. Japanese manufacturers make about 10,000 smaller-tonnage positive-displacement chillers annually. Screw and reciprocating chiller product lines include units capable of supplying chilled and hot water simultaneously and units for ice thermal storage systems.

China made about 2600 absorption chillers in 2000. Very few were single-effect, 50% were steam double effect, and 50% were direct-fired with oil and gas about equally specified as fuels. Sales of electric centrifugal chillers in 1999 and 2000 were about 850 chillers per year. Of these, 70% used HFC-134a refrigerant. Approximately half of these chillers were imported. The market for screw chillers in the 175-1400 kW range is 3000-4000 units per year. Most have been charged with HCFC-22 refrigerant but the use of HFC-134a is increasing. Air-cooled chillers account for 76% of the market, a major shift since 1997 when water-cooled units represented 67% of the market. Chiller sales are expected to grow 8.5% annually with the main market in Eastern China /ASH02/. More than half of all chiller sales (34,000 units in 2001) were heat pumps, with trends toward installing several small chillers instead of one large chiller. Screw and scroll chiller sales are increasing while demand for absorption chillers is slowing. Reciprocating chillers now are only 15% of the market. Unique to China is a major residential market for chillers and fan coil units for use in apartments. About 20,000 scroll chillers were sold in China in 2000. The bulk of these were in the 5-35 kW range.

In Korea, direct fired absorption chillers in the 350-1050 kW range have a large share of the market. Shipments in 2000 were estimated to be 1200 absorption chillers (80% direct fired). The centrifugal chiller market in Korea fluctuates between 200 and 430 units, peaking in 1997. Imported centrifugal chillers in 2000 amounted to 100 units. The market for reciprocating, screw, and scroll chillers fluctuates between 500 and 1800 units, peaking in 1990.

Taiwan has a market for 7000-8000 small reciprocating, scroll, and screw chillers per year. The absorption chiller market is small. Taiwan imports centrifugal chillers with a market fluctuating from 400 to 600 units per year.

8.1.4.3 European Market Characteristics /JAR00, JAR01, JAR02, DKV02/

In Germany, chillers with screw and scroll compressors increased their market share from 35% in 1997 to 49% in 1999. Of 4600 units sold in 1999, 60% were less than 100 kW and 80% were less than 400 kW. The 1999 market required 80 centrifugal chillers, 90 absorption chillers, and 10 direct-fired absorption chillers. Total chiller sales in 2001 are estimated to be USD ($) 150M. Screw chillers are used mainly in the 100-1000 kW range with the greatest concentration of sales in the 200-600 kW range. Roughly half use air-cooled condensers. In 2000/2001, less than 20% of chiller sales were for ratings below 100 kW. Over 50% of sales were in the 100 to 800 kW range. Reciprocating chiller sales value fell from 31% in 1999 to 27% in 2000 and are forecast at 22% for 2001. In terms of units the corresponding figures are 48%, 40%, and 34%.

France required 9000 chillers in 1999. Of these, 80% were less than 100 kW, 13% were between 100 and 400 kW, and 7% were larger than 400 kW. Reciprocating chillers accounted for 2/3 of those sold, but the market share of scroll and screw compressors is growing. In 2000, reciprocating chillers accounted for 40% of sales in terms of value and 60% in terms of numbers of units. Over 75% of chillers installed in 2000 used air-cooled condensers.

In Italy 23,000 chillers were sold in 1999. Of these, 80% were less than 100 kW and 10% were larger than 400 kW. Scroll and screw compressors were used in 75% of these chillers in 2000. Air-cooled condensers are used in most small and medium range units. Water-cooled condensers are more common in units over 1 MW in capacity. In 2000, 53 large absorption chillers (over 300 kW) were imported. Of these, 18 were double-effect and the remainder single-effect. No large absorption chillers were manufactured in Italy.

In the United Kingdom, 2900 chillers were sold in 1999. Of these, 50% had reciprocating compressors, 19% had screws, and 26% had scroll compressors. Around 60 centrifugal chillers are purchased each year in the U.K. About half of the chiller market in terms of value and number of units is in the range from 100 to 600 kW. Of the total number sold, over two-thirds use screw or scroll compressors. Scrolls fill in the capacity band below 200 kW with nearly 60% of sales concentrated in the 20-100 kW band. Over 85% of chillers sold in 2000 used air-cooled condensers.

The market in Spain was about $48M USD in 1999 and $69M USD in 2000. The chillers typically are small, with 40% of the units between 20 and 100 kW and 33% less than 20 kW. Of the total 7000 units sold in 2000, nearly 4000 were reciprocating chillers. Scroll compressors were used in about one-third of all chillers sold in 2000. Air-cooled condensers are the norm in Spain.

Total sales of centrifugal machines in Germany, France, the U.K., Italy, and Spain were around $34M USD in 2000, corresponding to over 300 machines. Germany was the largest user, followed by Italy.

8.1.4.4 India Market Characteristics

India is a manufacturer of large capacity centrifugal, screw, and reciprocating compressor based chillers. Most of the new chillers of 350 kW capacity and above are non-CFC chillers /JAR01/. The centrifugal chillers employ HCFC-123 and HFC-134a. Screw chillers use HCFC-22 and HFC-134a. The majority of reciprocating chillers employ HCFC-22. India is estimated by one source to require 150 large tonnage chillers (over 700kW) per year. Absorption chillers are estimated by the source to be about 30% of this number /Aga01/.

8.1.5 Inventories of Equipment and Refrigerants in Service

Accurate inventories of equipment in service around the world, and the types and amounts of refrigerants used in these chillers, are not available. Records of production and sales have been kept in a few countries (the United States and Japan, for example) and estimates are available for a few other countries, but most of the information needed does not exist. The information below addresses CFC chillers still operating in the U.S., Canada, and India. Perhaps this accounts for 25-40% of the CFC chillers in service around the world.

8.1.5.1 United States

A survey of chiller manufacturers, conducted by the Air-Conditioning and Refrigeration Institute (ARI) /Doo01/, revealed that by the end of 2001 approximately 41,000 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 2000, there were 3,235 chiller replacements and 913 conversions to non-CFC refrigerants to bring the year-end total to 35,664 chillers (45%) that no longer use CFCs. The prediction for future conversions is given in Table 8-1.

Table 8-1 *CFC Chiller Conversions and Replacements /Doo01/*

	Conversions	Replacements	Total	% of 80,000
Prior to 1/1/01	7,937	27,727	35,664	45
1/01 to 1/1/02	452	3,324	39,440	49
1/02 to 1/1/03	372	3,433	43,245	54
1/03 to 1/1/04	312	3,558	47,115	59

8.1.5.2 Canada /HRAI00/

An assessment of CFC chillers in Canada was undertaken in 2000 by the Heating, Refrigeration, and Air Conditioning Institute (HRAI). The conclusion reached was that there were 4707 CFC chillers in operation in Canada in 2000. The capacities ranged from 350 kW (100 tonnes) to 4200 kW (1200 tonnes). In 1995 there were 5486 CFC chillers in service. During the 1996-1999 period 179 of these were replaced by non-CFC chillers and 600 were converted to operate with non-CFCs. Most of the CFC chillers use CFC-11. The average capacity of these CFC chillers is approximately 1400 kW (400 tonnes).

8.1.5.3 India /Aga01/

Large capacity CFC-based chillers of varying capacities and for different applications have been installed in the country. Table 8-2 shows the type of chillers and the refrigerant used.

Table 8-2 *CFC-based Large Capacity Chillers in India /Aga01/*

Type of Chiller	**Capacity**	**Refrigerant**
Centrifugal	700 kW to 3000 kW	CFC-11, CFC-12, HCFC-123, HFC-134a
Screw Chiller	350 kW to 3000 kW	HCFC-22, HFC-134a, R-717 (ammonia)
Reciprocating	35 kW to 400 kW	CFC-12, HCFC-22, R-717 (ammonia)

One source /Aga01/ estimates that about 1500 chillers of capacity 350 kW (100 tonnes) and above are installed in India. The total installed capacity may be about 3 million kW. About 1000 metric tonnes of CFC may be installed in these chillers, most of which is CFC-11. These chillers have an expected operating life of 15 to 20 years beyond 2001 and will require CFCs for servicing until and unless these are retrofitted or replaced by non-CFC technologies.

There are a large number of medium and small capacity chillers (less than 350 kW) which operate on CFCs, primarily CFC-12. The capacities of these chillers range from 15 kW to 350 kW. These chillers are not included in the estimates above.

8.2 Introduction – Heat Pump Water Heaters

8.2.1 Heat Pumps for Water Heating

In water heating, the heat exchange process can benefit from a temperature glide on the refrigerant side to better match the temperature profile of the water side and thus minimise the heat exchanger losses. One example is heating of tap water, which normally is from 5-10 °C and to 60-80 °C. Another application which can benefit from a temperature glide is heating of process water in industrial processes and in hydronic heat distribution systems.

Most heat pumps currently in operation are electrically-driven closed-cycle compression type systems. Systems driven by gas engines, or absorption cycle heat pumps which are directly fired or employ waste heat, have found niche markets.

This chapter includes discussion of working fluids for heating-only and heat-recovery heat pumps. Reversible air-conditioners, which comprise a large share of residential heat pump installations in the USA, Japan, and other countries with a considerable cooling demand, are presented in Chapter 7. Heat pumps for industrial applications are discussed in Chapter 5.

8.2.2 Types and Volume of Equipment - Residential and Commercial/Institutional Applications

Heating-only heat pumps are used for space and water heating in residential, commercial/institutional buildings, industrial buildings, and in district heating and cooling plants. It is estimated that the total heating-only heat pump stock in residential and commercial sectors, including district heating, is roughly 1.7 million units with a total heating capacity of about 13,300 MW /HPC94a/, /Gil93/, /HPC98/.

Heating-only heat pumps in buildings are manufactured in all sizes ranging from 1 kW heating capacity for single room units, to 50-1000 kW for commercial/institutional 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. Refrigerant charges range between 0.1 and 1.5 kg/kW thermal output, with 1.0 and 0.5 kg/kW as estimated averages for the heat pump stock produced before and after 1994, respectively /UNE91, Ste98/. Heat pumps are becoming more compact with smaller refrigerant charge.

Heat pump water heaters, which heat tap water for sanitary purposes, are capturing a growing fraction of water heater sales in OECD countries. Commercial building applications have been more competitive than residential applications, though the residential systems are becoming more popular. By 1998, approximately 570,000 units had been installed in Europe /HPC93a, HPC98/.

Integrated units for space heating, space cooling, and tap water heating for commercial buildings also are becoming popular due to an increasing demand for cooling in modern office buildings in northern climates that originally did not require cooling. Integrated heat pumps have dual functions, delivering heat and cooling simultaneously. They supply heat to the distribution system by using recovered waste heat from other parts of the building (the cooling distribution system) as a heat source. In most cases both the heat and the cooling distribution systems are hydronic. There always is an additional heat source installed, e.g., seawater, which is used as a heat source when the heating demand is dominant, and heat sink when cooling demand is dominant. Integrated units are installed in larger commercial buildings and in district heating and cooling systems /HPC94b/.

Evaporation temperatures typically range from -10 °C to +10 °C, with condensation between 40 °C up to close to 80 °C depending on the heat source and the type of heat distribution systems in the buildings.

In the European countries and in the North-eastern part of the USA, hydronic heat distribution systems are used both in homes and in larger buildings. The use of hydronic systems decreased in the US during the past 20 years. However, the trend in Europe is toward the increased use of hydronic systems in new buildings, especially in the commercial sector. Low temperature radiant heating systems permitting distribution temperatures of 30-60 °C are common, giving the heat pump a low temperature lift and better efficiencies than traditional radiant heating systems. In smaller residential heat pumps (1-10 kW heating capacity) air is the most common heat distribution medium.

Heat sources include ambient and ventilation air, sea and lake water, sewage water, ground water, ground, rock, and industrial wastewater and effluent. Air, seawater, and ground source heat pumps dominate the market. Ground-source heat pumps, or "geothermal heat pumps", using ground/rock as a heat source have become more popular in recent years. It is the fastest growing heat pump application in both the US market and the Northern European market, and the trend is expected to continue /HPC98/. Decreasing investment costs, high reliability, low maintenance costs, stable operating conditions, and direct expansion concepts providing high efficiencies have made ground source heat pumps competitive compared to other sources.

8.2.3 Market Characteristics

Due to climate, standard of living, and other reasons, the majority of heating-only heat pumps in buildings are located in the northern part of Western Europe. Though most heat pump installations in Japan, USA, and Canada are reversible air-conditioners, there are a number of heating-only heat pumps in those countries. Heat pumps for heating only and heat recovery seldom are used in Article 5(1) countries. Most of the Article 5(1) countries are located near the Equator so they do not have a significant space heating demand.

The Russian Federation, China, and most of Eastern Europe have household energy consumption which, on average, is well below that of the Western world. The application of heat pumps in China is increasing quickly. They mostly are heat pumps units that supply hot water in the winter and cold water in the summer /HPC98/. Economic reforms and emerging democracies eventually may lead to a higher standard of living which, in turn, will result in higher domestic energy consumption. A significant problem in these regions is environmental pollution. Therefore, higher energy consumption for heating preferably should not be based on direct combustion of oil or coal. This may spur the demand for heat pump systems, resulting in a growing world market.

8.3 Refrigerant Choices

8.3.1 Positive Displacement Compressors and Water Chillers

Positive displacement compressors are used in the lower range of capacities for the water chiller spectrum. (Centrifugal compressors are more cost-effective at higher capacities.) To take maximum advantage of a compressor's displacement, positive displacement chillers employ refrigerants with lower volumetric flow rates per unit of cooling capacity and higher pressure levels than centrifugal chillers. Traditionally, HCFC-22 has been used widely as a working fluid for high pressure positive displacement chillers. CFC-12 was used prior to the 1990's as the working fluid for intermediate pressure positive displacement chillers.

Significant changes in positive displacement chiller refrigerant selections and chiller designs are occurring as a result of stratospheric ozone depletion concerns. CFC-12 was phased out in developed countries in 1996 and HCFC-22 is being phased out now in many European countries. Under the Montreal Protocol, as amended, HCFC production will phase down in the developed countries leading to a complete phase-out of production in 2030. Each country is at liberty to set its own phase-out schedule to meet its obligations under the Protocol. In the United States, HCFC-22 production for new equipment will cease in 2010. Production of HCFC-22 for service of units built before 2010 will continue until 2020. Phase-out dates for HCFC-22 are earlier in several countries. Some members of the EU, in particular, have accelerated their phase-out schedules since the 1998 report.

HFCs, HFC blends (including R-407C and R-410A) and to a much lesser extent ammonia and hydrocarbons have displaced HCFC-22 unit sales in positive displacement chillers.

8.3.2 Centrifugal Compressors and Water Chillers

Centrifugal compressors have inherently higher volumetric flow rates for a given physical size than positive displacement compressors. They are used in the higher range of capacities in the water chiller spectrum where they are more cost effective.

Prior to the CFC phase-out under the Montreal Protocol, CFC-11 was the most common choice in large centrifugal compressors followed by CFC-12. A smaller number of chillers used HCFC-22, CFC-113, CFC-114, and R-500.

Due to the CFC phase-out in developed countries, HCFC-123 and HFC-134a replaced CFC-11 and CFC-12, respectively, in new equipment.

8.3.3 Average Refrigerant Charge Levels in Water Chillers

Table 8-3 indicates the average amount of refrigerant per unit of cooling capacity of U.S. and Japanese manufacturers for chillers built in the 1990-95 period. Since this was a period when refrigerant conservation was receiving increased attention, little change is felt to have occurred since 1995. The average charge in the rest of the world is assumed to be similar to the weighted average of the average charge in the U.S. and Japan.

Table 8-3 *Average Refrigerant Charge in Air Conditioning Chillers in Service as a Function of Capacity and Type of Refrigerant*

Refrigerant	**kg/kW**
CFC-11	0.25
CFC-12	0.35
HCFC-22 Reciprocating-piston	0.34
HCFC-22 Screw and Centrifugal	0.35
HCFC-123	0.22
HFC-134a	0.35
R-500	0.33
R-717 (ammonia) direct expansion (DX) systems R-717 (ammonia) flooded evaporator systems	0.04-0.20 0.20-0.25
Hydrocarbons	0.14

The original version of Table 8-3 is found in /Cal91/. The data in the original table was reviewed in May 1996 by the U.S. Air-Conditioning and Refrigeration Institute (ARI). Some of the data was adjusted to reflect charge data for chillers of average efficiencies at the time, and to add data for R-500, ammonia, and hydrocarbons from best estimates of industry members.

8.3.4 Heat Pumps

In the past, the most common refrigerants for vapour compression heat pumps have been CFC-12, R-502, CFC-11 (heat recovery from centrifugal chillers), CFC-114, HCFC-22, and R-500. In developed countries HCFC-22 still is used as one of the main refrigerants in heat pumps. In Article 5(1) countries such as China, CFC-12 and HCFC-22 are commonly used.

8.4 Options for New Equipment

Except for a few "essential use exemptions", the Montreal Protocol and subsequent amendments have resulted in phase-out of production of CFCs for domestic use in developed countries and in a high level of activity in the industry seeking alternatives for the HCFCs. The search for alternatives resulted in a renewed understanding that ideal refrigerants do not exist /Cal97/, /Cal00/.

The selection of alternative refrigerants requires a balance between suitability including thermophysical properties and 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 need to account for the direct effects of refrigerant releases to the atmosphere and the energy-related (sometimes referred to as indirect) effect. The energy-related effect stems from the emission of carbon dioxide and other greenhouse gases from generation of power to operate the chillers. The energy-related component 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 effects, refrigerant release and energy-related, and combined measures such as of Total Equivalent Warming Impact (TEWI), Life-

Cycle Warming Impact (LCWI), or Life-Cycle Climate Performance (LCCP) are discussed in a number of references. /Cal93a, Cal93b, Cal98, Fis91, Kui00 and San97/.

Improved design and maintenance of systems to reduce leakage, design to minimise refrigerant charge quantities in systems, improved service practices, and reclaiming of refrigerant during servicing are practical and reasonable ways to reduce the emissions of all refrigerants to the atmosphere, thus minimising adverse environmental effects. To varying degrees in different countries, each of these practices is being implemented. Life cycle refrigerant needs of chillers have been reduced more than tenfold in the last 30 years /Cal99/.

Both the risk and capital investment necessary for redesign; retooling; training in operation, maintenance and service; marketing; etc. are particularly significant in equipment as large as water chillers and in a world where the customer expects an equipment life of 25 years or more. Based on such practical considerations, it seems that the "alternative technologies" which are most feasible for the current timetable are those which already exist in production, in particular vapour-compression with HFCs and HCFC-123. Other technologies which are suitable for water chilling are (1) the vapour-compression cycle using ammonia as a working fluid, (2) the absorption cycle, (3) zeotropic refrigerant mixtures, and (4) for small chillers, the vapour-compression cycle using hydrocarbon refrigerants.

8.4.1 Options for New Positive Displacement Compressor Chillers

8.4.1.1 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 Amendment to the Montreal Protocol call for the phase-down of HCFCs starting in 2004 in developed countries leading to phase-out for new equipment in 2020. 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. There is a freeze in HCFC production in Article 5(1) countries starting in 2016. The phase-out of individual HCFCs is being managed differently in various countries. The European Union member state countries mandated the phase-out of HCFC-22 beginning in 2001.

The planned HCFC-22 phase-out led to intense activity to find and characterise appropriate alternates. Much of this work was under the auspices of the Alternative Refrigerants Evaluation Program (AREP) of the Air-Conditioning and Refrigeration Institute (ARI) in the USA, with international participation. The refrigerants that were considered include various HFCs, zeotropic and azeotropic blends of these HFCs, ammonia, and HCs.

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 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. As a result, HFC-134a systems are more common successors to HCFC-22 chillers than R-410A chillers.

8.4.1.2 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 equipment sizes are similar. Thus, chiller costs are not significantly affected by the change from CFC-12 to HFC-134a, except for the increase in refrigerant and lubricant costs. However, compressors for HFC-134a require 50% larger displacement than for HCFC-22, so larger compressors and increased cost are encountered in a change from HCFC-22 to HFC-134a.

The direct global warming effect of HFC-134a is about 12% of that of CFC-12. The theoretical cycle efficiency is about 2% lower than for CFC-12. However, the excellent heat transfer characteristics of HFC-134a and design advances often offset the lower cycle efficiency. Thus, the TEWI due to HFC-134a is less than that for CFC-12 in new equipment. The direct global warming effect of HFC-134a is about 76% of that of HCFC-22. The cycle efficiency is similar for the two refrigerants.

Recently-developed 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.

8.4.1.3 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. 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. 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 °C) 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 (instead of the temperature glide observed in a DX heat exchanger). 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.

8.4.1.4 Other refrigerants: R-404A, R-507A, R-410A, other HFC blends, HFC-32

Azeotropic and near-azeotropic mixtures such as R-404A, R-507, and R-410A have been considered as possible HCFC-22 replacements. However, no non-flammable azeotrope has been found that matches the pressure-temperature relationships of HCFC-22. 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, is required to use R-410A in chillers. In time, R-410A may displace the use of R-407C in smaller chillers where sales volumes justify the development 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 °C or larger) and do not appear to offer significant performance benefits compared to R-407C. 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 Article 5(1) supply sources for long-term world-wide availability, 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 direct global warming potential 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. Systems using HFC-32 have not been commercialised yet.

8.4.1.5 Carbon Dioxide in the Transcritical Cycle

CO_2 is being investigated by several researchers 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 CO_2 (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. However, carbon dioxide does not offer competitive cycle energy efficiencies for typical water chilling applications. Therefore, there is not an environmental incentive to use carbon dioxide as a chiller refrigerant.

There has been no commercial application in chillers to date. 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 (a multiple of 5 between maximum operating pressure and burst pressure is common).

8.4.1.6 Ammonia

Ammonia (R-717) is an excellent refrigerant in terms of thermodynamic cycle efficiency. Ammonia has been in continuous use in a variety of applications longer than CFCs so there is a wealth of practical experience in the manufacture, operation, and maintenance of ammonia machinery systems. The number of compression stages required to use ammonia effectively in centrifugal chillers limits the practical application to machines with positive displacement compressors.

In the last ten years approximately 10 manufacturers in Europe have supplied chillers using ammonia as the refrigerant. These chillers are in the capacity range from 200 to 2000 kW with a few larger. One supplier offers screw chillers from 200 kW to 5800 kW and open or hermetic reciprocating units from 70 kW to 2200 kW. In Southeast Asia production is reaching 100 to 150 units per year. Ammonia chillers are being used in airports, supermarkets, hospitals, offices, and industrial buildings.

Application considerations with ammonia are more complex than for many other refrigerants because ammonia is a strong irritant gas that is slightly toxic, corrosive to skin and other membranes, and flammable. However, guidelines are readily available for safe design and application of ammonia systems /IEA98/. Wider acceptance requires that public officials become satisfied that the ammonia systems are safe 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).

Current applications are primarily limited to systems that are isolated from the general public. Recommended practice (ASHRAE Std. 15 and ISO/DIS 5149) limits the use of large ammonia systems in public buildings to those systems which utilise a secondary heat transfer fluid (which is intrinsic in chillers), confining the ammonia to the machine room where alarms, venting devices, and scrubbers can ensure safety. Comprehensive safety guidelines are available for chillers using ammonia so that releases are dispersed safely /BRE00/, /IIA99/. Modern, compact factory-built units contain the ammonia much more effectively than old ammonia plants.

Ammonia's chemical reactivity with copper in the presence of water prevents its use in hermetic compressor systems with copper-wound motors but motors with aluminium motor windings are now commercially available. There is a potential loss of energy efficiency with the change in material due to the higher electrical resistivity of aluminium compared to copper.

8.4.1.7 Hydrocarbons

Although hydrocarbon refrigerants have a long history of application in industrial chillers in petrochemical plants, before 1997/98 they were not used in comfort air conditioning chiller applications due to reservations about systems safety.

Several European manufacturers offer a range of hydrocarbon chillers. Air-cooled and water-cooled chillers for high and medium temperature applications are charged with HC-1270 (propylene), HC-290 (propane), and an HC-290/HC-170 (propane/ethane) blend. Cooling capacities range from 20 kW to 300 kW for the high temperature units and 30 kW to 150 kW for the medium temperature units. The refrigerant charge varies from 3 to 34 kg. Water cooled and air cooled chillers for low-temperature applications also are offered in capacities up to 45 kW. Reversible heat pump chillers using HC-290 as the refrigerant are available in capacities up to 173 kW with a maximum propane charge of 15 kg. The products use reciprocating compressors but introduction of screw compressors is planned. Efficiency is similar to that of equivalent HFC-134a products. Unit sales of hydrocarbon chillers are about 100 to 150 annually. The major markets have been office buildings, process cooling, and supermarkets. The chillers may be installed in a machine room with an explosion proof (non-sparking) fan for constant ventilation on the exterior of the chiller. An alternative is outdoor installation.

The cost of HC chillers may be higher than that of HCFC or HFC equivalents, partly due to the fact that hydrocarbon chillers still are a niche product market.

Hydrocarbons as HCFC-22 replacements exhibit favourable materials compatibility, oil solubility, and comparable thermodynamic efficiency. The most significant problem with hydrocarbons is their flammability which deters consideration for use in many applications. Refrigeration safety standards have been developed for hydrocarbon systems. European Standard EN 378 permits in indirect systems up to 5 kg in public areas, 10 kg in private/commercial areas, and the quantity is not limited in restricted/authorised access only areas. Detailed information on HC equipment design is provided in /ACR00/ and a UK Code of Practice for the design of refrigeration systems using A3 refrigerants is available /IR00/. It is reported that advances in refrigeration component design and the low density of hydrocarbon refrigerants permit charge sizes as low as 0.05 kg/kW per circuit /Col98/.

Several international standards committees and working groups (e.g. IEC61D and ISO/TC86/SC-1/WG-1) are discussing safety requirements for use of flammable refrigerants in a wide range of applications including chillers.

The engineers and technicians involved in development, manufacture, design, installation, operation, service, and removal of equipment employing flammable refrigerants require guidance and training on the additional hazards and precautions associated with their use.

8.4.2 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.

8.4.2.1 CFCs and Blends Containing CFCs: CFC-11, CFC-12, CFC-113, CFC-114, and R-500

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, but found wide use in Naval surface vessels and submarines. Production of CFCs 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. The relative condensing pressures at 38 °C are 0.145 MPa for HCFC-123, and 0.963 MPa for HFC-134a. The lower pressure refrigerant (HCFC-123) is usable in centrifugal chillers from 350 to 15,000 kW; while the higher pressure refrigerant (HFC-134a) is usable in the chillers up to 30,000 kW. Chillers employing these refrigerants are available with coefficients of performance in 2001 ranging from 6.1 (0.58 kW/ton) for HFC-134a to 7.3 (0.48 kW/ton) for HCFC-123. Product announcements indicate that chillers will be offered in 2002 or 2003 with COPs of 6.6 (0.53 kW/ton) for HFC-134a and 7.8 (0.45 kW/ton) for HCFC-123.

8.4.2.2 HCFC-22 and HCFC-123

HCFC-22 has been used in centrifugal chillers in capacities up to 32,000 kW. This refrigerant is subject to phase-out in new chillers in the United States under the Clean Air Act in 2010 and refrigerant for service will be produced until 2020. Different schedules exist in other countries.

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 has essentially ended.

HCFC-123 is used in centrifugal chillers from 350 to 15,000 kW. HCFC-123 combines a low environmental impact with the ability to replace CFC-11 in existing chillers of recent manufacture after suitable modifications are made. HCFC-123 currently is scheduled under the US Clean Air Act to be phased out as a refrigerant for new chillers in 2020 with production for equipment service until 2030. Installed, recovered, and stocked quantities may be used indefinitely.

Different schedules exist in other countries, but the Montreal Protocol currently calls for HCFC production for use in new equipment to cease in 2020, with continuing production for a small "service tail" until 2030. HCFC production in Article 5(1) countries is scheduled to be frozen in 2016 at 2015 levels and phased out in 2040.

8.4.2.3 HFC-134a

HFC-134a refrigerant is used in centrifugal chillers from approximately 350 kW 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 are not typically used.

8.4.2.4 HFC-236fa

Naval centrifugal chillers are built in the range from 440 kW to 2800 kW. Traditionally, CFC-114 has been used in ship-board centrifugal chillers where it is desirable to have the refrigerant pressure in the evaporator above atmospheric pressure to prevent inward leakage of moisture-laden air and subsequent corrosion problems. These applications are steadily being converted to HFC-236fa or are being replaced by HFC-134a chillers. Some work was done with HCFC-124 on an experimental basis.

HFC-236fa is in commercial production for use as a refrigerant, a fire suppressant, and as a specialty gas for semiconductor manufacturing. It has an ASHRAE-34 classification of group A1, the least hazardous group. HFC-236fa has been well qualified for materials compatibility by the U.S. Navy and is being used for long-service-life retrofits.

In the USA and most other countries, new shipboard chillers for the Navy are being designed for HFC-134a.

8.4.2.5 HFC-245fa and Other Refrigerants

HFC-245fa is a chemical developed for use in appliance insulation foam blowing. It will go into commercial production in 2003. This chemical can be used as a centrifugal chiller refrigerant with 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. No chiller manufacturer has announced plans to use HFC-245fa as a refrigerant.

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

It is difficult for a new refrigerant such as HFC-245fa or one of the blends to become accepted as a centrifugal chiller refrigerant. Such refrigerants must be available on a worldwide 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.

8.4.2.6 Design Issues with Zeotropes, Hydrocarbons, and Ammonia for Centrifugal Chillers

Zeotropic refrigerants are not suitable for use in the flooded evaporators that are used in all centrifugal chillers. The temperature glide observed with zeotropes in flooded evaporators manifests itself as 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.

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. Hydrocarbons HC-601 (pentane) and HC-601a (isopentane) have been proposed as alternatives for centrifugal chillers. These refrigerants have been shown to give good performance provided that rotor speed is increased to compensate for low molecular weight /Mac99/. The high boiling point of these hydrocarbons, which are liquid at normal atmospheric conditions, reduces some flammability concerns because leakage does not result in large vapour clouds. However, it also results in their operation at sub-atmospheric pressure, opening the possibility of air leakage into chillers. Subsequent compression of the hydrocarbon-air mixture poses a severe safety risk, particularly with quantities required for centrifugal chillers /Cal00/.

Ammonia is not a suitable refrigerant for centrifugal chillers because of the large number of compressor stages required to produce the pressure rise ("head") required for the ammonia chiller cycle.

8.4.2.7 Environmental Evaluation for Retention of HCFC-123 as a Refrigerant for Centrifugal Chillers

Refrigerant HCFC-123 has a favourable overall impact on the environment that is attributable to five factors: (1) a low ODP, (2) a very low GWP, (3) a very short atmospheric lifetime, (4) the extremely low emissions of current designs for HCFC-123 chillers and (5) the highest efficiency of all current options /Cal98/, /Cal00/. HCFC-123 became a key replacement for CFC-11 due to its similar properties to CFC-11, which permitted it to replace CFC-11 in new and existing chillers without extensive modification of equipment or equipment rooms. There was no other replacement with these characteristics, so HCFC-123 was critical to the transition away from CFCs in the chiller sector.

Although subject to production phase-out by 2020 for use in new equipment under the US Clean Air Act, HCFC-123 remains the most efficient refrigerant for water chillers. Published studies /Cal97, Cal98/ have shown that continued use of HCFC-123 in chillers would have imperceptible impact on stratospheric ozone while offering significant advantages in efficiency, thereby lowering greenhouse gas emissions from associated energy use. Based on integrated assessments, considering the tradeoffs between negligible impacts on stratospheric ozone and important benefits in addressing global warming, these studies recommend consideration of a phase-out exemption for HCFC-123.

8.4.3 Options for New Heat Pumps

Developed country manufacturers have introduced HFC alternatives to replace their HCFC heat pump models. HFC-134a and R-404A have been on the market for a number of years. The first models with R-407C as refrigerant entered the market in 1996/7. For heat pumps operating with higher temperatures (more than 55 °C), HFC-134a is the preferred refrigerant, especially in medium and large capacity units.

Non-ODP and low-GWP refrigerants are used for their environmental benefits as alternatives to CFCs and HCFCs in heat pump systems. The most commonly considered refrigerants in this group are ammonia, hydrocarbons (e.g., propane, propylene, and blends of hydrocarbons), and carbon dioxide. Annex 22, *"Compression Systems with Natural Working Fluids*" under the IEA Implementing Agreement on Heat Pumping Technologies (1995-98), among others, provides state-of-the-art information on compression heat pumps with ammonia, hydrocarbons, CO_2, and water, and establishes guidelines for design and safety recommendations for new heat pump installations.

Several northern European manufacturers (in Denmark, Germany, Sweden, Austria, and the United Kingdom) are producing small air/water or water/water units for residential and commercial applications using hydrocarbons as refrigerants. The units are limited in size and designed for low refrigerant charge.

Particularly in northern European countries, ammonia is applied in medium/large heat pump units in commercial buildings and district heating systems, with capacities ranging from about 200 kW to more than 1 MW.

8.4.3.1 HFC-134a

HFC-134a is similar to CFC-12 and R-500 in terms of thermodynamic and physical properties, and is the main successor to CFC-12 in medium temperature heat pump systems. HFC-134a is used in many new heat pump installations.

Above –10 °C evaporation temperature, the compressor efficiency and COP of a heat pump system is close to that of CFC-12 /HAU93/. Extensive liquid subcooling is recommended to improve system energy efficiency. The volumetric refrigeration capacity of HFC-134a typically is 2-3% lower than with CFC-12 at 0 °C evaporation temperature so a slightly higher compressor capacity is needed.

8.4.3.2 Other Pure HFC and HFE Alternatives

HFC-152a was considered a promising alternative refrigerant to CFCs due to its favourable thermodynamic and physical properties and low GWP factor. There are many examples of successful small heat pumps with HFC-152a in Scandinavia and China /Nil91/, UNE91/, UNE94/. Adequate safety precautions must be taken when designing and maintaining new heat pump plants with HFC-152a because it is flammable.

Several pure HFC and HFE alternatives have been investigated to replace CFC-114 in high-temperature heat pumps. In the USA and Japan a number of partially-fluorinated propanes plus two- and three-carbon ethers have been synthesised. Their properties suggest that as pure fluids and blends they could be considered for heat pump applications. However, these alternatives have not been commercialised yet and the cost of manufacturing them may be too high for them to become practical alternatives /Biv97/.

8.4.3.3 HFC Blends

R-404A, R-407C, and R-410A are the preferred HFC blends to replace R-22 in heat pump applications. The blends are less efficient than the HCFC-22 they replace. Systems have to be optimised in order to bring the performance in line with HCFC systems through enhanced surface heat exchangers, effective control systems, and improved compressor design.

R-404A is one of the most used HFC blends to replace R-502. It is a near-azeotrope with a temperature glide of less than 1 K and a volumetric heating capacity that is about 15% higher than that of R-502.

R-407C is a replacement for HCFC-22. R-407C has a temperature glide of 7.2 K at 1 bar, while the saturation pressure and volumetric heating capacity are about the same as for HCFC-22. The discharge temperature is somewhat lower than that for HCFC-22, as is the Carnot efficiency.

R-410A is a binary blend that has near-zero temperature glide. Its normal boiling point is approximately 10 °C lower than that for HCFC-22, resulting in a 50% higher pressure level. The volumetric heating capacity is approximately 50% higher than for HCFC-22.

8.4.3.4 Ammonia

Ammonia heat pumps typically achieve a 3-5% higher energy efficiency than systems using CFC-12, HCFC-22, or HFC-134a /UNE94/. The volumetric refrigeration capacity is approximately the same as for HCFC-22 and about 40% higher than for CFC-12 and HFC-134a. High pressure (40 bars) reciprocating compressors are commercially available, raising the maximum condensing temperature from 55 °C (25 bar) to about 78 °C.

Ammonia yields high compressor discharge temperatures, and at high temperature lifts two-stage compression is necessary to avoid operational problems. Consequently, initial costs will increase by 15-20% and energy efficiency will increase 30-35% /UNE94/, /Ste98/. Semi-hermetic ammonia compressors of large swept volumes (power input up to 100 kW) as well as soluble lubricants (polyglycols) have been introduced /Tie96/.

Ammonia is popular in northern Europe and has been applied in a number of medium-size and large capacity heat pumps, mainly in Scandinavia, Germany, Switzerland, and the Netherlands /HPC93b/, /HPC94b/, /Kru93/, /Tok98/. In Norway, 10-20 ammonia heat pumps with heating capacities ranging from 200 to 2000 kW are installed yearly. This is only 2% of all new installations, but due to the large capacity of the ammonia heat pumps, the heat delivery from these few heat pumps is close to 40% of the total heat delivery from all new installations regardless of refrigerant. An increasing number of ammonia heat pumps are integrated systems, simultaneously heating and cooling, installed in commercial buildings, district heating and cooling systems, and industry.

System safety requirements for ammonia heat pumps are similar to those for ammonia chillers which were discussed in Section 8.4.1.5 above.

8.4.3.5 Hydrocarbons

Hydrocarbons are emerging as a viable option for replacement of CFCs and HCFCs in small, low-charge residential heat pumps. The most important hydrocarbons for medium-temperature heat pump applications are propane (HC-290), propylene (HC-1270), and blends of ethane/propane. Several northern European manufacturers are using HC-290 or HC-1270 as refrigerants in small residential and commercial water-to-water and air-to-water heat pumps.

The volumetric refrigerating capacity of HC-290 is approximately the same as for HCFC-22 and in a practical application HC-290 will yield about the same energy efficiency as HCFC-22. Maximum condensing temperature with standard 25-bar equipment is about 68 °C. Heat pump performance evaluations for hydrocarbons and comparisons vs. HCFC or HFC refrigerants are the subject of continuing research.

When designing new heat pump systems with propane or other flammable refrigerants, adequate safety precautions must be taken to ensure safe operation and maintenance. Typical safety measures include addition of tracer gases, 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. Several standards that regulate the use of hydrocarbons in heat pumps exist or are being developed in Europe, Australia, and New Zealand (KYS96, DIN 7003, UVV-VBG 20, BS 4434, prEN 378).

8.4.3.6 Carbon Dioxide Used in the Transcritical Process

Carbon dioxide was used as a refrigerant before CFCs entered the market 70 years ago. It has no ODP or GWP, is non-flammable, low toxicity, and is compatible with normal lubricants and common system construction materials. At 0 °C the volumetric refrigerating capacity of CO_2 is between five and eight times higher than for other refrigerants, subsequently reducing the required compressor displacement. The pressure ratio also is greatly reduced compared to conventional refrigerants, contributing to increased compressor efficiencies. However, systems must be designed to withstand the high pressure (above 100 bar) required for CO_2.

The transcritical CO_2 cycle exhibits a significant temperature glide on the high temperature side. Such a glide can be of benefit in a counter-flow heat exchanger. A heat pump water heater benefiting from temperature glide entered the Japanese market in April 2001. It raises the temperature of tap water from 5-10 °C up to 70-80 °C and has a heating capacity of 4.5 kW /Kus01/.

Compressors capable of handling the high pressures of CO_2 in applications such as a heat pump water heater with a heating capacity of 22 kW are reported to be available from a European company /Zak00/. Production of compressors from 5.6 kW to 15 kW for field testing has begun /JAR02/.

A CO_2 heat pump can produce hot water at temperatures up to 100 °C without operational problems, while traditional heat pump systems often are restricted to hot water temperatures below 55 °C. (Ammonia heat pumps can deliver 78 ^{o}C hot water.)

8.4.4 Alternative Technologies

8.4.4.1 Absorption Chillers

Absorption-cycle chillers are mass-produced and well supported by a cadre of experienced technicians. Heat-activated absorption water chillers are a viable alternative to the vapour-compression cycle for some installations. Three of the four processes that comprise the traditional refrigeration cycle are used in the absorption system. The compression process is replaced by a solution circuit consisting of an "absorber", a "generator", and a "solution pump" which are complemented by an evaporator, a condenser, and an expansion control device. The most commonly used working fluids are ammonia with a water absorbent in small sizes and water with a lithium bromide absorbent in large capacities.

Absorption chillers once dominated the large chiller market. They were replaced by vapour-compression chillers reflecting technology advances and shifts in the relative cost of gas and electricity. Single-stage absorption chillers powered by hot water or steam still outnumber multistage machines driven by hot water or steam or single- and two-stage direct-fired machines. Triple effect machines have been developed but not commercialised.

Because they have low efficiency, direct-fired single-stage absorption systems generally cannot compete with electric vapour-compression systems on an economic basis. 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. In a few localities, natural gas rate structures are particularly favourable compared to electric rate structures, making direct-fired, single-stage absorption viable. A key factor in the economic viability of absorption is the penalty on electric vapour-compression chillers imposed by electricity demand charges [demand is continuously averaged over an integrating interval (typically 15 minutes), and a demand charge per kW is applied over the full billing period, or over a longer period, up to the following 12 months]. Demand charges are common in several countries for commercial and industrial customers. Other local peculiarities, such as a shortage of electrical generating capacity or high initial electrical connection charges, also favour the choice of absorption.

During the past fifteen years, double-effect absorption chillers have been developed and produced with primary-energy-based efficiencies that approach 50% to 60% of those of vapour-compression systems. For example, double-effect absorption chillers have a COP of 1.0 to 1.2 based on heat source energy input. Electrical vapour-compression systems have a COP of the order of 6.5 which must be multiplied by the heat-source-to-electricity delivery efficiency of the power plant and distribution system - perhaps 33%.

Triple-effect absorption systems can achieve efficiencies closer to vapour-compression systems. However, attainment of cost and performance goals in multi-stage machines remains a challenge.

Absorption chillers are inherently larger and considerably more expensive than vapour-compression chillers so absorption systems have had only limited market success in the western market as indicated in Section 8.1.4. In Asia, where electricity prices are much higher or where electricity demand exceeds supply, absorption chillers dominate the market.

A factor which limits changeovers from CFC or HCFC vapour-compression chillers to absorption is the inability to retrofit in many existing buildings because the access ways are not large enough to allow for the absorption chiller to be delivered to the existing machine room.

8.4.4.2 Absorption Heat Pumps

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

Absorption heat pumps for heating of residential buildings are not common. In industry absorption heat pumps are employed on a minor scale only. In Sweden and Denmark a number of installations are in operation to supply heat in district heating networks. They recover heat from flue gas cleaning systems in refuse incineration plants or use geothermal heat as the heat source.

8.4.4.3 Water as a Refrigerant for Chillers

Water is a thermodynamically attractive refrigerant which is non-toxic, non-flammable and has no adverse impact on the environment. However, it is a very low pressure refrigerant, with a condensing pressure of 4.2 kPa (0.042 bar) at 30 °C and a suction pressure of 1.6 kPa (0.016 bar) at 9 ^{o}C. Traditionally water has been used in specialty applications with steam aspirators, rarely with vapour compressors except in the case of mechanical vapour re-compression systems. 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.

Recent applications use water as a refrigerant to chill water or to produce ice slurries by direct evaporation from a pool of water. These systems today carry a cost premium of more than 50% above conventional systems. Some installations have been in use for a few years for cooling air in South African gold mines, cooling a toy factory in Denmark, and space cooling of an office building in Germany. The system installed in Denmark is reported to have energy consumption 30% lower than comparable ammonia systems. In the South

African system, circulation of an ice slurry instead of water reduced the mass of water circulated, leading to a significant reduction in pumping cost.

8.5 Options for Existing Equipment (Retrofits)

Table 8-1 shows that there is still a large stock of chillers, particularly centrifugal chillers, now in service which employ CFCs. 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 these 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-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.

8.5.1 Positive Displacement Chillers

A positive displacement compressor inherently can be applied to handle a number of different refrigerants and cycle pressure ratios so long as its motor has adequate power, the compressor can meet pressure codes with the refrigerants, and the compressor 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.

8.5.1.1 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.

8.5.1.2 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 screw 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 8.4.1 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.

The acceleration of the phase-out of HCFC-22 in some countries could have serious consequences for the stock of HCFC-22 chillers in service in these countries at the time of the phase-out. Alternative retrofit refrigerants primarily are R-407C, discussed in the previous paragraph, 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% increased 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. It has a temperature glide of 4-5 °C. Laboratory test results for chillers using this refrigerant have not been reported.

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 generally 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.

8.5.1.3 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 refrigeration duty. However, they are not attractive as replacements for HCFC-22 in chillers. Their energy efficiency for chiller operating conditions is lower than that of HCFC-22 and other alternatives discussed above.

8.5.2 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.

The replacement option is frequently chosen for older CFC centrifugal chillers. Manufacturers have developed new HCFC and HFC chillers offering significantly improved energy efficiency compared to most CFC chillers in service. The savings in energy costs often justify the complete replacement of an ageing CFC chiller with a new HCFC or HFC chiller.

8.5.2.1 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 had to be replaced with materials that are compatible with HCFC-123. Materials used in motors of older hermetic chillers generally are not compatible with HCFC-123, requiring motor rebuilds or replacement. System capacity may be reduced between 0% and 20% depending on heat exchanger effectiveness and matching of the compressor to the load. Change-out of the compressor to a higher capacity model or purchase of additional chillers may be necessary. With a suitable compressor, cycle efficiency will be reduced about 1-2% in theory, negligibly in practice. An optimised conversion designed for the specific machine will minimise the loss of capacity and efficiency and in some cases may trade one for the other. If the original chiller was somewhat oversized, which is a frequent circumstance, then the loss of capacity due to retrofit may not be a problem and the efficiency of CFC-11 may be essentially matched or even increased.

8.5.2.2 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 tip speeds than CFC-12, so impeller and/or gearbox replacement may 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 3-5% 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.

8.5.2.3 Other Candidates to Replace CFC-12

Several refrigerants have been suggested as drop-in replacements for CFC-12 in centrifugal chillers. One is R-416A, a blend which has a small temperature glide (2-3 °C). There is a possibility that this temperature glide, and the cycle performance of this refrigerant which was developed for automotive air conditioning, may cause its performance to be lower than for 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 a mixture of HFC-134a and HFC-227ea. It is offered by one refrigerant manufacturer now and is said to be a near-azeotrope. Laboratory test results for chillers using this refrigerant have not been reported. However, it has been used as a CFC-12 retrofit in chillers in Europe and is said to be satisfactory.

8.5.2.4 Candidates to Replace HCFC-22

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 replace the compressor with a larger compressor and convert the system to use HFC-134a. The manufacturer of the system should play an active part in the conversion to assure success.

8.5.2.5 Other Refrigerant Possibilities for Centrifugal Chillers

HFC-236fa is being 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.

8.5.3 Heat Pumps

The retrofit options cited for chillers at the beginning of this Section 8.5 apply to heat pumps as well.

8.5.3.1 CFC-11 Alternatives

Examples of CFC-11 heat pump retrofits are rare. The trend seems to be replacement of CFC-11 equipment with new HFC-134a equipment. A few units with R-407A have been installed where the customer preferred it, and also R-410A has been applied in new small units.

8.5.3.2 CFC-12 and R-500 Alternatives

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 better 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 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 2-4 °C.

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 8.4.3.5.

8.5.3.3 R-502 Alternatives

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 cooling capacity that is about 15% higher than that of R-502. R-404A may result in a capacity decrease and increase in specific energy consumption giving COPs about 10-20% lower than R-502 depending on system design and operating temperatures.

HCFC-22 and HCFC blends can use either mineral oil or alkylbenzene lubricants 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 pressure is nearly the same. 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, high discharge temperatures when operating at high temperature lifts 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 no compressor modifications are needed. Section 8.4.3.5 discussed the safety issues that arise in a conversion from R-502 to a hydrocarbon refrigerant.

8.5.3.4 HCFC-22 Alternatives

R-407C is the most common HFC blend used for replacing HCFC-22 in heat pumps. R-407C has a large temperature glide (5-7 °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 no compressor modifications are needed. The maximum achievable condensing temperature when using standard 25-bar equipment increases from about 61 °C to 68 °C, Hydrocarbons are compatible with mineral oil and the materials commonly used in refrigeration equipment. Section 8.4.3.5 discussed the safety issues that arise in a conversion from R-502 to a hydrocarbon refrigerant. Heat pumps in Germany have been converted successfully to propane /HPC93c/.

8.6 Future Need For CFCs

Production of CFCs for domestic use ceased in the developed countries by the end of 1995 in response to adjustments to the Montreal Protocol made in London in 1990 and Copenhagen in 1992. Major chiller manufacturers stopped production of CFC chillers in 1993. However, much of the existing stock of installed equipment still needs CFCs for servicing. It is difficult to know whether recycling efforts will provide a sufficient supply of CFCs to meet the servicing needs until the remaining machines are replaced or retrofit. At some point in the future, recovered refrigerants from chillers being retired are expected to create a surplus of CFC refrigerants.

8.7 Article 5(1) Countries

Chillers and water-heating heat pumps are used less in the developing countries than in the developed countries but the technologies tend to be the same, with the equipment often imported or produced locally in a joint venture with a developed-country chiller manufacturer. Thus, the latest technologies in equipment, refrigerants and servicing equipment and practices are available to all countries (e.g. ARI and UNEP jointly conducted workshops on "Chillers and Refrigerant Management" in Thailand, Kenya, Bahrain, Indonesia and Zambia /UNE95/). Because chillers tend to be employed in large and sophisticated cooling systems, they require, and generally have, more skilled maintenance staffs in all countries than is true for some types of cooling equipment. Thus, there is less difference seen in the service practices in developed and developing countries than might be true for domestic refrigeration, for example.

While production of CFCs is permitted in the Article 5(1) countries until 2010, their use in new equipment is decreasing to permit these countries to benefit from the latest designs and technologies available in the world. In fact, some Article 5(1) countries are already banning the import or manufacture of equipment using CFC refrigerants. Developing countries that wish to export products to developed countries have a further incentive to accelerate their transition away from CFCs.

Asia (India) /Aga01/

India is one of the large volume CFC-consuming countries similar to China. It is a producer of CFCs and HCFCs as well as a manufacturer of large capacity centrifugal, screw, and reciprocating compressor-based chillers. There are a number of manufacturing facilities within the country for all types of compressors and systems. Some of these manufacturing facilities are 100% owned by Indian companies and some are joint ventures with multinational companies. Market information for India is given in Section 8.1.4.4. Inventory estimates for equipment and refrigerants appear in Section 8.1.5.3.

East Asia /JAR01/

The chiller market size has been substantial in Hong Kong, Malaysia, Thailand, Singapore, Indonesia, and the Philippines. Demand fell in 1998 and 1999 because of economic conditions but began to recover in 2000. 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.

Africa: /Dev98/ and /Kau98/

In general, it may be assumed that most African countries rely on imported technology and machinery for chiller applications. Thus, the installed base will be largely HCFC-22 for smaller machines and CFC-11 and CFC-12 for larger machines, with HCFC-123 and HFC-134a beginning to appear in new centrifugal chillers.

Large machines employing water and ammonia refrigerants are known to be used in industrial applications. In South African gold mines, large machines using CFC-11, HCFC-22, and HFC-134a refrigerants are being used. One water machine producing an ice slurry was manufactured in Israel.

Brazil: /Pei02/

Estimates based on surveys conducted for preparation of the National CFC Phase-out Project indicate that there are about 700 CFC (60% CFC-11 and 40% CFC-12) centrifugal chillers used in industrial process refrigeration and building air-conditioning. It is recognised that there may be a small number of chillers, especially older ones, which have not been caught by the survey. The survey also indicated that some 28 tonnes of CFC-11 and 60 tonnes of CFC-12 were consumed in servicing these chillers during 2000. This includes the “top-up” of refrigerant losses during equipment operation as well as the venting of all, or part, of the refrigerant charge during service and repair activities. The use of CFCs for the cleaning of systems during repair, as well as the overcharging of refrigerant, may also contribute to this consumption.

CFC chillers continued to be installed up until 1993. The majority of the existing chillers were installed in the late 1980s and the early 1990s. While there has been replacement of older CFC chillers with noon-CFC chillers during the past 8 years, this was because of the age of the chillers being replaced rather than for environmental reasons. Very few CFC chillers have been retrofitted to use non-CFC refrigerants. As the average lifetime of a chiller in Brazil is around 25 years, a substantial number of CFC chillers installed between 1982 and 1993 will still have remaining anticipated working lifetimes of between 1 to 11 years when CFCs are phased-out in Brazil in 2007.

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9 Vehicle Air Conditioning

9.1 Introduction

Vehicle mobile air conditioning systems (often referred to as MACs) include all air conditioning (A/C) of road vehicles, such as automobiles, trucks, and buses. Bus A/C has been included for completeness even though buses account for only a small portion of the global market.

Conventional automobile and truck A/C systems are similar in design, components, cooling capacity, and refrigerant charge. To provide the required comfort, these systems must have the capability of cooling down a previously parked, hot vehicle. Typical cooling capacities for these systems are on the order of 2.5 – 10 kW. Buses do not have a cool down requirement, as they are cooled down before passengers board and only have to maintain a comfortable temperature. Because of their size and the greater number of passengers (up to 50), their cooling capacity is typically 5 times higher than that of automobile and truck A/C systems and their refrigerant charge is about 10 times greater. Many of the bus system components (e.g., heat exchangers, valves, fittings, tubes) resemble those of residential A/C systems more than automobile A/C systems. The compressor is typically an open type 4 or 6 cylinder, reciprocating compressor with a displacement of 400 to 800 cc, driven by the vehicle engine (pulley and belt). Fin-and-tube heat exchangers, with or without louvered fins, are used, as are thermostatic expansion valves. A high percentage of bus A/C systems are roof-top units. In recent years, the air conditioning of smaller, 20 to 30 passenger buses has become increasingly important.

Vehicles built before 1995 used CFC-12 as the refrigerant. Since then, in accord with the intent of the Montreal Protocol, essentially all new vehicles with A/C have been equipped with HFC-134a, a zero ODP chemical, as the refrigerant.[9] As a result, HFC-134a has now replaced CFC-12 as the globally accepted MACs refrigerant and the industry is busy expanding global production to meet the increasing demand. As this demand grows, so will the need to provide the servicing infrastructures (equipment and training) necessary to properly maintain these systems throughout the world. CFC-12 vehicles will generally be scrapped and off the road by 2008 except for those countries still producing CFC-12. Retrofitting CFC-12 systems to use HFC-134a has been addressed in the 1998 TOC Report. Assuming successful phase out of CFCs by 2008, essentially all vehicles on the road are expected to be using HFC-134a, the MACs industry will stabilise, and the transition from CFC-12 will be complete. There is a possibility that an alternative refrigerant system might be introduced prior to 2008 to compete with HFC-134a.

Concerns about global warming associated with HFC-134a emissions have created the need to assess the impact of the MAC industry on man-made greenhouse gas emissions. This involves assessing industry emissions as well as emission-reduction initiatives for environmental impact and cost-effectiveness. Such initiatives include both improving the current system and investigating possible alternative refrigerant systems that offer lower climate impact. Greenhouse gas emissions from MAC systems come from refrigerant leakage

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[9] Note: New vehicles manufactured in some Developing Countries continued use of CFC-12 beyond 1995.

and carbon dioxide emissions from the fuel used to operate (and carry the weight of) the MAC system. Both must be taken into account to measure the climate impact of alternatives.

Recovery and recycling (R&R) of CFC-12 was deemed so important to preventing unnecessary emissions that many countries passed laws against intentional refrigerant venting to the atmosphere. The Multilateral Fund of the Montreal Protocol funded technician training and the purchase of CFC-12 R&R equipment for service facilities in Article 5(1) Countries. Similar funds are not currently available for HFC-134a, or for any other refrigerant under consideration as a replacement for HFC-134a. Preventing unnecessary HFC-134a emissions via R&R is becoming increasingly widespread and represents a 'best practice' in environmental protection. All countries should consider the value of requiring on site refrigerant recovery and recycling at repair shops.

9.2 Options for Future Vehicle Air Conditioning Systems

The cost of changing from the current HFC-134a system to a new replacement refrigerant will be significant for the entire industry, from investments in manufacturing to equipment and training for the service industry. It is important to remember that the conversion from CFC-12 to HFC-134a, which did not involve major system changes, cost the U.S. industry alone an estimated $5 billion; $3.5 billion for manufacturers (for development, testing validation, retooling and manufacturing) and $1.5 billion (for tools, equipment and training) for the service industry /VOG96/. Changes required for the CFC-12 to HFC-134a conversion were minor, consisting of improving compressor designs and lubrication, and developing more efficient condensers.

Enabling the global service industry to understand and effectively repair alternative refrigerant systems that incorporate new technologies will be an enormous challenge. With approximately 233,000 automotive service shops and over 1 million service technicians in the /MOT01/ United States alone, training would represent a major undertaking. Service standards, procedures, equipment and training must be developed and implemented in widespread fashion to provide service for such systems wherever they are sold and operated.

9.2.1 Safety Aspects of Future Vehicle Air Conditioning Systems

CFC-12 and HFC-134a systems are regarded as being safe for the intended use. Replacement refrigerant systems must also provide a comparable level of safety, both for vehicle occupants and service technicians. SAE J639, SAE J1739, QS 9000 and refrigerant manufacturer's safety data information all serve as reference documents for designing safe systems.

9.2.2 Trans-critical Carbon Dioxide Systems (Figure 9-1)

Trans-critical carbon dioxide (CO_2) systems are being developed for production by several vehicle manufacturers in co-operation with global component and system suppliers. The trans-critical carbon dioxide system looks similar to today's system but operates at much higher pressures, up to five times that of HFC-134a systems on the high pressure side of the system, and up to ten times on the low pressure side. As a result, they require completely redesigned components using new manufacturing processes to withstand the increased pressure, as well as additional components and controls to allow operation at, or near, optimum energy efficiency. Investment for capital equipment will be substantially greater than for the changeover from CFC-12 to HFC-134a. Additional components and more sophisticated system controls required are expected to increase consumer cost versus the current HFC-134a systems.

Many patents have been issued for CO_2 A/C and heat pump systems over the past 5 years, attesting to the strong interest in developing CO_2 systems.

9.2.3 Systems Using Flammable Refrigerants

The use of flammables (mainly HFC-152a and HC-290) has been proposed for vehicle air conditioning. While they are excellent refrigerants, they do carry the burdens of flammability and explosion, particularly for use in current vehicle A/C system designs. Today's system designs are not certified to safely use flammable refrigerants. The potential for leakage into the passenger cabin presents a potential safety hazard for the occupants.

Future systems could continue to utilise direct expansion with designed-in safety or adopt system designs based on secondary loop technology. For direct expansion systems, safety enhancements might include normally closed shut-off valves in the system that are closed when the system is off and when the air bags deploy (or an equivalent safety system). These valves would divide the system into isolated containment zones and protect the passenger and engine compartments in the event of a collision. A secondary loop system (Figure 9-2) would overcome the concern of leakage into the passenger cabin by allowing the refrigerant to be contained under hood and completely separated from the airflow that provides cooling to the passenger compartment.

9.2.3.1 Propane (HC-290)

One noteworthy aspect of using propane, the best hydrocarbon choice for secondary loop systems, is its availability; it is used universally for heating and cooking. As a result, its safe handling is widely understood and practised by the general global population, whether literate or not. This could be an advantage in the Article 5(1) countries of the world. For systems using propane, the charge for a mid-size vehicle would be relatively small, on the order of 300 grams, based on the molecular weight of the refrigerant and the lower refrigerant charge required by the secondary loop system. However, due to its extreme flammability, the use of propane would likely be restricted to secondary loop systems.

9.2.3.2 HFC-152a (Figure 9-3)

HFC-152a offers a more attractive option than propane. HFC-152a is an HFC with a very low global warming impact (120 vs. 1300 for HFC-134a) and much lower flammability than propane /ANSI97/.

9.3 Refrigerant Recovery and Recycling

Efforts in the early 1990's by SAE, industry, and the US EPA led to the development of equipment and procedures to recover and recycle refrigerant used in vehicle air conditioning systems. Before R&R equipment was available, refrigerant was simply vented to the atmosphere prior to, and often during, service.

Real service shop experience obtained from the Mobile Air Conditioning Society-Worldwide (MACS-W) 2000 Field Survey of member shops sheds more light on the effectiveness of refrigerant recovery and recycling. A detailed review of their findings shows that 68% of the 313 vehicles in for service had recoverable charge that averaged 88% of the original specified charge. The average for all vehicles serviced (including those coming in with no residual charge) was 66% of the original charge. Assuming 6% refrigerant losses during the recycling process, the amount of refrigerant recycled and ready for reuse averages 60% of the original specified charge. Therefore, the average need for new refrigerant for recharging at service would be 40% of the original charge. Exhibits 1 & 2 and Table 9-1 detail revised HFC-134a emissions scenarios based on this new information. In addition, the average amount of refrigerant required in current vehicles was found to be 1.05 kg for CFC-12 systems and 0.91 kg for HFC-134a systems.

MACs have been designed to use a single component refrigerant. Blends of refrigerants have been sold internationally as direct replacements for both CFC-12 and HFC-134a MACs. In most instances, these blends contain HCFCs. They have not been tested for use in MACs and anecdotal reports from service shops indicate a higher rate of system failures associated with their use. Since the components of blend refrigerants can escape from the system at different rates, the composition of the blend continually changes. This makes on site recovery and direct reuse impractical. Without the ability for a service facility to recover/recycle, or properly dispose of, these blend refrigerants, technicians have little choice but to release the remaining system charge to the atmosphere.

Recycling is currently required in the U.S. and some other nations of the world. In 1990, 50% of the world's population of vehicles with air conditioning was located in the U.S. As the world vehicle population reaches the anticipated one billion by 2015, over 2/3 of these vehicles will reside outside of the United States. Given this, refrigerant recovery/recycling in all developed and developing countries must be considered, and, where possible, should be made mandatory to minimise the release of refrigerant to the atmosphere.

9.4 Article 5(1) Country Issues

The situation in the developing countries (Article 5(1) countries) differs significantly from that of developed countries. Developing countries tend to have older vehicles that are not as well maintained. A/C service sometimes consists of simply adding refrigerant to a leaky system without repairing the leak. Service without R&R equipment means refrigerant must be vented into the atmosphere. Given such conditions, as much as 80% of the total CFC-12 consumed in some of these countries is used to refill MAC systems. CFC-12 is also known to be used to refill HFC-134a systems in some countries, due to its lower price and greater availability. Thanks to the Montreal Protocol, production of CFC-12 (and, ultimately, its availability) will cease and be replaced by HFC-134a, which has only 16% of the global warming potential of CFC-12. This, coupled with the significantly reduced HFC-134a charges and improved system designs, will dramatically reduce the environmental impact of MACs in developing countries.

Recovery and recycling of CFC's and HFCs, a very effective service procedure to limit emissions, is not currently practised in many developed and developing countries. The economic attractiveness for the service sector to perform R&R is often not sufficient, given the low cost and availability of CFC-12, particularly in Article 5(1) countries. Mandatory programs can result in increased use of R&R, but may be difficult to enforce. It is expected in the future that the decreasing supply of CFC-12 and the higher cost of HFC-134a, combined with international political pressure to limit emissions, will provide added incentive not to waste refrigerants by unnecessary venting.

9.5 Conclusions and Outlook

Different MAC systems are on the horizon as vehicles become equipped with hybrid electric and fuel cell propulsion systems, each with its own heating and air conditioning needs. These changes will occur first in developed countries long before they are affordable in other parts of the world. MAC systems associated with these changes will likely include electric hermetic systems and heat pump systems, in addition to the current non-hermetic engine-driven A/C system. The current industry emphasis appears to be focussed on improving HFC-134a systems and developing carbon dioxide systems.

The decision of which refrigerant(s) to choose will be made based on considerations, such as A/C system fuel usage, cost, heat pump capability, safety, servicing, and any legal concerns.

The greatest effect will be in the service sector, where more than one type of vehicle air conditioning system technology could exist in a given country due to importation of vehicles from different vehicle manufacturers. Providing appropriate service equipment and service technician training for multiple types of MACs will be essential to the successful introduction of any new technology.

A significant number of nations have country refrigerant management programs in place (e.g., mandated refrigerant recycling and service technician training) that allow them to handle HFC-134a in an environmentally responsible manner.

Each nation will have to determine its own approach to reducing its emissions of ozone depleting substances and greenhouse gases. Experience from the Montreal Protocol showed us that the ability of nations to accommodate change varies widely. These nations will certainly be no less financially challenged as they cope with reducing their emissions of greenhouse gases.

Deciding which type of vehicle air conditioning system should be installed in new vehicles requires careful consideration. It is important that vehicle makers and governmental agencies have access to factual information about current and future air conditioning technologies, and that they work together to achieve the desired success. This will allow informed decisions leading to future vehicle air conditioning systems that will be a benefit for the consumer and the environment.

9.6 References

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/MOT01/	Motor Service Data, Adams Business Media 250 Wacker Drive Suite 1150 Chicago, IL 60606
/VOG96/	Vogelsberg, F. A., “An Industry Perspective- Lessons Learned and the Cost of CFC Phaseout”, 1996 CFC and Halons Conference, Proceedings, pages 881-889, 1996

Transcritical Carbon Dioxide System

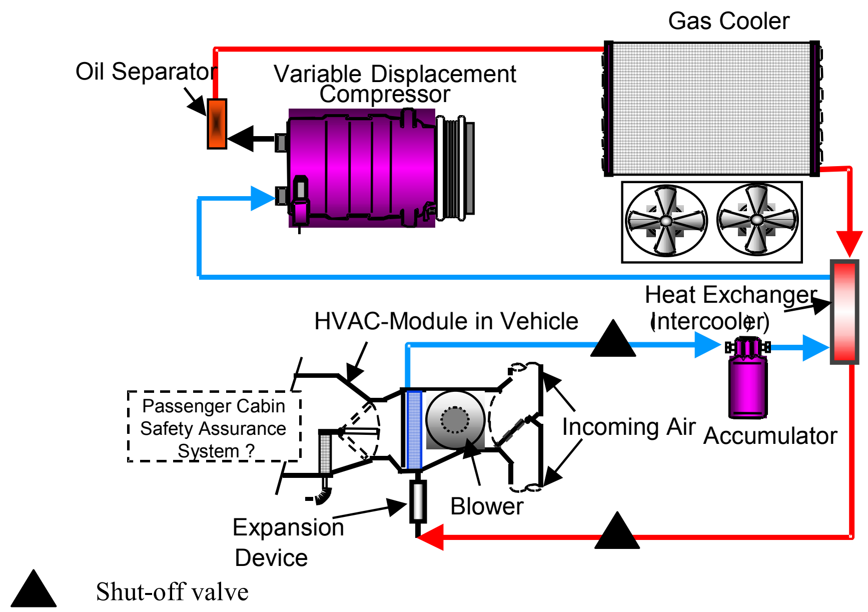


Figure 9-1

Secondary Loop System

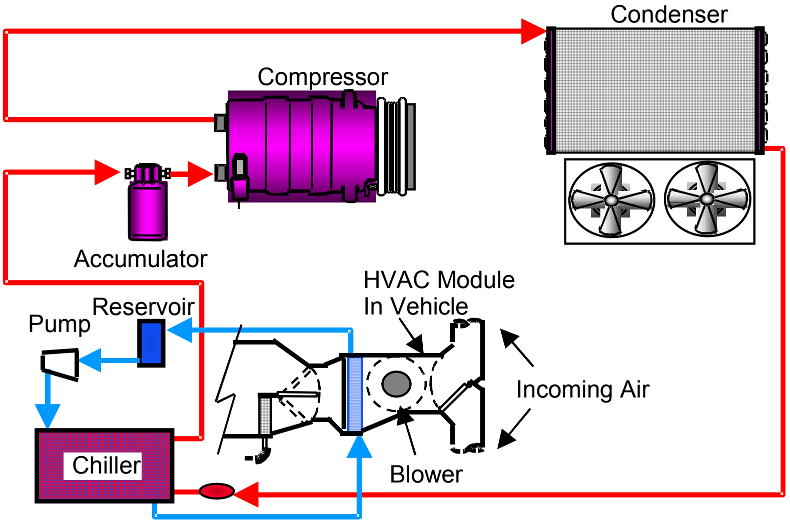


Figure 9-2

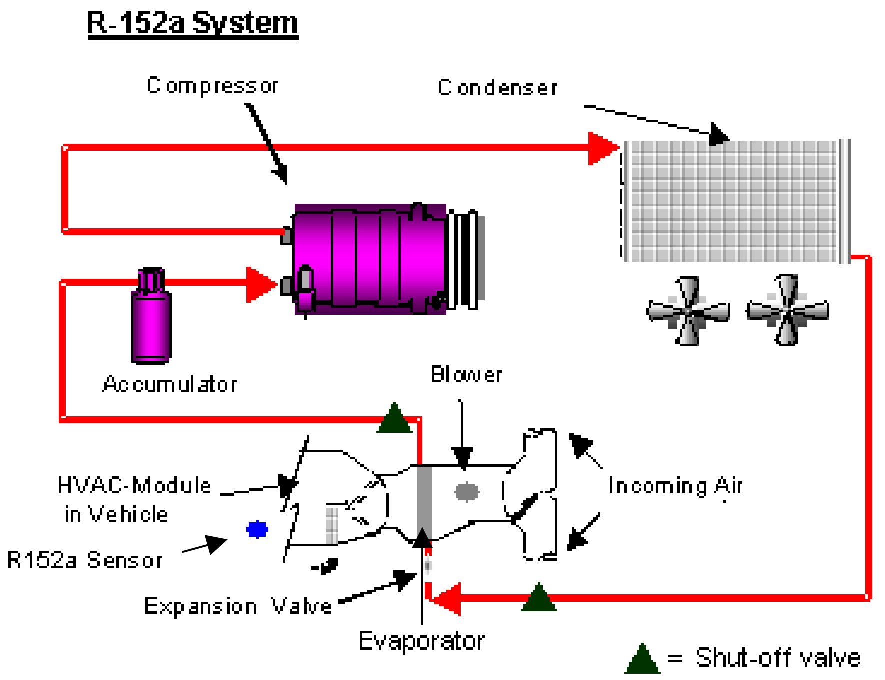

R-152a System
Compressor
Condenser
Accumulator
Blower
HVAC-Module in Vehicle
Incoming Air
R152a Sensor
Expansion Valve
Evaporator
▲ = Shut-off valve

Figure 9-3

Exhibit 1 - Current HFC-134a Emissions Scenario

Current (2000) Emission Parameters

- 2 Recharges / 12 year lifetime
- Average system serviced contains 66% of the original specified charge
- Average system charge = 0.91 kg
- Recycling process losses = 6% of original specified charge
- Charge recoverable at scrap = 40% of OE charge (estimated)

Note: To find the system problem, refrigerant is often added to bring the system to full charge. Without R&R, this charge is vented to the atmosphere. The estimated impact on lifetime emissions is an additional 0.50 OEM charge.

$$\boxed{\begin{array}{l}\text{Lifetime Emissions} = \underset{\substack{\uparrow\\ \text{Initial OE Charge}}}{\text{OE Charge}} + \underset{\substack{\uparrow\\ \text{Service Recharges}}}{(2)(0.40)(\text{OE Charge})} - \underset{\substack{\uparrow\\ \text{Recovery at Scrap}}}{0.4\,(\text{OE})}\\ \quad\text{(With Recycling)}\end{array}}$$

Emissions Estimates

Case 1: No Recycling at Service, No Recovery at Scrap

Lifetime Loss = 0. 91 + (2.5)(1)(0.91) - 0 = 3.19 kg HFC-134a

Annual Emissions = 0.266 kg HFC-134a → 345 kg CO_2-equiv.

Case 2: Recycling at Service, Recovery at Scrap

Lifetime Loss = 0.91 + (2)(0.40)(0.91) - 0.4(0.91) = 1.27 kg HFC-134a

Annual Emissions = 0.106 kg HFC-134a → 138 kg CO_2-equiv.

Exhibit 2 - Future HFC-134a Emissions Scenario

Future (~2008) Emission Parameters

- 1 Recharge / 12 year lifetime
- Average system serviced contains 66% of the original specified charge
- Average system charge = 0.80 kg
- Recycling process losses = 6% of original specified charge
- Charge recoverable at scrap = 40% of OE charge (estimated)

Note: To find the system problem, refrigerant is often added to bring the system to full charge. Without R&R, this charge is vented to the atmosphere. The estimated impact on lifetime emissions is an additional 0.50 OEM charge.

$$\boxed{\begin{array}{l}\text{Lifetime Emissions} = \underset{\substack{\uparrow\\ \text{Initial OE Charge}}}{\text{OE Charge}} + \underset{\substack{\uparrow\\ \text{Service Recharges}}}{(1)(0.40)(\text{OE Charge})} - \underset{\substack{\uparrow\\ \text{Recovery at Scrap}}}{0.4\,(\text{OE})}\\ \quad\text{(With Recycling)}\end{array}}$$

Emissions Estimates

Case 1: No Recycling at Service, No Recovery at Scrap

Lifetime Loss = 0.8 + (1.50)(0.80) - 0 = 2.00 kg HFC-134a

Annual Emissions = 0.167 kg HFC-134a → 217 kg CO_2-equiv.

Case 2: Recycling at Service, Recovery at Scrap

Lifetime Loss = 0.8 + (0.40)(0.8) - 0.4(0.8) = 0.800 kg HFC-134a

Annual Emissions = 0.067 kg HFC-134a → 87 kg CO_2-equiv.

Table 9-1 *HFC-134a and HFC-134a CO_2-equivalent Emissions from Mobile Air Conditioning vs. Refrigerant R&R*

Current HFC-134a Systems (2001) *					
	Total industry average HFC-134a emissions kg/vehicle/year	HFC-134a to service vehicle for its lifetime % OE charge/year	Total industry CO_2-eq emissions Kg/vehicle/year (from HFC-134a emissions only)	Lifetime HFC-134a emissions kg/vehicle	Lifetime CO_2-eq emissions mt/vehicle (from HFC-134a emissions only)
No R&R	0.267	29	345	3.19	4.15
50% R&R	0.187	21	242	2.23	2.90
100% R&R	0.106	12	138	1.27	1.65
Future HFC-134a Systems (2008 +) *					
No R&R	0.167	21	217	2.00	2.60
50% R&R	0.117	15	154	1.40	1.82
100% R&R	0.067	8	87	0.80	1.04

Estimated global utilisation of Refrigerant Recovery and Recycling in the MACs industry is expected to be 60% in 2002, rising to 75% by 2008-10.

10 Refrigerant Conservation

10.1 Introduction

Refrigerant 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 conservation decreases the dependency on newly manufactured refrigerant. 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. Article 5(1) countries have the opportunity to leverage the knowledge gained from developed countries during their implementation of conservation programs.

10.2 What's New Since the Last Assessment

Africa
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.

As a specific 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.

An impediment remains in CFC-12 remains relatively inexpensive. Increases in the illegal smuggling of CFCs originating in Eastern Europe has occurred. Therefore, continued training of Customs officials is necessary.

Brazil
The Brazilian government has established a refrigerant conservation program that banned the use of disposable refrigerant cylinders. The Brazilian Association of Domestic End Commercial Appliances has certified an estimated 1500 service shops, employing nearly 3000 service technicians. It is estimated that these certified shops recycle nearly 3.5 MT of CFC-12 per month from the domestic refrigeration and air-conditioning sector.

Through a National CFC Phaseout Plan, approved in July 2002 by the Multilateral Fund, the Brazilian government is planning to establish eight refrigerant reclamation centres within the next two years. In certain regions of the country, recycling and reclamation activities have begun in advance of the full implementation of the National CFC Phaseout Plan. The national plan anticipates the training of 35,000 refrigeration service technicians and the distribution of refrigerant recovery equipment to the technicians. The national plan includes efforts to establish a CFC recovery program in conjunction with the installation of the refrigerant reclamation centres. In addition, Brazil has a destruction facility that accepts contaminated refrigerant for incineration by rotary kiln.

Eastern Europe

Several Eastern European countries, including Slovenia and Russia, have been successful in implementing new refrigerant recovery programs. Mandatory recovery procedures, distribution of refrigerant recovery units, and to a large degree service technicians have been trained. However financing continues to be a problem, since there is no state support for recovery programs. In addition, illegal importing from Yugoslavian states has become a source of concern.

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.

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 were extracted and destroyed. 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 becomes effective during 2003, and will add a consumer-recycling fee to the price of each new car sold in Japan.

10.3 Introduction

Refrigerant conservation is now a major consideration in refrigerating system design, installation, and service. Environmental impacts from refrigerant release include not only ozone depletion, but also global warming. Safety issues come into play for refrigerants such as hydrocarbons or ammonia. Conservation also addresses the servicing needs of existing equipment; for as CFC and HCFC production is reduced to eventual termination, refrigerant supplies will dwindle and recovered quantities will be necessary for both developed and Article 5(1) countries.

While progress has been made in limiting refrigerant emissions over the last several years, refrigerant conservation is an issue that continues to require recognition. Conservation can be applied to all kinds of refrigeration and air-conditioning equipment and to all phases of the equipment life cycle through (1) design and construction of leak-tight and easily serviced systems, (2) leak detection and repair, (3) recovery during service, and (4) recovery at disposal.

Recovery/recycling/reclaim requirements have now been implemented for a few years in different countries and have shown results. However, many countries have yet to implement such requirements. Few countries have developed comprehensive containment policies including both recovery and leak tightness. Initiatives generally originate from the field where refrigerant begins to be regarded as too expensive to be wasted.

10.3.1 Definition of Refrigeration Conservation and Nature of Emissions

Refrigerant emissions to the atmosphere are often called losses without distinguishing the causes. However emission types are very different, and it is important to identify them in order to limit them. 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); and
- Losses at equipment disposal are due to venting, rather than recovering refrigerant at the end of the system's life.

10.3.2 Reduction of Emissions Through Leak Tightness

Experience in different countries has shown that air-conditioning and refrigeration equipment manufactured over the past few years have been designed to be tighter than air-conditioning and refrigeration equipment manufactured earlier. 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 USA 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 studies involved a large sample of transport refrigeration units and commercial refrigeration systems, and refrigerant emissions were compared over time for units built before and after introduction of the Dutch regulatory program. 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) of various ages 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%, and 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 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 these 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 nationwide). Furthermore the NOKS study revealed that the emissions were attributable to only 8% of the installations, and 92% had no emissions at all that year /IEA02/.

10.3.3 Reduction of Emissions Through Recovery and Reuse

Recovery and reuse of used refrigerant greatly reduces the emissions of refrigerant resulting from venting during maintenance, service, repair, or disposal. To recover refrigerant means to remove refrigerant in any condition from an appliance and to store it in an external container. The purpose of recovery is to extend the lifespan of the refrigerant and decrease the dependency on virgin refrigerant, by placing it back into service.

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.

For countries that have implemented mandatory reclamation requirements have found incremental increases in the amount of refrigerant reclaimed. The case of 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.

Japan reported that 690 tonnes per 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.

10.4 Options in Encouraging Refrigerant Conservation

Countries with established markets have 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 containment through different means. In the first years, research and development (R&D) programs were funded to identify emission sources and develop containment 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 containment where ignorance of environmental issues was the primary problem.

Direct regulation also became a point of emphasis for governments. Many governments improved containment 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 containment. While governments have found direct regulation to be a successful means of containment, it requires a strong commitment to legal or financial enforcement incentives in order to reach significant results.

10.4.1 Financial Incentives

Financial incentives can encourage containment by making emissions more costly for users or by making containment 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 tax breaks for investing in recovery/recycling equipment or other refrigerant containment technologies.

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 that must be faced in establishing a deposit-refund system are (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.

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 containment 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.

Tax breaks for investing in refrigerant containment equipment and technologies are another government means of coercing containment. 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 in untaxed, and therefore relatively inexpensive 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.

Financial incentives may be easier than direct regulations to develop and more flexible than direct regulation. Financial incentives allow markets to find the most cost-effective containment 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 Non-Article 5(1) countries, and for CFCs in many Article 5(1) 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 containment without being unduly burdensome, and financial incentives will be undermined if a black market in illegally imported refrigerants is allowed to operate. In Article 5(1) 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.

10.4.2 Direct Regulation

For purposes of refrigerant containment, 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; and possibly
- Restrictions or limitations on who can purchase or sell ODS refrigerants.

To the extent possible, 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. However, they 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.

Non-Article 5(1) countries have taken a number of steps aimed at reducing emissions of ODS refrigerants via direct regulation. These regulations cover a wide spectrum from restricting the supply of refrigerants by limiting the importation and restricting the sales of refrigerants; requiring emissions reduction practices during the service and disposal of appliances; and mandating 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; and the financial impact of enforcing such regulations. Such regulations should not be attempted unless the governmental body is willing to invest in the enforcement of the regulations and strict prosecution of those who violate such regulation. As long as the price of keeping the regulated substance is lower than the price of the substitution, the risk is high of not seeing changes made.

10.4.3 Examples of Existing Regulation

Refrigerant emissions are already regulated in a number of countries, mostly as a component of the implementation of the CFC phase-out. 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.

10.4.3.1 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 the 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 rules, 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 p.p.m.), 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 p.p.m. 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.

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.

10.4.3.2 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 refrigerant mixture, and subsequent emissions resulting from 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. Perspective importers must petition the U.S. EPA for approval prior to transport from the country of origin.

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.

10.4.3.3 Certification of Service Companies and Technicians

More and more governments have become aware that handling regulated products may well mean creating certification for technicians and/or companies.

In the U.S., a technician certification program for technicians as well as companies who perform maintenance, service, repair, or disposal that could be reasonably expected to release refrigerants into the atmosphere is well established. 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 will have to be registered and 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 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/.

10.5 Containment

Refrigerant emissions from cooling systems must be minimised to protect the environment. Fortunately, containment is consistent with the function and structure of air-conditioning and refrigeration systems. Cooling systems are designed as sealed units to provide long term operation. Containment 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 containment.

Containment 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 determines 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 that 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.

10.5.1 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 also minimise 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 containment of the refrigerant over the intended life of the equipment.

Among recommendations for containment, 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.

10.5.2 Charge Minimising

Minimising the refrigerant charge will also reduce the quantity of possible emissions. Because little attention has historically been given to the full charge of equipment, its quantity is not often known (except for small manufactory-built equipment)

Overcharging of equipment is common, as the amount of refrigerant contained in refrigerant receivers is not always known. Refrigerant receivers are vessels that contain useless refrigerant stocks. 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 impossibility 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.

10.5.3 Installation

Proper installation of refrigerating systems contributes to the proper operation and containment 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 service requirements later on. Proper charging and weighing techniques along with careful system performance and leak checks should be practised during first few days of operation. The installer also has the opportunity to find manufacturer's defects before the system begins operation. The installation is critical for maximum containment over the life of the equipment.

10.5.4 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 containment more cost-effective.

Technician training is essential for the proper handling and containment 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 scrapping 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 searches for and repairs of leaks.

10.6 Leak detection

Leak detection is a basic element, both in constructing and servicing cooling equipment, as it makes it possible to measure and improve containment 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.

10.7 Refrigerant recovery

The need to handle refrigeration containment 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.
- **Dispose** means to destroy used refrigerant in an environmentally responsible manner.

Refrigerant recovery equipment has been developed and is available with a wide range of features and prices. Some specific explosion proof equipment also exists for recovery of flammable refrigerants. Testing standards have been developed to measure equipment performance for automotive /SAE/ and non-automotive /ISO/ applications. Although liquid recovery is the quickest, 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 time periods may limit the practical usage of recovery equipment on the majority of refrigeration or air-conditioning equipment that contain up to five kg of. In order to reach the vacuum levels that are required in some countries for larger systems, vapour recovery will be used after liquid recovery /Clo 94/. Performances of recovery equipment and recovery methods are described below.

10.8 Recycling, Reclamation, Destruction

10.8.1 Recycling

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 does not quantify contaminants nor identify mixed refrigerants /Kau92/. Consequently 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. Right now, 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 Article 5(1) countries where access to qualified laboratories is limited and shipping costs are prohibitive. In most cases, there are no inexpensive field instruments to measure the contaminant levels after processing.

10.8.2 Refrigerant Reclamation and Separation

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 being 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. This 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 their guarantee conditions. Reclaiming has the advantage to make it easily possible to measure amounts of refrigerant, which have actually been recovered. 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 a concern because of 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.

10.8.3 Refrigerant Destruction

Destruction plants exist in Europe, Japan and North America. There are no identified plants available in low consuming Article 5 (1) or CEITs countries, which may lead to needs of transporting dangerous wastes. Two installation types are available to destroy CFCs:
- Public or commercial installations which have the advantage of being accessible in return for payment. They are often capable of treating several families of chemical products; and
- 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 request 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/.

10.9 Refrigerant Conservation in Article 5(1) Countries and CEITs

10.9.1 Introduction

Although the wide range of conditions in Article 5(1) countries make generalisation difficult, a few characteristics emerge across the refrigeration infrastructures that distinguish Article 5(1) countries from those of developed countries. These characteristics argue for the adoption of somewhat different strategies for containing and conserving refrigerant in Article 5(1) 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(1) countries; thus, they remain relatively inexpensive in most such countries. In fact, CFC refrigerants are reportedly less expensive than ever in some Article 5(1) countries. This decreases economic incentives to conserve CFC refrigerants. Thus, in order to succeed, conservation approaches must either make efficient use of technicians' time and equipment or be backed 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, Article 5(1) 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, destruction in existing incinerators may be an alternative.

- *Lack of scheduled maintenance.* In many Article 5(1) countries, routine scheduled maintenance of air-conditioning and refrigeration equipment has been rare in the past. To successfully implement conservation approaches, which rely heavily on regular maintenance, countries would have to change attitudes toward and provide incentives for such routine scheduled maintenance.

- *Unreliable power, parts, and supplies.* In many Article 5(1) countries, frequent voltage fluctuations increase the incidence of compressor burnouts, which aggravate refrigerant contamination problems and discourages refrigerant recycling. The same voltage fluctuations may also damage electrical recovery equipment, which in combination with difficulty in obtaining 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(1) 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(1) 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), experience indicates that retrofitting and recovery are more difficult to implement and that the emphasis should be put on containment.

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(1) countries makes the selection of new equipment especially important. Labour intensive retrofits may be attractive in some Article 5(1) 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(1) countries. Experience has shown that in order to be effective, containment programs must match equipment with training and continuing 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 Article 5(1) countries consuming low volumes of ODS in critical refrigerant sectors include these different aspects /UNE98/.

In order to meet the target of the CFC phase-out, emphasis should be placed not only on replacing CFCs in new and existing equipment, but also on refrigerant conservation through recovery/recycling/reclaim and leak reduction.

10.9.2 Refrigerant Conservation and Containment in 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 demands for air-conditioning is increasing, as tourists visiting these countries 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. The majority of operators of refrigeration equipment has no basic education or training in refrigeration, but learn on the job. Examples from other countries have shown that good-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 smuggled.

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 suitable legislation, regulations, and recovery and recycling schemes being developed will create incentives for recycling.

10.9.3 Refrigerant Management Plans (RMPs)

The Refrigerant Management Plan is an integrated approach that includes the participation of industry, institutions, and end users to phase out ozone depleting substances in low volume consuming countries. Those African countries, particularly the 14 countries participating in the RMPs implemented by GTZ in co-operation with UNDP and UNEP (i.e., Botswana, Ethiopia, Lesotho, Kenya, Malawi, Mauritius, Mozambique, Namibia, Seychelles, Swaziland, Tanzania, Uganda, Zambia and Zimbabwe) are currently implementing action plans that have been developed within a regional perspective.

The RMP's role is essential to aid CFCs users to be able to reduce and subsequently phase-out their consumption in a co-ordinated planned and cost effective manner. It will do so through the implementation of actions such as appropriate and adequate training of technicians in good practices, containment of refrigerants, and retrofitting equipment; introducing new technologies; establishing recovery and recycling programs for refrigerants; training of customs officers to follow up on the new import regulations; and introduction of harmonised regional standards. These activities are considered vital for implementing a planned phase-out in the refrigeration and air conditioning sector.

All 14 countries share common problems in development of RMPs:
- Lack of clear policy and legislation on CFCs, particularly imports, recovery/recycling, and containment;
- Ignorance of customs officials in respect to identifying CFCs and following up on the new import regulations;
- Low level training of refrigeration and air-conditioning technicians;
- Lack of availability of alternative refrigerants and their spare parts;
- Influx of low cost second hand refrigeration equipment;
- Lack of public awareness; and
- Insufficient ODS-data base.

Phase-out strategy includes a combination of regulatory measures, development of new policy framework, emission reduction activities, and training and public awareness components. Most of the countries have considered the following:
- Increasing the import duties on CFC refrigerant;
- Introduction of consumption tax and/or import duty adjustments on ODS and ODS-based equipment;
- Mandatory registration and licensing of service agents and technicians;
- Formulation of Codes of Practice for technicians;
- Encouraging the conversion of existing CFC-12 systems to non-ODS systems;
- Introduction of product labelling requirements;
- Introduction of revised harmonised tariff codes to identify ODS and ODS based equipment;

- Ban on the use of CFCs in new equipment;
- Development of a national recovery and recycling strategy;
- Installation of appropriate charging systems;
- Installation of compressor protection devices on new and existing domestic refrigerators;
- Training of technicians in conservation, retrofitting, new technologies, and recovery and recycling;
- Training of customs officers in recognising ODS and ODS refrigeration and air conditioning equipment.

None of the participating 14 countries produce ozone depleting substances or more specifically Annex A CFCs; therefore, imports from abroad form the source of CFCs, either in the form of virgin CFCs or equipment containing CFCs. The systems or equipment can be new; however, the majority is second hand.

10.9.3.1 Implementation of RMPs

The 14 countries can be grouped according to the amount of ODS that is being managed by the projects proposed in the RMPs. There are three countries (Lesotho, Seychelles and Swaziland) with a consumption of less than 10 ODP tonnes; eight countries (Botswana, Ethiopia, Malawi, Mauritius, Mozambique, Namibia, Uganda, and Zambia) with a consumption between 10 and 80 ODP tonnes; and three countries (Kenya, Tanzania and Zimbabwe) with a consumption of over 80 ODP tonnes.

The RMPs will continue to co-ordinate, enforce and provide a framework for the successful implementation of ODS phase-out activities in these countries:

Country	ODP tonnes	Remarks
Ethiopia	22.0	Recovery and recycling efforts are currently underway.
Kenya	166.9	Service garages recover 90% of the CFC in motor vehicle air conditioners. Commercial refrigeration companies recover most of the CFC from installations with more than 1 kg charge. Approximately 7.2 metric tonnes of CFC will be recovered and recycled every year.
Malawi	12.2	Consumption of CFCs takes place within the refrigeration and air-conditioning service sector in servicing domestic equipment and the maintenance of refrigeration and air-conditioning systems in the tourist industry.
Mauritius	30.3	The expected results are that with the consecutive training of trainers and technicians a CFC emission reduction of 40% will be reached for servicing operations.
Mozambique	20.0	Refrigeration and air-conditioning are of vital importance for the Mozambique economy.

Namibia	13.9	The expected results are that with the consecutive training of trainers and technicians a CFC emission reduction of 40% will be reached for servicing operations.
Seychelles	2.2	Following training of technicians in good maintenance practices, a 30% reduction in consumption of CFC-12 is expected. Seychelles expects the elimination of the use of R-11. Recovery and recycling program could enable Seychelles to accelerate the phase-out of CFC-12.
Tanzania	89.9	In order to reduce refrigerant emissions, Tanzania is undergoing training of refrigeration technicians on recovery and recycling techniques, retrofitting of existing systems, and training on new alternative technologies.
Uganda	10.01	Is in the process of implementing a recovery and recycling project. The equipment has been delivered and training has been completed.
Zambia	29.0	Implementation of the recovery and recycling projects combined with the training of trainers and training of technicians projects will ensure a reduction in the use of virgin CFCs as well as a substantial reduction in venting of CFCs.
Zimbabwe	354	Currently, the level of training of those working in the refrigeration sector is very low. Training of trainers concurrent with training of service technicians of the larger industries and importing companies is ongoing.

10.9.3.2 Technician Training Programs

There will be several years during which ODS and non-ODS based equipment will be operated side by side in Africa. Training will ensure that maintenance and repairs will be done appropriately. All technicians working in the refrigeration sector will have technical and practical knowledge in avoiding venting of CFCs. In order to achieve the aimed CFC phase-out objectives, an integrated training program on good refrigeration practices and improved servicing techniques like leak testing and flushing is being implemented. A total of 140 trainers from the 14 countries have been trained abroad in order to provide a pool of qualified trainers within the region. Technician training will bring about immediate awareness amongst the technicians, in regards to both conservation of ODS refrigerants and alternative ozone friendly refrigerants. Most countries have established certification systems and refrigeration associations that will ensure national and regional capacity building for future refrigeration technicians.

10.9.3.3 Training of Customs Officers

Training activities targeted at customs officers to create awareness and equip them with the necessary tools to monitor ODS imports has also been undertaken in some countries and also on a regional basis. A total of 420 customs officers from the 14 countries have been trained in proper recognition of ODS and ODS containing systems. Customs officers have also been trained in proper checking, recognition, testing, and monitoring of ODS imports. The intensive training of customs officers is undertaken against a backdrop of emerging problem of smuggled ODS. It is believed that implementation of ODS phase-out may rely to a large extent on enforcing import restrictions by customs. The training of Customs officers is being integrated with the implementation of the regulation concerning ODS imports in the specific countries.

10.9.3.4 Recovery and Recycling

Abrupt changes in the refrigeration and air-conditioning industry will affect the ability of these sectors to perform, in turn affecting their important roles in the economies. The recovered CFCs will meet the demand for CFCs needed for servicing and maintenance for along time to come. Implementation of the recovery and recycling projects combined with the training of technicians will ensure a reduction in the use of virgin CFCs as well as a substantial reduction in venting of CFCs. The combination of the projects will ensure the meeting of the proposed early phase-out dates as set in most countries. Training courses, accreditation, and certification schemes have been developed targeting technicians in order to come to grips with the problem faced by the servicing sector where there is a large number of small users and technicians. Most countries have accredited certain training institutions to offer training for technicians and engineers in recovery and recycling. Most countries have established national programs to recover and recycle refrigerant.

10.9.3.5 Public Awareness

Even though some service companies are aware of the new environmentally friendly refrigeration technologies, the incentives to change to these new technologies might be too low because of the high prices of the new technologies and lack of consumer awareness thus causing low demand. Higher consumer demand for non-ozone depleting technology will therefore assist the service companies in providing means for their customers to purchase non-ODS systems or retrofit their refrigeration and air conditioning systems to non-ODS systems.

10.9.3.6 Harmonisation of Standards for the Refrigeration Sector

An important tool in reducing ODS emissions in the region is harmonised standards. Currently none of the 14 countries have official standards for non-ODS refrigeration technology in place. RMPs will assist these countries in developing new standards for the refrigeration sector within the region.

10.9.3.7 Impact of RMPs

The successful implementation of the various components of the RMPs (e.g., training and education, implementation of legislation and regulations, and economic instruments) will lead to the effective phase-out of ODS well within the requirements of the Protocol.

Annex I: Recent Global Production and Consumption Data for Fluorochemicals

AI.1 Introduction

This section provides data on global production and consumption of CFCs during the period 1986-2000, during 1989-2000 for HCFCs and during 1990-2000 for HFC-134a. As defined by the Montreal Protocol, consumption equals production plus imports minus exports (minus destruction). Data sources have 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. Data has also been included from UNEP as appearing in Production and Consumption of Ozone Depleting Substances 1986-1999 published by the Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ) GmbH, Eschborn /GTZ01/. CFC production and consumption data have also been compared to the data in the TEAP Progress Report 2002, Volume 2, Replenishment of the Multilateral Fund for the period 2003-2005 /TEA02/.

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, AFEAS data accuracy for HCFCs is significantly lower reflecting the reality that most of the AFEAS reporting is from developed countries and developing countries are assuming a growing portion of production for these compounds. As such, UNEP is more accurate in capturing this information than AFEAS. The data accuracy of AFEAS reporting of CFCs has low value at this point as the majority of production is currently in Article 5(1) Parties. Developed country production is limited to that used for essential uses or export to Article 5(1) markets. UNEP data are the prime source of quality information for CFCs.

CFC and HCFC production and consumption has been presented as from:

- the group of Article 5(1) Parties
- certain non-Article 5(1) Parties belonging to the OECD group (defined as OECDnA5 in this report, which are Western European countries, USA, Canada, Japan, Australia and New Zealand; this has been done since the OECD group also contains Article 5(1) Parties) and
- other non-Article 5(1) Parties which includes the ones in Central and Eastern Europe.

AI.2 Data Analysis

CFC Production Data (1986-2000)

Table AI-1 provides data for production for the period 1986-2000. For the non-Article 5(1) Parties such production has dropped from 909 to 53 ODP ktonnes over these years- a reduction of 94%. Remaining production is to meet domestic essential use exemptions and for export to Article 5(1) Parties. This production appears to have stabilised at about 50 ODP ktonnes however; this will likely decrease further with shut down of Russian production of CFCs, which was 25 ktonnes in 2000. Over the time period 1986-2000, the CFC production has increased in Article 5(1) countries from 44 to 73 ODP ktonnes representing an increase of 66%. Such production actually peaked in 1996 with minor declines over the next few years. Again this seems to be currently decreasing as projects to shut down CFC production facilities are being implemented. Production in China, India, Argentina and Venezuela will decrease further in the future as CFC production is being decreased in accordance with the Montreal Protocol schedules and in accordance with agreements with the Executive Committee of the Multilateral Fund. CFC production in Eastern Europe has dropped some 76% during the period from 107 to 26 ODP ktonnes, which is expected to drop to zero after 2000.

Overall, the reduction to date from all sources has been from 1071 ODP ktonnes to 126 ktonnes or 88%. Some error is likely in these reported amounts, as there is no accounting for any illegal production activity, which is suspected but not documented.

AFEAS data, once the most accurate of all sources, is no longer of value for deriving production data for CFCs. AFEAS companies now account for ca. 27% of all global CFC production and the UNEP data are far more reliable for any analyses of this product family.

CFC Consumption Data (1986-2000)

Data for CFC consumption have been prepared by clustering Argentina, Brazil, Mexico and Venezuela, a second grouping of China, India and Korea and a third group of Article 5(1) other. Data are separated for Central and Eastern Europe and then finally OECD non-Article 5(1) Parties. These data are presented in Table AI-2 along with a figure illustrating the total annual consumption for Article 5(1) and the total consumption of all Parties.

Total consumption by all Parties has dropped during this period from 1070 ODP to 138 ODP ktonnes. Much of this 87% decrease occurred by 1996 concurrent with the phase-out of CFC consumption in the developed world. Since that time, the rate of decrease is slight amounting to about 18% over the 1996-2000 period. Consumption in Argentina, Brazil, Mexico and Venezuela has levelled at about 21 ODP ktonnes/yr (but is assumed to further decrease with the Brazil phase-out plan in place). The consumption of China, India and Korea doubled between 1986 and 1995 peaking in that year. It has since dropped 51% to 45 ODP ktonnes in 2000 as transitions are occurring to alternative products. Production in China and India exceeds consumption indicating that they serve as a source of CFCs for use by other Article 5(1) Parties.

CFC consumption in non-Article 5(1) countries has decreased to only 5 ODP ktonnes/yr. for essential uses. The remaining consumption of about 26 ODP ktonnes in Central and Eastern Europe where consumption has dropped 74% since 1986. There has been good agreement between production and consumption numbers, which can be seen when comparing Tables AI-1 and AI-2.

HCFC Production Data (1989-2000)

Data for HCFC production are presented in Table AI-3 and Figure AI-3. Summarised are both AFEAS and UNEP data representing HCFC- 22, -124, -141b and -142b. Absent from AFEAS data are any references to HCFC-123 due to AFEAS reporting criteria requiring a minimum of three producers. Regulatory decisions in Europe ban HCFC use in new equipment and foams etc. after 2003; they are only allowed for servicing. US regulations concerning HCFC use as blowing agents following HCFC-141b phase-out now suggest that HCFC-124 will not find appreciable use outside refrigeration and air conditioning applications.

AFEAS data show an increase in production from 1989 from 12,743 ODP-tonnes levelling out over the period 1997-2000 at about 30,000 ODP-tonnes. HCFC-141b has increased in volume each year and has accounted for most of this increase. HCFC-22 grew from 12,075 ODP-tonnes in 1989 to a peak of 14,918 ODP-tonnes in 1996. Production then decreased slightly to a total of 13,411 ODP-tonnes in 2000. This reduction of 10% is a reflection of reduced demand from beginning conversions from HCFC-22 in refrigeration and air conditioning applications to non-ODS substitutes and to improved practices in HCFC-22 use.

Production in Argentina, Brazil, Mexico and Venezuela peaked in 1997 and has since dropped to the same level in 1999 as in 1989, and to 274 ODP-tonnes in 2000. At only 274 ODP-tonnes, production in these countries does not constitute a major global supply source (this in contrast with their tripling of the HCFC consumption from 1130 to about 3000 ODP-tonnes in the year 2000).

China, India and Korea made sharp increases in 1993 and 1994 and then again in 1999. The total increase was from 249 ODP-tonnes in 1989 to 5,013 ODP-tonnes in 1999 and to 6713 ODP-tonnes in the year 2000 (of which about 6,000 ODP-tonnes are produced in China. Korea did not report any production in 2000. This may be an anomaly, because of the fact that it did report production in 1999). If one compares it to the consumption, see below, it makes China and India exporters of HCFC chemicals at about 1,300 ODP-tonnes per year. The almost 30-fold increase has made particularly China (and to a lesser extent, India) a significant source of HCFCs.

The agreement of UNEP and AFEAS data has improved significantly indicating more complete reporting by Parties to UNEP. Note that AFEAS data include production in Argentina, Brazil and Mexico but do not account for China, India and Korea, as the AFEAS companies do not have production facilities in these Parties.

With increased production activity in China, India and Korea of HCFCs, their production in OECDnA5 countries has dropped from a former 94% to a 2000 level of 83%.

HCFC Consumption Data (1989-2000)

HCFC consumption data are included in Table AI-4. There is generally very good agreement between the consumption and the production data. Exceptions exist for 1994 and 1996 where consumption is significantly lower than either production data from AFEAS or UNEP. As the AFEAS and UNEP data are consistent, and the consumption data are created from a bottom-up summation of Parties' submissions to UNEP, it is likely that there was incomplete reporting of consumption for 1994 and 1996 from Parties.

Total consumption for all Parties has increased on a fairly continuous basis (except for 1996 during which there was a dip; however, this was a year for which data reported might be incomplete). Consumption between 1989-1999 increased from 14,184 to 37,097 ODP-tonnes, and to 37,712 in 2000, which implies a total increase of about 160% for the years 1989-2000. Growth in Argentina, Brazil, Mexico and Venezuela was from 418 to 1799 ODP-tonnes, and to about 3,000 ODP tonnes, a very significant increase, i.e. almost a doubling in one year. This suggests business growth based on alternatives to CFCs. HCFC consumption in Central and Eastern Europe decreased during 1989-1999 by 36%; however, significant increases during 2000 suggest transition from CFC use.

Consumption in China, India and Korea increased from 991 to 5355 ODP-tonnes or 540% over the period 1989-2000. The increase had appeared to peak in 1995 with declines during following years. There were dramatic increases in HCFC consumption between 1998, 1999 and 2000 going from 1756 to 5355 ODP-tonnes in just two years.

Non-Article 5(1) consumption has grown from 12,152 to 25,281 ODP-tonnes or 108% during the period 1989-2000. It appears that after the consumption has peaked at about 27000 ODP-tonnes in these countries that a decrease has started, shown by the consumption of 25,281 ODP-tonnes in the year 2000. This is likely the result of the implementation of regulations on HCFC use in Europe, where it is or will be prohibited in all types of foams and in charging new refrigeration and AC equipment. Also, specific end uses for certain HCFCs have been phased out in the U.S. which may have further limited the overall demand.

Over the period 1989-1999, the portion of HCFCs consumed by OECDnA5 Parties has averaged about 80% of the total. Most recently, this has fallen to 61% in 2000 largely due to consumption growth in China, India and Korea and a significant reduction in such use in non-Article 5(1) Parties in 2000. It is expected that the proportion of HCFC global consumption in all Article 5(1) countries will increase as the HCFC use restrictions will have serious impacts on the consumption in Europe and the U.S. These will force users to convert to non-ODS alternatives to HCFCs. It is notable that AFEAS data, provided by major producers mainly in developed countries, represents 83% of total consumption for the year 2000.

HCFC Consumption in Different Sectors

A sectoral analysis of HCFC use based on AFEAS data input is provided in Table AI-5. These data represent about 86% of global consumption. The largest consumption of HCFCs was in the closed cell foam application as blowing agents and represents 53% of all HCFC on an ODP-weighted basis. This was due to the use of HCFC-141b. This application is declining and will be phased out in Europe and will also have been phased out in the US by the end of 2002. Therefore, total consumption in this sector should be decreasing shortly.

This will be somewhat offset by growth in Article 5(1) countries.

Use in refrigerants was nearly as large on an ODP-weighted basis with 47% of the total. The vast majority of this was from HCFC-22 with minor amounts from the use of HCFC-124 and HCFC-142b mostly as components in refrigerant blends. It is expected that blends will grow somewhat in the future, as these are service replacements, which can be used for CFC installations with minor modifications.

HFC-134a Production

Data for the production of HFC-134a is available from the AFEAS database. AFEAS companies represent nearly 100% of the commercial supply of HFC-134a with only developmental quantities currently (year 2000) being produced in China, India and Korea. The data appear in Table AI-6.

Production has increased rapidly and consistently to meet growing HFC-134a demand as a replacement for what were formerly CFC applications. There was a distinct break in this trend with the 2000 data, which were 1% lower than that for 1999. There appears to be both a slowing of replacement growth rate as well as a significant downturn in business activity both contributing to this change in growth pattern. Production has increased to a current annual rate of 132 kilotonnes. Of this, about 111 ktonnes or 84% of the total is for refrigeration.

Data are not yet available for other HFCs due to AFEAS collection criteria. There are regulatory oversight groups collecting global HFC production and/or consumption data at this time. It is uncertain how such information will be reported in the future as the Kyoto Protocol addresses emissions rather than production or consumption.

Concluding Remarks

Production Summary

Tonnes	**1989**	**1995**	**1999**	**2000**
CFCs	1,032,000	265,000	146,000	138,000
HCFC	257,891	338,230	449,236	451,066
HFC-134a		73,800	133,700	132,000
ODP-tonnes				
CFC	1,032,000	265,000	146,000	138,000
HCFC	2,032	4,566	9,539	11,932
Total	1,046,184	292,904	183,097	175,213
Reduction	-	72%	82%	83%

(CFC ODPs=1.0, for HCFCs, 1995-2000 an average ODP of 0.082 has been applied; for 1989 the ODP of HCFC-22 has been used)

CFC use has dropped 87% globally since 1989 largely due to the phase-out of its use in developed countries. With the current cap in Article 5(1) countries and reductions in use during the rest of this decade, this use will continue to drop. HCFC production has increased but has levelled off. It is expected that this will begin a downturn, as use in developed countries will be reducing due to current regional and national regulations that are even more restrictive than those of the Montreal Protocol. The latter will mandate reductions in consumption of 35% in developed countries in 2004. This will be slightly offset due to expected Article 5(1) Party increases as HCFCs play an important role in facilitating CFC phase-out in those countries. HFC-134a has emerged as the key agent in replacing CFC use in many applications. Its production has levelled due to improved product stewardship in selection of uses, minimisation of emissions during use, and, in certain regions, recovery and recycle. The net impact of these activities is to reduce the net ozone depletion by about 83% as compared to the levels seen in 1989.

Consumption and Production Data CFCs, HCFCs and HFCs: Graphs and Tables

Table AI-1

Historic Production Data of CFCs- (Sources UNEP and AFEAS) – (ktonnes)

	1986	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
AFEAS													
AFEAS (ktonnes)	976	962	659	605	526	426	234	146	80	57	52	42	36
AFEAS (ODP-weighted)	895	859	587	544	481	405	221	136	77	56	52	42	36
UNEP (ODP-weighted)													
Argent/Braz/Mex/Venez	29	24	25	27 (17)	27 (17)	31	35	31	24	26	20	23	13
China/India/Korea	15	33	35 (21)	40 (26)	41	52	78	78	85	74	81	75	60
Total Article 5.1 (plus adj)	44	57	60	67	68	83	113	109	109	100	101	98	73
Eastern Europe	107	106	104	84	62	41	43	40	17	27	14	18	26
OECDnA5 (incl S. Africa)	920	879	613	527	461 (449)	360	186	100	34	35	32	32	27
Total Production (UNEP)													
A5.1 and Non A5.1	1071	1042	777	678	591	484	342	249	160	159	147	148	126
OECDnA5 group (UNEP)	909	869	607	522	457	356	184	99	34	49	46	50	53
OECDnA5 gr. (AFEAS)	866	835	552	517	454	374	186	105	53	57	52	42	36
%OECDnA5 group	85	83	78	77	77	74	54	40	21	31	31	34	42
Total Article 5.1 (plus adj)	44	57	60	67	68	83	113	109	109	100	101	98	73
Eastern Europe	107	106	104	84	62	41	43	40	17	27	14	18	26
OECDnA5	909	869	607	522	457	356	184	99	34	49	46	50	53

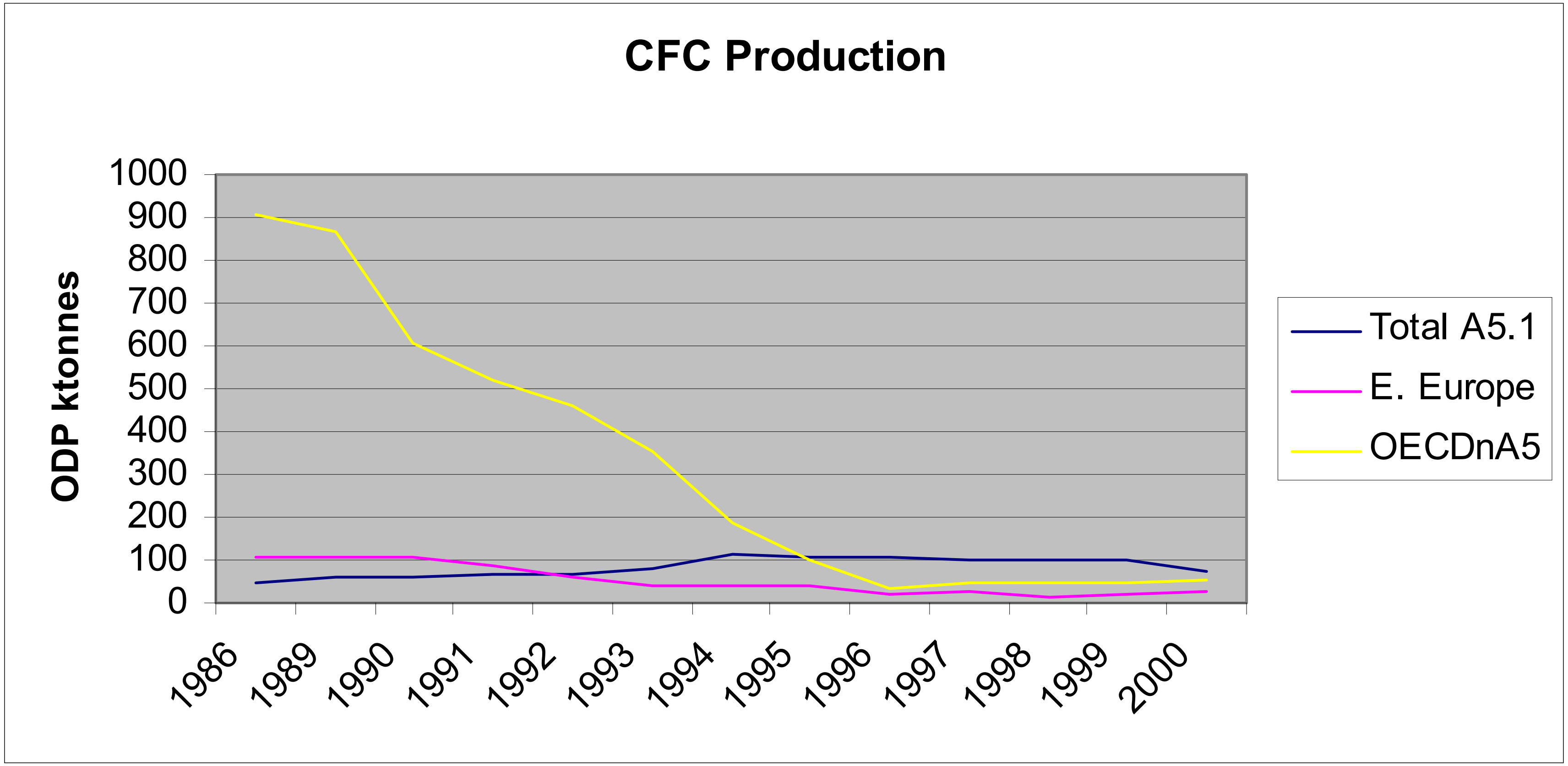

CFC Production
ODP ktonnes
1000
900
800
700
600
500
400
300
200
100
0
1986
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Total A5.1
E. Europe
OECDnA5

Table AI-2

Historic Production Data of CFCs, 1986-2000 (Source UNEP) – (ODP ktonnes)

	1986	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Argentina/Brazil/Mexico/Venezuela	29	25	26	25	17	23	28	25	25	21	20	21	18
China/India/Korea	41	63	42	50	81	82	88	92	73	58	61	55	45
Other A 5.1 countries	54	53	41	40	52	49	50	51	45	64	56	45	45
Total Article 5.1 (UNEP data)	124	141	109	115	150	154	166	168	143	143	137	121	108
Central/Eastern Europe (Russian Fed)	141 (100)	136 (99)	116 (99)	50 (39)	50 (37)	40 (30)	31 (23)	27 (21)	16 (12)	14	15	17	26
OECDnA5 group	788	740	497	436	352	279	149	67	8	7	7	8	5
Other non-Article 5.1	17	15	7	5	8	8	3	3	0	0	0	0	0
Total Consumption (UNEP) Non A5.1	958	897	626	493	412	329	183	97	24	21	22	25	30
Total Consumption (UNEP)	1070	1032	729	606	560	481	349	265	168	164	159	146	138
% OECDnA5 in total	74	72	68	72	63	58	43	25	5	4	4	5	4

	1986	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Total Article 5.1 (UNEP data)	124	141	109	115	150	154	166	168	143	143	137	121	108
Total Consumption (UNEP)	1070	1032	729	606	560	481	349	265	168	164	159	146	138

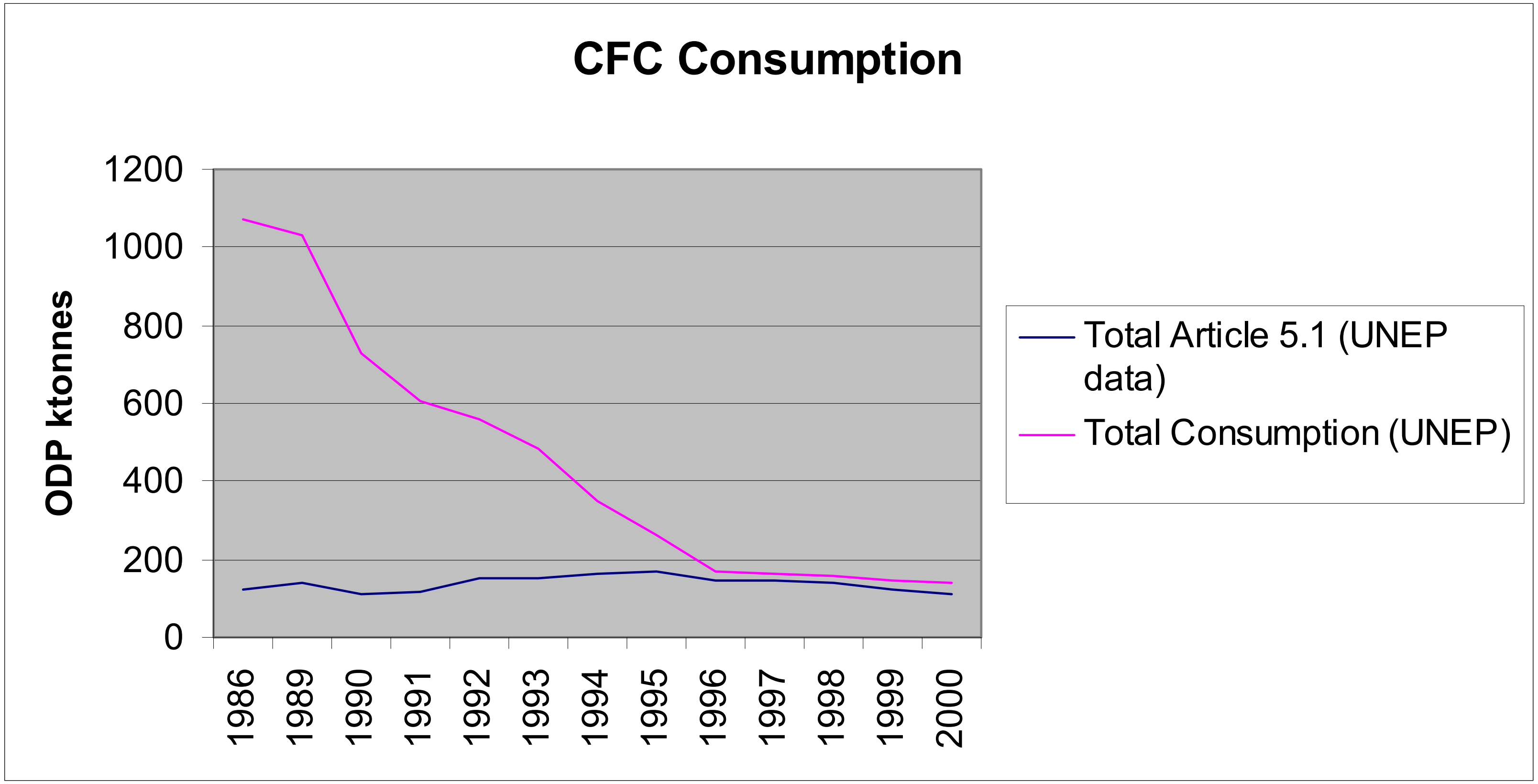
CFC Consumption
ODP ktonnes
1200
1000
800
600
400
200
0
1986
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Total Article 5.1 (UNEP data)
Total Consumption (UNEP)

Table AI-3

Historical Production Data of HCFCs (Sources UNEP and AFEAS) (tonnes)

	1989	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
AFEAS										
AFEAS	229825	289759	318134	359948	398430	435308	418424	432762	430151	422555
AFEAS (ODP-weighted)	12743	16969	20197	24618	28422	30822	29305	31069	31263	30847
UNEP (ODP-weighted)										
Argentina/Brazil/Mexico/Venezuela	353	475	461	452	421	505	523	439	372	274
China/India/Korea	249	731	1212	1840	1877	1831	1526	1522	5013	6713
Total Article 5.1	602	1206	1673	2292	2298	2336	2653	1960	5385	6987
Eastern Europe	1084	267	172	198	184	74	72	67	146	169
OECDnA5 (including S. Africa)	12181	12469	10078	20220	25335	26264	27143	30621	30676	30240
A5.1 & Non A5.1	13867	13942	20875	27266	30180	28674	29868	32648	36207	37228
OECDnA5 Group (UNEP)	12181	13232	18946	24689	27641	26264	27143	30621	30676	30240
OECDnA5 group (AFEAS)	12390	16494	19736	24166	28001	30317	28782	30630	31263	30847
% OECDnA5 (UNEP) in total	88	95	91	91	92	92	91	94	86	83

	1989	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
AFEAS (ODP-weighted)	12743	16969	20197	24618	28422	30822	29305	31069	31263	30847
Total Article 5.1	602	1206	1673	2292	2298	2336	2653	1960	5385	6987

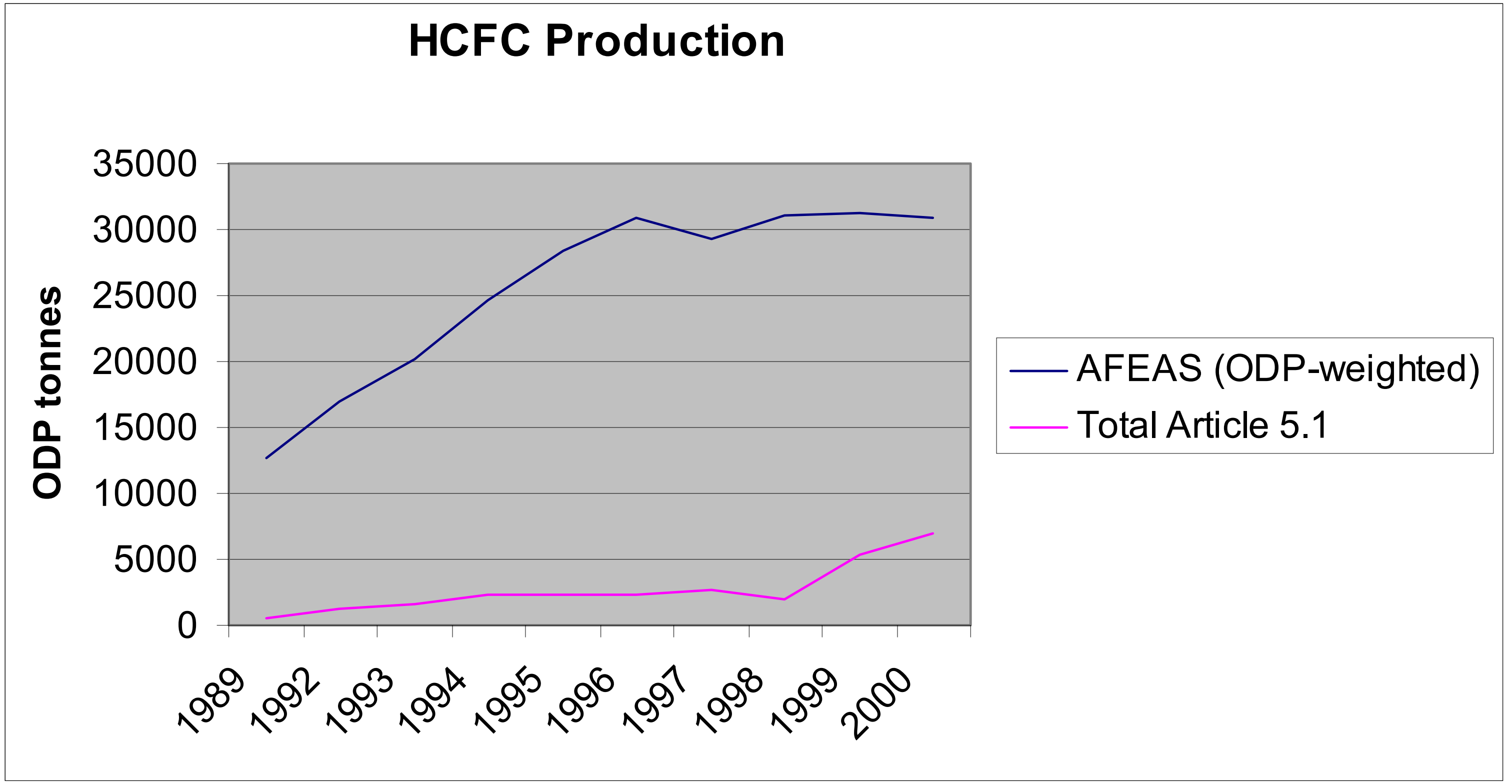

HCFC Production
ODP tonnes
35000
30000
25000
20000
15000
10000
5000
0
1989
1992
1993
1994
1995
1996
1997
1998
1999
2000
AFEAS (ODP-weighted)
Total Article 5.1

Table AI-4

Historic Consumption of HCFCs, 1989-2000 (Source UNEP) (ODP-tonnes)

	1989	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
UNEP										
Arg/Braz/Mex/Venez	418	423	642	769	971	866	1017	1130	1799	3023
China/India/Korea	991	748	1407	2140	2392	2265	1516	1756	4871	5355
Other Art 5.1 countries	623	591	693	616	1203	1646	3383	3442	2869	3554
Total Art 5.1 (UNEP data)	2032	1762	2742	3525	4566	4777	5941	5311	9539	11932
Central/Eastern Europe	564 (437)	316 (267)	258 (172)	228 (107)	259 (84)	195 (73)	345	304	362	586
OECDnA5 group	10605	12009	15727	21684	26780	19780	23788	27080	26995	24695
Other non-Art 5.1	290	271	353	469	471	324	134	42	165	
Total consumption (UNEP) non A5.1	12152	12641	16392	18214	23338	20300	24268	27427	27523	25281
Total Art 5.1 (UNEP data)	2032	1762	2742	3525	4566	4777	5941	5311	9539	11932
%OECDnA5 in total (UNEP)	75	83	82	84	83	79	80	84	74	68
Total consumption (UNEP)	14184	14403	19134	21739	27904	25077	30209	32793	37062	37213

	1989	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Total nonA5.1	12152	12641	16392	18214	23338	20300	24268	27427	27523	25281
Total Art 5.1 (UNEP data)	2032	1762	2742	3525	4566	4777	5941	5311	9539	11932
Total consumption (UNEP)	14184	14403	19134	21739	27904	25077	30209	32793	37062	37213

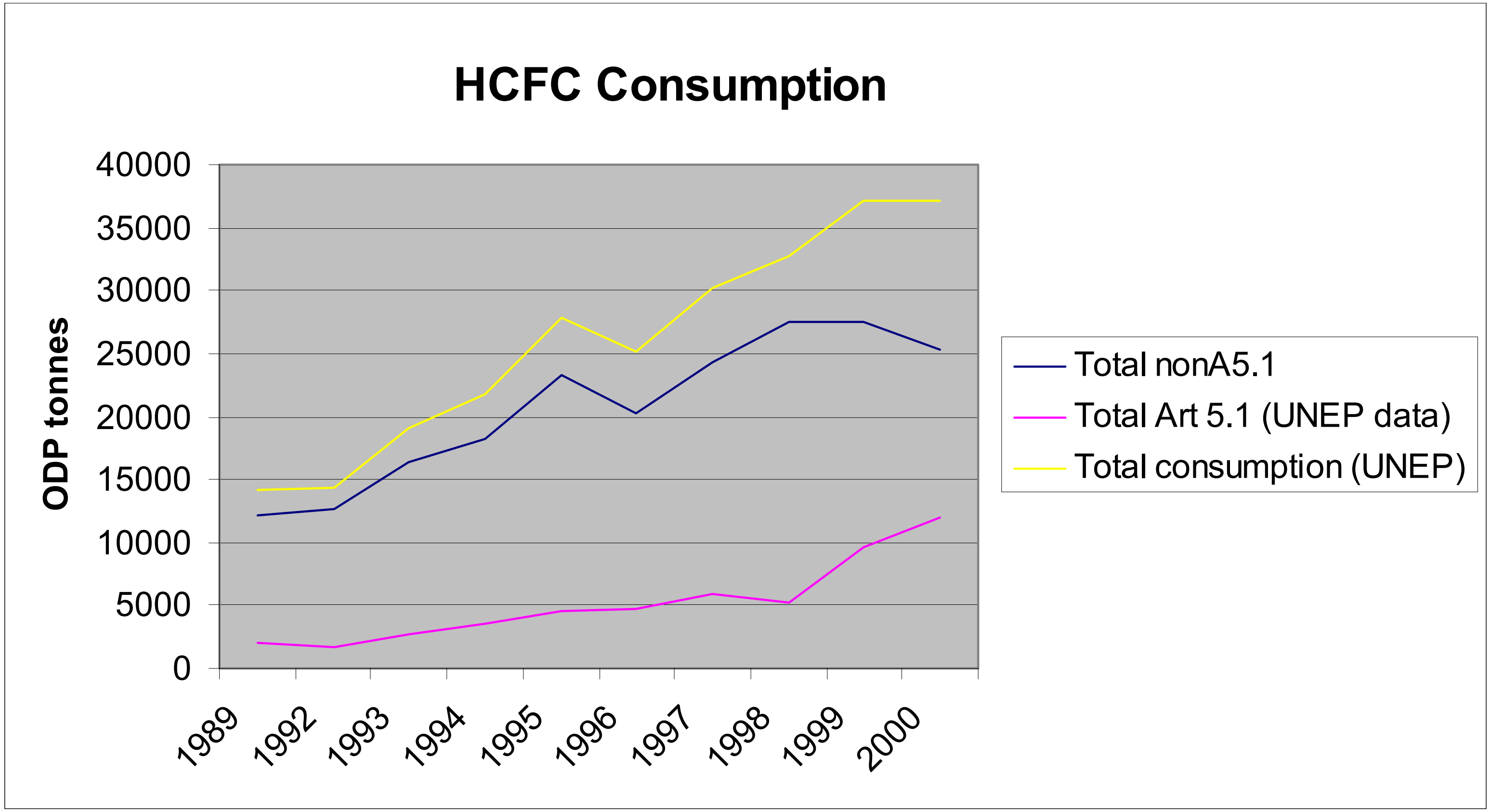
HCFC Consumption
ODP tonnes
40000
35000
30000
25000
20000
15000
10000
5000
0
1989
1992
1993
1994
1995
1996
1997
1998
1999
2000
Total nonA5.1
Total Art 5.1 (UNEP data)
Total consumption (UNEP)

Table AI-5

1999 use of HCFCs in different sectors

	HCFC-22	**HCFC-141b**	**HCFC-142b**	**HCFC-124**	**Total**
RAC	91.7%		2.1%	76.9%	41%
Closed cell foam	3.4%	91.2%	97.4%		53%
Solvents		8.8%	0.1%		4%
Others	4.8%		0.3%	23.1%	2%
RAC	12739		60	50	12849
Closed cell foam	474	13272	2686	0	16432
Solvents		1278	4		1282
Others	667	9	7	15	698
Totals	**13880**	**14559**	**2757**	**65**	31261

Source: AFEAS in percentages per HCFC and in ODP tonnes

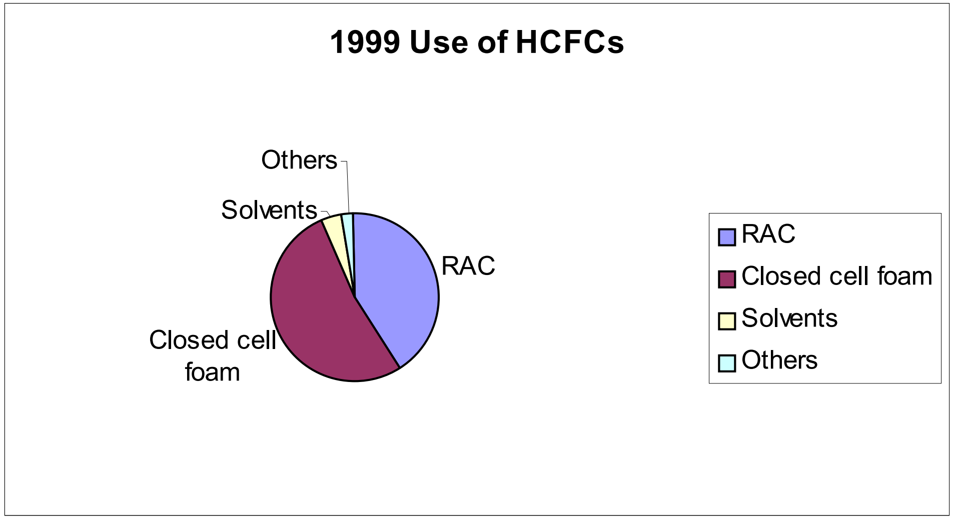
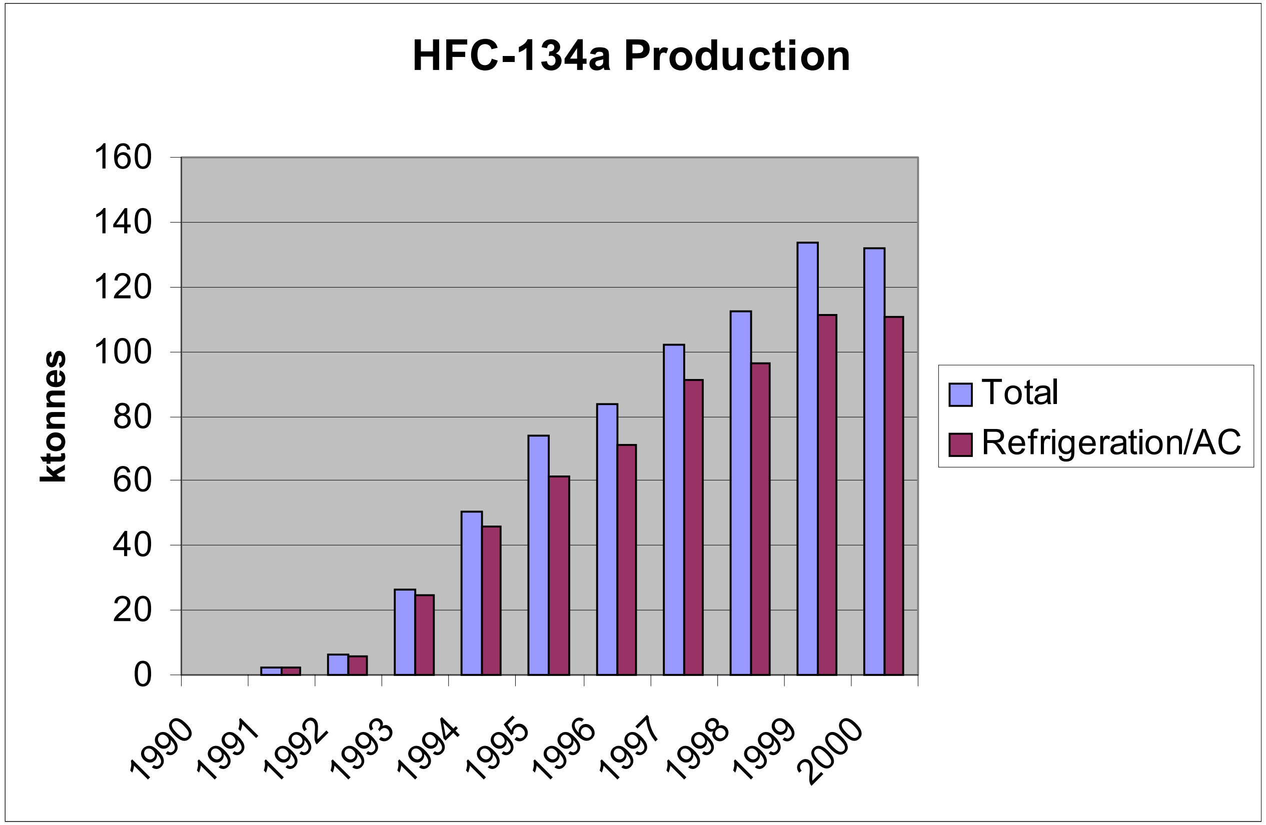


Table AI-6

Historic HFC-134a production (ktonnes)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Total	0.2	2.2	6.4	26.5	50.4	73.8	83.7	101.9	112.2	133.7	132
Refrigeration/ AC	0.08	2.1	6	24.5	46.1	61.3	71	90.9	96.6	111.2	110.7
% total RAC	40%	95%	94%	92%	91%	83%	85%	89%	86%	83%	84%



Annex II: Glossary

A/C	Air Conditioning
AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
Article 5(1)	Article 5, paragraph 1 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: azeotropic: with a behaviour as pure fluids near azeotropic: similar to azeotropic blends (small temperature glide) 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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Annex IV: Physical, Safety, and Environmental Data for Historical, Current, and Candidate Refrigerants

		physical data				safety data				environmental data			
refrigerant number	chemical formula - common name	molecular mass	NBP (°C)	Tc (°C)	Pc (MPa)	TLV-TWA (PPM)	LFL (%)	HOC MJ/kg	Std 34 safety group	atmospheric life (yr)	ODP	GWP 100 yr	status
CFC-11	CCl3F	137.37	23.7	198.0	4.41	C1000	none	0.9	A1	45	1.000	4600	M
CFC-12	CCl2F2	120.91	-29.8	112.0	4.14	1000	none	-0.8	A1	100	0.820	10600	M
BCFC-12B1	CBrClF2 - halon 1211	165.36	-4.0	154.0	4.10		none			11	5.100	1300	M
CFC-13	CClF3	104.46	-81.5	28.9	3.88	1000	none	-3.0	A1	640	1.000	14000	M
BFC-13B1	CBrF3 - halon 1301	148.91	-58.7	67.1	3.97	1000	none		A1	65	12.000	6900	M
FIC-13I1	CF3I	195.91	-22.0	122.2	3.88		none			<0.1	0.000	1	
FC-14	CF4 - carbon tetrafluoride	88.00	-128.0	-45.6	3.75		none		A1	50000	0.000	5700	K
HCFC-21	CHCl2F	102.92	8.9	178.3	5.18	10	none		B1	2.0	0.010	210	M
HCFC-22	CHClF2	86.47	-40.8	96.1	4.99	1000	none	2.2	A1	11.9	0.034	1700	M
HFC-23	CHF3 - fluoroform	70.01	-82.0	26.1	4.83	1000	none	-12.5	A1	260	0.000	12000	K
HCC-30	CH2Cl2 - methylene chloride	84.93	40.2	237.0	6.08	50	13		B2	0.46	0.000	10	M
HCFC-31	CH2ClF	68.48	-9.1			0.1					0.010		M
HFC-32	CH2F2 - methylene fluoride	52.02	-51.7	78.1	5.80	1000	14.4	9.4	A2	5.0	0.000	550	K
HCC-40	CH3Cl - methyl chloride	50.49	-24.2	143.1	6.67	50	8.0		B2	1.3	0.020	16	M
HFC-41	CH3F - methyl fluoride	34.03	-78.1	44.1	5.90					2.6	0.000	97	K
HC-50	CH4 - methane	16.04	-161.5	-82.6	4.60	1000	4.8		A3	12.0	0.000	23	
CFC-113	CCl2FCClF2	187.37	47.6	214.1	3.39	1000	none	0.1	A1	85	0.900	6000	M
CFC-114	CClF2CClF2	170.92	3.6	145.7	3.26	1000	none	-3.1	A1	300	0.850	9800	M
CFC-115	CClF2CF3	154.47	-38.9	80.0	3.12	1000	none	-2.1	A1	1700	0.400	7200	M
FC-116	CF3CF3 - perfluoroethane	138.01	-78.2	19.9	3.05	1000	none		A1	10000	0.000	11900	K
HCFC-123	CHCl2CF3	152.93	27.8	183.7	3.66	50	none	2.1	B1	1.4	0.012	120	M
HCFC-124	CHClFCF3	136.48	-12.0	122.3	3.62	1000	none	0.9	A1	6.1	0.026	620	M
HFC-125	CHF2CF3	120.02	-48.1	66.0	3.62	1000	none	-1.5	A1	29	0.000	3400	K
HFE-E125	CHF2-O-CF3	136.02	-42.0	81.3	3.35					150	0.000	14900	
HFE-E134	CHF2-O-CHF2	118.03	6.2	160.8	4.23		none			26.2	0.000	6100	
HFC-134a	CH2FCF3	102.03	-26.1	101.1	4.06	1000	none	4.2	A1	13.8	0.000	1300	K
HCFC-141b	CH3CCl2F	116.95	32.1	206.8	4.46	500	5.8	8.6		9.3	0.086	700	M
HCFC-142b	CH3CClF2	100.49	-9.1	137.1	4.07	1000	6	9.8	A2	19	0.043	2400	M
HFC-143a	CH3CF3	84.04	-47.2	72.7	3.76	1000	7.0	10.3	A2	52	0.000	4300	K
HFE-E143a	CH3-O-CF3	100.04	-24.1	104.9	3.63		flam			4.4	0.000	750	

		physical data				safety data				environmental data			
refrigerant number	chemical formula - common name	molecular mass	NBP (°C)	Tc (°C)	Pc (MPa)	TLV-TWA (PPM)	LFL (%)	HOC MJ/kg	Std 34 safety group	atmospheric life (yr)	ODP	GWP 100 yr	status
HFC-152a	CH3CHF2	66.05	-24.0	113.3	4.52	1000	4.8	17.4	A2	1.4	0.000	120	K
HCC-160	CH3CH2Cl - ethyl chloride	64.51	13.1	187.3	5.27	100	3.6	20.6		<1	0.000		M
HFC-161	CH3CH2F - ethyl fluoride	48.06	-37.1	102.2	4.70		3.8			0.3	0.000	12	K
HC-170	CH3CH3 - ethane	30.07	-88.6	32.2	4.87	1000	3.1		A3		0.000	~20	
HE-E170	CH3-O-CH3 - dimethyl ether	46.07	-24.8	127.0	5.37	1000	3.3	31.8		0.015	0.000	1	
FC-218	CF3CF2CF3 - perfluoropropane	188.02	-36.8	72.0	2.67	1000	none		A1	2600	0.000	8600	K
HFC-227ea	CF3CHFCF3	170.03	-16.4	101.7	2.93	1000	none	3.3		33	0.000	3500	K
HFC-236fa	CF3CH2CF3	152.04	-1.4	124.9	3.20	1000	none		A1	220	0.000	9400	K
HFC-245fa	CHF2CH2CF3	134.05	14.9	154.1	3.64	300	none	6.1	B1	7.2	0.000	950	K
HFE-E245cb1	CH3-O-CF2-CF3	150.05	5.9	133.7	2.89		flam			4.7	0.000	160	
HC-C270	-CH2-CH2-CH2- - cyclopropane	42.08	-33.5	125.2	5.58		2.4	49.7			0.000		
HC-290	CH3CH2CH3 - propane	44.10	-42.2	96.7	4.25	2500	2.1	50.3	A3		0.000	~20	
FC-C318	-CF2-CF2-CF2-CF2-	200.03	-6.0	115.2	2.78	1000	none		A1	3200	0.000	10000	K
HFE-E347mmy1	CF3-CF(OCH3)-CF3	200.05	29.4	160.8	2.55					3.4	0.000	330	
R-400(50/50)	R-12/114 (50.0/50.0)	141.63	-20.8	129.1	3.94		none		A1		0.835	10000	M
R-400(60/40)	R-12/114 (60.0/40.0)	136.94	-23.2	125.6	4.01		none		A1		0.832	10000	M
R-401A	R-22/152a/124 (53.0/13.0/34.0)	94.44	-32.9	107.3	4.61	1000	none		A1		0.027	1100	M
R-401B	R-22/152a/124 (61.0/11.0/28.0)	92.84	-34.5	105.6	4.69	1000	none	-2.7	A1		0.028	1200	M
R-401C	R-22/152a/124 (33.0/15.0/52.0)	101.03	-28.3	111.7	4.37		none		A1		0.025	900	M
R-402A	R-125/290/22 (60.0/2.0/38.0)	101.55	-48.9	75.8	4.22	1000	none	-1.4	A1		0.013	2700	M
R-402B	R-125/290/22 (38.0/2.0/60.0)	94.71	-47.0	82.9	4.52	1000	none	-1.6	A1		0.020	2300	M
R-403A	R-290/22/218 (5.0/75.0/20.0)	91.99	-47.8	87.0	4.70	1000	13.0		A1		0.026	3000	M
R-403B	R-290/22/218 (5.0/56.0/39.0)	103.26	-49.2	79.7	4.32	1000	none		A1		0.019	4300	M
R-404A	R-125/143a/134a (44.0/52.0/4.0)	97.60	-46.5	72.1	3.73	1000	none	-6.6	A1		0.000	3800	K
R-405A	R-22/152a/142b/C318 (45.0/7.0/5.5/42.5)	111.91	-32.6	106.1	4.29	1000	none		d		0.018	5200	M
R-406A	R-22/600a/142b (55.0/4.0/41.0)	89.86	-32.5	116.8	4.86		8.2		A2		0.036	1900	M
R-407A	R-32/125/134a (20.0/40.0/40.0)	90.11	-45.0	82.3	4.52	1000	none	-3.6	A1		0.000	2000	K
R-407B	R-32/125/134a (10.0/70.0/20.0)	102.94	-46.5	75.0	4.13	1000	none	-1.8	A1		0.000	2700	K
R-407C	R-32/125/134a (23.0/25.0/52.0)	86.20	-43.6	86.0	4.63	1000	none	-4.9	A1		0.000	1700	K
R-407D	R-32/125/134a (15.0/15.0/70.0)	90.96	-39.2	91.4	4.47	1000	none	-4.3	A1		0.000	1500	K

		physical data				safety data				environmental data			
refrigerant number	chemical formula - common name	molecular mass	NBP (°C)	Tc (°C)	Pc (MPa)	TLV-TWA (PPM)	LFL (%)	HOC MJ/kg	Std 34 safety group	atmospheric life (yr)	ODP	GWP 100 yr	status
R-407E	R-32/125/134a (25.0/15.0/60.0)	83.78	-42.7	88.5	4.70	1000	none	-4.8	A1		0.000	1400	K
R-408A	R-125/143a/22 (7.0/46.0/47.0)	87.01	-44.6	83.1	4.29	1000	none	5.7	A1		0.016	3000	M
R-409A	R-22/124/142b (60.0/25.0/15.0)	97.43	-34.4	109.3	4.70	1000	none	3.0	A1		0.039	1500	M
R-409B	R-22/124/142b (65.0/25.0/10.0)	96.67	-35.6	106.9	4.74		none		A1		0.033	1500	M
R-410A	R-32/125 (50.0/50.0)	72.58	-51.4	72.5	4.90	1000	none	-4.4	A1		0.000	2000	K
R-410B	R-32/125 (45.0/55.0)	75.57	-51.3	71.0	4.81		none		A1		0.000	2100	K
R-411A	R-1270/22/152a (1.5/87.5/11.0)	82.36	-39.5	99.1	4.95	1000	5.5		A2		0.030	1500	M
R-411B	R-1270/22/152a (3.0/94.0/3.0)	83.07	-41.6	96.0	4.95	1000	7.0	6.5	A2		0.032	1600	M
	R-1270/22/152a (3.0/95.5/1.5)	83.44	-41.8	95.5	4.95		none				0.032	1600	M
R-412A	R-22/218/142b (70.0/5.0/25.0)	92.17	-38.0	107.2	4.90	1000	8.7		A2		0.035	2200	M
R-413A	R-218/134a/600a (9.0/88.0/3.0)	103.95	-30.6	98.5	4.07		8.8		A2		0.000	1900	K
R-414A	R-22/124/600a/142b (51.0/28.5/4.0/16.5)	96.93	-32.9	112.7	4.68	1000	none	3.6	A1		0.032	1400	K
R-414B	R-22/124/600a/142b (50.0/39.0/1.5/9.5)	101.59	-32.9	111.0	4.59		none		A1		0.031	1300	M
R-415A	R-22/152a (82.0/18.0)	81.91	-37.2	102.0	4.96		5.6	2.7	A2 r		0.028	1400	M
R-415B	R-22/152a (25.0/75.0)	70.19	-26.9	111.4	4.65	1000	WCF		A2 p		0.009	520	M
	R-22/152a (52.0/48.0)	75.30	-32.2	108.0	4.82	1000	12.4	9.7			0.018	940	M
	R-22/152a (60.0/40.0)	76.95	-33.6	106.7	4.86	1000	none	16.2			0.020	1100	M
R-416A	R-134a/124/600 (59.0/39.5/1.5)	111.92	-24.0	107.0	3.98			7.8	A1		0.010	1000	M
R-417A	R-125/134a/600 (46.6/50.0/3.4)	106.75	-39.1	87.0	4.04		none		A1		0.000	2200	K
R-418A	R-290/22/152a (1.5/96.0/2.5)	84.60	-41.6	96.2	4.98		8.9	1.7	A2 p		0.033	1600	M
R-419A	R-125/134a/E170 (77.0/19.0/4.0)	109.34	-43.8	79.2	4.00		none	10.0	A2 p		0.000	2900	K
	R-22/124/600 (50.0/47.0/3.0)	102.64	-32.9	110.4	4.59	900	none				0.029	1100	M
	R-23/32/134a (4.5/21.5/74.0)	83.14	-42.2	89.0	4.90		none				0.000	1600	K
	R-23/125/143a (20.0/36.0/44.0)	90.16	-64.8	67.3	4.03						0.000	5500	K
	R-32/125/134a/600 (10.0/42.0/45.0/3.0)	96.64	-42.2	87.2	4.40						0.000	2100	K
	R-32/125/143a (10.0/45.0/45.0)	90.69	-48.4	72.0	4.05		none				0.000	3500	K
	R-32/125/143a/134a (2.0/41.0/50.0/7.0)	95.82	-46.8	72.9	3.81		none				0.000	3600	K
	R-32/125/143a/134a (10.0/33.0/36.0/21.0)	90.80	-49.4	77.5	4.01		none				0.000	3000	K
	R-32/134a (25.0/75.0)	82.26	-40.3	93.7	4.83		wff				0.000	1100	K
	R-32/134a (30.0/70.0)	79.19	-41.8	92.4	4.94	1000	wff				0.000	1100	K

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refrigerant number	chemical formula - common name	molecular mass	NBP (°C)	Tc (°C)	Pc (MPa)	TLV-TWA (PPM)	LFL (%)	HOC MJ/kg	Std 34 safety group	atmospheric life (yr)	ODP	GWP 100 yr	status
	R-125/22 (70.0/30.0)	107.51	-47.4	73.7	4.04		none				0.010	2900	M
	R-125/134a/152a (35.0/40.0/25.0)	94.15	-35.0	95.5	4.14	1000	wff				0.000	1700	K
	R-125/143a/290/22 (42.0/6.0/2.0/50.0)	95.70	-47.7	81.0	4.45	1000	none				0.017	2500	M
	R-125/152a/227ea (40.0/5.0/55.0)	136.53	-38.6	87.2	3.58	1000	none				0.000	3300	K
	R-134a/142b (80.0/20.0)	101.71	-24.1	107.4	4.11		frac				0.010	1500	M
	R-134a/142b (80.6/19.4)	101.73	-24.2	107.2	4.11		none				0.008	1500	M
	R-134a/142b (88.0/12.0)	101.84	-24.9	104.8	4.09						0.005	1400	M
	R-161/13I1 (80.0/20.0)	56.60									0.000	9.8	?
	R-161/218/13I1 (65.4/18.2/16.4)	64.88									0.000	1600	?
	R-170/290 (6.0/94.0)	42.90	-50.0	93.2	4.42		1.9				0.000	~20	M
	R-218/134/600 (32.7/62.8/4.5)	115.36									0.000	3500	K
	R-290/600a (50.0/50.0)	50.15	-32.8	114.8	4.04		2.0	49.8			0.000	~20	
	R-600a/600 (50.0/50.0)	58.12	-6.5	143.6	3.73		1.6				0.000	~20	
R-500	R-12/152a (73.8/26.2)	99.30	-33.6	102.1	4.17	1000	none		A1		0.605	7900	M
R-501	R-22/12 (75.0/25.0)	93.10	-40.7	95.9	4.76		none		A1		0.231	3900	M
R-502	R-22/115 (48.8/51.2)	111.63	-45.2	80.2	3.92	1000	none		A1		0.221	4500	M
R-503	R-23/13 (40.1/59.9)	87.25	-87.8	18.4	4.28	1000	none				0.599	13000	M
R-504	R-32/115 (48.2/51.8)	79.25	-57.7	61.1	4.33		none				0.207	4000	M
R-505	R-12/31 (78.0/22.0)	103.48	-30.0	117.8	4.73		none				0.642		M
R-506	R-31/114 (55.1/44.9)	93.69	-12.3	142.2	5.16		none				0.387		M
R-507A	R-125/143a (50.0/50.0)	98.86	-46.7	70.9	3.71	1000	none	-5.5	A1		0.000	3900	K
R-508A	R-23/116 (39.0/61.0)	100.10	-87.4	10.8	3.67	1000	none		A1		0.000	12000	K
R-508B	R-23/116 (46.0/54.0)	95.39	-87.3	14.0	3.93	1000	none		A1		0.000	12000	K
R-509A	R-22/218 (44.0/56.0)	123.96	-49.8	68.6	3.61	1000	none		A1		0.015	5600	M
	R-32/600 (90.0/10.0)	52.58	-51.1	84.8	6.15		flam				0.000	500	K
	R-32/600 (95.0/5.0)	52.30	-51.4	81.4	5.99		flam				0.000	520	K
	R-32/600a (90.0/10.0)	52.58	-53.1	74.2	5.27		flam				0.000	500	K
	R-32/600a (95.0/5.0)	52.30	-52.6	75.9	5.51		flam				0.000	520	K
	R-134a/600a (80.0/20.0)	88.64	-29.5	111.3	4.81		3.9				0.000	1000	K
	R-218/152a (83.5/16.5)	144.11	-35.2	86.8	3.44						0.000	7200	K

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R-600	CH3-CH2-CH2-CH3 - butane	58.12	-0.6	152.0	3.80	800	1.5	49.5	A3		0.000	~20	
R-600a	CH(CH3)2-CH3 - isobutane	58.12	-11.7	134.7	3.64	800	1.7	49.4	A3		0.000	~20	
R-601	CH3-CH2-CH2-CH2-CH3 - pentane	72.15	36.1	196.6	3.37	600	1.4			<<1	0.000	11	
R-601a	(CH3)2CH-CH2-CH3 - isopentane	72.15	27.8	187.2	3.40	600	1.0				0.000		
R-610	CH3-CH2-O-CH2-CH3 - ethyl ether	74.12	34.6	214.0	6.00	400	1.9				0.000		
R-611	HCOOCH3 - methyl formate	60.05	31.8	214.0	5.99	100	4.5		B2		0.000		
R-630	CH3(NH2) - methylamine	31.06	-6.7	156.9	7.46	5	4.9				0.000		
R-631	CH3-CH2(NH2) - ethylamine	45.08	16.6	183.0	5.62	5	3.5				0.000		
R-704	He - helium	4.00	-268.9	-268.0	0.23		none		A1		0.000		
R-717	NH3 - ammonia	17.03	-33.3	132.3	11.33	25	15.0	22.5	B2		0.000	<1	
R-718	H2O - water	18.02	100.0	373.9	22.06		none		A1		0.000	<1	
R-729	air	28.97	-194.2	-140.6	3.79		none				0.000	0	
R-744	CO2 - carbon dioxide	44.01	-78.4	31.0	7.38	5000	none		A1	>50	0.000	1	
R-764	SO2 - sulfur dioxide	64.06	-10.0	157.5	7.88	2	none		B1		0.000		
HCC-1130	CHCl=CHCl - dielene	96.94	47.8	243.3	5.48	200	5.6						M
HC-1150	CH2=CH2 - ethylene	28.05	-109.4	9.2	5.04	1000	2.7		A3		0.000		
HC-1270	CH3CH=CH2 - propylene	42.08	-47.7	92.4	4.66	660	2.0		A3		0.000	~20	

NBP = normal boiling point; Tc = critical temperature; Pc = critical pressure; 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), "wff" signifies that the worst case of fractionation may be flammable; HOC = heat of combustion; 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 the source documents before use. JMC-2003.01.12