MONTREAL PROTOCOL
ON SUBSTANCES THAT DEPLETE
THE OZONE LAYER

1998 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee

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

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Executive Summary: Refrigeration, Air Conditioning and Heat Pumps

This Refrigeration, A/C and Heat Pumps Technical Options Committee Report forms part of the regular assessments to be carried out pursuant to Article 6 of the Montreal Protocol. It is also part of the 1998 assessment of the Technology and Economic Assessment Panel. The 1998 Technical Options Committee included 48 representatives from African, Asian, European, Latin and North American countries. Several drafts of the report were made, reviewed by the separate chapters and discussed in six TOC meetings, held in Denmark, France and in the United States in 1996 and 1997, and in India, Norway and Germany in 1998. The report was peer reviewed and was completed in a TOC meeting following the peer review.

CFC production has been phased out in the non-Article 5(1) countries, and phase-out is underway in the Article 5(1) 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, mainly as blends of HFCs. As a result, HFCs have currently gained a large share of the replacement market. A rational approach to phase out the consumption of HCFCs as transitional chemicals should allow a minimum time period to permit the industry to develop and commercialise alternatives and a rational phasing in of new equipment in order to avoid high obsolescence costs. For the short term, the transitional HCFCs still form a valid, global option for refrigeration and A/C equipment. However, for the long term, there remain (in addition to various non vapour compression methods) only five important different refrigerant options for the vapour compression cycle:

- hydrofluorocarbons (HFCs, HFC-blends with 400 and 500 number designation);
- ammonia (R-717);
- hydrocarbons and blends (HCs, e.g. HC-290, HC-600, HC-600a etc.);
- carbon dioxide (CO_2, R-744)
- 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 mitigate these concerns, though sometimes at the cost of greater capital investment or lower energy efficiency. Energy efficiency relates directly to global warming and greenhouse gas emissions. Therefore, it remains an important issue for all refrigeration technologies, and should be considered along with the factors described above, since it is directly related to global warming.

Next to ozone depletion, global warming is the main environmental issue governing the selection of refrigerant technologies for the near-, mid- and long-term. Although this issue is not covered by the Montreal Protocol, it nevertheless forms an important criterion in the ongoing "environmental acceptability" discussion. Interest in ammonia and the hydrocarbons is stimulated, at least in part, by the fact that the HFCs are greenhouse gases for which emissions may be controlled in future. However, safety aspects also imply stringent emission controls for ammonia and hydrocarbons. Similarly, energy efficiency research is partly spurred by the role of energy production in carbon dioxide emissions.

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. Equipment using water has been developed 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.

CFC production in the developed countries shows a decrease from 866 to 53 ODP-ktonnes in the years 1986 and 1996, respectively. The total production volume in Article 5(1) countries seems to have stabilised over the period 1994-1996. CFC production in all Article 5(1) countries amounted to 109 ODP-ktonnes in 1996. The total global CFC production available for consumption in the Article 5(1) countries in the year 1996 was in the order of 145-150 ODP-ktonnes. If CFC production facilities in the Article 5(1) countries would continue production in the order of 110 ODP-ktonnes annually, exports by non-Article 5(1) countries can be rapidly reduced. This is because Article 5(1) consumption is expected to decrease due to project implementation and national measures being implemented by many Article 5(1) Parties.

HCFC production increased from about 12.7 ODP-ktonnes in 1989 to about 30.8 ODP-ktonnes in 1996 in countries which have facilities belonging to the AFEAS manufacturer group. According to the 1996 manufacturers' data, the largest ODP consumption of HCFCs was not in refrigeration and air conditioning, but in the foams sector (HCFC-141b). HCFC global consumption is expected to decrease from 412 to 163 ktonnes between the years 1998 and 2015, respectively. HFC-134a production has shown a continuous growth over the period 1990 -1996, with a consumption of about 74 and 84 ktonnes in the years 1995 and 1996, respectively, which represents growth percentages of 45 and 13 percent. Annual HFC-134a consumption for all applications in the year 2015 is forecast to be 207 ktonnes. This represents an increase of about 250 percent between 1997 and 2015; this figure includes 174 ktonnes for the use of HFC-134a in refrigeration and A/C. The same growth percentage also applies for the consumption of other HFCs in the 1997-2015 period (forecast consumption of 133 ktonnes in 2015). These growth estimates should be considered against a substantial decrease in HCFC consumption over the period 1997-2015.

All manufacturers in non-Article 5(1) countries have transitioned from CFC-12 to non-ODS refrigerants in new domestic refrigeration equipment. Transitions in the developing countries are occurring faster than the prior to the Montreal Protocol requirements. Preferred alternatives were assessed considering safety, environmental, functional and performance requirements. Broad based OEM refrigerant alternatives have narrowed to

HFC-134a and HC-600a. Both can provide safe, reliable and efficient domestic refrigerators and freezers. Analysis of regional requirements and consumer - selected product differences provides insight into refrigerant selections. Field repair complexity is expanding with the introduction of new refrigerants which involves several potential issues and OEMs should be consulted regarding proper repair procedures for their equipment. Equipment design for use with CFC-12 should be carefully assessed for safety prior to undertaking drop-in repair, particularly when using flammables. There is a significant difference in field repair rates between developed and developing countries, at approximately 2 percent or 10 percent, respectively. Differences result from use environment, extended life and uncertain power service, aggressive transport conditions and deficient service training. The premium value of capital goods relative to labour expense in many countries promotes component rebuilding by small, decentralised service shops. This has the strategic consequence of extending the use of obsolete materials and components. CFC-12 continues to globally dominate the aftermarket service demand. Energy efficiency of domestic refrigeration is a subject of accelerating interest. Retirement and replacement of less efficient older units and extended application of conventional state of the art technology could result in large reductions in global energy consumption.

Commercial refrigeration includes a wide range of equipment. While the refrigeration capacity of centralised systems in supermarkets varies typically from 20 kW to 1000 kW, stand-alone equipment capacities are comparable to domestic equipment. Stand-alone equipment traditionally used CFC-12; most new equipment uses HFC-134a. Several manufacturers in the UK, Denmark and Sweden have introduced small commercial equipment using various hydrocarbons. The expected more rapid HCFC phase-out in Europe has led to the choice of R-404A and R-507A in new, centralised systems. In some European countries certain industries are supplying units that either use ammonia or hydrocarbons. However, HFC blends as economically preferred refrigerants form the usual choice, due to safety considerations and initial costs. A number of units have been installed to evaluate the advantages and the drawbacks of indirect systems (using a secondary circuit with heat transfer fluids), and new concepts for direct expansion using water cooling, now in operation, are also being evaluated. Other developmental efforts are focused on improving energy efficiency, minimising charge size, and minimising refrigerant emissions. The early CFC phase-out in some Article 5(1) countries and their level of refrigerant consumption (which can be up to 50 percent of the overall country CFC consumption), provide incentives for both system owners and repair shops to replace CFC-12 with low- or non-ODP refrigerants.

Most industrial systems are custom made and erected on site. Therefore, the refrigerant choice has to be evaluated on a case-by-case basis, whether it concerns a new installation or the retrofit of an existing one. Ammonia and HCFC-22 are currently the most commonly used refrigerants for industrial refrigeration including cold storage and food processing; it is expected that ammonia will increase its importance in the future. In these sectors CFCs have been replaced by new systems using ammonia, HCFC-22 and HFCs, where the currently used HFCs are HFC-134a, R-404A and R-507A. The blend R-410A is expected to become the leading HFC in future. Hydrocarbons and CO_2 are applicable for specific applications. Retrofit activities in the industrial sectors have been lower than expected several years ago, although the various retrofit options, i.e., HCFC-22, HCFC blends and HFCs have proven to be viable solutions. In a certain number of cases retrofit cannot be performed due to economic or technical reasons, and the systems have to be replaced. Compared to industrial refrigeration, cold storage and food processing is a more important sector in the Article 5(1) countries; the refrigerants used are, to a certain degree, CFCs as well as the substitutes HCFC-22 and ammonia.

Air cooled air conditioners and heat pumps ranging in size from 2 kW to 420 kW comprise the vast majority of the air conditioning market. Nearly all of these units use HCFC-22 as working fluid; this represents an inventory of approximately 423 ktonnes of HCFC-22. There has been significant progress made in developing HCFC-22 alternatives for this category of products. Hydrocarbon refrigerants might also be suitable replacements for HCFC-22 in some categories of products: air-to-water heat pumps and possibly very low charge level air-to-air systems. Article 5(1) Parties will have a significant need for the transfer of reclamation and retrofit technologies. At least one retrofit candidate for HCFC-22 is commercially available: the HFC-blend R-407C.

The continuously growing number of water chillers for air conditioning, in service around the world, uses refrigerants including fluorocarbons (CFCs, HCFCs, HFCs), ammonia and hydrocarbons. The chillers employing the fluorocarbons dominate in terms of the installed base and new production, due to relatively low initial costs. Because the HCFCs and HFCs are relatively similar to the CFCs physically and chemically, they can often replace the CFCs in new and existing chillers with less extensive modification of chillers and equipment rooms than are required for other replacement refrigerants. However, the ammonia and hydrocarbon chillers are enjoying some growth, particularly in Northern Europe. The largest chillers, those with the highest cooling capacity, employ centrifugal compressors, where the smaller chillers have traditionally employed reciprocating piston compressors. Today, these are being complemented, and in come cases replaced, by screw and scroll compressors. The principal changes that have occurred since the 1993-1995 period are (i) the phase-out of the use of CFC-11 in existing chillers has been significantly slower than forecast in 1994, (ii) the use of ammonia in new systems has grown more rapidly than anticipated in 1994, (iii) very low emission chillers are now being installed by all manufacturers, and (iv) hydrocarbon chillers have been introduced on several regional markets.

Transport refrigeration includes refrigeration in ships, railcars, containers and road transport equipment; it also includes refrigeration and air conditioning on merchant ships, buses and railcars. Most systems that used CFCs in 1994 have been retrofitted or scrapped, except for refrigerated containers and trucks, due to the large existing CFC fleets. Particularly in all segments of transport refrigeration, the emission rate can be significant, due to the rough operating conditions; therefore containment and maintenance are very important together with system design improvement. In ships, nearly all systems use HCFC-22 but HFCs offer the preferred future option. Apart from HFCs, there is limited work on alternatives including hydrocarbons, ammonia, air-cycle and CO_2 for new systems in transport refrigeration. About half of the refrigerated containers and road vehicles still use CFC-12 today, but retrofit options, mainly HCFCs and HFCs, are fully available (only in some cases hydrocarbon options exist).

By the end of 1994, all automobile manufacturers had converted mobile air conditioning systems to HFC-134a. Existing vehicles with CFC-12 air conditioning are expected to be phased out due to "old age" by the year 2008. The major issue remaining is to encourage all countries, particularly the Article 5(1) Parties, to phase out the use of CFC-12 in motor vehicles as soon as possible and prevent unnecessary emissions during servicing. Accordingly, automobile manufacturers and their international associations have provided information on available retrofit technology, recovery and recycling of refrigerant, service technician training, and current service and retrofit trends; this has already been used in several Article 5(1) country Refrigerant Management Plans. Manufacturers of HFC-134a systems are working to improve their designs to minimise refrigerant charge and refrigerant emissions, and to maximise total system energy efficiency. Hydrocarbons and CO_2 have been proposed as possible long-term replacements for HFC-134a and are being evaluated. New vehicles are expected to be equipped with HFC-134a until an alternative is developed and commercialised that offers comparable performance, reliability and safety characteristics, and an economically viable global warming advantage.

It is estimated that the total existing heating-only heat pump stock in the residential, commercial/industrial and district heating sectors is roughly 1.7 million units, with a total heating capacity of about 13,300 MW. The corresponding figures for industrial heat pumps are 8,500 units with a total heating capacity of 3,000 MW. Virtually all heat pumps are in use in the developed countries. HFCs are the most important alternative refrigerant for heat pumps, both for retrofit and in new installations: HFC-134a is applied in medium/large capacity units as a replacement for CFC-12, where R-404A, R-407C and R-410A are the most promising HFC blend alternatives to replace HCFC-22. So far, the number of heat pump retrofits has been lower than expected. Ammonia has in the recent years attained a small, but growing market share in medium and large capacity heat pumps in Northern Europe; propane, propylene and certain hydrocarbon blends are being used in a limited number of residential heat pumps, mainly in Europe. In addition, the use of CO_2 is being evaluated and components for CO_2 have been developed.

Refrigerant conservation is critical both to maintaining the stock of existing CFC equipment and to minimising any environmental (e.g., global warming) or safety (e.g., flammability) impacts that may be associated with the transition away from ozone-depleting substances. Parties may wish to consider taking measures to encourage conservation. Measures successfully applied in the past have included financial incentives and regulations making containment compulsory. In Article 5(1) countries, important first steps include tightening up systems by finding and repairing leaks, and recovering refrigerant when opening the system for service. To be effective, conservation technologies must be matched by technician training and, in some cases, adaptation of technology. Replacing CFCs in new and existing equipment; ending the purchase of CFC equipment; and conservation through recovery, recycling and leak reduction are all steps that could be taken in the short term by Article 5(1) Parties in order to meet the initial 1999 control measures.

Executive Summaries of all Chapters

This Refrigeration, A/C and Heat Pumps Technical Options Committee Report forms part of the regular assessments to be carried out pursuant to Article 6 of the Montreal Protocol and is again part of the 1998 assessment work of the Technology and Economic Assessment Panel, as requested by the Parties in Vienna in 1995 (in Decision VII/34). Nine chapters of the full Report deal with application areas; one deals with refrigerant conservation, and one chapter gives historic data for fluorocarbon refrigerant production and consumption, as well as future estimates. The report also includes annexes with summaries of all important properties for all known refrigerants. The 1998 Technical Options Committee included 48 representatives from African, Asian, European, Latin and North American countries. Several drafts of the report were made and reviewed. Results were discussed in six TOC meetings, which were held in Denmark (Aarhus), France (Paris) and the United States (Washington D.C.) in 1996 and 1997, and in India (New Delhi), Norway (Oslo), and Germany (Nürnberg) in 1998. The report has been peer reviewed by a number of refrigeration institutions and associations, as well as by NGOs.

The economic impact of refrigeration technology is far more significant than generally believed; 300 million tonnes of goods are refrigerated. While the yearly consumption of electricity in this sector may be huge, and where the investment in machinery and equipment may approach $ 100,000 million, the value of the products treated by refrigeration approximates four times this amount.

CFC production has been phased out in the non-Article 5(1) countries, and the CFC phase-out is underway in the Article 5(1) countries. In both the non-Article 5(1) and the Article 5(1) countries, HCFCs and HFCs have been the primary substitutes for CFCs. In many applications, although not in all, alternatives to HCFCs have become commercially available, mainly as blends of HFCs. As a result, HFCs have currently gained a large share of the replacement market. However, a rational approach to phase out the consumption of HCFCs, being transitional chemicals, could include a minimum time period to permit the industry to develop and commercialise alternatives. This has been applied to refrigerants but only partly to the equipment that uses the HCFCs. This approach should provide for a rational phasing in of new equipment in order to avoid high obsolescence costs due to the need to continue servicing existing equipment.

In the short term, the ransitional HCFCs are a valid, global option for refrigeration and A/C equipment. However, for the long term, there remain only five important different refrigerant options for the vapour compression cycle (in addition to various non vapour compression methods):

1. hydrofluorocarbons (HFCs, HFC-blends with 400 and 500 number designation);
2. ammonia (R-717);
3. hydrocarbons and blends (HCs, e.g. HC-290, HC-600, HC-600a etc.);
4. carbon dioxide (CO_2, R-744);
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. Energy efficiency remains an important issue for all refrigeration technologies, and should be considered along with the factors enumerated above, since it is directly related to global warming.

Next to ozone depletion, global warming is the main issue governing the selection of refrigerant chemicals for the near- mid- and long-term. Although this issue is not covered by the Montreal Protocol, it nevertheless forms an important criterion in the ongoing "environmental acceptability" discussion. Interest in ammonia and the hydrocarbons is stimulated, at least in part, by the fact that the HFCs are greenhouse gases for which emissions may be controlled in future. However, safety aspects also imply stringent emission controls for ammonia and hydrocarbons. Similarly, energy efficiency research is partly spurred by the role of energy production in carbon dioxide emissions.

In all energy related uses, the relation between the CO_2 produced in electricity generation (to operate the product) and the direct global warming of the substitute chemical has to be taken into account. The 'Total Equivalent Warming Impact' (TEWI) concept includes direct and indirect global warming effects. However, it is no criterion to decide upon certain options from an investment point of view since it does not take into account life cycle costs and related investment aspects. Options for energy efficient operation of equipment form an important issue in each of the chapters of this 1998 TOC Refrigeration Assessment report.

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 CO_2 equipment is under development for certain applications, with the first demonstration components having reached the market. Equipment using water as the refrigerant has been developed and may see some increase in use in limited applications. Several committees are working to develop standards to permit the use of new refrigerants. It is the intent of companies to reach world-wide acceptance of standards.

Global CFC and HCFC Production and Consumption Data-Estimates for the Near Future

CFC and HCFC production data have been accumulated through publications by manufacturing companies of the AFEAS group and from UNEP publications that report countries-provided annual data on production - and consumption. CFC production in non-Article 5(1) countries shows a decrease from 866 to 53 ODP-ktonnes in the years 1986 and 1996, respectively. By contrast, the countries China, India and Korea, increased their

CFC production from 41 to 85 ODP-ktonnes between 1992 and 1996. However, the aggregated total production volume in Article 5(1) countries seems to have stabilised over the period 1994 - 1996.

CFC production in all Article 5(1) countries amounted to 109 ODP-ktonnes in 1996. The total global CFC production available for consumption in the Article 5(1) countries in 1996 was approximately 145-150 ODP-ktonnes. This includes quantities illegally imported to developed countries. CFC production in China, India and Korea was smaller than their consumption until 1995; this implies imports from non-Article 5(1) countries in the order of 0 - 14 ODP-ktonnes during 1994 - 1996.

CFC consumption in non-Article 5(1) countries amounted to 8 ODP-ktonnes in 1996, compared to 788 ODP-ktonnes in the year 1986. Based on non-Article 5(1) country production of 53 ODP-ktonnes in 1996, one can conclude that the majority of 1996 exports went to countries other than China, India and Korea (approximately 30-35 ODP-ktonnes).

If Article 5(1) countries were to continue producing on the order of 110 ODP-ktonnes annually, exports by non-Article 5(1) Parties could be rapidly reduced. This is because Article 5(1) consumption is expected to decrease due to project implementation and national measures being implemented by many Article 5(1) Parties.

HCFC production increased from 12,743 ODP tonnes in 1989 to 30,822 ODP tonnes in 1996 in countries which have manufacturing facilities belonging to the AFEAS group. The percentage of the HCFC production that took place in the non-Article 5(1) countries amounts to 91-95 percent of the aforementioned quantities. The increase between 1994 and 1995 was caused largely by an increase in the production of HCFC-141b; and the increase between 1995 and 1996 by an increase in HCFC-22 production. According to the 1996 manufacturers' data, the largest ODP consumption of HCFCs was not in refrigeration and air conditioning, but in the foams sector (HCFC-141b).

Forecasts for future HCFC and HFC consumption have been derived by averaging forecast data submitted by developed country manufacturers, which yields a best estimate. HCFC global consumption is expected to decrease from 412 to 163 ktonnes between the years 1998 and 2015, respectively. There is a significant decrease in the HCFC consumption in the non-Article 5(1) countries after 2003 due to halting the production of most closed cell foams using HCFC-141b. It is estimated that the HCFC consumption in Article 5(1) countries in 1996 is larger than the capacity used for production, although the quantity is not substantial.

HFC-134a production has shown a continuous growth over the period 1990 - 1996, with a consumption of about 74 and 84 ktonnes in the years 1995 and 1996, respectively. This represents growth of 45 percent and 13 percent, respectively. The major contributor to this growth has been the refrigeration and A/C sector. The HFC-134a consumption forecast for all applications in the year 2015 equals 207 ktonnes, which is an increase of about 250 percent between 1997 and 2015; this figure includes 174 ktonnes for the use of HFC-134a in refrigeration and A/C. The same growth percentage also applies for the consumption of other HFCs in the 1997-2015 period (forecast consumption of 133 ktonnes in 2015). These growth estimates should be considered against a substantial decrease in HCFC consumption over the period 1997-2015. The HCFC consumption in the developed countries in 2015 is estimated to be only 15 percent of the consumption in 1997.

Domestic Refrigeration

All non-Article 5(1) country manufacturers have transitioned from CFC-12 to non-ODS refrigerants in new equipment. Transitions in the Article 5(1) countries are occurring faster than the Montreal Protocol requirements. Preferred alternatives were assessed for safety, environmental, functional and performance requirements. Broad-based OEM refrigerant alternatives have narrowed to HFC-134a and HC-600a. Both can provide safe, reliable and efficient domestic refrigerators and freezers. Multiple local and national codes, standards and regulations govern the use of domestic refrigeration equipment. Analysis of regional requirements and consumer-selected product differences provides insight into refrigerant selections.

Field repair complexity is expanding with the introduction of new refrigerants which involves several potential issues and original equipment manufacturers should be consulted regarding proper repair procedures for their equipment. Equipment designed for use with CFC-12 should be carefully assessed for safety prior to undertaking drop-in repair, particularly when using flammables. There is a significant difference in field repair rates between developed and developing countries, with estimates of approximately 2 percent and 10 percent, respectively. Differences result from use environment, extended life and uncertain power service, aggressive transport conditions and deficient service technician training. The premium value of capital goods relative to labour expense in many countries promotes component rebuilding by small, decentralised service shops. This has the strategic consequence of extending the use of obsolete materials and components.

Estimated refrigerant consumption for domestic refrigerators grew from about 15.5 ktonnes in 1992 to about 17.7 ktonnes in 1996. CFC-12 represented 99 percent of the 1992 demand versus 60 percent of the demand in 1996. CFC-12 continues to dominate the aftermarket service demand.

Energy efficiency of domestic refrigeration is a subject of accelerating interest. Retirement and replacement of less efficient, older units and extended application of conventional state-of-the-art technology could result in large reductions in global energy consumption. Cumulative new unit energy use reductions up to 70 percent have occurred over the past twenty-five years.

Commercial Refrigeration

Commercial refrigeration includes a wide range of equipment. The refrigeration capacity of centralised systems in supermarkets varies typically from 20 kW to 1000 kW, but for stand-alone equipment the capacities concerned are in the same range as for domestic equipment. In the past five years, significant events introduced changes in commercial refrigeration techniques. In centralised systems, R-502 has been successfully replaced by HCFC-22 and HCFC-22 based blends (R-408A and R-402A/B). The use of these blends provide satisfactory performance and has permitted maintaining and, in some cases, improving energy efficiency of systems.

Stand-alone equipment, particularly small equipment, traditionally used CFC-12; most new equipment uses HFC-134a. Since German manufacturers started to use isobutane (HC-600a) for refrigerators and freezers, some manufacturers in Denmark, India, Sweden and the UK have introduced small commercial equipment using various hydrocarbons. The expected more rapid HCFC phase-out in Europe has led to the choice of R-404A and R-507A in new systems, both in centralised systems (medium and low temperatures) and in stand-alone equipment for low temperature applications. For field-erected systems, due to detergent and hygroscopic characteristics of POE oils, new issues have to be handled by installers and contractors. Those include a lower level of evacuation before charging, better control of moisture content of oil and refrigerant, and better level of leak tightness.

Indirect systems using heat transfer fluids (also called «secondary refrigerants») have been installed in several European countries. These systems are intended to minimise refrigerant charge and consequently should decrease refrigerant emissions, at the expense of lower system efficiency. With proper choice of materials and added safety provisions the use of secondary loops also permits consideration of the use of ammonia or hydrocarbons, in systems located in machinery rooms. Medium temperature systems operating with heat transfer fluids are usually satisfactory but problems arise in low temperature applications. Due to pumping power of heat transfer fluid and to additional difference of temperature at the primary heat exchanger, the indirect systems structure implies higher energy consumption than achievable with direct systems. R&D projects have been developed to enhance the energy efficiency of the secondary circuit. Ice-slurry systems, CO_2 vapour-liquid loop and CO_2 cascade systems complement traditional secondary loops using brines or anti-freeze solutions. Field tests are under way for some of those technical options.

Interesting developments are also appearing in single stage direct expansion systems aiming at minimising refrigerant charge. A new concept, developed in the US and in Europe, consists in installing compressors in the sales area within sound-proofing boxes, and the condensing heat is transferred out of the store by a water cooling circuit.

In some European countries certain industries are supplying units that either use ammonia or hydrocarbons. However, HFC blends as economically preferred refrigerants form the usual choice, due to safety considerations and initial costs. A number of units have been installed to evaluate the advantages and the drawbacks of indirect systems (using a secondary circuit with heat transfer fluids), and new concepts for direct expansion using water cooling, now in operation, are also being evaluated. Other developmental efforts are focused on improving energy efficiency, minimising charge size, and minimising refrigerant emissions. Due to the early CFC phase-out in some Article 5(1) countries and the level of refrigerant consumption (which can be up to 50 percent of the overall country consumption), the activity of repairing CFC-charged equipment may provide the opportunity to replace CFC-12 refrigerants with low- or non-ODP refrigerants.

Cold Storage

The consumption of chilled and frozen food world wide amounts to some 350 million tonnes per year, making cold storage and food processing one of the most important sectors of refrigeration. A variety of applications within the food and beverage industries are served by refrigerating systems ranging from some 50 kW refrigeration effect up to several MW of cooling.

No new refrigerant options have emerged since the last Montreal Protocol assessment. Ammonia has further strengthened its position as the leading refrigerant for cold storage and food processing in many European countries. There is a growing interest in other regions as well, largely driven by new "low charge" technology, which allows a very substantial reduction in refrigerant charge (up to 90 percent in some cases). Transfer of low charge technology, together with increased emphasis on teaching and training in ammonia refrigeration, are regarded as key elements in making ammonia a viable option to replace CFCs in Article 5(1) countries.

HCFC-22 is still the dominant refrigerant in countries with strict regulations concerning the use of ammonia, but a gradual replacement by non-regulated fluids is foreseen from 2000-2005 onwards. In Europe, HCFC consumption for new systems is already declining, as a result of the expected accelerated HCFC phase-out in Europe, and existing national regulations in several European countries. HCFCs represent a cornerstone in reducing the dependency on CFCs in Article 5(1) countries in the short term.

HFCs have relatively low critical temperatures, making cycle efficiencies deteriorate at high condensing temperatures. The performance of air cooled HFC systems in tropical climates, typical for many Article 5(1) countries, has to be adequately addressed. HFCs (mainly HFC-134a, R-404A and R-507A) have gained approximately 10 percent of the cold storage and food processing market in the industrialised world. HFC consumption in Article 5(1) countries is believed to be insignificant. A considerable growth is expected with the phasing out of HCFCs. It is anticipated that R-410A will account for an increasing proportion of the halocarbon market after the period 2003-05, and that it may become the leading industrial fluorocarbon refrigerant in the long term. Using R-410A, the system pressure will be 50 percent higher, therefore special efforts should be made to address the system tightness.

Hydrocarbon units are available and a growing market can be observed in some European countries, although market shares are insignificant so far. Renewed CO_2 technology for low temperatures, e.g. its application in the lower stage of cascade systems and as a secondary refrigerant in indirect systems, has reached the stage of practical application.

Service refrigerants containing HCFCs as well as some HFCs, such as HFC-134a (for CFC-12) and the blends R-404A and R-507A (for R-502), have fulfilled their expectations as retrofit refrigerants. Due to lower costs and simpler retrofit procedures, the majority of retrofits has involved HCFCs. Hydrocarbons may be used with insignificant chemical implications, but flammability restricts their practical applicability. A minor number of conversions to ammonia has occurred in cold storage and food processing.

However, generally retrofit activity has been rather low, and three out of four CFC systems are believed to be still in operation. Refrigerants for service are supplied from recycled fluids and from stockpiled resources. A substantial increase in retrofit activity is inevitable in the near future as industry stocks of CFCs run low.

Compared to industrial refrigeration, cold storage and food processing is a more important sector in the Article 5(1) countries; the refrigerants used include CFCs, as well as the substitutes HCFC-22 and ammonia.

Industrial Refrigeration

Industrial refrigeration covers a wide range of uses and operating conditions within the chemical industry (including petrochemical and pharmaceutical), the oil and gas industry, the metallurgical industry, plastic moulding, and various other uses. System capacities span from some 20 kW up to several MW of cooling, while the temperature range goes from below –100 C (approximately –90 C in conventional systems) to above ambient temperature. Some small special purpose units, e.g. ultra low temperature freezers, may also be classified under this current sector. Most industrial systems are custom made and erected on site; therefore, the refrigerant choice has to be evaluated on a case-by-case basis, whether it concerns a new installation or the retrofit of an existing one.

R-508A and HC-170 have successfully superseded CFC-13 and R-503 in the bottom stage of cascade systems for the lowest temperatures. Near-azeotropic mixtures (e.g. HFC-32/HFC-125 and HFC-125/PFC-218/HC-290) are available for applications previously covered by R-13B1, although with somewhat lower specific capacities. These new fluids can also be applied in retrofits. From approximately -45 C and upwards, the picture is not very different from the one described for "Cold Storage and Food Processing". Ammonia has gained major market shares in those countries where it already had a strong position, particularly in Europe. In other regions only a moderate increase in ammonia has occurred.

Many countries have turned to HCFCs, primarily HCFC-22. However, the use of HCFCs is expected to decline after 2000 (which has already happened in Europe). Most probably, HFCs will be the major successors, leading to a very substantial increase in HFC market shares from the current 10-20 percent. Industrial use of HFCs predominantly involves R-404A and R-507A. These blends have proved to be generally applicable, including in flooded systems commonly used in the industrial sector. In the future, R-410A may become an even more important industrial refrigerant, due to its higher volumetric capacity and a somewhat better cycle performance.

Low charge unit systems with hydrocarbons have achieved noticeable interest for industrial applications in some European countries. However, only a limited number of systems have been installed so far. Combined needs for cooling and heating, which are commonly found in many industries, can be efficiently met by CO_2 in a trans-critical cycle. A possible commercialisation, however, is still 5-10 years away.

HCFC-22 has apparently been preferred in the majority of retrofits. Other common options, which all have proved to be well-suited, include blends containing HCFCs, such as R-401A and R-409A which replace CFC-12 (only in direct expansion systems); the blends R-402A, R-403B and R-408A replace R-502 (in all types of systems). Conversions to HFCs have been successfully performed in a number of cases. The important fluids are HFC-134a (replacing CFC-12) and R-404A and R-507A (replacing R-502).

Hydrocarbons may easily replace CFCs from a technical point of view. However, in practice, most conversions are restricted to systems located in areas where relevant safety measures are already put in place. A limited number of industrial systems has been retrofitted to use ammonia.

Air Conditioning and Heat Pumps (Air Cooled Systems)

On a global basis, air-cooled air conditioners and heat pumps ranging in size from 2.0 kW to 420 kW comprise the vast majority of the air conditioning market. Nearly all of these units use HCFC-22 as the working fluid. An estimated $1700x10^6$ kW of air conditioner and heat pump refrigeration capacity is installed world-wide. Assuming an average charge of approximately 0.3 kg per kW of capacity, those 1700 million kW of installed capacity represent approximately 423 ktonnes of HCFC-22.

Significant progress has been made in developing HCFC-22 alternatives for this category of products since the last Montreal Protocol assessment. The results of current research programs and recent new product introductions indicate that the two HFC blends R-410A and R-407C are the leading candidates to replace HCFC-22 in these categories of products. Unitary equipment using both R-410A and R-407C is already commercially available in some regions of the world. Widespread commercial availability of systems using HFC refrigerants in the developed countries is very likely to occur between 1999 and 2005. At least one promising retrofit candidate is commercially available; the HFC-32/ 125/ 134a zeotropic blend, R-407C. It is likely that HFC-134a will be commercialised in larger capacity (>100 kW) unitary products. Hydrocarbons have seen limited commercialisation in portable air conditioners and de-humidifiers.

Hydrocarbon refrigerants may also be suitable replacements for HCFC-22 in some categories of products: air-to-water heat pumps and possibly very low charge level air-to-air systems. In addition, R-744 (CO_2) is the focus of significant research activities that could result in the commercialisation of trans-critical cycle products within the next 5-10 years. While alternative cycles are important and could have a long range penetration of this market, the impact of these technologies on the HCFC phase-out will be limited by high first costs, commercialisation timelines and long market development intervals.

The estimated demand for HCFC-22 in the Article 5(1) countries is expected to increase nearly three-fold, i.e., to 52,000 tonnes by 2015. This represents nearly 62 percent of the 1996 world demand for HCFC-22 for this category of products. Article 5(1) countries will have a significant need for the transfer of reclamation and retrofit technologies. Technologies, programmes and policies that can accelerate the Article 5(1) countries transition to non-ODP technologies could significantly reduce this demand.

Air Conditioning (Water Chillers)

The continuously growing number of water chillers for air conditioning, in service around the world, uses refrigerants including fluorocarbons (CFCs, HCFCs, HFCs), ammonia (NH_3) and hydrocarbons (HCs). The chillers employing the fluorocarbons dominate in terms of the installed base and new production, due to relatively low initial costs. Because the HCFCs and HFCs are relatively similar to the CFCs physically and chemically, they can often replace the CFCs in new and existing chillers with less extensive modification of chillers and equipment rooms than are required for other replacement refrigerants. However, the ammonia and hydrocarbon chillers are enjoying some growth, particularly in Northern Europe. Interest in ammonia and the hydrocarbons is stimulated, at least in part, by the fact that the HFCs are greenhouse gases for which emissions may be controlled in future (under the Kyoto Protocol).

The largest chillers, those with the highest cooling capacity, employ centrifugal compressors, where the smaller chillers have traditionally employed reciprocating piston compressors. Today, these are being complemented, and in come cases replaced, by screw and scroll compressors.

CFCs were the dominant refrigerants for centrifugal chillers before 1993 when they started to be phased out of production in the non-Article 5(1) countries. Following CFC production phase-out in non-Article 5(1) countries at the end of 1995, replacement or retrofit of CFC chillers has been slower than was forecast in 1993, and the majority of the CFC chillers in service in 1993 are still operating on CFC refrigerants today. This creates a continuing need for CFCs for service of these chillers. This need can only be met from stockpiled or recovered refrigerants. The dominant refrigerants for new equipment today are HCFCs and HFCs. HCFC-22 was the traditional refrigerant in most positive displacement compressor chillers, complemented by ammonia in some applications.

Chillers are used less in Article 5(1) countries than in non-Article 5(1) countries, but the technologies tend to be the same, with the equipment often imported or produced locally in a joint venture with a non-Article 5(1) country chiller manufacturer. Thus, the latest technologies in equipment, refrigerants, and servicing equipment and practices are available to all countries.

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 other types of cooling equipment. Thus, there is less difference seen in the service practices in developed and developing countries than this may be the case for domestic refrigeration.

While consumption of CFCs is permitted in Article 5(1) countries until 2009, their use in new equipment is currently decreasing to permit these countries to benefit from the latest designs and technologies available in the world.

The principal changes since the 1993-1995 are (i) the phase-out of the use of CFCs (particularly CFC-11) in existing chillers has been significantly slower than forecast in 1994, (ii) the use of ammonia in new systems has grown more rapidly than anticipated in 1994, (iii) very low emission chillers are now being installed by all manufacturers, and (iv) hydrocarbon chillers have been introduced in several regional markets.

Transport Refrigeration

Transport refrigeration includes refrigeration in ships, railcars, containers, swap bodies and road transport equipment. It also includes refrigeration and air conditioning on merchant ships, and in buses and railcars. In all segments of transport refrigeration, emission rates can be significant, due to the rough operating conditions; therefore containment and maintenance are very important together with system design improvement.

Most systems that used CFCs in 1994 have been retrofitted or scrapped, except for refrigerated containers and trucks due to the large existing CFC fleets. In ships, most systems use HCFC-22, though R-407C and R-404A are current options. For the future, R-410A is expected to become the dominant refrigerant in this sector.

About half of the 410,000 refrigerated containers still use CFC-12, and half of these will still be in use beyond the year 2003. HFC-134a predominates in new units. The number of refrigerated railcars and swap-bodies remains relatively small; furthermore, there are about 1,000,000 refrigerated road vehicles in use. Half of these still use the refrigerants CFC-12 or R-502. Current new equipment production uses HFC-134a, R-404A, or HCFC-22, and some units with R-410A are already available. Research into hydrocarbon, solar and cryogenic systems is in progress.

Most systems on merchant ships use HCFC-22 and CFC use has declined significantly since 1994. Fishing fleets and naval vessels form a significant part of this sector. The market penetration of bus and railcar air conditioning is increasing, and new equipment changes from HCFC-22 to HFC-134a. Generally, this equipment is characterised by a significant leakage rate. Although, there seem to be huge regional differences, since bus air conditioning is often stated to have relatively low leakage rates.

Generally, HFCs are the preferred future refrigerant options, though there is limited development work on alternatives including hydrocarbons, ammonia, the air cycle and CO_2. HCFC and HFC retrofit options exist for systems in use (only in some cases hydrocarbon options exist). Application of the HCFC retrofit options will be restricted by local legislation in some countries, especially in Europe. There is a need to concentrate on containment, training and efficiency issues, and to accept the imminent non-availability of HCFCs in some countries.

Automotive Air Conditioning

By the end of 1994, all automobile manufacturers had converted mobile air conditioning systems to HFC-134a. Existing vehicles with CFC-12 are expected to have phased out due to "old age" by the year 2008. Overall, the change from CFC-12 to HFC-134a will not only eliminate all ozone layer impact but will also result in a 92 percent reduction in the "global warming impact" of mobile air conditioning. The major issue remaining is to encourage all countries, particularly the Article 5(1) countries, to phase out the use of CFC-12 in automotive air conditioning as soon as possible while, in the meantime, preventing unnecessary emissions to the atmosphere. Accordingly, automobile manufacturers and their international associations have provided information on available retrofit technology, recovery and recycling of refrigerant, service technician training, and current service and retrofit trends; this has already been used in several Article 5(1) Refrigerant Management Plans. The recommendations provided to Article 5(1) countries are based on the successes experienced in developed countries.

Manufacturers of HFC-134a systems are working to improve their designs to minimise refrigerant charge and refrigerant emissions, and to maximise total system energy efficiency. Hydrocarbons and carbon dioxide have been proposed as possible long-term replacements for HFC-134a and are being evaluated. Although concerns exist regarding the potential global warming impact of HFC-134a emissions from mobile A/C, new vehicles are expected to be equipped with HFC-134a until an alternative is developed and commercialised that offers comparable performance and reliability characteristics, and an economically viable global warming advantage.

Heating-only Heat Pumps

Heating-only heat pumps are used for space and water heating in residential, commercial/-institutional and industrial buildings. In industry 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. Virtually all heating-only heat pumps are electric closed-cycle compression type systems.

The majority of heating-only heat pumps in buildings are located in the North of Western Europe. Though most heat pump installations in Japan, USA and Canada are reversible air-conditioners, there is also a considerable number of heating only heat pumps in these countries. It is estimated that the total existing heating-only heat pump stock in the residential, commercial/ industrial and district heating sectors is roughly 1.7 million units, with a total heating capacity of about 13,300 MW. The corresponding figure for industrial heat pumps is 8,500 units, with a total heating capacity of 3,000 MW.

HCFCs are generally accepted as a part of the solution for a rapid CFC phase-out, especially for Article 5(1) countries, and HCFC-22 is the most important refrigerant in this category. Several European countries have regulations on HCFCs in order to phase them out more rapidly than agreed under the Montreal Protocol.

HFCs are at the moment the most important alternative refrigerant for heat pumps, both for new installations and for retrofits. Retrofits have occurred at a lower rate than expected. HFC-134a is applied for retrofitting of existing heat pumps using CFC-12 and for charging of new installations. HFC-134a heat pump technology is considered fully mature for new systems. The demand for HFC-134a as well as for other HFCs is expected to increase in the coming years. R-407C, R-410A and R-404A are currently the most promising HFC blend-alternatives to replace HCFC-22 in new equipment. Units with R-404A and R-407C are already on the market, and R-410A units are expected to enter the market shortly.

Ammonia has -in recent years- attained a small, but growing market share as refrigerant in medium and large capacity heat pump systems in Northern Europe. The phase-out of the CFC production and further technology development, may accelerate its market penetration in Europe, but also in Japan and in the United States.

Hydrocarbon blends, as well as pure hydrocarbons such as propane and propylene, are used in a certain number of residential heat pumps, mainly in Europe. Technology development and improved safety measures have reduced safety hazards and improved public acceptability. The number of hydrocarbon heat pumps is limited, but they are expected to play an increasingly important role in the next years in the small and medium capacity range.

Carbon dioxide is a promising long-term environmentally friendly refrigerant for certain application areas, amongst which heating only heat pumps. The use of CO_2 is being evaluated and some components for CO_2 based systems are already commercialised. The most promising CO_2 heat pump applications are heat pump water heaters and heat pump dryers. Heat pump water heaters are expected to enter the market in the course of the next decade.

The refrigerant volume in use in this sector is estimated at 10,600 tonnes, with 45 percent being CFCs, 42 percent HCFCs, 11 percent HFCs and 2 percent ammonia (base year 1998). Assessments indicate that the total annual refrigerant demand for heat pumps will be about 2,000 tonnes in the year 2005, of which 70-80 percent will be HFCs and the rest will consist of HCFCs, ammonia and hydrocarbons. It can be assumed that, from scrapped and retrofitted heat pump equipment, 40 percent of the refrigerant inventory can be recovered. In this way, approximately 1,400 tonnes of CFCs and 1,800 tonnes of HCFCs can be made available for reuse between the year 1998 and 2005. This would still be only 50 percent of the expected demand for CFCs and HCFCs for servicing of existing heat pump installations during that same period.

Refrigerant Conservation

Until a few years ago, refrigerant conservation was considered to be important only for proper system function. Venting refrigerants during service and disposal was a common practice. The realisation that emissions of CFC and HCFC refrigerants led to stratospheric ozone depletion changed this, and refrigerant conservation is now a major consideration in refrigerating system design, installation, and service.

The benefits of refrigerant conservation include not only environmental protection and improved equipment efficiency and performance, but, in the case of refrigerants that are being phased out, the preservation of dwindling refrigerant stocks. Such stocks often provide the only source of refrigerant for servicing existing equipment. In the case of refrigerants that are substitutes for CFCs and HCFCs, conservation is critical to minimising any environmental (e.g., global warming) or safety (e.g., flammability) impacts that may be associated with the transition away from ozone-depleting substances.

Refrigerant conservation both saves money and is the most direct way to reduce emissions. Techniques to encourage conservation include information dissemination, financial incentives, and direct regulations. Without at least one of these measures, experience shows that refrigerant recovery will not take place.

Refrigerant conservation has several basic elements:

- properly design and install new equipment so as to minimise actual or potential leaks;
- leak-tighten existing systems so as to reduce emissions, both from systems that continue to use CFCs and from systems that are retrofitted;
- improve service practices, including recovery, permitting continued system operation with reduced need to add refrigerant;
- make sure that refrigerant is recovered at system disposal.

Good service practices, including regular leak detection and repair efforts and routine refrigerant recovery each time the system is opened, can significantly reduce refrigerant loss. Training of installers, operators, and service operators is required to accomplish both proper cooling system operation and refrigerant conservation.

Over the past three years, a number of technologies and practices for improving refrigerant conservation have been developed and implemented. In several countries, equipment is now being built to be more leak tight than it was five years ago, and leak detection and repair is being implemented regularly.

In the developed countries, the number of recovery equipment models has significantly increased over the last three years, and recovery techniques have reached maturity. Standards have been written in order to measure the performance of equipment, and methods have been developed to make recovery more efficient. Refrigerant removed from a refrigerating system may be returned to the same system after recycling. It may be required that refrigerant be reclaimed before it can be reused in another system to make sure that the contaminant level will not damage the equipment or degrade its performance. In all cases, refrigerant reuse requires taking measures to avoid mixing refrigerants.

Refrigerant which is too contaminated for reuse will ultimately have to be destroyed. At present, high temperature incineration is about the only practical method of destroying CFC and HCFC refrigerants, but other technologies may emerge in future.

In the Article 5(1) countries, an important priority is maintaining systems in proper operating condition, including tightening up systems by finding and repairing leaks, and to recovering refrigerant when opening the system. In order to be effective, conservation technologies must be matched by technician training and, in some cases, adaptation of technology. In addition, strong government incentives may be necessary to ensure that conservation occurs. Refrigerant conservation through recovery, recycling, reclamation and leak reduction are as important to achieving Article 5(1) controls as replacing CFCs in new and existing equipment.

1 Introduction - Montreal Protocol Process

1.1 Montreal Protocol Developments

In 1981, in response to the growing scientific consensus that CFCs and halons would deplete the ozone layer, 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. The Convention provided a framework for international co-operation in research, environmental monitoring and information exchange.

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 percent of the 1986 levels by the year 1998 and called for a freeze in production of specified halons at 1986 levels starting in 1992. By April 1991, 68 nations had already ratified the Protocol: these countries represented over 90 percent of the 1991 world production of CFCs and halons.

A list of CFCs, halons and other substances as controlled under the original Montreal Protocol and its amendments decided after 1987 (1990, 1992 and 1997) is shown in Table 1.1 (the ODP values represent the current values mentioned in the Annex to the Montreal Protocol).

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 endorsed during the 3rd Meeting of the Parties in Nairobi, 1991; Parties also requested the assessments to be 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).

*Table 1.1 Substances controlled by the Montreal Protocol, status 1998 (ODP values relative to CFC-11) **

	Annex A	
Group I		ODP
CFC - 11	Trichlorofluoromethane	1.0
CFC - 12	Dichlorodifluoromethane	1.0
CFC - 113	1,1,2-Trichloro-1,2,2-trifluoroethane	0.8
CFC - 114	1,2-Dichlorotetrafluoroethane	1.0
CFC - 115	Chloropentafluoroethane	0.6
Group II		
Halon 1211	Bromochlorodifluoromethane	3.0
Halon 1301	Bromotrifluoromethane	10.0
Halon 2402	Dibromotetrafluoroethane	6.0
	Annex B	
Group I		
CFC - 13	Chlorotrifluoromethane	1.0
CFC - 111	Pentachlorofluoroethane	1.0
CFC - 112	Tetrachlordifluoroethane	1.0
CFC - 211	Heptachlorofluoropropane	1.0
CFC - 212	Hexachlorodifluoropropane	1.0
CFC - 213	Pentachlorotrifluoropropane	1.0
CFC - 214	Tetrachlorotetrafluoropropane	1.0
CFC - 215	Trichloropentafluoropropane	1.0
CFC - 216	Dichlorohexafluoropropane	1.0
CFC - 217	Chloroheptafluoropropane	1.0
Group II		
CCl_4	Carbon Tetrachloride (Tetrachloromethane)	1.1
Group III		
1,1,1-Trichloroethane	Methyl Chloroform (1,1,1-Trichloroethane)	0.1

Annex C

Group I

Partially halogenated fluorochemicals (40 compounds including HCFC-21, HCFC-22, HCFC-123, HCFC-124, HCFC-141b, HCFC-142b) all with ODPs of less than 0.12, are defined as transitional substances by the Montreal Protocol under Annex C.

Group II

Hydrobromofluorocarbons (34 compounds with ODPs estimated to vary from around 0.1 up to 1.00)

Annex E

MeBr	Methyl Bromide	0.6

* ODP values are estimates based on the information available when these chemicals were added to the Protocol and they were used to calculate compliance quotas. More recent ODP values are shown in Annex II; these are more indicative of the relative potency of substances to deplete ozone.

Table 1.2 ***Status of Control Schedules as of October 1998***
(After Decisions Taken at the 7th, 8th and 9th Meeting of the Parties)

DEVELOPED COUNTRIES

Annex A - Group I
Chlorofluorocarbons: CFC-11, -12, -113, -114 and -115 (reference level: 1986)

100 % reduction by	**January 1, 1996**

Annex A - Group II
Halons: halon 1211, halon 1301 and halon 2402 (reference level: 1986)

100 % reduction by	**January 1, 1994**

(with possible exemptions for essential uses for both Group I and Group II)

Annex B - Group I
Other fully halogenated CFCs
CFC-13, -111, -112, -211, -212, -213, -214, -215, -216, -217 (reference level: 1986)

100 % reduction by	**January 1, 1996**

Annex B - Group II
Carbon Tetrachloride (reference level: 1989)

100 % reduction by	**January 1, 1996**

Annex B - Group III
1,1,1-trichloroethane (reference level: 1989)

100 % reduction from 1989 levels by	**January 1, 1996**

Annex C - Group I
HCFCs (reference level: 1989): 2.8% of the ODP weighted 1989 CFC consumption,
PLUS the ODP weighted level of the 1989 HCFC consumption

Freeze by	**January 1, 1996**
35 % reduction from base allowable level by	**January 1, 2004**
65 % reduction from base allowable level by	**January 1, 2010**
90 % reduction from base allowable level by	**January 1, 2015**
99.5 % reduction from base allowable level by	**January 1, 2020**
100 % reduction from base allowable level by	**January 1, 2030**

Annex C, Group II
HBFCs

100 % reduction by:	**January 1, 1996**

Annex E
Methyl Bromide

Freeze at 1991 levels by	**January 1, 1995**
25 % reduction from base allowable level by	**January 1, 1999**
50 % reduction from base allowable level by	**January 1, 2001**
70 % reduction from base allowable level by	**January 1, 2003**
100 % reduction from base allowable level by	**January 1, 2005**

Table 1.2 ***Status of Control Schedules as of October 1998 (Continued/...)***
(After Decisions Taken at the 7th, 8th and 9th Meeting of the Parties)

ARTICLE 5(1) - DEVELOPING COUNTRIES

Annex A - Group I
Chlorofluorocarbons: CFC-11,-12,-113,-114, -115 (reference level: average of 1995/97)

Freeze by:	**July 1, 1999**
50% reduction by:	**January 1, 2005**
85% reduction by:	**January 1, 2007**
100% reduction by:	**January 1, 2010**

Annex A - Group II
Halons: halon 1211, halon 1301 and halon 2402 (reference level: average of 1995/97)

Freeze by:	**January 1, 2002**
50% reduction by:	**January 1, 2005**
100 % reduction by:	**January 1, 2010**

(with possible exemptions for essential uses for both Group I and Group II)

Annex B - Group I
Other fully halogenated CFCs
CFC-13, -111, -112, -211, -212, -213, -214, -215, -216, -217
(reference level: average of 1998/2000)

20% reduction by:	**January 1, 2003**
85% reduction by:	**January 1, 2007**
100 % reduction by:	**January 1, 2010**

Annex B - Group II
Carbon Tetrachloride (reference level: average of 1998/2000)

85% reduction by:	**January 1, 2005**
100 % reduction by:	**January 1, 2010**

Annex B - Group III
1,1,1-trichloroethane (reference level: average of 1998/2000)

Freeze by:	**January 1, 2003**
30% reduction by:	**January 1, 2005**
70% reduction by:	**January 1, 2010**
100 % reduction by	**January 1, 2015**

Annex C - Group I
HCFCs (reference level: 2015 consumption)

Freeze by:	**January 1, 2016**
100 % reduction by:	**January 1, 2040**

Annex C, Group II
HBFCs

100 % reduction by:	**January 1, 1996**

Annex E
Methyl Bromide (reference level: average of 1995/1998)

20 % reduction by:	**January 1, 2005**
100 % reduction by:	**January 1, 2015***

* dependent on review of the relevant decision (taken at the 9th Meeting) by the Parties in the year 2003

At their 4th Meeting in Copenhagen, Denmark, 1992, 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 5th Meeting of the Parties in Bangkok, in November 1993, the Parties decided a replenishment of US$ 510 million for the period 1994-1996. At this 5th meeting, the Parties also decided that the feasibility of control schedules for HCFCs in the Article 5 paragraph 1 countries should be investigated (V/19). With the phase-out date approaching, the Parties discussed the definition of those uses of ozone depleting substances which could be classified as "essential uses" under the Montreal Protocol at their 6th Meeting in Nairobi, in 1994. At this 5th Meeting, the Parties also requested studies on the relative effects of accelerated HCFC and methyl bromide controls for the developed countries.

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.

At their 8th Meeting in San Jose, Costa Rica, the Parties discussed the Replenishment of the Multilateral Fund, and decided a total funding of US$ 540 million for the period 1997-1999. Updated and more detailed Terms of Reference for the Technology and Economic Assessment Panel (compared to the original 1989 one) were decided and were given in an Annex to the Meeting Report (see below).

The 9th Meeting of the Parties, held in Montreal in September 1997, had not only to deal with a full agenda, but was also set to commemorate the 10th Anniversary of the Montreal Protocol (signed 16 September 1987). The 10th Anniversary of the Protocol was celebrated by the Meeting of the Parties in a separate session (on 16 September, the International Day for the Preservation of the Ozone Layer); a Tenth Anniversary Colloquium was also organised, which highlighted the achievements under the Protocol in separate sessions on natural sciences, social sciences and technology. The most important topics dealt with by the Meeting of the Parties were related to a strengthening of control measures on HCFCs and methyl bromide; they also considered trade restrictions, a licensing system for imports and exports of controlled substances and several other issues. A phase-out schedule for methyl bromide for both the developed and the developing countries was decided (phase-out in 2005 and 2015, respectively, the latter dependent on the results of a review study to be carried out in 2003); no further changes to HCFC controls were decided (see Table 1.2, for the control schedules valid after the Montreal Meeting of the Parties). The outcome of the 9th Meeting in Montreal clearly shows that the focus of the ozone layer protection under the Montreal Protocol has shifted from the strengthening of control schedules towards managing the use of controlled substances, and towards managing non-compliance (also in data reporting).

The 10th Meeting of the Parties, to be held in Cairo in November 1998, will consider quarantine and preshipment uses of methyl bromide, exports of controlled substances to Article 5(1)Parties, imports of products, the use of process agents and a number of other issues. This meeting also will formally request a study for the determination of the Replenishment of the Multilateral Fund for the period 2000-2002.

The present status (October 1998) is that the Montreal Protocol has been ratified by 167 countries, Parties to the Protocol (the Vienna Convention has been ratified by 168 countries, Equatorial Guinea has only ratified the Convention). The London Amendment has been ratified by 123 Parties and the Copenhagen Amendment by 80 Parties. The Montreal Amendment has been ratified by 2 countries (Canada and Chile) and will enter into force on 1 January 1999 provided that at least 20 instruments of ratification, acceptance or approval have been deposited (or, if this is not the case, 90 days after this requirement has been fulfilled).

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 Science, and on Environmental Effects, a Technical Assessment and 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 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. Since 1993, the UNEP Technology and Economic Assessment Panel (TEAP) has 7 standing Technical Options Committees (TOCs):

(1) **Aerosols, Sterilants, and Miscellaneous Uses** Technical Options Committee
(2) **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
(7) **Economics** 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. A number of specific aspects studied by the TEAP and its TOCs are described below.

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 – 98 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 1993-98 period).

In 1995 a Task Force on CEIT Country Aspects reported to the Parties the specific circumstances of countries with economies in transition (CEITs) with respect to the compliance with the Montreal Protocol. In Vienna, the Parties requested (VII/34) an update report by the end of 1996. This update report was compiled by the TEAP Task Force in the course of 1996 and submitted to the Meeting of the Parties in that same year. It formed an adequate background information for a number of discussions by the Implementation Committee in dealing with non-compliance issues, particularly from countries from the Commonwealth of Independent States, as well as the Baltic countries.

In 1995, a TEAP Working Group on Process Agents drafted a report which was extensively reviewed and submitted to the Open Ended Working Group. On the basis of the information provided, the Parties took a decision "Continued Use of Controlled Substances as Chemical Process Agents after 1996" (VII/10) which allowed to consider the use of process agents as feedstock use for a limited number of years. However, the Parties preferred to further consider the process agent issue after this first report and requested an update report. As a result, a new Process Agent Task Force under the TEAP was established which conducted several meetings in which a report was drafted; this was submitted to the Parties as part of the TEAP April 1997 annual report. Since no further decisions were taken at that stage, the Parties have taken up this issue again in 1998 and are requesting a new report on process agents from a TEAP Task Force in the year 2001.

The 7th Meeting of the Parties in Vienna requested the TEAP to also prepare a report for submission to the 8th Meeting of the Parties, to enable the Parties to make a decision on the appropriate level of the 1997-1999 replenishment of the Multilateral Fund for the implementation of the Montreal Protocol. The Parties directed the TEAP to take into account a large number of aspects of the Montreal Protocol, including all relevant decisions, and to consult with the Executive Committee of the Multilateral Fund and other relevant sources of information during the composition of the report. A Replenishment Task Force was established under the TEAP; this Task Force prepared a report which was part of the June 1996 annual TEAP report. This replenishment report formed the basis for discussions which led to a final decision on the Replenishment of the Multilateral Fund at a level of US $ 540 Million, which decision was taken at the Meeting of the Parties in San Jose, Costa Rica.

In Vienna the Parties also requested the Technology and Economic Assessment Panel *"(e) with regard to its organisation and functioning: (i) proceed with efforts to increase participation of Article 5(1) country experts, subject to budgetary constraints and to improve geographical and expertise balance; (ii) present procedures and criteria for the nomination and selection of members of the Technology and Economic Assessment Panel; (iii) request the secretariat to appoint a small advisory group from both Article 5(1) and non-Article 5(1) Parties to meet with the Technology and Economic Assessment Panel and to report back to the Parties on progress made; and (iv) report to the Parties at the thirteenth OEWG in 1996, including a description of member expertise highlighting relevance, affiliation, country of residence....its methods of operation, including appointment of members to subsidiary bodies, promotion to chair.....options proposed for restructuring the Technology and Economic Assessment Panel and its Technical Options Committees and Working Groups......."*(VII/34). As a result, the Panel met twice with the "Informal Advisory Group", the IAG, chaired by Dr. Kozakiewicz from Poland; the Informal Advisory Group reported back to the Parties that good progress was made in the organisation and functioning of the Panel, and that restructuring of the TEAP was proceeding. As a result, the Panel presented its updated Terms of Reference to the Parties (these are part of the meeting report of the 8th Meeting of the Parties to the Montreal Protocol in Costa Rica, 1996). The TEAP also presented, in each of its annual reports (1996, 1997 and 1998) a disclosure of interests of all its members and an overview of its membership. Currently (status October 1998) the Panel has 23 members (of which three co-chairs) from 17 countries; almost 48% is from Article 5(1) and CEIT countries. The seven Options Committees have at least two co-chairs, one from a developed and one from an Article 5(1) country; both co-chairs are automatically member of the Technology and Economic Assessment Panel.

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 current status is that the SBSTA adopted a paragraph under "Methodological Issues; Emission Inventories" at its 8th Meeting in Bonn, 2-12 June 1998, which states: *"The SBSTA recognised that methodological issues arising from the (Kyoto) Protocol including, for example, guidance for estimating and reporting hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride, need to be evaluated.... 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."*

The request made by the Parties in Vienna on "Control Measures Concerning Halons and Other Measures" (VII/12) was considered by the TEAP and its Halon Technical Options Committee (HTOC); the TEAP and its HTOC subsequently reported to the Parties in the June 1996 annual report. On the "Availability of Halons for Critical Uses" (VIII/17), the TEAP and its Halon Technical Options Committee reported in the April 1997 annual report. In 1996 and 1997, the Parties requested the TEAP to report on questions relating to the feasibility of, and problems with the early decommissioning of halon systems (VIII/17 and IX/29). TEAP and its HTOC reported on this issue in the April 1998 annual report and elaborated on allocated production, annual emissions and inventories, specifically for Western Europe, Australia, North America and Japan.

As a response to a request made in Vienna, 1995, to describe "Options for a Transitional Strategy for MDIs" (VII/34), the TEAP and its Aerosols TOC updated the 1994 information and provided the Parties with it in the June 1996 annual TEAP report. Parties requested more information on the transition in 1996 via "Promotion of Industry's Participation on a Smooth and Efficient Transition Away from CFC-based MDIs" and "Measures to Facilitate a Transition, etc." (VIII/10 and 11); the TEAP and its Aerosols TOC extensively reported on this transition strategy in the April 1997 annual report. In Montreal in 1997, the Parties requested the Technology and Economic Assessment Panel to continue the work on the transition strategy and to submit the final report to the 10th Meeting of the Parties (IX/19). In response to the above mentioned requests by the Parties, the TEAP and its Technical Options Committee issued the "Final Report on Issues Surrounding a Transition to Non-CFC Containing Treatments for Asthma and COPD and National Transition Strategies" in its April 1998 annual report.

In response to requests of Parties on "Trade in Methyl Bromide" (VII/7) and on "Critical Agricultural Use Exemption of Methyl Bromide" (VII/29) information on methyl bromide was provided in the June 1996 annual report. More information was contained in the April 1997 annual report as a response to requests from the Parties concerning information on "Control of Trade in Methyl Bromide with Non-Parties" and "Critical Agricultural Uses of Methyl Bromide" (VIII/15 and 16). At their 7th meeting in Vienna, 1995, the Parties requested a "Review of Methyl Bromide Controls" (VII/8) and requested the TEAP to prepare a report to the 9th Meeting of the Parties, in order to enable them to consider further adjustments to the control measures on methyl bromide. A Methyl Bromide Task Force also prepared a report on the economic feasibility of alternatives to methyl bromide, which report formed part of the 1997 annual TEAP report. The information provided by the TEAP formed the basis for decisions concerning adjusted control schedules for methyl bromide for both the developed and the developing countries. These decisions were taken at the 9th Meeting of the Parties to the Montreal Protocol (the 10th Anniversary Meeting) in Montreal in 1997. As a result, the control schedules for the different substances as currently valid are given in Table 1.2.

As part of the reporting on "Progress" by the TEAP, it was felt necessary to give more information on the use of flammable refrigerants, since this issue has become gradually more important since the introduction of flammable refrigerants in domestic equipment in the years 1992-1993. A subcommittee out of the TOC Refrigeration reported on the use of flammable refrigerants to the TEAP in 1997, and the report has been part of the TEAP 1997 annual report.

Coming back to the three Assessment Panels, the 1995 Vienna Meeting of the Parties to the Montreal Protocol reconvened the 1994 UNEP Assessment Panels, being the Scientific, Environmental Effects and Technology and Economics Assessment Panels. The three international panels were requested to update their reports on:

- the scientific findings and observations regarding stratospheric ozone depletion and related phenomena and issues;
- the environmental and public health effects of stratospheric ozone depletion;
- the technical feasibility and earliest possible date in each of the major use sectors, of reducing emissions and phasing out production and consumption of controlled (ozone depleting) substances and the related anticipated economic concerns.

As far as the dates are concerned, the Parties decided "*to request the three Assessment Panels to update their reports of November 1994 and submit them to the Secretariat by 31 October 1998 for consideration by the Open-ended Working Group and by the Eleventh Meeting of the Parties to the Protocol in 1999.*". Together with the Science and Environmental Effects Assessment reports, the 1998 TEAP assessment report -together with the 1998 TOC assessment reports- forms the direct response to the above-mentioned decision.

The 1998 Technical and Economic Assessment study has been carried out by the Technology and Economic Assessment Panel and its seven Technical Options Committees. The seven Committees consisted of more than 300 experts from a large number of countries (for a list see the annex to the Technology and Economic Assessment Report 1998). The 1998 Technical Options Committees consist of several members of the 1991 and 1994 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.teap.org)

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

This Technical Options Committee 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 1998 assessment work of the Technology and Economic Assessment Panel (requested by the Parties in Vienna (VII/34)). The information collected (particularly in the form of the Executive Summary) will also be part of the Technology and Economic Assessment Report 1998.

The Technical Options Report on Refrigeration, A/C and Heat Pumps has been drafted in the form of a number of chapters (nine chapters on application areas, one chapter on refrigerant conservation, one chapter which gives historic data for refrigerant production and consumption, as well as estimates for future HCFC and HFC production, and annexes, with an important one on thermodynamic properties for all known refrigerants, see below, in section 1.4). The structure of the report was chosen similar to the structure of the 1994 Technical Options Committee Assessment Report.

Table 1.3 ***"Member countries" of UNEP's Refrigeration, A/C and Heat Pumps Technical Options Committee***

Brazil	Italy	Switzerland
Canada	Japan	Thailand
China, PR	Kenya	Tunisia
Denmark	Netherlands	Uganda
France	Norway	United Kingdom
Germany	Russian Federation	United States
India	Sweden	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 1998 Technical Options Committee included 48 representatives from African, Asian, European, Latin and North American governments, universities and companies, as well as independent experts (see Table 1.3). Affiliations of the Committee members are listed in Table 1.4 (about 50 organisations were involved in the drafting of the report). The names of all the experts 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 1997, draft end 1997, draft March 1998, draft June 1998, peer review draft July 1998 and final report October 1998). Preliminary committee meetings were held in Denmark (Aarhus) and in France (Paris) in 1996 and 1997. Drafting and reviewing meetings were held in the United States (Washington D.C.), India (New Delhi), Norway (Oslo), and Germany (Nürnberg) in 1997 and 1998.

As stated, the structure of the Refrigeration Technical Options Committee Report is similar to the Report of the Refrigeration Technical Options Committee in 1994, except for the fact that the report does not contain separate chapters on the aspects of developing countries and on information dissemination and research. With technology proceeding rapidly, the report is no simple update of the 1994 report, but all options described in 1994 are re-examined taking into account the present scale of technological developments.

Table 1.5 Organisations involved in the peer review of the UNEP TOC Refrigeration Report

ARI	*Air Conditioning and Refrigeration Institute*
ASERCOM	*European Association of Compressor Manufacturers*
BIR	*British Institute of Refrigeration*
CCSEE	*Brazilian Industry Council*
DKV	*German Refrigeration Society*
Greenpeace	*Greenpeace International*
IIR	*International Institute of Refrigeration*
JRAIA	*Japanese Refrigeration and Air Conditioning Industry Association*
NOVEM	*Dutch Organisation for Energy and Environment*

The report has been peer reviewed by a number of institutions and associations, each of them reviewing the different sections in a co-ordinated effort in a tight timeframe (see Table 1.5).

Table 1.4 ***Affiliations of the members of UNEP's Technical Options Committee on Refrigeration, A/C and Heat Pumps***

Ammonia Partnership AB,	Sweden
ARI, Air Conditioning and Refrigeration Institute,	U.S.A.
Batam,	Tunisia
Behr GmbH,	Germany
Calm (Consultant),	U.S.A.
Calor Gas Limited,	UK
Carrier Corporation,	U.S.A.
Copeland Corporation,	U.S.A.
CRT Cambridge,	UK
Daikin Industries Ltd.,	Japan
Dehon Service SA,	France
Delphi Automotive Systems	U.S.A.
DTI,	Denmark
DuPont de Nemours, E.I.,	U.S.A.
Ecole des Mines Paris,	France
Elf Atochem SA	France
Embraco SA,	Brazil
FKW Hannover	Germany
General Electric, Appliance Division,	U.S.A.
Haukas (Consultant),	Norway
ICP Ozone, Moscow,	Russia
IEA Heat Pump Centre,	Netherlands
Indian Inst. Technology IIT New Delhi,	India
Int. Institute of Refrigeration IIR,	France
L&E Teknik og Management,	Denmark
Makerere University, Kampala,	Uganda
Matsushita Electric Ind. Corporation Ltd.,	Japan
Matsushita Refr. Co.,	Japan
Maua Institute of Technology,	Brazil
Ministry of Fisheries, Hanoi,	Vietnam
Ministry of Industrial Development,	Kenya
Multibrás SA Eletrodomésticos,	Brazil
Nairobi University, Mech. Eng,	Kenya
Nat. Chemical Laboratory Pune,	India
Nat. Inst. Stand. Technology Boulder,	U.S.A.
Re/genT Co	Netherlands
Sitec Consultancy	Germany
SINTEF Energy Research, Trondheim	Norway
Solvay Fluor und Derivate GmbH,	Germany
Sulzer Friotherm Ltd.,	Switzerland
Sun Test Engineering,	U.S.A.
Technical University Eindhoven,	Netherlands
Tecumseh India,	India
Thai Compressor Manufacturing Co. Ltd.,	Thailand
The Trane Company,	U.S.A.
Unitor Ships Service, Oslo	Norway
University of Trento,	Italy
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 $ 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 60-140 W and contains less than 100-150 g 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.

It is clear that, to date, any technology using CFCs is globally out of date; however, investment in HCFC technology is still subject to strategic considerations on the availability of HCFCs, on the availability of replacement chemicals, on considerations on greenhouse gas emissions from replacements, and above all, on economic aspects of investments in certain equipment (if not considered fully mature) and on aspects of equipment operation. It is obvious, however, that one will observe differences between developed and developing countries. It is therefore maybe not surprising to note that in the USA, the majority of the CFC chillers has not been retrofitted and is still in operation, using recycled or maybe stockpiled CFC material.

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 chapter 2 of the 1994 UNEP TOC Refrigeration, A/C and Heat Pumps report, 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, although not in all, alternatives to HCFCs have become commercially available, mainly as blends of HFCs. As a result, HFCs have currently gained a large share of the replacement market. However, a rational approach to phase out (after the 1996 freeze in the developed countries) the consumption of HCFCs, as transitional chemicals, should allow a minimum time period to permit the industry to develop and commercialise alternatives (which has to date been undertaken from a refrigerant perspective, but only partly from an equipment perspective), and should further allow a rational phasing in of new equipment (i.e. replacements for the HCFC equipment) in order to avoid high obsolescence costs. This particularly relates to the servicing of existing equipment. Too early or premature measures to phase out transitional chemicals could be counter productive because it may encourage users to continue with CFC refrigerants which are still available from various sources (i.e., it implies no incentive for refrigeration equipment manufacturers to invest in non-ODP technology, including HFC and non-fluorocarbon technology). In particular the necessary incentives remain to be provided to Article 5 paragraph 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 1994 TOC Refrigeration assessment report). The larger part of the 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.

As a conclusion, a phasedown schedule for HCFCs has to take into account many different effects. In refrigeration and air conditioning this also relates to obsolescence and long term servicing needs, in fact to confidence at the user level. While not making any recommendation here for certain phase-out schedules, it will be clear that a later phase-out date combined with a low ceiling in the consumption ("cap") will be stimulating conversions more than earlier phase-out dates with a higher ceiling in consumption. An early phase-out date (as e.g. decided in several European countries) will be giving a clear signal 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.

Next to ozone depletion, global warming is the main issue governing the selection of refrigerant chemicals for the near- mid- and long-term. Although this issue is not covered by the Montreal Protocol, it nevertheless forms an important criterion in the ongoing "environmental acceptability" discussion. In all energy related uses, the relation between the CO_2 produced in electricity generation (to operate the product) and the direct global warming of the substitute chemical has to be taken into account. This was already described in the 1989 UNEP TOC Refrigeration report, and, more extensively, in the 1991 UNEP TOC Refrigeration report. AFEAS, the Alternative Fluorocarbon Environmental Acceptability Study, cosponsored by the US Department of Energy, conducted a study in 1990/91 /AFE91/ into the importance of the global warming potential of substitutes compared to the efficiency in the operation of energy related applications. The concept of total equivalent warming impact (TEWI) was developed to combine the effects of emissions of chemicals in various sectors with the indirect effects of energy consumption from the combustion of fossil fuel and electricity production. The summary of this 1991 AFEAS report was attached to the 1991 Options report.

AFEAS, again cosponsored by the Department of Energy, conducted a study "Energy and global warming impacts of not-in-kind and next generation CFC and HCFC alternatives" and published a report in 1994 /AFE94, also Cal93/. Namely, alternative chemicals and technologies had to be considered as substitutes for CFCs, HCFCs, in the use of the vapour compression cycle for refrigeration and air conditioning. In the AFEAS report these included (i) HFCs with a zero ODP for use in conventional vapour compression cycles (ii) hydrocarbons and carbon dioxide based vapour compression cycles (iii) ammonia compression systems (iv) water based vapour compression systems (vi) air cycle and thermoacoustic compression systems (vii) Stirling cycle refrigeration (viii) absorption and adsorption heat pumping and/or refrigeration cycles, and (ix) magnetic and thermoelectric refrigeration.

The AFEAS report examined the 1994 status of each of these technologies and their potential as alternatives to the, at that time, existing technologies based on CFCs and HCFCs. In addition, the report contained an evaluation of the total equivalent warming impacts (TEWI) for those alternative technologies which are close enough to commercialisation that performance data are available. This study presented -in contrast to the earlier publication- comparison data on a 100 year (GWP) time horizon basis. A summary of the 1994 AFEAS report was attached to the 1994 TOC Refrigeration Assessment report; information from the 1994 AFEAS report has also been used in the drafting of this 1998 TOC Assessment report.

In 1997 AFEAS and DOE (Oak Ridge National Laboratory) published the study "Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies". This study was undertaken "to assess the significant developments that have occurred in HFC-blends (i.e. R-404A, R-407C, R-410A and R-507A) and the application of non-fluorochemicals such as hydrocarbons (HCs), carbon dioxide (R-744) and ammonia (R-717) as refrigerants or foam insulation blowing agents. New data made it possible to perform an objective evaluation of the energy and global warming impacts of these "third generation" refrigerants and blowing agents /AFE97/. Analyses were made for end-use applications in North America, Europe and Japan with cultural and technical differences in each region. The results of this 1997 report indicated important regional differences in TEWI for some applications, such as commercial refrigeration and, particularly, mobile air conditioning /AFE97/; non-fluorocarbon options received particular attention here. For further information one is referred directly to the AFEAS report and its executive summary, see also /Mar97/.

The TEWI concept includes direct and indirect global warming effects; it is of a certain value for political decisions. However, it is no criterion to decide upon certain options from an investment point of view since it does not take into account life cycle costs and related investment aspects. It should be combined with a component that considers these issues, if it should determine choices at a user level.

As long as there are no (national) instruments to direct consumers to select equipment and chemicals according to TEWI criteria, it will be the investment rather than the overall global warming effects which will be determining. This was elaborated by Kuijpers in a paper presented for the IIR Conference in Delhi, 1998 /Kui98/ and already earlier in several presentations in 1995-1996. It can be anticipated that, in the near future, more adequate approaches to compare global warming effects against refrigerants chosen and life cycle costs will be developed.

As stated, for the short term, the transitional HCFCs still form a valid, global option for refrigeration and A/C equipment. 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:

1. hydrofluorocarbons (HFCs, HFC-blends with 400 and 500 number designation);
2. ammonia (R-717);
3. hydrocarbons and blends (HCs, e.g. HC-290, HC-600, HC-600a etc.);
4. carbon dioxide (R-744);
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.

Interest in ammonia and the hydrocarbons is stimulated, at least in part, by the fact that the HFCs are greenhouse gases for which emissions may be controlled in future However, safety aspects also imply stringent emission controls for ammonia and hydrocarbons. Similarly, energy efficiency research is partly spurred by the role of energy production in carbon dioxide emissions.

Energy efficiency remains an important issue for all refrigeration technologies, and should be considered along with the factors enumerated above, since it is directly related to global warming. Although the global warming aspect does not form a direct issue within the framework of the Montreal Protocol, considerations on energy efficiency and direct global warming will and should play an important role in the selection of future chemicals. 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 1998 TOC Refrigeration Assessment report.

Ozone depletion as it has been addressed via the Montreal Protocol, has always dealt with control regimes for the production and consumption of ozone depleting chemicals. Only a total ban has been considered to eventually result in an adequate environmental benefit in the mid to long term. The current -or future- users of non-ODP chemicals including HFCs (which includes, in fact, the political decision makers) have been "educated" by the Montreal Protocol. They have a different experience than those which have built up experience with the possibilities of phase-outs or emission reductions of man-produced gases (carbon dioxide etc.) under the Framework Convention on Climate Change, UNFCCC /Mar97/. Because of a familiarity with the Protocol mechanisms one often observes a tendency to consider a global ban on HFC consumption which is not consistent or logical under the Framework Convention on Climate Change /Kuj98/. The Convention 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.

On a chemical basis, global warming has been consistently reduced during recent years by a change from CFCs to non-ODP chemicals. It is often mentioned that any further reduction should be compared with the original global warming of the chlorine containing compounds. Particularly the chemical industry (HFC manufacturers) questions the fact that CFC emissions are not taken into account in baseline scenarios for the Kyoto Protocol. This would show a significant reduction of the emissions of global warming gases over the period 1986-1996; nevertheless, scientists also state that ozone depletion partly counterbalances the global warming effect of the CFCs, which makes this issue rather complex (the increase in global warming from CFCs is often stated to be offset by about 30% due to ozone depletion). It is maybe right that the Climate Change Convention and the Kyoto Protocol (therefore) only consider gases that are not already controlled and phased out under the Montreal Protocol. These aspects are therefore not further considered in the separate chapters of this report /IIR97/.

1.4.3 Set up of the 1998 TOC Refrigeration, A/C and Heat Pumps report

Chapter 2 presents the historic production and consumption of CFCs, HCFCs and HFCs and uses as sources the data published by AFEAS, and the data reported to UNEP's Ozone Secretariat. It compares these data and draws some conclusions regarding the tendencies. In a second instance, chapter 2 gives estimates for the future production/ consumption of HCFCs and HFCs mainly based confidential data from chemical manufacturers, which were more or less "averaged" to produce non-biased, "objective" estimates for the next 20 year period.

Chapters 3, 4, 5 and 9 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 6 deals with industrial refrigeration and is in fact an update of the chapter in the 1994 TOC Assessment report. Chapters 7, 8 and 11 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 10 describes the options for mobile air conditioning; in a first instance, it deals extensively with HFC-134a, but it also evaluates the potential the options carbon dioxide and hydrocarbons will have. Chapter 12 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.

Annex I analyses the TEWI factor -particularly its usefulness and its limitations- for different scenarios. Annex II lists the representative physical, safety and environmental properties of refrigerants (compare chapter 2 in the 1994 TOC Assessment report).

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.

1.5 References

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2 Recent Global CFC and HCFC Production and Consumption Data; Estimates for Near Future Usage of Fluorochemicals

2.1 Introduction

This chapter provides data on the global production and consumption for CFCs over the period 1986-1996 and for 1989-1996 for HCFCs. Consumption is defined in the Montreal Protocol. These data have been assembled from chemical manufacturer sources (submitted to the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS)) and from data submitted to UNEP by both non-Article 5(1) and Article 5(1) Parties to the Montreal Protocol. Much more information has become available since the 1994 TEAP Assessment, reducing the need for extrapolation compared with earlier versions.

The text highlights uncertainty about specific data.

The CFC and HCFC production and consumption has been allocated between:

- the group of all Article 5(1) countries,
- certain non-Article 5(1) Parties belonging to the OECD group (defined as OECDnA5 in this report, which are the Western European countries, the 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 Central and Eastern European countries).

Using data from several sources (mainly confidential information from fluorocarbon manufacturers) preliminary estimates are given for the global use (and developed country use in several cases) of HCFCs and HFCs during the next twenty years. Section 2.2 describes the data sources for CFC and HCFC production and consumption. Section 2.3 presents available data and makes some observations regarding the use of CFC and HCFC chemicals up to 1996. Section 2.4 presents some estimates for the future use of fluorocarbon chemicals (particularly HCFCs and HFCs).

2.2 Data Sources for CFC and HCFC Production and Consumption

CFC and HCFC production data from the companies that comprise the AFEAS group have been independently audited. These companies are primarily located in the OECDnA5 group of countries (see definition in section 2.1), however, production in Argentina/Brazil/Mexico/Venezuela is also included (see the report: "Production, Sales and Atmospheric Release of Fluorocarbons through 1996, AFEAS, Washington, D.C., 1996).

The AFEAS group also reports an estimation of global production and sales of CFCs, and relies on UNEP data for an estimation of the share of the AFEAS HCFC production and sales in the global production.

The UNEP report "Production and Consumption of Ozone Depleting Substances", issued in September 1997 presents data on consumption and production for each of the Parties through 1995. UNEP/OzL.Pro9/ImpCom/20/3 presents updated information for the year 1995 and also for the year 1996. The September 1997 UNEP report was updated and corrected for inconsistencies by the end of July 1998, and submitted to the Refrigeration, A/C and Heat Pumps TOC. The latter document presents the most current and thorough information available from the UNEP Ozone Secretariat.

From a combination of sources, reasonably reliable trends for CFC and HCFC production and consumption up to 1996 can be derived.

Country programmes have not been taken into consideration, since most do not present data up to 1996.

2.3 Data Analysis

2.3.1 CFC production 1986 - 1996

Table 2.1 presents a summary of the information for the production of CFCs from AFEAS and UNEP sources as specified above.

CFC production data published by AFEAS shows a decrease from 895 (1986) to 77 ODP-ktonnes in the year 1996. The AFEAS group contains some companies in Article 5(1) Countries. The AFEAS Article 5(1) production data can be determined via the UNEP production data. In this way it is possible to calculate the production data for the companies from the developed countries that belong to the AFEAS group (defined as OECDnA5 data, see section 2.1). Subtracting UNEP production data for a country from total AFEAS data yields production data for the OECDnA5. The results show production has decreased from 866 in 1986 to 53 ODP-ktonnes in the year 1996.

Production data for several groups of countries can be determined using UNEP data. Although there have been fluctuations (after making corrections for the years when data were not submitted) in the production in South and Central America, the 1996 consumption is comparable to the 1989-1992 production. On the other hand, production in China, India and Korea has increased from 41 ODP-ktonnes in 1992 to 85 ODP-ktonnes in 1996. However, the total Article 5(1) CFC production seems to have stabilised over the period 1994-1996.

Total global production as reported to UNEP has sharply decreased, from 1071 ODP-ktonnes (1986) to 160 ODP-ktonnes in 1996.

The OECDnA5-production derived from AFEAS is lower than OECDnA5-production data reported to UNEP for the years 1986-1990 and comparable for the years 1991-1995. However, 1996 production reported to UNEP for the OECDnA5 group is significantly lower (36%) than the production that can be derived via the AFEAS data. The reason for this inconsistency is uncertain.

Total Article 5(1) CFC production amounted to 109 ODP-ktonnes in 1996. OECDnA5 CFC production was estimated at 40-45 ODP-ktonnes for the year 1996. Of this amount a maximum of 8 ODP-ktonnes is for essential uses including laboratory and analytical applications) and the remainder is for export. This implies that 145-150 ODP-ktonnes production of CFCs was available for consumption in Article 5(1) or available for illegal import to non-Article 5(1) countries.

2.3.2 CFC consumption 1986-1996

CFC consumption data have been derived for groups of countries from data submitted to UNEP. These groups include four South American Article 5(1) Parties, China, India, Korea, and a group defined as "other" Article 5(1) Parties produce CFCs.

Table 2.2 shows the CFC consumption data for the period 1986-1996. Consumption in Article 5(1) Parties except for China/ India/ Korea is relatively constant. China/India/Korea show a growth from 1986 through 1995 and a decrease in 1996 (mainly due to a sharp decrease in consumption reported by China).

Total consumption reported to UNEP is in reasonable agreement with Table 2.1 for all non-Article 5(1) and Article 5(1) Parties - consumption of 166 ODP-ktonnes in 1996 and production of 160 ODP-ktonnes for 1996.

The OECDnA5 group reports 8 ODP-ktonnes consumption for 1996, which can be attributed to essential use consumption (this is in agreement with production for essential use discussed earlier in this section).

Consumption for Argentina/Brazil/Mexico/Venezuela is at the same level as production. This implies that these countries will export only small quantities, probably to other countries in the region.

Production in China/India/ Korea was smaller than the demand through 1995; this would imply imports from non-Article 5(1) Parties in the order of 0-14 ODP-ktonnes during 1994-1996. It appears that the 30-35 ODP-ktonnes exported from non-Article 5(1) Parties in recent years was largely to Article 5(1) Parties other than China/India/Korea.

The reports indicate that of the total 1996 Article 5(1) consumption of 143 ODP-ktonnes, 109 ODP-ktonnes are produced in these countries. This implies exports of 36 ODP-ktonnes from non-Article 5(1) Parties to Article 5(1) Parties. This is consistent with the figures from 2.3.1. Figures from previous years indicate exports by non-Article 5(1) Parties of 59 ODP-ktonnes (1995), 53 ODP-ktonnes (1994), 71 ODP-ktonnes (1993).

If Article 5(1) Parties continue to produce approximately 110 ODP-ktonnes per year in 1997-1999, non-Article 5(1) exports may decrease rapidly as Article 5(1) Parties reduce consumption after 1999, as required by the Protocol.

Table 2.1 ***Historic production data of CFCs, 1986-1996 (Sources UNEP and AFEAS) (ODP-ktonnes or ktonnes)***

	1986	1989	1990	1991	1992	1993	1994	1995	1996
AFEAS									
AFEAS (kt)[1 2]	976	962	659	605	526	426	234	146	80
AFEAS (ODP-weighted)	895	859	587	544	481	405	221	136	77
UNEP [3] (ODP-weighted)									
Arg/Bra/Mex/Ven	29	24	25	27 (17)[4]	27(17)[5]	31	35	31	24
China/India/Korea/Roman	15	33	35 (21)[6]	40 (26)[7]	41	52	78	78	85
Total Article 5(1) (plus adjustments)	44	57	60	67	68	83	113	109	109
Eastern Europe	107	106	104	84	62	41	43	40	17
OECDnA5 group (incl. S. Africa)	920	879	613	527	461 (449)[8]	360	186	100	34[9]
Total Production (UNEP) A5(1) and Non A5(1)	1071	1042	763	678	591	484	342	249	160
OECDnA5 group(UNEP)	909	869	607	522	457[8]	356	184	99	34
OECDnA5 gr. (AFEAS)	866	835	552	517	454	374	186	105	53
Unallocated	43	34	55	5	3	-18	-2	-6	-20
% OECDnA5 group (UNEP) in total	85	84	80	77	77	74	54	40	21
% AFEAS in total (UNEP)	84	82	77	80	81	84	65	55	48

1 AFEAS normally reports non-weighted ODP production
2 AFEAS data includes production from OECDnA5 group countries and from Argentina/Brazil/Mexico/Venezuela
3 UNEP data contain inconsistencies or anomalies in some reporting years (some adjustments need to be made for an adequate comparison)
4 Mexico did not report data in 1991 (estimated at 10 ktonnes)
5 Brazil did not report data in 1992 (estimated at 10 ktonnes)
6 India and Korea did not report data in 1990 (estimated at 14 ktonnes)
7 India and Korea did not report data in 1991 (estimated at 14 ktonnes)
8 Greece did not report data in 1992 (estimated at 12 ktonnes)
9 After corrections made by UNEP, 30 July 1998, from 39 down to 34 ktonnes

Table 2.2 Historic consumption data of CFCs, 1986-1996 (Source UNEP) (ODP-ktonnes)

	1986	1989	1990	1991	1992	1993	1994	1995	1996
UNEP [1]									
Arg/Bra/Mex/Ven	29	25	26	25	17 [2]	23	28	25	25
China/India/Korea/ Romania	41	63	42 [3]	50 [3]	81	82	88	92	73
Other Article 5(1) countries	54	53	41	40	52	49	50	51	45
Total Article 5(1) (UNEP data)	124	141	109	115	140	154	166	168	143
Central/Eastern Europe (Russian Federation) [4]	141 (100)	136 (99)	116 (99)	50 (39)	50 (37)	40 (30)	31 (23)	27 (21)	16 (12)
OECDnA5 group	788	740	497	436	352	279	149	67	8
Other non-Article 5(1)	17	15	7	5	8	8	3	3	0
Total Consumption (UNEP) Non A5(1)	958	897	626	493	412	329	183	97	23
Non-allocated [5]	12	6	6	2	2	2	0	0	-1
Total Consumption non-A 5(1) and A 5(1) (UNEP)	1082	1038	735	608	552	483	349	265	166
% OECDnA5 in total	72	71	67	71	64	58	43	25	5

1 UNEP data often lacks full data reporting, particularly from developing countries
2 Brazil did not report 1992 data
3 India and Korea did not report the 1990 and 1991 data
4 Consumption in Russia significantly changes after CIS has been formed; consumption reported by Russia is lower than estimated by the TEAP Task Force in 1995; the Task Force estimated for 1994 a consumption by Russia of 34 kt and for all CIS and Baltics 42 ktonnes; estimates for Russia for 1990 and 1992 were 67 and 36 ktonnes, respectively
5 Separate totals calculated from separate UNEP country data; non-allocated implies the difference in the totals calculated and the official UNEP-totals

2.3.3 HCFC production data 1989-1996

Table 2.3 presents a summary of AFEAS and UNEP HCFC production data. HCFC-123 and -124 are not included in AFEAS data, due to AFEAS reporting criteria. However, HCFC-124 production could significantly increase if adopted as an interim replacement for HCFC-141b as a blowing agent.

AFEAS data shows an increase from 12,743 ODP-tonnes in 1989 to 30,822 ODP-tonnes in 1996. The increase from 1994 to 1995 was largely due to an increase in HCFC-141b production, and the increase from 1995 to 1996 was largely due to an increase in HCFC-22 production.

UNEP data shows production for several groups of countries. Argentina/Brazil/Mexico/Venezuela production did not increase from 1992-1995, but increased by 20% in 1996. 1997 data is not yet available. From 1989-1993, production in China/India/Korea increased sharply, but has since stabilised. As a result, the total Article 5(1) production data do not show significant changes from 1994-1996.

UNEP global production data show an increase from 24.7 ODP-ktonnes in 1994 to 26.3 ODP-ktonnes in 1996, a moderate increase of 6%. However, there are inconsistencies in data collection and reporting that may affect the accuracy of the figures. Data were corrected to account for the lack of Japanese data for 1994 and 1995, and the US government data reported by manufacturers differ from the data reported by UNEP.

Comparing the OECDnA5 group production data reported to UNEP with the OECDnA5 production data reported by AFEAS, there is reasonable agreement for the years 1989, 1993, 1994 and 1995 (less than 5% differences).

However, the production data reported to UNEP for the year 1996 is significantly lower than the data reported by AFEAS. HCFC production for OECDnA5 countries reported by UNEP for 1996 is about 15% lower than the one reported by AFEAS. It seems likely that the data submitted to UNEP are not complete, particularly since there is a decrease in HCFC ODP-weighted production from 1995 to 1996, which seems unrealistic. It may be that an update of the data reporting will explain these differences (the same type of inconsistency can also be observed for the year 1992, which has so far been impossible to explain).

The percentage of the global HCFC production that is taking place in the OECDnA5 group of countries amounts to 92-106%, according to UNEP and AFEAS based estimates.

2.3.4 HCFC consumption data 1989-1996

HCFC consumption data have been derived for groups of countries from data submitted to UNEP.

Table 2.4 shows the consumption data for HCFCs for the period 1989-1996. Consumption of HCFCs has been increasing for almost the entire period 1989-1996. The consumption in the countries China/India/Korea is relatively constant during the period 1994-1996 (it cannot be predicted whether this trend will continue after 1996). For "other" Article 5(1) Parties, the increase in consumption is substantial during the period 1994-1996 (95 and 37 percent per annum increase, respectively). A reason for this sharp increase is difficult to explain. It may be related to a conversion from CFCs to HCFCs (since CFC consumption in these countries has not increased, actually decreased during 1994-1996, however by a relatively smaller amount of 10 percent).

As can be observed, the total consumption in Article 5(1) Parties as reported to UNEP has always been substantially larger than the total production in Article 5(1) Parties (with smaller differences for China/India/Korea).

In this report, the total consumption data for all countries have been determined from data for country groups and from totals published by UNEP. If certain inconsistencies (particularly the non-data reporting by Japan in 1994 and 1995) are corrected for, some years production figures are larger than consumption figures (1993, 1994, 1996), for other years consumption figures are larger than the figures for production (1989, 1992, 1995) (6 percent larger). Table 2.4 shows that 1994 and 1995 consumption of HCFCs in the OECDnA5 group of countries is 83 percent of the global total consumption.

Assuming that production in Central and Eastern Europe is not exported to Article 5(1) Parties, 5 - 8 percent of the HCFCs produced in non-Article 5(1) countries is exported to Article 5(1) Parties. This percentage seems reasonable when taking into account that the OECDnA5 group of countries consumes 83 percent of the global production (and Article 5(1) Parties have an 8-10 percent share in the global production).

Table 2.3 Historic production data of HCFCs (tonnes or ODP-tonnes), 1989-1996 (sources UNEP and AFEAS)

	1989	1992	1993	1994	1995	1996
AFEAS [1]						
AFEAS	229825	289759	318134	359948	398430	435308
AFEAS (ODP-weighted)	12743	16969	20197	24618	28422	30822
UNEP [2] (ODP-weighted)						
Arg/Bra/Mex/Ven	353	475	461	452	421	505
China/India/Korea/ Romania	249 [3]	731	1212	1840	1877	1831
Total Article 5(1) (plus corrections)	602	1206	1673	2292	2298	2336
Eastern Europe	1084	267	172	198	184	74
OECDnA5 (incl. S. Afr.)	12181	12469	10078 [4]	20220	25335 [9]	26264 [9]
Total A5(1) & Non A5(1)	13867	13942	11923	22710	27817	28674
Total (UNEP) adjusted A5(1) & Non A5(1)	13867	13942	20875 [4]	27266 [5]	30180 [6,7]	28674
OECDnA5 gr (UNEP)	12181	13232	18946	24689 [5]	27641 [6,7]	26264
OECDnA5 gr (AFEAS)	12390	16494	19736	24166	28001	30317
Unallocated	-209	-3262	-790	523	-360	-4053 [8]
% OECDna5 (UNEP) in total	88	95	91	91	92	92
% AFEAS (OECDnA5) in total (UNEP)	89	118	95	89	93	106

1 AFEAS data includes production from OECDnA5 countries and from Argentina/Brazil/Mexico/Venezuela
2 UNEP data contain inconsistencies or anomalies in some reporting years (some adjustments need to be made for an adequate comparison)
3 China did not report data for 1989 (data have not been estimated)
4 USA did not report data for 1993 (data estimated in the OECDnA5 group total)
5 Japan did not report data for 1994 (data estimated from the 1993/96 profile)
6 Japan did not report data for 1995 (data estimated from the 1993/96 profile)
7 OECD data were corrected for the US contribution for 1995 (UNEP mentions 14893 ODP tonnes for 1995 where manufacturers submitted 12503 ODP tonnes to the US government)
8 The difference in 1996 may originate from incomplete data reporting to UNEP (1998 status)
9 After corrections made by UNEP, 30 July 1998, a reduction of 197 ODP-tonnes in 1995, and an increase of 680 ODP-tonnes in 1996

Table 2.4 Historic consumption data of HCFCs, 1989-1996 (Source UNEP) (ODP-tonnes)

	1989	1992	1993	1994	1995	1996
UNEP [1]						
Arg/Bra/Mex/Ven	418	423	642	769	971	866
China/India/Korea/ Romania	991	748	1407	2140	2392	2265
Other Article 5(1) countries	623	591	693	616	1203	1646
Total Article 5(1) (UNEP data)	2032	1762	2742	3525	4566	4777
Central/Eastern Europe (Russian Federation) [2]	564 (437)	316 (267)	258 (172)	228 (107)	259 (84)	195 (73)
OECDnA5 group	10605	12009	15727	21684 [3]	26780 [3]	19780 [4]
Other non-Article 5(1)	290	271	353	469	471	324
Total Consumption (UNEP) Non A5(1)	12152	12641	16392	18214	23338	20300
Non-allocated [5]	693	45	54	-4347	-4172	1
Total Consumption non-A 5(1) and A 5(1) (UNEP)	14184	14403	19134	21739	27904	25077
Total Consumption non-A 5(1) and A 5(1) (calculated plus unalloc.)	14877	14448	19188	26086	32076	25078
% OECDnA5 in total (UNEP plus unalloc.)	71	83	82	83	83	79

1 UNEP data often contains a lack of reported data in several years, particularly from developing countries
2 Consumption in Russia significantly changes after CIS has been formed
3 Japan did not report data in 1994 and 1995 (estimated at 4170 ODP tonnes)
4 Decrease in consumption due to decrease in reported EC consumption from 1995 to 1996 (4494 ODP tonnes)
5 Separate totals calculated from separate UNEP country data; unallocated implies the difference in the totals calculated and the official UNEP- totals

2.3.5 HCFC consumption in sectors

According to the 1996 AFEAS data, the largest ODP consumption was in the foams sector (HCFC-141b). Table 2.5 shows some percentages for the different HCFC chemicals for the year 1996, taken from the 1996 AFEAS report.

Table 2.5 Use of the different HCFC-chemicals in the different sectors according to AFEAS, in percentages per chemical and in ODP-tonnes for the year1996

	HCFC-22	HCFC-141b	HCFC-142b	HCFC-124	Total (ODP tonnes)
RAC	84.9%	2.2%	3.0%	48.3%	
Closed cell foam	3.0%	87.6%	91.8%		
Emissive uses	12.1%	-	5.2%	51.7%	
Solvents		9.3%	-		
Others		0.9%	-		
RAC	12670	288	72	52	**13082**
Closed cell foam	445	11644	2274	-	**14363**
Emissive uses	1797	-	161	55	**2013**
Solvents	-	1240	-	-	**1240**
Others	-	124	-	-	**124**
Totals	**14912**	**13296**	**2507**	**107**	**30822**

In ODP-tonnes, the largest use of HCFCs is in the rigid (closed-cell) foam sector. A comparable amount in ODP tonnes is consumed in the refrigeration and air conditioning sector, mainly due to the use of HCFC-22.

Partly based upon this data and trends in production and consumption data described earlier, estimates can be made for future use. As a starting point, the production in AFEAS reported companies of 435 metric ktonnes, or 30.8 ODP weighted ktonnes can be taken.

2.4 Estimates for Future Use of Chemicals

2.4.1 HCFC chemicals

In this section, estimates are given concerning the future global consumption of HCFCs (and HFCs) by using:

- extrapolated data from fluorocarbon manufacturers;
- information from UNEP data reporting;
- data from the 1998 UNEP TOC Refrigeration and Foams Assessment Reports and from earlier TOC reports; and
- assumptions on the replacement of CFCs and HCFCs.

Efforts have been undertaken to estimate the global HCFC consumption for 1997-2015. Several manufacturers provided (on a confidential basis) their best estimates for the consumption of HCFCs (sometimes split up over different application areas). Data on the future consumption of HFCs were also submitted (on a confidential basis). Both data have been used to derive a "best guess" scenario for future global consumption of HCFCs and HFCs, by averaging the different forecasts. HCFC-123 and HCFC-124 production data could not be used since only one manufacturer produces these chemicals (not included in historic AFEAS data either).

The AFEAS reported HCFC production quantity was 435 metric ktonnes for all uses in 1996. Table 2.6 shows the estimated future HCFC use, both globally and for developed countries.

Table 2.6 Estimates of total HCFC consumption and the HCFC consumption in non Article 5(1) Countries (ktonnes) (this table also includes figures for the consumption in the developed countries for refrigeration/ A/C)

Year	Total Consumption	Developed Countries Consumption	Developed Countries Refrigeration / A/C Consumption
1997	404	323	126
1998	412	330	231
2000	387	293	214
2005	258	155	118
2010	204	80	60
2015	163	55	40

It should be noted that the differences between the values submitted by the different manufacturers was large. The values given in the table have been averaged over the data provided. For the years 2005-2015 lowest and highest estimates have therefore been discarded (the year 2015 has been selected since it is the year for when HCFC consumption should be reduced by 90 percent relative to the base allowable level under the Montreal Protocol). In this model the significant decrease in developed countries' consumption of HCFCs after 2000 has been attributed to a phase-out in the production of closed cell foams using HCFC-141b. This aspect is well reflected in Figure 2.1 which illustrates the likely future regional trends in HCFC-141b use for rigid foams.

It should also be observed that the estimates for Article 5(1) consumption (from the difference between the global and the developed countries consumption) are larger than the capacity used for production in 1996, although not substantially. It is uncertain in how Article 5(1) production capacity will grow during 1998-2010, if at all.

It should be noted that the HCFC consumption for refrigeration and A/C uses is assumed to remain at a level of 40 ktonnes in the year 2015 in the developed countries, which may be somewhat over-estimated.

The above model estimates are based upon an approach that takes into account recent experience from the market with certain likely reductions factored in (phase-out of HCFC-141b etc.) known at this stage.

2.4.2 HFC-chemicals

AFEAS, in its 1996 report, published data on the production of HFC-134a (in metric tonnes) and the volume of sales to the Refrigeration/ A/C sector. These are shown in Table 2.7.

Table 2.7 Historic HFC-134a production (ktonnes)

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
Total	0.2	2.2	6.4	26.5	50.4	73.8	83.7
R/ A/C	0.08	2.1	6.0	24.5	46.1	61.3	71.0
% total R/ A/C	41%	97%	93%	92%	92%	83%	85%

Where the table shows a continuous growth in HFC-134a production over the period 1990-1996, percentage growth for the years 1995 and 1996 were 45 percent and 13 percent respectively (with production of about 74 and 84 ktonnes). The major proportion is used in the refrigeration and air conditioning sector, although its share is slightly decreasing in 1995 and 1996 compared to previous years.

Several manufacturers have provided estimates of future consumption of HFC-chemicals, both for HFC-134a and for other HFC-chemicals (HFC blends in refrigeration, HFCs in foams and HFCs in other uses). Results are presented in Table 2.8, both for global total use and for global use in the refrigeration and A/C sector.

Table 2.8 Estimates for HFC consumption (ktonnes) (the table does not take into account consumption of HFCs such as HFC-152a)

	Total HFC-134a	**Total R/ A/C HFC-134a (% in total)**	**Total other HFCs**	**Total R/ A/C other HFCs (% in total)**
1997	87	69 (79%)	10	9 (90%)
1998	103	79 (77%)	18	14 (78%)
2000	127	99 (78%)	29	22 (76%)
2005	163	128 (79%)	77	50 (65%)
2010	187	154 (82%)	110	74 (67%)
2015	207	174 (84%)	133	96 (72%)

The figures show an increase of about 250% over the period 1997-2015 for the use of HFC-134a in all uses (from 87 to 207 ktonnes). The same growth percentages also apply to refrigeration and air-conditioning uses. These growth estimates should be considered against a decrease in HCFC consumption over the period 2000-2015. The use of HFC chemicals other than HFC-134a is also predicted to significantly increase over the period. For the refrigeration and air conditioning sector, the large expected increase in the use of "other HFCs" can be balanced against a decrease in the use of HCFC chemicals.

In Table 2.8, the consumption of certain HFCs such as HFC-152a, has not been included (although this may constitute 40 - 50 ktonnes for 1997-2015). Their consumption has not been reported due to an inadequate set of data.

3 Domestic Refrigeration

3.1 Introduction

All non-Article 5(1) countries and many Article 5(1) countries have completed transitions from CFC-12 applications to ozone-safe refrigerants in new equipment. Article 5(1) country transitions to CFC-free models are occurring in advance of the Montreal Protocol requirements and the predictions of the 1994 Assessment Report of this committee. National transition schedules in Article 5(1) countries are influenced by local regulatory initiatives and the availability of components and resources, including those obtained through the Multilateral Fund. Schedules are also influenced by engineering time to re-design and certify CFC-free models. Local market pressure is still not a strong driver to industrial conversion in most developing countries. Selection of alternative refrigerants involves many factors, such as energy efficiency, product configuration, local regulatory environment, investment capital availability, technology availability and service needs. Technology availability is sometimes facilitated by relationships with partners from developed countries. These, and selected other factors, will be discussed in this chapter to provide the reader an appreciation and awareness of key selection decision criteria. Brief summary comments on refrigerator insulation are included as an Annex because of the critical dependence of refrigerator efficiency on thermal insulation performance.

3.2 New Equipment Alternative Refrigerants

Numerous refrigerants have been assessed as candidate replacements for CFC-12 in domestic refrigerator-freezer applications over the past decade. Alternative refrigerant properties have been previously reported /UNE95/. A summary update is included in the annex of this report. The list of alternatives being broadly considered has now been reduced to two: HFC-134a and HC-600a. No significant new candidates are expected to surface because of the extensive development costs and supply infrastructure requirements. Niche candidates, such as HFC-152a and related blends in China, will continue to receive development effort due to reasons such as regional availability. No new general purpose candidates are anticipated. Various drop-in blends are expected to continue to receive development effort, but their target applications will be after-market service, not new production units.

Successful candidates must have successfully completed comprehensive life-cycle assessments integrating analyses of production, transport, use, service and disposal requirements. Conceptual decision criteria are shown in Exhibit 3.1; candidate application criteria include safety, environmental, functional and performance requirements.

3.2.1 Safety considerations

Minimum product safety requirement benchmarks have been established by the hazard-free characteristics of historic products. These product characteristics have contributed to an infrastructure of local and national codes, standards and regulations which comprise the application environment. Principal among these are safety, performance and energy efficiency. There are a myriad of other regional requirements such as building codes, electrical codes, fire regulations, transportation and warehousing regulations, toxic materials content restrictions, disposal regulations and production site emission constraints. Candidates must demonstrate compliance with this environment under all use and reasonably foreseeable abuse situations. A proper course of action may be to modify selective codes, standards and regulations for compatibility with candidate refrigerants. This will typically require interaction with various special interest groups. It is likely there will be regional differences in criteria which result in regional differences in preferred refrigerants for domestic refrigeration applications. The reader is counselled to complete an assessment of the applicable regulatory situation prior to finalising design alternatives or materials selections. Brief comments regarding product standards are noted below. Application environment criteria are generally established in broader based documents such as building codes, fire codes and transportation codes. These are typically administered on a regional or local basis.

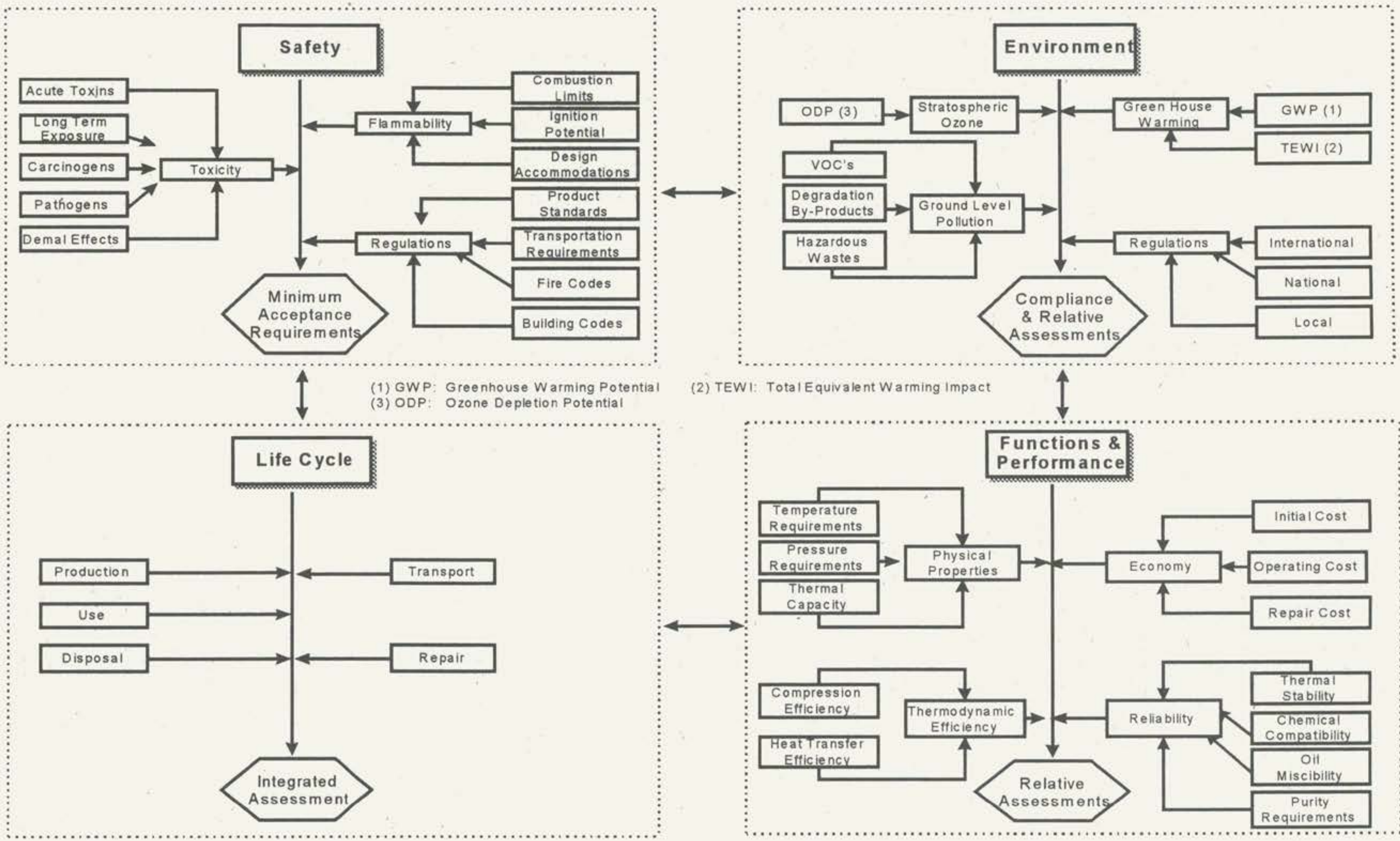

Exhibit 3.1. Conceptual Decision Criteria for Domestic Refrigerator Refrigerants

Refrigerant flammability introduces additional requirements which must be considered as fundamental criteria for the product design and the application environment. Product standards throughout the world are being modified to include minimum requirements responsive to needs introduced by significant differences in the flammability of candidate refrigerants. For reference, ASHRAE Safety Group designations commonly used in the US list HFC-134a as A1 (low toxicity, non flammable) and HC-600a as A3 (low toxicity, highly flammable). Multiple, country-specific regulatory standards exist. These are typically derivatives of the basic refrigerator-freezer standards combinations prevalent in South America and Europe /ISO5149, EN378.1, IEC335/, North America /ASH15, UL250, UL984, UL2182/, and Asia /MITI/. These standards generally apply to OEM unit construction. At least one additional standard /UL2205/ has been developed for after-market service.

General refrigerator-freezer construction type -- fresh food only, freezer only, manual defrost, cycle defrost, auto-defrost -- and, within a general type, the specific evaporator construction used are very significant factors regarding interpretation of the regulatory standards. Understanding these limited design parameters, coupled with an awareness of construction types prevalent in various global regions, should provide the technical reader insight to the underlying reasons for different preferred refrigerant selections in different global regions. Further, understanding general differences in climate, consumer lifestyles and living environments could provide insight regarding why various global regions historically evolved toward particular construction types.

An extended discussion of considerations for the use of flammable refrigerants is contained in an April 1997 UNEP report addressing the topic /TEA97/. To ensure awareness of possible hazards with first order homogeneous mixing assumptions it is recommended that individuals conducting risk assessments for the application of these materials review ignition studies conducted at Centre d'Energetique, Ecole des Mines de Paris /Clo96/, and in the United States by Underwriters Laboratories /Gro96/ and A.D. Little in co-operation with the Factory Mutual Research Center /Kat96/. These three independent studies substantially agree. Additional refrigerator flammability studies conducted by the University of Karlsruhe and by the U.S. Environmental Protection Agency at Underwriters Laboratories are also appropriate for review. Discussions addressing more comprehensive application considerations may also be of interest, /Aga97, McI95/.

3.2.2 Environmental considerations

Both HFC-134a and HC-600a have zero ozone depletion potential. HFC-134a is a greenhouse gas. HC-600a is a Volatile Organic Compound which may be a local regulatory compliance issue. Effective refrigerant recovery can mitigate both of these concerns. Factors essential to constructing effective refrigerant recovery programs are discussed in Chapter 12 of this report. Applicable regulatory requirements for production and market regions should be assessed for compatibility with the specific application being considered.

3.2.3 Functions & performance

Both HFC-134a and HC-600a will provide safe, reliable, efficient domestic refrigerators and freezers with properly designed units. Their applications are uniquely different, but equally effective. The 1994 Assessment Report of this committee cautioned against the application of flammable refrigerants in no-frost refrigerator-freezers /UNE94/. No-frost products containing HC-600a are now being offered in Europe. Either remote electrical components or the application of premium cost special fans, switches and defrost controls is necessary. Evaporators outside the storage volume (cold wall type) may be desirable to minimise risks or redesign needs /TEA97/.

On a comparative basis, efficiencies obtained with HFC-134a and HC-600a are approximately equivalent /Fis94, Del96, Wen96/. As concluded in a study sponsored by AFEAS and U.S. Department of Energy, “The broad scatter makes it impossible to draw any definitive conclusions and indicate that equivalent efficiencies can be obtained with either refrigerant” /AFE97/. For equivalent capacity, HFC-134a requires 12% greater compressor displacement than CFC-12 and HC-600a requires 80% greater compressor displacement. The reduced gas density of HC-600a reduces gas-borne noise transmission relative to HFC-134a. Conversion to either of these candidate refrigerants will require increased capital and product costs. There are no known systemic reliability problems with properly manufactured refrigerator-freezers applying either type of refrigerant. The millions of units containing each type being produced annually attest to the reliability of domestic refrigerator-freezers containing either of these alternative refrigerants.

3.2.3.1 HFC-134a unique comments

HFC-134a requires a synthetic polyol ester oil and a molecular sieve dryer such as XH7 or XH9. Polyol ester oils are hygroscopic and require enhanced manufacturing process control to ensure low system moisture level. HFC-134a is chemically incompatible with some of the electrical insulation grades historically used with CFC-12. Conversion to the electrical insulation materials typically used for HCFC-22 applications may be necessary. HFC-134a is not miscible with silicone oils, phthalate oils, paraffinic oils and waxes. Their use should be avoided in fabrication processes for components and assemblies which contact the refrigerant. Common use examples are motor winding lubricants, cutting fluids in machining operations and drawing lubricants. Trace levels of contaminants can promote long-term chemical degradation within the system. Careful attention to system cleanliness and avoidance of potential sources for contamination are essential. Fluid incompatibilities can lead to capillary tube plugging in service. The control of fluids and processes to avoid the consequences of capillary tube plugging such as decreased capacity or system breakdown is not technically complex. Tens of thousands of HFC-134a containing units are produced every day. Proper control does require competent manufacturing practices and attention to detail /Swa96/.

3.2.3.2 HC-600a unique comments

HC-600a uses familiar naphthenic mineral oil and a molecular sieve dryer such as XH6. Competent manufacturing processes are required for reliable application but HC-600a does not demand cleanliness control beyond historic CFC-12 practices. HC-600a has a 1.8% lower flammability limit in air, amplifying the need for proper factory ventilation and appropriate electrical equipment standards. This flammable behaviour also introduces incremental product design considerations such as preventing leaking refrigerant access to electrical components, type of electrical components if accessible to leaking refrigerant, avoidance of brazing operations on charged systems (lock-ring joints are commonly used) and more robust protection of refrigerant system components from mechanical damage which could result in refrigerant leaks. Low refrigerant liquid density results in low charge weights which in-turn elevates the required control precision at the refrigerant charge stations. Standards require a 99.5% minimum pure HC-600a. Current manufacturing practice uses 97.5-99.5 % pure HC-600a. These high purities provide both thermodynamic performance and protection against toxicity of probable impurities such as benzene, a carcinogen, and n-hexane, a neurotoxin /OOR95/.

3.2.4 Refrigerator construction characteristics

Key refrigerator-freezer design attributes influencing refrigerant selection are type of unit, storage volume, electrical components located within the storage volume, electrical components located outside the storage volume, and evaporator configuration.

3.2.4.1 Type of unit

The basic type of refrigerator-freezer will influence system pressures, frost build-up, location and type of electrical components, evaporator temperature, consequence of refrigerant leakage, etc. Example variations are shown below.

- Refrigerator alone, freezer alone, refrigerator-freezer
- Manual defrost, cycle defrost, auto-defrost
- Cold wall, hot wall, air side heat exchange
- Forced convection, natural convection

These variations are listed for information only and will not be discussed. They drive the variability in the other design attributes which will be briefly discussed regarding their contributions to refrigerant selection.

3.2.4.2 Storage volume

As storage volume increases, the cooling capacity required increases and, as a result, the quantity of refrigerant required to properly charge the unit increases. Similarly, thermal gradients increase with expanding distance and these dictate when it becomes necessary to convert from natural to forced convection in order to maintain gradients at an appropriately low value for proper food preservation. Storage volume and refrigerant charge determine the maximum potential concentration of leaked refrigerant in a confined space. The type of convection influences the probability of gas stratification within the confined space as well as the need for added electrical components (fan motors, switches).

3.2.4.3 Electrical components located within the storage volume

As unit complexity increases these expand in number and function: cold control, light, switches, defrost heaters, anti-sweat heaters, thermostats, fan motor(s), ice maker, ice dispenser motor, water valve(s), sensors, indicators, etc. Non-passive components increase the required cooling load. To a first approximation, the greater the number of components, the greater the chance of an electrical arc occurring. Higher current switching loads further increase the chance of an electrical arc occurring. Further, many of these components directly influence product performance and present significant design challenge if remote location is desired. If remote location cannot be achieved in a practicable design, significant cost could be involved in upgrading component ratings and performance for regulatory code compliance when applied within the storage volume with HC-600a.

3.2.4.4 Electrical components located outside the storage volume

This attribute has little influence on refrigerant selection unless the components are specifically relocated from a design preferred and historic interior location. In this event, any cost premiums and performance compromises necessary to accomplish the relocation must be integrated within the overall alternative refrigerant selection decision.

3.2.4.5 Evaporator configuration

There are several general types of evaporators commonly used in domestic refrigerators-freezers. Foamed-in-place evaporators, common in Europe, reduce the probability of leaking refrigerant accumulating in the refrigerator-freezer storage volume. Any refrigerant leakage must migrate through the refrigerator liner to enter the food storage compartment. This results in a reduced probability for refrigerant to accumulate within the food storage compartment. In addition to providing a diffusion barrier, the refrigerator liner also shields this type of evaporator from impact or sharp object damage. Alternatively, air side evaporators are located within the food storage compartment. State-of-the-art designs are typically surface-enhanced thin wall aluminium. These are normally shielded by an access cover. Auto-defrost versions have line-of-sight radiant defrost heaters in close proximity to the evaporator. Leaking refrigerant can accumulate within the food storage compartment. The radiant heaters and evaporator fan motors are two readily available high current electrical components with the potential to create an electrical arc.

3.2.5 Refrigerant alternative assessment and selection

Detailed analysis of the proposed application and unique regional situation are essential to properly assess available options. Specific information must be thoroughly reviewed following accumulation of technical information from sources such as refrigerant suppliers, compressor suppliers, product regulatory agencies, refrigerator-freezer trade associations, etc. 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. Refrigerant selection is a strategic business decision, it is not a short-term tactical option.

3.3 Field Repair

Reliable information regarding domestic refrigeration field repair practices, repair frequency and type and quantity of fluids consumption is difficult to obtain. Original equipment manufacturer data refer mostly to early failures during original warranty periods. These are not sufficient to form a comprehensive picture. Following the warranty periods, only a minor fraction of field repairs are conducted by original equipment manufacturer service personnel. The major fraction of out-of-warranty field repairs are conducted by a large number of individual and small company service shops with no established reporting infrastructures.

The premium value of capital goods relative to labour expense in many countries further exacerbates the situation by promoting component rebuilding in small, decentralised service shops. This practice precludes monitoring field repair frequency through after-market service parts flow. The variable quality of field repair resulting from this practice further increases the field repair frequency. This practice is strategically important since it extends the application period for obsolete materials and components. In addition to extending the demand for ozone depleting substances, this extension also maintains demand pressure on the power generation and distribution infrastructure through voiding the opportunity to retire components with energy efficiencies well below current practices.

3.3.1 Field repair practices

Field repair is a general term encompassing service, drop-in, conversion and rebuild options. These options are defined in the glossary of this report. Field repair of new production refrigerator-freezers containing either HFC-134a or HC-600a refrigerant should be restricted to the ***service*** technique using the originally specified refrigerant. Specific training of service engineers and technicians is crucial in order to enable them to master additional requirements of the non-ODS techniques – flammability of hydrocarbons and work discipline for HFC-134a. This circumstance will not be further discussed, nor will the decision to replace the product be discussed. Comments will focus on techniques applied to field repair of CFC-12 containing systems. These options are summarised in

Exhibit 3.2, Field Repair of CFC-12 / Mineral Oil Systems. The reader is cautioned to consult original equipment manufacturers regarding proper field repair techniques for their equipment. If refrigerants and lubricants other than original design intent are to be used with original equipment components, the compatibility of component materials with the proposed alternatives must be specifically reviewed. The refrigerator-freezer product configuration also must be reviewed for compatibility with the intended alternative refrigerant. This assessment should be performed by personnel familiar with the specific design criteria employed. It should not be delegated to a service technician or other individual who is not in possession of in-depth product technical awareness.

3.3.1.1 **Service** *field repair*

This technique uses new or recycled CFC-12 when repairing the unit. The original equipment naphthenic mineral oil or alkyl benzene synthetic oil continues to be used. Any failed components are replaced with parts similar to those used on the original equipment. This technique has been used since CFC-12 containing refrigerator-freezers were introduced in the early 1940's. It is the simplest and most reliable approach, requires no additional training, and will most likely continue as long as CFC-12 is available at a reasonable cost. Options to extend CFC-12 availability through conservation and recycling efforts are discussed in Chapter 12 of this report.

3.3.1.2 **Drop-in** *field repair*

This is an area of high interest because it avoids the dependency on uncertain CFC-12 supply, reduces ozone depleting substance use and offers the potential for economic field repair protocols. *The technique changes the refrigerant without changing the lubricant; the original equipment naphthenic mineral oil or synthetic alkyl benzene oil continues to be used. Any failed components are replaced with parts similar to those used on the original equipment.* There are numerous drop-in refrigerant candidate refrigerants. These range from replacement refrigerant candidates to blends developed to approach volumetric capacity parity with CFC-12. Supply sources range from highly technical multi-national companies to unknown individual entrepreneurs. The refrigerant and refrigerant blends listed in Exhibit 3.2 are examples of candidates from responsible national and multi-national companies. This is not intended to be an inclusive listing. As cautioned above, the original equipment manufacturer should be consulted regarding the compatibility of proposed field repair protocols and materials with their products. Potential concerns include:

Exhibit 3.2 Field Repair Of CFC-12 / Mineral Oil Systems

Field Repair Method	Repair Type	Advantages	Disadvantages
Use virgin or recycled CFC-12 with either: Same compressor and oil or New CFC-12 compressor and new mineral oil	Service	Compressor material compatibility Compressor reliability System performance Minimise service complexity	Cost and availability of CFC-12 good now but future is uncertain
Replace CFC-12 refrigerant with HFC-134a and retain original mineral oil and change dryer	Retrofit	Acceptable performance in specific limited applications	Insolubility issues: oil logging and capillary tube restrictions Performance Material incompatibilities Brazing more critical
Replace CFC-12 refrigerant with HC-600a / HC-290 blend or C1 (HFC/HC azeotrope), retain original mineral oil and ensure flammability safety	Retrofit	Moderate cost Cooling capacity same as CFC-12	Each appliance manufacturer must endorse service procedure (potential flammability issues). National regulations may prohibit.
Replace CFC-12 refrigerant with non CFC "drop-in" alternate: 1. R-401A (HCFC/HFC Zeotrope – MP39); alkylbenzene oil with wear additive	Retrofit	Moderate cost Avoids dependence on CFC-12 availability	Inquire to compressor manufacturers regarding material compatibility and compressor reliability Performance issues on some product configurations Transitional due to HCFC content (excluding R-413A) Possible flammability concerns with R-406A Adds refrigerants to service infrastructure
2. R-406A (HCFC/HC Zeotrope – GHG12); original mineral oil 3. R-409A (HCFC Zeotrope –FX56); original mineral oil 4. R-413A (PFC/HFC/HC Zeotrope –ISCEON49); original mineral oil	Drop-In		

Replace CFC-12 refrigerant with HFC-134a and mineral oil with polyol ester oil. Change XH6 dryer to XH9. Do not change compressor.	Retrofit	Moderate cost	Reduced cooling capacity Service complexity (mineral oil flush) Material compatibility issues Probable capillary tube plugging Brazing more critical
Replace CFC-12 compressor with HFC-134a compressor and polyol ester oil Change XH6 dryer to XH9	Retrofit plus compressor change	Compressor material compatibility Compressor reliability Issues known and understood	High cost Service complexity (mineral oil flush) Some performance degradation
Replace CFC-12 compressor with HC-600a compressor and mineral oil	Retrofit plus compressor change	Compressor reliability and materials compatibility	High cost Each manufacturer must endorse service procedure (potential flammability issues). National regulations may prohibit. Space and compressor availability uncertain

- Incompatibility of polymeric materials within the compressor with a candidate refrigerant having possibly elevated solvency.
- The performance of any given refrigerator-freezer when using alternative refrigerants is almost always unknown. Charge quantities and techniques are example uncertainties.
- Flammable refrigerants introduce considerations which are interactive with the unique product configuration being considered such as leak accumulation potential and access to electrical ignition points.
- Multiple blend options burden the field repair infrastructure with the need to inventory multiple fluids, increased technician training, and possible increased substitution errors.

As CFC-12 availability and cost become more of a concern, some progress is being made in the use of the ***drop-in*** technique. Oceania and Western Europe are the more frequent application locales with interest in the United States and Canada accelerating. Little information is available from the Eastern Bloc, but technical literature infers accelerating interest. Where CFC-12 is still readily available at low cost, there is little incentive to deviate from the ***service*** technique.

3.3.1.3 **Retrofit** *field repair*

These techniques range from simple changing of refrigerant, lubricant and dryer (if required) to extensive changes of compressor, refrigerant, lubricant, dryer, modifying the expansion device, and purging the system to remove residual original equipment materials from the system.

The simple ***retrofit*** technique has little acceptance. It has the lowest cost but it does not retire the risk of subsequent failure. This may be the highest risk option of any field repair technique. Unless an effective way to replace the compressor lubricant and purge the refrigeration system of residual impurities is invented, this will not an acceptable option. Little development effort or attention is being devoted to this option.

HFC-134a and HC-600a are the only practicable refrigerants to consider for the extensive ***retrofit*** techniques which include compressor replacement. As cautioned above, the original equipment manufacturer should be consulted regarding the compatibility of proposed field repair protocols and materials with their products. Potential concerns include necessary changes to the electrical components and their locations, desirable changes to some aluminium evaporators, and whether regulations may prohibit the desired procedure. Technology is readily available to implement this option. Optimum charge level will not be known for either HFC-134a or HC-600a, which will likely result in less than optimum performance. Some additional loss of performance is possible with CFC-12 ***retrofit*** to HFC-134a without including the approximate 10% condenser surface area increase incorporated in original equipment redesigns for sub-tropic application conditions. This would typically only become an issue if application stress approaches sub-tropic conditions.

3.3.2 Frequency of sealed system field repairs

The disperse and uncoordinated nature of the domestic refrigerator-freezer field repair infrastructure results in limited data for the frequency of sealed system field repairs. Committee opinion is reasonably consistent in the following frequency estimates, expressed as annual percentage of installed base:

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

These estimates were used to predict the service refrigerant demand shown in Table 3.1. These estimates predict significant residual demand for CFC-12 following OEM phase-out in Article 5(1) countries. Rationales offered for this significantly higher repair frequency 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, (particularly in the "informal" service network). Additionally, as previously discussed, in many Article 5(1) countries the premium value of capital goods results in compressors being more normally rebuilt versus replaced. This cottage industry rebuilding, with its inherent high quality variability, will also contribute to high repair frequency. In non-Article 5(1) countries the distribution of failures is estimated to be 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 this distribution is estimated to be 3% and 7% respectively.

3.3.3 Field repair concerns

A number of concerns have been expressed concerning field repair of domestic refrigerator- freezers. The following comments are offered on selected items.

3.3.3.1 Zeotrope charging errors

Not considered to be a significant issue with adequate, training and appropriate care. Experience has demonstrated that liquid charging techniques avoid anticipated blend fractionation issues. Standardisation on a regional basis of blends provided for ***drop-in*** repair technique would reduce field risks of technician error.

3.3.3.2 HFC-134a system moisture sensitivity

Favourable production and field service experience in countries such as Brazil, Indonesia, Japan, Malaysia, Mexico, Tunisia and the United States does not indicate any systemic basis for concern regarding HFC-134a system moisture sensitivity. However, the generally informal after-warranty service network introduces concern regarding the adequacy of properly trained service personnel. It is essential to have properly trained service personnel using appropriate service procedures to avoid issues.

3.3.3.3 Flammable refrigerants

Production and field experience in Europe with properly trained technicians using appropriate procedures /EC097/ and properly designed products /IS05149, EN378.1, IEC335/ does not indicate any systemic concerns. Elimination of brazed or soldered joints has been effectively accomplished through the use of reliable lock-ring joints. Knowledgeable technical contributors consistently recommend that domestic refrigerator-freezers designed for use with CFC-12 only be converted or retrofitted for use with flammable refrigerants after careful and proper attention to assure flammability safety. Required reconfigurations may make many candidate retrofits not economically feasible. An extended discussion of this topic is available for the interested reader /Aga97/.

3.3.3.4 Refrigerant purity requirements

This concern is directed toward hydrocarbon refrigerants and recycled refrigerants of all types. All OEM manufacturers using HC-600a refrigerants originally specified 99.5% minimum purity because potential impurities presented performance and toxicity concerns. Several OEM manufacturers now specify the more readily available and lower cost 97.5%, HC-600a. Impurity concerns are avoided through appropriate specifications.

3.3.4 Refrigerant conservation and recycling

Refrigerant recovery during field repair and product disposal situations is frequently cited as an opportunity to reduce emissions of ozone depleting substances and to extend their availability for service. Both objectives are valid and achievable. Service and disposal recovery of refrigerants is being practised in many non-Article 5(1) and Article 5(1) countries. Some of these practices are backed by regulations having severe civil and criminal penalties for non-compliance. Commercially proven technology is available to implement necessary actions using equipment available with a wide range of features and prices. This topic is more thoroughly discussed in Chapter 12 of this report.

3.4 Refrigerant Consumption

The shift in global consumption patterns is shown in Exhibit 3.2. New information has resulted in significant revision to some numbers previously reported for 1992 consumption. These data clearly demonstrate significant differences among global regions in the alternative refrigerant selected to replace CFC-12. General comments follow which elaborate on regional refrigerant choice. Parameters influencing refrigerant choice were discussed in Section 3.2.

3.4.1 Western Europe

Conversion has been fully completed to either HC-600a (approximately 35% of 1996 production) or to HFC-134a. Servicing of CFC-12 systems is generally performed with CFC-12 to date. Simple system retrofit repairs using refrigerant blends such as R-409A or R-413A are endorsed by some manufacturers and are gaining acceptance. At least one large manufacturer favours CFC-12 system service be accomplished through fully retrofitting of the system to use HFC-134a.

3.4.2 Eastern Europe

Conversion in the western part of this region began along with Western European countries and is fully completed to HFC-134a in a number of countries (e.g. Poland, Hungary, Slovenia, Slovakia, Lithuania, Bulgaria). In the Russian Federation, Belarus and Ukraine the larger manufacturers have partially converted their facilities to HFC-134a but continue to produce a significant number of refrigerators with CFC-12. The smaller manufacturers in these countries have not converted yet which also holds for manufacturers in, for example, Azerbaijan and Uzbekistan. For the region as a total it is estimated that 50 to 60% of the total production volume has been converted to HFC-134a. A few companies are reported to be considering or have planned a subsequent conversion to hydrocarbons. Servicing of CFC-12 systems is generally performed with CFC-12 to date. Simple system retrofit repairs to use various refrigerant blends is expected to gain acceptance as CFC-12 availability becomes more limited.

3.4.3 North America

Conversion has been fully completed to HFC-134a. CFC-12 has satisfied field service demand to date, but uncertain availability is a definite future concern.

3.4.4 South America & Central America

Most imported or locally made refrigerators continue to use CFC-12. Within 2 or 3 years most production is expected to shift to HFC-134a with a few models shifting to HC-600a. Short-term service is expected to use CFC-12 with some HFC and/or HCFC blends being considered for the medium term due to uncertain CFC-12 availability.

3.4.5 Asia & Oceania

Australia, Japan, New Zealand, Thailand and Taiwan have completed conversion from CFC-12 to HFC-134a. The limited volume Japanese use of R-502 has been converted to HCFC-22. In addition to the HFC-134a applications, approximately 1% to 2% of Oceania production uses HC-600a. Approximately one-half of Malaysia 1996 production had been converted to HFC-134a with the balance still using CFC-12. China had converted 20% of 1996 refrigerator production from CFC-12 -- 10% to HFC-134a, 8% to HC-600a, and 2%

to an HCFC-22/ HFC-152a blend. Transitions continued in China during 1997 with the more frequent conversion being to HC-600a. One Indian manufacturer introduced limited CFC-12 free units in 1998 using HFC-134a. Both HFC-134a and HC-600a are under consideration as alternatives to CFC-12 for the balance of Indian production and for Pakistan production. Service to date has generally consumed original design intent fluids, with simple system retrofit to use various refrigerant blends gaining acceptance in Australia.

3.4.6 Africa & Mid East

Many nations are in the process of converting from CFC-12 to HFC-134a refrigerant for domestic appliance applications. At least one Turkish manufacturer is using an HC-600a/HC-290 blend. Present information indicates Egypt, South Africa and Tunisia /Kal98/ have completed transition to HFC-134a. Most other countries are also in transition to HFC-134a with a few, generally characterised as having high social political tension, continuing to use CFC-12. Servicing is generally performed with CFC-12 which is readily available at low cost. Conversion to HFC-134a and low quantity imports of HC-600a containing units require the service sector to provide capability for all three refrigerants.

3.5 Developing Country Considerations

In spite of difficulties limiting economy and technology, many developing countries have advanced ahead of schedule in their industry conversions. However, servicing remains a very important issue in these countries, in part due to the extended useful life of appliances and power conditions (power cuts and voltage fluctuations) adversely affecting product reliability. As a result, change of refrigerant charge is likely to occur within the lifespan of a significant proportion of refrigerators.

Servicing is mostly undertaken by the informal sector. Training of service engineers and technicians is necessary to enable them to master additional requirements related with the flammability of hydrocarbons and moisture sensitivity of HFC-134a. Proper handling of HC-600a is crucial to avoid safety risks, while with HFC-134a capillary plugging may occur if moisture is allowed to contaminate the ester oil over certain limits. In addition, the correct oil type must be used in order to avoid compressor breakdown.

These and other issues of concern to developing countries are conveniently discussed throughout the main text.

3.6 Energy Efficiency

The energy efficiency of domestic refrigerator-freezers is a subject of accelerating consumer and regulatory interest in many global regions. Widespread voluntary energy conservation efforts primarily have been driven by the need to avoid investments for energy generation and to avoid excessive peak load electrical demand. The rapid growth of energy demand in developing countries will likely lead to broadened refrigerator energy regulations to reduce peak energy demands and to reduce energy generation capacity investment needs.

Retirement and replacement of significantly less efficient, older, installed units and universal application of already widely practised state-of-the-art commercial technology could result in large reductions in global energy consumption. For example, a typical 1997 U.S. refrigerator-freezer consumes only 30 % of the energy required by a typical 1972 U.S. production model /AHA97/. Similar claims can be made for models produced in several countries. Technology areas expected to be key contributors to further refrigerator-freezer energy efficiency enhancements are discussed below.

Table 3.2 Estimated 1992 And 1996 World Production Of Domestic Refrigerator - Freezers With Corresponding Refrigerant Type

	1992 *					1996				
	OEM Units (million)	**OEM Refrige-rant**	**OEM Use (tonnes)**	**Service Refrige-rant**	**Service Use ** (tonnes)**	**OEM Units (million)**	**OEM Refrige rant**	**OEM Use (tonnes)**	**Service Refrige-rant**	**Service Use (tonnes)**
Western Europe	16.3	CFC-12	2275	CFC-12	70	11.0	HFC-134a	1200	CFC-12	40
						6.0	HC-600a	400	HFC-134a	
									HC-600a	
Eastern Europe	7.5	CFC-12	1500	CFC-12	225	5.5	CFC-12	300	CFC-12	200
							HFC-134a	340	HFC-134a	30
North-America	11.6	CFC-12	1750	CFC-12	130	13.1	HFC-134a	2400	CFC-12	115
									HFC-134a	30
Central/ South-America	4.0	CFC-12	600	CFC-12	970	7.7	CFC-12	1200	CFC-12	1200
Asia & Oceania (sub-total 19.2)										
Japan	7.0					18.5	CFC-12	3000	CFC-12	3000
S.E.-Asia (incl India)	6.5	CFC-12	3160	CFC-12	3160	12.5	HFC-134a	2000	HFC-134a	110
Oceania (Austr. NZ.)	0.7	R-22	75	R-22	15	1.0	R-22	150	R-22	30
China	5.0					0.2	HC-600a	20		
						1.0	Other	100	Other	10
Africa & Mid-East	5.2	CFC-12	840	CFC-12	840	4.6	CFC-12	800	CFC-12	800
						0.9	HFC-134a	150	HFC-134a	15

TOTAL WORLD	63.8	R-22 CFC-12	75 10125	R-22 CFC-12	15 5395	82.0	CFC-12 HFC-134a HC-600a Other	5300 6090 420 250	CFC-12 HFC-134a HC-600a Other	5355 210 10 40

*/UNE94/
** Re-estimated 1992 Service Demand consistent With 1996 Assumptions

3.6.1 Improved compressor efficiency

Continued compressor improvements are expected to be incremental, as opposed to quantum, improvements. Diminishing returns are being influenced in-part by the cost-to-benefit ratio of precision tolerance manufacturing techniques required for improvement. Design efforts for further improvements are focused towards :

- Mechanical optimisation through reducing friction at all bearing load surfaces and exploring construction materials with conductivity optimised to provide thermal isolation or improve thermal dissipation.
- Electrical changes to enhance motor efficiency such as winding slot shape optimisation, winding slot fullness percentages, and the use of lower speed motors with larger displacement compressors to benefit volumetric efficiency through improved gas compression.
- Lubrication studies to lower bearing friction and seal critical gas compression areas while also improving efficiency through improved fluid heat transfer providing cooler operation. Lubrication improvements coupled with optimised bearing designs are allowing the use of lower viscosity oils which reduce parasitic losses through reduced viscous drag.
- Gas flow optimisations through components such as valves, ports and mufflers are minimising pressure drops throughout the compressor and reducing parasitic losses. Careful attention to minimising re-expansion volumes is further reducing parasitic losses.

Continuous refrigeration capacity adjustment through frequency modulation of fixed displacement compressors has been demonstrated by several investigators using inverter controlled drive motors. Two Japanese manufacturers have applied these inverter controlled compressors to mass produced high efficiency models. Annual production volume of these models grew to approximately 700,000 units per year over the 1995 to 1997 period. Energy improvements are variable and are dependent on the specific application refrigerator design characteristics. Product noise level modulation with capacity modulation is another attribute of these inverter controlled compressors. High cost-to-benefit ratio and distinctive noise variability hamper universal application of inverter controlled compressors, but global expanded use of this technology for improved energy efficiency is expected to occur.

Concepts to explore the application of significantly higher efficiency linear motors applied to free-piston compressors are in a preliminary research phase with unresolved concerns involving gas bearing reliability which must be answered prior to any commercial considerations. Capacity adjustment of free-piston compressors is conceptually possible with cost-effective voltage modulation, but resolution of the significant linear motor application issues is essential prior to commercial consideration.

Refrigerator-freezer efficiency improvements from any type of capacity modulation will be derived from thermodynamic enhancements and avoidance of pressure equilibration cycle losses. Results achieved are variable with a general enhancement estimate being about 10%. The reader is cautioned to carefully assess reported results to ensure that benefits are properly allocated and not compounded by variable motor or mechanism efficiencies.

3.6.2 Improved component efficiencies

Incremental efficiency improvements to evaporator and condenser heat exchange efficiencies are expected to continue. Probably the largest opportunity for global efficiency improvement with air side convection heat exchangers is to extend the application of the high efficiency surface configurations already in wide spread use. Extended use of improved efficiency fan motors, particularly evaporator fan motors, similarly leverages enhanced component efficiency benefits already being realised by state-of-the-art manufacturers. Electronically commutated evaporator fan motors offer additional efficiency benefits for forced convection systems, but have constrained applicability throughout the world because of their high cost-to-benefit ratio. Free market dynamics have not been shown to motivate consumers to purchase high efficiency refrigerator freezers. Purchase decisions indicate cost savings from reduced energy consumption have not been sufficient to justify higher initial purchase costs. Artificial drivers, such as government energy regulations or purchase rebate incentives, have been necessary to significantly alter the purchase decision.

3,6.3 Advance vapour compression cycles

The Lorenz and Meutzner cycle continues to be the subject of technology demonstration projects. The system configuration requires dual evaporators and inter-coolers in combination with a zeotropic refrigerant blend to provide cooling in the refrigerator and freezer compartments. As previously reported, efficiency gains as high as 26% have been predicted with simulation analyses /San91/. Experimental demonstration of greater than 20% efficiency improvement versus a CFC-12 conventional system configuration was reported using HCFC/ HFC blends as part of the Sino-US CFC-Free Super-Efficient Refrigeration Project /Fin97/. U.S. patents describe an alternate dual evaporator system configuration utilising an inter-cooled two-stage compressor and a phase separator with a constant boiling pure refrigerant or azeotropic refrigerant blend /Jas90, Day93/. Efficiency improvements are comparable to those predicted for the Lorenz-Meutzner cycle. Both of these approaches are limited to two compartment refrigerator-freezers and are not applicable to the large fraction of global production concerned with single compartment products.

These advance cycles have not been developed to a level sufficient for broad commercial application. Each of these cycles has a unique concern: zeotrope composition control and two-phase heat exchange complications implicit with the Lorenz-Meutzner cycle; and compressor losses implicit to the cycle applying the pure or azeotropic refrigerant. Additional complications anticipated for all advance systems include: acute sensitivity to refrigerant charge level; control systems less tolerant of wide ambient temperature variations and more vulnerable to transient instability; and reduced reliability driven by unproven components and a significantly increased number of hermetic joints. Development efforts on these advance cycles should continue, but they are not ready for commercial consideration. Premature introduction could undermine receptivity for commercial application at a later time following validation of concept feasibility.

3.6.4 Alternative refrigeration technologies

Selected not-in-kind refrigeration technologies, such as Stirling systems, continue to be pursued for special applications or situations with primary application drivers different from conventional domestic refrigerator-freezer application criteria. Example unique drivers are portability or absence of dependence on electrical energy supply. The 1994 report of this committee concluded that all technologies being explored are not energy efficient or cost competitive with conventional vapour-compression technology for domestic refrigerator- freezers /UNE94/. A domestic refrigerator prototype equipped with a Stirling cooler and secondary heat transfer loop was recently reported to have comparable efficiency to analogous vapour compression systems /Ber98/. The development of this system is still in the prototype stage. Cost-effectiveness, reliability and producibility of the Stirling concept in this application has not been demonstrated. Consequently, it is again concluded that alternative technologies do not offer options for replacement of vapour-compression refrigeration in the short or mid term. As a result, an update assessment of alternative, not-in-kind, technologies is not included with this discussion.

3.6.5 Improved insulation

Heat leakage through the cabinet structure dominates efficiency losses in a typical, modern refrigerator-freezer. Improved insulation has received significant research effort to minimise the wall losses which comprise a large fraction of the total cabinet losses. This topic is outside the scope of this discussion but an Annex presenting a brief summary discussion is included with this report because of the critical influence of thermal insulation on refrigerator efficiency. The interested reader is referred to Annex 3.1 of this report.

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Annex to Chapter 3

Refrigerator Thermal Insulation Comments

Heat leakage through the cabinet structure dominates efficiency losses in a typical, modern refrigerator-freezer. Improved insulation has received significant research effort to minimise the wall losses which comprise a large fraction of the total cabinet losses. Two dominant alternatives have emerged to replace the CFC-11 historically used as the blowing agent for refrigerator-freezer insulating foams: the hydrocarbon cyclopentane, and HCFC-141b. Cyclopentane is the primary selection of European manufacturers. HCFC-141b is the primary selection of North American manufacturers. Japanese manufacturers are currently using both substitutes, depending upon the specific application requirements. This selection of different materials for what superficially appears to be the same application in different global regions is driven by complex integration of many differing factors such as:

- Alternative optimisation perspectives for the trade-offs required among product energy efficiency, global warming, ozone depletion, and end-of-life disposal.
- Factory emission regulations and constraints.
- Consumer-driven refrigerator storage volume and dwelling unit floor space requirements.
- Power generation energy sources.

The interested reader is referred to two discussions of selection criteria presented at the 1997 Polyurethane World Congress by individuals respectively employed by major American and German refrigerator-freezer manufacturers /Mel97, Wen97/.

HCFC-141b is an interim solution which is being regulated from existence under the Montreal Protocol. Candidate blowing agents currently being considered to replace HCFC-141b include HFC-134a, HFC-245fa, HFC-365mfc, cyclopentane and CO_2. All of these have zero ozone depletion potential, but have different thermal insulation properties, and differences in other application parameters such as cost, process requirement, investment needs, etc. Availability of these candidates ranges from developmental compound, not yet commercially available, to readily available. Comprehensive information, including toxicity assessment, is not yet available for all of these HCFC-141b blowing agent alternatives, prohibiting definitive informed comment at this time. A preliminary comparison of various application parameters is shown in the Table below /Alb97, Bro97, Dee98, Doe97, Haw96, Zip97/. Caution should be exercised when applying these data to decision analyses since relative performance results may vary with specific regional foam formulations. Toxicity is not included since any confirmed issue will result in rejection of the alternative for this food storage application.

Blowing Agent Comparisons *

Characteristic	**HCFC-141b**	**HFC-134a**	**HFC-245fa**	**HFC-365mfc**	**Cyclopentane**
Ozone Depletion Potential	0.11	0	0	0	0
Global Warming Potential (100 yr.)	630	1300	820	840	11
Foam Thermal Conductivity Index	100	117	101	102	113
Refrigerator Energy Use Index	100	112	101	Not Available	110
Relative Foam Aging Rate	Base	Worse	Better	-	Worse
Flammability	Marginal	No	No	Yes	Yes
Density Index	100	108	98	-	119
Compressive Strength Index	100	100	98	-	120

* /Alb97, Bro97, Dee98, Doe97, Haw96, Zip97/

Fibreglass is still a popular insulation material for low-end refrigerators in some Article 5(1) countries. Fibreglass is gradually being replaced by polyurethane-based technology as redesign for new, more energy efficient models occurs.

Vacuum insulation panels continue to be a frequently cited opportunity to improve energy efficiency of refrigerators and freezers. Performance, reliability and cost trade-offs versus other energy efficiency improvement alternatives has, to date, restricted their application to niche or demonstration products. Broad-based, full-line application of vacuum insulation panels has not been initiated by any domestic refrigerator-freezer manufacturers in the world. As stated in the 1994 Assessment Report by this committee:

> "Vacuum insulation panels are supplements to ... not substitutes for foam insulation, nor do they radically alter the amount or thermal effectiveness of foam required for refrigerator-freezers. They arguably are more properly viewed as energy enhancing assembly components" /UNE94/.

Events since 1995 have borne out this perception. Several manufacturers – American, European and Japanese – have produced limited-quantity, high-end models selectively applying vacuum insulation panels. All refrigerator-freezer applications have used these panels in combination with polyurethane foam insulation. Conceptual developments continue to be actively pursued with limited extensions to commercial process development. Multilayer diffusion barriers, getters, open cell thermoplastic foam or particulate silica fillers, and accelerated performance prediction techniques are areas of focused development. Perception continues to be that high cost to benefit ratios, uncertain long-term reliability and the continuing need for breakthrough fabrication process development restricts consideration of vacuum panels to niche application opportunities.

Accelerating product energy standards and additional environmental regulations in many regions of the world could dictate alteration of current assessment criteria and thereby change current regional perceptions of the optimum candidate, or significantly influence choices in regions with no current prejudice regarding the choice. Techniques such as the TEWI analysis discussed in a separate Annex of this report could provide an objective approach to help assimilate the body of knowledge into cohesive strategies appropriate for various environmental circumstances.

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4 Commercial Refrigeration

4.1 Introduction

Commercial refrigeration is composed of 3 different families of equipment:

- **Stand-alone equipment** where all the components are integrated: wine coolers, beer machines, ice cream machines, all kind of display cases sold as stand-alone equipment. Sometimes they are called plug-in systems or self-contained.

- **Condensing units** separated from the cooling (evaporator) equipment; which can be a small cold room, process equipment or a vending machine. A condensing unit is composed of one (or two) compressor(s), a condenser and a receiver and it may be in a remote location or a machinery room.

- **Central systems** where compressors are located in a machinery room. Two systems are typical: direct and indirect systems.

  * **Direct systems** are widespread and easy to design. The refrigerant circulates from the machinery room to the sales area, where it evaporates in display cases. It then returns in gas phase to the suction port of compressors.

  * **Indirect systems** are composed of primary heat exchangers where a heat transfer fluid is cooled down, pumped towards the display cases where it recovers heat and then comes back in the primary heat exchanger.

Central systems are found in all kinds of supermarkets. It is possible to gather numbers on those commercial facilities. Interest in the refrigerating system by owners has been renewed due to the change of refrigerants.

The picture is different for stand-alone equipment and condensing units.

Condensing units are usually installed by contractors in a great variety of shops, convenience stores,... The data of refrigerant bank and energy consumption are uncertain. Considering the issues involved in options for new and existing equipment, condensing units follow the trends presented by central systems.

Stand-alone equipment could either be bought or rented and no special attention is paid to the refrigeration system by the end-user. Only companies which install and maintain this equipment have the knowledge on the refrigerant used.

Stand-alone equipment, freezers, all kinds of small equipment are used in many Article 5(1) countries. Many technical issues of small commercial equipment are similar to those encountered for domestic refrigeration and the reader will take advantage of information given in the relevant chapter of this report.

Medium and Low Temperature Applications

For all these systems, two levels of temperatures (medium temperature for preservation of fresh food and low temperature for frozen products) suggest the use of different refrigerants.

Fresh products are maintained in the range of 1°C to 10°C and up to 14°C but the evaporating temperature for the equipment varies between -15°C and -6°C depending upon a lot of factors: the type of product, the type of display case (closed or open); the type of system (direct or indirect) and the distance between the display cases and the machinery room. The CFC and HCFC refrigerants for medium range temperatures are CFC-12, R-500, R-502 and HCFC-22.

Frozen products are kept at different temperatures (from -12°C to -18°C) depending on the countries. Ice creams are kept from -20°C to -22°C. Usual evaporating temperatures are in the range of -35 to -40°C. The CFC refrigerant was R-502; HCFC-22 and R-404A are now widely used.

4.2 Data on Systems and Refrigerant Charges

Commercial refrigeration structures are very different, even in neighbouring countries due to very different consumption habits, regulation of opening hours, leadership of brand names and wealth of people. Even the definition of supermarket varies. In this document a supermarket is a store selling mainly food and having a sales area surface between 400 m^2 and 1,500 and up to 2,500 m^2 in certain countries. Very large supermarkets also exist with a total sales area surface larger than 20,000 m^2 but the food sales area represent around one third of this surface.

Structure of Food/Beverage Sales Areas

In Table 4.1, numbers for Europe, United States and Japan are based on specific studies while for the rest of the World, numbers are only estimations.

Table 4.1 Number of supermarkets

	Europe[EUR97]	USA[ADL96]	Japan	Rest of the World
Number of Supermarkets	44,000*	30,000	18,000**	*23,000*

* of which 4 000 having a sales area > 2 500 m^2 [EUR97] ** of which 2 700 having a sales area > 1 500 m^2

Display cases, vending machines are installed in a great variety of other sales areas: small traditional stores, convenience stores, gas stations,... of which the sales area surface is smaller than 400 m^2. As a consequence, the number of stand-alone equipment is rather difficult to evaluate even in non-Article 5(1) countries. Table 2 gives the best evaluation based on available data.

Table 4.2 **_Evaluation of the number of commercial equipment._**

	Europe[EUR97]	USA[ADL96]	Japan	Rest of the World
Centralised Systems	44,000*	30,000	18,000	*23,000*
Condensing Units	1,000,000	870,000	382,000	*600,000****
Stand-alone Display Cases	2,400,000	2,100,000	3,500,000	*2,000,000*
Miscellaneous	-	7,250,000**	6,000,000	

* limited data availability implies that the number of centralised systems in table 4-2 is the same as the number of supermarkets which is not completely adequate (some supermarkets are running only with condensing units).
** including 1,200,000 of ice-makers. *** of which at least 300 000 are listed in Brazil

Energy Consumption

Studies performed in France and in Japan indicate that the average annual energy consumption of supermarkets is between 600 kWh/m^2 and 1 MWh/m^2 per year /PIC96/, the high consumption range corresponding to some Japanese stores. 35% to 44% of the consumption is due to refrigeration.

Table 4.3 **_Sharing of the energy consumption of refrigeration /PIC96/._**

Energy use	Energy consumption (%)
Compressors	58
Lighting inside display case	24
Ventilation and defrosting	18
Total	**100**

Table 4.3 shows that energy consumption of display cases includes lighting, ventilation and defrosting which represent 42% of the energy consumption of the refrigeration equipment in supermarkets.

Energy Efficiency

Energy efficiency of these refrigeration systems depends on the temperature range. Various measurements performed on site show refrigeration coefficient of performance between 1 and 1.5 for low range temperatures (cycles -40°C/+40°C or +50°C). For medium range temperatures (cycles -15°C/+40°C or +50°C) the COPs vary between 2.4 and 2.8. For high temperatures met under tropical climates, energy efficiency is in the low range value. The global energy efficiency of the system is linked to several parameters: pressure losses related to the circuit length, system control, and condensing pressure. Policies for reduced energy consumption have been implemented in various countries and energy labelling of display cases is under study in Europe.

Refrigerants: The Bank

Table 4.4 Refrigerant stock (metric tonnes) for commercial refrigeration.

Europe[EC97]	USA[EPA97]	Japan	Rest of the World
35,000	45,000	20,000	*25,000*

Various documents /AFC98/, /EC97/, /EPA97/, permit an evaluation of the refrigerant bank per type of store. The bank is dependent on the sales area surface and also on the ratio between fresh and frozen food. In developed countries the estimate is that centralised refrigerating systems represent 75% of the total refrigerant charges and small commercial refrigeration equipment represents 25%. In Article 5(1) countries the sharing between centralised systems and small commercial equipment is different and at present the global ratio is around 50% each.

Another important point is the frequency of remodelling or ***refurbishing***. Because remodelling may be an opportunity to refrigerant change the knowledge of frequency can help in the projection of refrigerant change schedule. In developed countries remodelling is done when the equipment is between 7 and 10 years old.

4.3 Options for New Equipment

Options for new equipment depend directly on regulations but also on anticipation of their updating. In Europe, HCFC regulation may become more severe and consequently change to alternative refrigerants for new equipment may be accelerated.

4.3.1 Stand-alone equipment

The principal refrigerant choice for small refrigerating equipment is similar to choices for domestic refrigeration. For instance, wine coolers, water fountains, vending machines primarily use HFC-134a. In UK, Germany, Denmark and Sweden some equipment use various HC blends such as HC-600a/290 in addition to HC-600a. Following most of the European compressor manufacturers, Japan and some other countries such as Brazil, manufacture compressors for refrigerators and small commercial refrigeration systems using HCs for the European market. For specific technical issues on the use of HCs for stand-alone equipment, the reader will refer to chapter 3.

Below are presented options for larger equipment, in particular condensing units:

HCFCs
In Europe, the use of HCFC-22 in new systems is starting to decrease because of the availability of zero ODP solutions and forecasted changes on HCFC regulations. In the US, the shift from R-500, CFC-12, R-502 has been made with HCFC-22.

HFCs
For low temperature applications, R-404A and R-507A are the major options for new equipment in many countries (including Article 5(1) countries).

Compressors using POE oils dedicated to R-404A are available from all manufacturers of hermetic compressors to be used in this application.

For low temperature applications, the energy efficiency of this option is slightly higher than the HCFC-22 option. However, for medium range temperature applications, the energy efficiency is slightly lower.

The energy efficiency of systems using R-404A decreases rapidly when the condensing temperature is higher than 50°C. This point shall be taken into account and condensers shall be oversized in order to limit the decrease of energy efficiency. Also this disadvantage may be counteracted partly by introducing a liquid-gas heat exchanger. This component is not expensive and permits 3 to 4% of energy savings. In Japan, because of this energy efficiency problem with high condensing temperature when using R-404A, R-407C is being investigated.

HCs
A few companies, mainly located in Europe (UK, Sweden, Denmark, Germany and Austria) but also in India and Australia, are charging equipment from about 100 g up to 1.5 kg of HCs (R-600a, R-290 and various blends of R-600a/R-290 or R-290/R-170) in commercial stand-alone display cases.

The limits of HCs charge depends highly on specific standards and national regulations. For example IEC 335-2-24 allows the use of flammable refrigerants up to 150 g but the U.S. ASHRAE 15 in combination with buildings codes forbid the use of HCs in commercial applications and so does French regulation. In the UK, standard BS 4434 limits charges to 1.5 kg (taking into account practical limit) and the use of HCs is prohibited in spaces which contain ignition sources.

CO_2
Stand-alone display case prototypes running with CO_2 have been developed in Norway. These units are single stage systems with water cooled condensation /NEK98/.

4.3.2 Centralised systems

Until 1989, virtually all systems located in machinery rooms were direct expansion. Since 1995, extensive work has been invested in evaluating indirect systems using heat transfer fluids, in particular to lower HCFC or HFC refrigerant charge or to permit their replacement by ammonia or HCs. Direct expansion systems with CFCs, HCFCs or HFCs still represent more than 95% of the centralised systems.

♦ Direct Systems

Technical options for centralised direct expansion systems are based on the same three families of refrigerants as for stand-alone equipment.

HCFCs
Due to update of European regulation the move from HCFC-22 to new refrigerants in new equipment may be accelerated.

HFCs
The use of R-404A is the major option in Europe in low temperature and in medium range temperature refrigeration systems. For medium temperature, HFC-134a is also used but many owners prefer to manage one single refrigerant for all systems located in the same machinery room. R-407C has been tested in a number of cases, but is not considered a major option.

For field erected installations, installers are facing several new problems linked to the use of HFC refrigerants because of new oils to be used with these refrigerants. Because of their detergent and hygroscopic characteristics POE oils require significant changes in several major points of contractors operations:

1. Compatibility of refrigerant and oil with various elastomers used in fittings needs to be checked.
2. New refrigerants imply new specifications for cleanliness of components and in particular copper tubes because of detergent characteristics of POE oils.
3. More complete evacuation is needed to avoid moisture.

Most of these rules are easier to apply to factory-built systems than to field built systems. They require re-training of personnel of small companies. Nevertheless, in Europe, several hundreds of centralised systems operate with R-404A and no significant technical problem has been encountered.

In Japan, equipment manufacturers consider introducing PolyVinyl Ether lubricants to replace POE. Since PVE lubricants have tight hydrolysis proof they can be used like usual lubricants.

HCs
HCs are being used for some direct systems in smaller convenience stores and gas station forecourts within the UK. Depending upon the size of the system, indirect circuits may be required in order to conform to the relevant safety standards.

CO_2
Cascade systems using ammonia at the first stage and CO_2 at the low temperature stage have been developed in Norway and Sweden. In this system CO_2 works as refrigerant and not as heat transfer fluid, and circulates in the sales area, evaporates in the heat exchanger of the display case and circulates back to machinery room in gas phase where it is condensed on ammonia/CO_2 evapo-condenser.

Some prototypes are also developed for single stage systems for medium temperature or low temperature applications [NEK98].

New Developments

One major disadvantage of direct expansion centralised systems is the large refrigerant charge. Average charges are in the range of :

- 1 to 1.5 kg/kW (cooling capacity) for medium temperature; and
- 3 to 4 kg/kW (cooling capacity) for low temperature,

this results in total refrigerant charges varying from 0.3 metric tonne to 1.5 metric tonnes depending on the store sales area.

In the United States and in Europe new solutions have been introduced for minimising the circuit length, refrigerant charge and also increase energy efficiency.

The principle consists of installing condensing units composed of compressor racks and water condensers in sound proofing boxes inside the sales area itself. Condensing heat is extracted out of the store by a water circuit. The water circuit can be cooled on water tower and in this case for non sub-tropical climate the average condensing temperature is lower than those obtained with air condensers since the reference temperature is the wet bulb temperature and not the dry air temperature.

These systems present some significant advantages: reduction of the refrigerant charge by almost 50%, minimisation of pressure losses on the suction line, improvement of the energy efficiency and, because of water cooling, the connecting mode of the condensing heat recovery system is easier.

These new technologies have introduced a significant change in the design of direct expansion systems.

♦ **Indirect systems : HFCs, Ammonia, CO_2 and HCs**

The primary refrigerants used in indirect systems are :

- ammonia: it is estimated that about 50 systems using ammonia are installed in supermarkets in Europe; in Japan, some pilot installations also exist;
- HCs: one German company offers either propylene or propane as primary refrigerant in systems installed in supermarkets; about ten systems are operating with charges of several kilograms of HC. Propane and HC blends systems are also installed in UK and Sweden;
- HFCs: there are also a number of systems using R-404A as primary refrigerant and heat-transfer fluids for the secondary loop.

For systems with heat-transfer fluids (HTF), there is a difference between medium temperature applications and low temperature applications. For the first category, technical solutions have been well known for a long time, in particular for cold production in the food industry and fruit storages where MPG (Mono-Propylene-Glycol) is mostly used. One of the advantages is the minimisation of temperature variations between on/off cycles.

In contrast, for low temperature applications, appropriate heat transfer fluids are new and their number is increasing. However increased viscosity of the heat transfer fluid with decreasing temperature requires significant additional pumping energy to obtain efficient heat transfer in the air coil.

New Developments

Heat transfer fluids require a number of technological improvements. Due to the need to lower energy losses associated with temperature differences within the final heat exchanger, as well as within the primary heat exchanger, two innovative techniques deserve attention:

- several pilot systems have been developed with CO_2 used as heat-transfer fluid. In some cases CO_2 is used with liquid/gas phase change and then CO_2 evaporates partially in the air heat exchanger and is condensed again in the primary heat exchanger;
- solid/liquid phase-change HTF called ice slurries have been developed. This solution is promising since up to 40% out of the ice solid phase remains in a slurry state.

Indeed tests indicate that there is no more temperature variation at the final heat exchanger but the primary heat exchanger requires additional development. Primary heat exchangers with scraped surfaces are expensive and imply a large temperature difference between the ice slurry and the refrigerant. More sophisticated heat exchangers with production of ice slurry by a direct circulation of a water-ethanol mixture in water look promising but their cost is prohibitive for now. Also the energy consumption for stirring ice slurry in order to prevent agglomeration has to be addressed /Kau98/.

In short, ice-slurries systems are subject to R&D efforts and some pilots exist but technical and commercial maturity is not reached yet.

Different issues have to be addressed for indirect systems /COO97/:

1. The initial cost compared to a direct expansion system could be as much as 20% more and the pay-back has to be justified via reduced servicing cost over sufficiently long time periods.
2. For all heat transfer fluids, attention has to be paid to corrosion, food compatibility and flammability. As skilled commercial refrigeration contractors are not so numerous in these domains, training of personnel and updating of practices are significant issues.
3. Attention must be paid to the design of primary heat exchanger for small refrigeration capacity due to refrigerant distribution in the heat exchanger.
4. Energy efficiency. The comparison between direct and indirect systems is complicated because energy efficiency is a moving target for both systems.

   The structure of indirect system implies:

   - an additional difference of temperature because of the heat transfer fluid loop;

- additional energy consumption because of the pumping energy necessary for the fluid circulation.

One of the solutions adopted for limiting the temperature difference is to increase heat exchange surfaces but changes of the system shall remain limited because of related additional costs. Compromises chosen at present imply either energy consumption in the same range as non-optimised direct expansion systems or 5 to 15% energy consumption increase compared to well designed ones.

4.4 Options for Existing Systems

The retrofit options depend on the life time of equipment, the national regulation and prices of refrigerants. Retrofit options are completely different for stand-alone equipment and for centralised systems.

4.4.1 Stand-alone equipment

A general statement for retrofit of sealed stand-alone systems is: when a sealed system is running well, regardless of refrigerant, the best option is to leave things as they are.

When a fully-brazed system needs repairing, as indicated in section 3.3 of the chapter on domestic refrigeration, it is recommended to verify first guidelines by the manufacturer regarding possible refrigerant change implemented during repairing. One of the options is to repair and recharge with the same refrigerant, a second option is to charge with drop-in blends and a third option consists in the system conversion but could require either oil change and/or the possible change of some components.

4.4.2 Centralised systems

In non-Article 5(1) countries, refrigeration equipment of supermarket is partially or totally renewed every 7 to 10 years. Major reasons are as follows: ageing of display cases, improvement of their facing, or remodelling of the sales area. In this latter option, significant changes can also be made in machinery rooms.

CFC-12 Retrofit
There are two widely used options for retrofit of CFC-12 equipment. One option is to use blends, usually containing HCFC-22 (for example R-401A or R-409A), with limited retrofit efforts. The other option is conversion from CFC-12 to HFC-134a which involves several steps, including the change of mineral oil to synthetic oil, of the expansion device and the replacement of the filter dryer.

R-502 Retrofit
Due to lubricants, retrofits are mainly from R-502 to HCFC-22 based blends (for example R-402A/B, R-408A). Studies performed on energy consumptions 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.

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 only, it may be worth using HCFC-22 and changing the expansion valve. This option is not typical.

HCFC-22 Retrofit

Because HCFC-22 is still available for the maintenance of the refrigeration system it is essentially a political decision to make this kind of 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. Also there may be elastomer issues due to shrinkage following removal of HCFC-22. These technical issues are established from CFC-12 to HFC-134a retrofit experience.

4.5 Conservation of Refrigerants and Options for Limitation of Emissions

In various countries (US /EPA97/, France /CLO98/, NL /NET95/) studies have been initiated to analyse levels and causes of refrigerant emissions, thus providing a basis for corrective actions.

A level of annual emissions in the range of 15 to 30 % of the initial charge seems to be usual for centralised systems. A number of emission sources are linked to poor installation, poor maintenance and piping failures. However, owners of installations are becoming more and more concerned by refrigerant emissions and both design and maintenance of systems are improving. Consequently refrigerant emissions should decrease in the near future.

R-502 phase out resulted in global plans to recover and retrofit. Due to the large amount of R-502 in existing systems and cost of repurchase, a significant quantity of this refrigerant has been recovered in some European countries.

Initial Leak Tightness

Before charging refrigerant in new systems a complete leak test should be performed. The test procedure should include : the normal system operating mode, operating and test pressure, leak detector sensitivity and proper specifications of fittings. This initial procedure of leak-tightness control is essential, especially if access to some components is restricted after installation.

Refrigerant Use Monitoring

This first step is already being implemented by some countries. Records of refrigerant consumption and reason for recharging or top-up should be maintained.

Leak detection should be carried out in conjunction with recharging. Once the leak is located and repaired, the location of this leak should be recorded. These data permit analysis and identification of leak prone components.

Fast and Efficient Recovery Equipment
Recovery should be compulsory and should be included during servicing, particularly when retrofitting. It is necessary to make sure that the efficiency of recovery equipment is adequate and especially that it can recover liquid refrigerant with mass-flow rates in the range of 200 kg/h due to short delay for maintenance actions in commercial applications.

Accurate weighing of initial charge and recovered refrigerant is important and these data should be recorded in a log-book for each compressor rack.

Room Air Monitoring and Leak Tightness Control
The cost/benefit analysis of installing refrigerant area monitors in the machinery room should be undertaken. Multi-sensor detectors trigger alarms in case of leakage. In case of rupture, use of leak detectors will signal a problem before high value food spoilage.

Indication of a leak by an area monitor will lead to comprehensive leak detection to locate and correct the leak. This is much more efficient than periodic leak check when it is not known whether a measurable leak exists.

Analysis of Failure Causes
Failure Modes and Effects Analysis (FMEA) is widely used in industries such as automobile manufacturing and aerospace. It can be used as a framework for analysing incidents and ruptures to avoid repetition.

4.6 Developing Country Aspects

There are not as many R-502 systems in supermarkets of Article 5(1) countries. Existing large supermarkets built in the last 20 years use HCFC-22 in their centralised systems. Small and medium supermarkets use CFC-12 in refrigeration systems with condensing units. Use of stand- alone equipment with CFC-12 is common.

Even though CFCs are still available in Article 5(1) countries, the move to the use of HFC or other low or non-ODP refrigerants has been initiated, especially in stand-alone equipment. This can be explained by the fact that equipment manufacturers export in non-Article 5(1) countries.

The same observation applies to commercial refrigeration where new equipment is charged with HFC while HCFC-22 is used in existing equipment. This is due to the presence of European supermarket chains in Article 5(1) countries.

For Article 5(1) countries that manufacture refrigeration components and equipment, options for new equipment are similar to those described in paragraph 4.3.1. Large OEM companies are on the way to convert their products to non-CFC technologies, often supported by Multilateral Fund projects. There is a problem in the very large segment of national medium and small enterprises, manufacturing all kind of display cases, cabinets, water coolers, etc. These companies will need special attention in terms of financial and technical support. Some companies convert equipment from CFC-12 to HFC-134a and some other companies from CFC-12 to HCs. In India, one manufacturer charges new ice-cream freezers with HCs.

In contrast with what is occurring in non-Article 5(1) countries, the use of R-404A in centralised systems can present some problems related to compatibility and cleanliness. These problems are due to the need for more stringent procedures of manufacturing of components (pipes, etc.) and field installation. In these countries an effort of training and establishment of standards for manufacturing and installation should be carried out.

Considering the options for existing systems, Article 5(1) countries can present specific issues. In contrast with what occurs in non-Article 5(1) countries, the activity of repairing used refrigeration equipment, mainly in the domestic and commercial segments, is a common practice. Cost of new equipment is much higher than the cost of repair service mainly because of the low cost of labour involved in this activity.

In some large Article 5(1) countries, annual CFC use in the commercial servicing sector is reported to reach 50% of the total CFC consumption. Due to this fact and also because of the early CFC phase-out in some Article 5(1) countries, the activity of repairing CFC-charged equipment may provide the opportunity to replace CFC-12 refrigerants with "drop-in" HCFC-22 based blends. In some cases, HC-blends are also considered but the use of flammable refrigerants requires thorough training of operators, especially because repairing activity is a sector with little or no structure.

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5 Cold Storage And Food Processing

5.1 Introduction

Refrigeration for cold storage and food processing (including the beverage industry) belongs to industrial refrigeration. With respect to food processing, the following sub-sectors may be identified: 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/.

Since cold storage and food processing is a rather homogeneous area of use and of very significant size and economic importance, also in Article 5(1) countries, they are treated separately in this report. Other application areas of industrial refrigeration are discussed in the next chapter. Chapter 9 (Transport Refrigeration) covers fishing boats with fish processing plants.

The annual consumption of frozen food world-wide amounts to more than 30 million tonnes per year. Over the last decade, consumption has increased by 50% and it is still growing. 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. The amount of chilled food is about 10-12 times greater than the supply of frozen products, making a total volume of refrigerated food of some 350 million tonnes per year /IIR96/.

Chilling and freezing are also of growing importance in Article 5(1) countries, not least for treating high value food products for the export markets. Even in 1984, about half of the fish landed in developing countries, corresponding to over 15 million tonnes, was refrigerated at certain stages of processing, storage or transport /Lis84/. In addition, a considerable volume of meat, fruit and vegetables for domestic consumption and export has to be kept under cooling or freezing conditions during storage and transport.

Frozen food in long term storage is generally kept at –20°C to –30°C, while –40°C is typical for the freezing process. In so called "super-freeze", the product is kept at –50°C. Chilled products are cooled and stored at temperatures from –1°C to 10°C.

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. Such systems are generally custom made and erected on site. Indirect systems with liquid chillers or ice banks are used to a lesser extent, primarily for cooling purposes.

System size may vary from cold stores of 50 kW cooling demand 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 ammonia, in one as well as in two-stage arrangements.

5.2 Current Status

5.2.1 Industrialised countries

Information about the development since the last assessment (1994 Report) has been gathered partly through an enquiry among organisations, companies and individuals dealing with industrial refrigeration.

The process of phasing out CFCs in existing systems has moved much slower than previously anticipated. According to the survey, three out of four CFC systems are still in operation. Some 70,000 tonnes of CFCs are estimated to be banked in these systems.

CFCs have not been applied in new systems in industrialised countries for several years. The CFC ban, in force from January 1, 1996 (1995 in many European countries) brought no new situation regarding new installations.

No additional refrigerant options have emerged since 1994/95. Refrigerants for cold storage and food processing are selected among fluids including ammonia, HCFC-22, HFC-134a, HFC blends and also hydrocarbons.

Ammonia has further strengthened its position as the leading refrigerant for cold storage and food processing and other industrial applications in many European countries, especially in the north. The new low charge technology has achieved a particularly strong position in Europe and even led to expansion into less traditional use areas for ammonia such as centralised systems for cooling and/or heating.

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

Unit systems with hydrocarbons are commercialised, also these with the low charge designs. CO_2 have come a long step closer to commercialisation.

Significant improvements or expansion in alternative technologies have not been reported.

5.2.2 Article 5(1) countries

Ammonia was commonly used in the past for cold storage and other industrial applications in many Article 5(1) countries and still has a strong market position. In Argentina, for example, ammonia covers about 90% of the food industry /Gom96/. In other regions, in particular in French speaking countries, CFCs and HCFCs have been the refrigerants of choice. In other regions, including a large country such as India, a more even distribution between ammonia and halocarbons (mainly HCFC-22) can be found. So far, HFCs are not applied to any significant extent.

Over a couple of decades, halocarbons have improved their market position even in countries with long experience with ammonia. Knowledge about ammonia refrigeration has regressed, especially among young people, and lack of ammonia competence is noticed as a growing problem /Pér96/. Renewed emphasis on teaching and training will be required to keep ammonia refrigeration at the current level of activity, not to mention regaining market shares or expanding into new use areas.

There are several reasons for the transfer from ammonia to CFCs and HCFCs. The halocarbons are considered to be more easy to handle, halocarbon systems are believed to require less operator attendance and initial costs may be lower (up to a certain system size). Structural changes, e.g. towards more distributed and smaller cold stores, have further increased the short term economic benefits of halocarbons over ammonia since halocarbon technology can more easily be handled by small, local enterprises.

Conventional ammonia technology, with large specific refrigerant charges, still prevails. The use of ammonia may not comply with current standards and regulations, or simply be less attractive due to stronger concerns about local safety. Modern system designs, with refrigerant charges reduced to only small fractions compared to yesterday's technology, may increase applicability and feasibility of the refrigerant. The development in Europe indicates how Article 5(1) countries should approach ammonia for new systems. Introduction into new application areas may even be possible. However, some revision of standards may be required.

5.3 Refrigerant Options for New Equipment

5.3.1 Ammonia

Compared to the billions of tonnes of ammonia produced annually by living mammals, bacteria etc., emission from refrigeration systems will be insignificant and without any influence on the global environment. This advantage has to be weighed up against its toxicity and flammability. More than 100 years of experience has shown that ammonia is safe to use as a refrigerant, provided that relevant safety codes are adhered to. Besides, regained emphasis on ammonia technology has further increased the practical safety level, through new designs (low charge) and better understanding of main safety issues (related to, e.g. materials, ignition of flammable concentrations, explosion development, gas spreading, etc.). However, national regulations vary considerably between countries, and thereby the practical applicability of this refrigerant.

Low charge ammonia technology is regarded as being fully mature. Liquid chillers with minimum charge have been designed and optimised. Specific charges below 30 grams per kW refrigeration output have been reported /Tyc96/, and, at the same time, achieving maximum efficiency. Charge reduction has been achieved through the use of plate type heat exchangers or spray type tube and shell evaporators. Compared to conventional chillers with pool boiling evaporators, refrigerant charge has been reduced by up to 90%.

The low-pressure receiver system is an efficient alternative to traditional pump circulation in distributed systems for cold stores and other applications. It has a small charge and may be applied for any refrigerant /Pea96/. The technology is particularly well suited for systems in the lower to medium capacity ranges, typical for many Article 5(1) countries and may improve the economic feasibility of ammonia in these countries.

Ammonia has excellent heat transfer properties and, due to its low molecular weight and high critical temperature, also very favourable cycle performance. As a result, cold storage and food processing systems with ammonia are known to be more efficient than similar systems with CFCs or HCFC-22. Taking into account that its global warming potential is zero, ammonia systems normally give the lowest TEWI when direct systems are applied (which is the case in the majority of cold storage and food processing applications).

Ammonia is very competitive with respect to initial costs above certain system capacities, especially for site erected systems. In smaller systems, and when liquid chillers are used, halocarbon systems are generally less expensive. Taking operating costs into account, the economic break even point may move towards smaller systems.

For low temperature applications two-stage systems have to be applied. One-stage systems could be designed with oil cooled screw compressors.

In several European countries, especially in the north, industry immediately turned to ammonia in response to the CFC problem. Current market shares are estimated to be up to 80%. There are great variations within the region, however. On average, approximately half of all European new systems are expected to be with ammonia. A further growth may be expected from the turn of the century, along with the strengthened HCFC phase out schedule within the European Union.

In the United States, ammonia has approximately 90% market share regarding systems of 100 kW cooling capacity and above in custom engineered process use /IIAR97/. The majority of these systems are found within the food industry and cold storage, where ammonia is the dominant refrigerant.

Ammonia has not been commonly used for cold storage and food processing in Japan. This may change in the future, although only small market shares are expected in the short term.

The use of ammonia has long traditions in Oceania (Australia and New Zealand). 30-40% of new installations in the sector are believed to be with this refrigerant. A significant future growth is also expected in this market.

5.3.2 HCFC-22

From a technical point of view, HCFC-22 may replace CFC-12 and R-502 in new systems. To replace R-502 for freezing, two-stage compression may have to be applied. In most cases, improvements in energy efficiency may result. However, HCFCs are themselves regulated by the Montreal Protocol, although with reasonable amounts available until 2020. The European Union has announced accelerated phase out (to be completed by 2015). Some European countries have even stricter regulations. In Sweden, for example, HCFCs are no longer allowed for new systems.

HCFC-22 has become the most important refrigerant to replace CFCs in cold storage and food processing in the USA. A similar development is believed to apply for Japan and some other countries. HCFC-22 is supposed to keep its market position in the short term but decline gradually because HCFC-22 is a controlled substance.

In Europe, the use of HCFC-22 and other HCFCs are affected by the accelerated phase-out. Even though HCFCs have filled some of the void after the CFCs, it is believed that HCFC consumption for new systems has declined when the entire region is considered. The moving away from HCFCs is expected to accelerate. Consumption for new systems will most probably be insignificant by 2005.

5.3.3 HFCs

HFC-134a and HFC blends with insignificant temperature glide, e.g. R-404A, are considered to be technically fully mature for application in the sector under consideration. The fact that hygroscopic ester oil has to be used is not believed to affect practical system reliability, provided that proper routines for service and maintenance are followed.

R-404A and R-507A are currently the most used HFCs within cold storage and food processing. These blends are generally preferred to HFC-134a due to higher volumetric capacity and lower system cost, even though HFC-134a may give some 10% higher efficiency at cooling conditions. HFC-134a is not a candidate for freezing applications.

R-404A and R-507A are primarily replacements for R-502. System performance is comparable or slightly less at moderate condensing temperatures but may be substantially less at high condensing, partly due to lower critical temperature for the HFCs. This has to be adequately addressed in relation to HFC technology transfer to Article 5(1) countries, of which a great number belong to regions with a tropical climate.

System efficiencies may be improved by different means (e.g. staging, floating condensing temperatures and (external/internal) liquid subcooling), as well as by component optimisation, such as improved heat transfer surfaces and more efficient compressors. However, this tends to increase capital costs.

In the future, the high capacity refrigerant R-410A is expected to gain market shares and probably become the leading fluorocarbon for industrial applications. Compressor volume requirements will be considerably less compared to other refrigerants (except from CO_2), and compressor efficiencies will benefit from high system pressure. Combined with somewhat better cycle efficiency compared to the blends mentioned above, practical energy efficiency will be comparable to that of HCFC-22. Using R-410A, the pressure is 50% higher, therefore special efforts should be made to address the system tightness.

HFC blends with significant glide are not suited for large, distributed refrigerating systems, in particular when evaporators are of flooded design. For this reason, blends such as R-407C are not used to any significant extent for cold storage and food processing. A certain application in industrial liquid chillers with direct expansion, e.g. with plate type evaporators, may be foreseen.

HFCs currently cover about 10% of the cold storage and food processing market in Europe. In the USA, HCFCs are still preferred to HFCs for halocarbon applications and HFC proportion may be less than in Europe. Initial cost of cold storage and food processing systems with R-404A or R-507A are higher compared to HCFC-22, provided similar system design. HFC technology for cold storage and food processing systems is regarded as being mature and may be transferred to Article 5(1) countries. Higher costs and more stringent requirements related to service and maintenance, in particular in countries with a humid climate, may delay market penetration. Energy efficiency of air cooled systems in tropical climates has to be adequately addressed.

5.3.4 Hydrocarbons

A growing market for low charge hydrocarbon chillers can be noticed in some European countries, especially in Sweden and the United Kingdom. So far, market shares are insignificant, although several manufacturers have produced ranges of chillers and other packaged equipment. Performance of HC-290 is comparable to HCFC-22. HC-290, HC-1270 and blends are commercially available.

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

5.3.5 Carbon Dioxide

Renewed CO_2 technology for low temperatures, e.g. food freezing, has reached the stage of practical application. Cascade systems with CO_2 in the lower stage (ammonia in the upper) have proved to be economically comparable to conventional two-stage ammonia systems for medium sized food processing systems (300-400 kW cooling effect at –40°C). For large systems (2 MW cooling effect), 15% saving in investment may be obtained with the cascade system. The two-system types are more or less equivalent with respect to energy efficiency.

Through cascading with CO_2, the amount of ammonia 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 condenser respectively).

5.4 Retrofits

5.4.1 General

The term "retrofit" is used here to cover all conversions to non-CFC refrigerants in existing systems, whether or not system modifications may be required.

Service refrigerants containing HCFCs and some HFCs are main refrigerant options for retrofitting cold storage and food processing systems. Experience has shown that fluids from both groups may be applied with favourable results.

Refrigerant blends with significant temperature glide are applicable only with dry expansion, which is common only in the smaller cold storage and food processing systems. This is particularly with regard to HCFC blends designed to replace CFC-12 but also some HFC mixtures, such as fluids in the HFC-407-series.

Due to low cost and simple retrofit procedures, 60-70% of retrofits so far have involved HCFCs, including blends with HCFCs. Since HCFCs contain chlorine, system chemistry is the least affected and there is no requirement for ester oil. HFCs have been preferred in some 25% of the cases (Sweden represents an exception: due to very strict regulations on HCFCs, most CFC retrofits have involved HFCs).

Retrofit to ammonia may be technically feasible for some larger cold storage and food processing systems, where steel is used as construction material. The survey reveals a certain number of such conversions.

Hydrocarbons may be used with insignificant chemical implications but flammability restricts the option to a very limited number of systems.

5.4.2 CFC-12 systems

Most retrofits of CFC-12 systems have involved HCFC-22, R-401A or R-409A (HCFC blends). R-413A is another alternative: it is an HFC/PFC-blend with some isobutane added to improve mineral oil solubility, so that oil flushing may be omitted (experience indicates that oil return efficiency depends on temperature). R-413A is classed as A1/A2 by ASHRAE, which means that, e.g. remaining gas after a gas phase leakage may be flammable.

Provided good conditions for oil return, HCFC-22 may be used for retrofit (change of thermal expansion valve, reduction of compressor speed). The above-mentioned service refrigerants may be applicable, provided that their significant temperature glide can be accepted.

Retrofit to HFC-134a has proved to be technically safe, provided that the old oil is well cleaned out and replaced by ester oil and the system thoroughly dried and evacuated. A certain loss in capacity may result, along with a certain reduction in COP.

5.4.3 R-502 systems

Most CFC systems for cold storage and food processing in industrial countries are with R-502. Similar to CFC-12 systems, HCFC-22 and blends with HCFC-22 have been the preferred retrofit fluids in the majority of cases.

HCFC-22 has been used for simple retrofit, particularly for cooling applications, where the higher discharge temperature of the HCFC does not pose a problem. Similar simple retrofits have been achieved for freezing conditions in the case of open type compressors. Normally, liquid injection or (preferably) system redesign from one to two stages may be required at low evaporation temperatures.

R-402A and R-408A are the most commonly used HCFC blends for R-502 retrofit. In addition, R-403B has been used to a smaller extent. No serious technical problems with any of the service fluids have been reported. Capacity and energy efficiency are basically similar to R-502. A certain increase in condensing pressure has to be addressed.

HFCs such as R-404A and R-507A are suitable to replace R-502. They have only small temperature glides and could be charged into all types of R-502 systems, including those with flooded evaporators. Capacity may be reduced by some 5%, together with a somewhat greater increase in specific energy consumption, depending on the retrofitting procedure. As previously discussed, losses in capacity and efficiency will increase with increasing condensing temperatures.

Provided that established procedures are adhered to, retrofit to R-404A or R-507A represent technically safe solutions.

Technically, HCs can be applicable for old R-502 systems, particularly as discharge temperatures are comparable, if not lower. Due safety measures should be taken as the system is not designed for flammable refrigerants.

5.5 HCFC requirements

The current situation regarding HCFC alternatives for new systems may be described as follows:

- ammonia is technically feasible in all types of systems, but practical application may be restricted in some countries for legal reasons;

- HFC technology is considered to be fully mature (with regard to selected HFCs such as HFC-134a, R-404A and R-507A);
- system components for R-410A are expected to be available in the short to medium term;
- hydrocarbons are technically feasible for all types of systems but practical application restricted by safety codes and national regulations;
- CO_2 - technology is readily available for certain low temperature applications, technology for general purposes may be commercialised in the midterm (5-10 years).

Therefore, it would clearly be technically possible to manage without HCFCs in new systems for cold storage and food processing without major problems.

Reasons for continued use of HCFCs are cost (compared to any refrigerant, depending on system size and application) and energy efficiency (compared to currently available HFCs). 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/. Ammonia technology may not be well known, or ammonia use may be restricted by safety regulations.

R-404A and R-507A may be used in retrofitting industrial HCFC-22 systems, in most cases with only minor system modifications. Major disadvantages are a 5-10% drop in energy efficiency (in some cases more, depending on operating conditions) and the global warming potentials (GWPs) of the HFCs.

Some DX-systems may be converted to R-407C. However, capacity loss at low temperatures and possible fractionation effects in distributed systems may restrict the number of applications.

Some large systems with HCFC-22 have been designed for future retrofit to ammonia (steel as the main construction material). Special care has to be taken to remove all remaining HCFC-22, since chemical reaction will occur between the two compounds.

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 ammonia, differences in initial costs may be even more significant than in industrialised countries, since systems are generally smaller in size. Since cost is a limiting factor in CFC phase out, availability of HCFCs may reduce the CFC problem in these countries, while lack of HCFCs may prolong dependency of CFCs.

HCFCs have to be available for new systems and for CFC retrofit in Article 5(1) countries in the short to mid term, and for service purposes (in all countries) in a longer term perspective.

5.6 Service Requirements

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. The situation may be regarded as being similar in the case of HCFCs as well.

Virgin CFCs are no longer marketed in developed countries, service needs are covered by stockpiled and recycled refrigerant. Illegal imports of chemicals, which is said to occur both in Europe and the USA, cover an unknown percentage.

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/. This figure seems to correspond well with information from other sources, e.g. Swedish investigations (see below).

Historically, some refrigerant has been vented deliberately during service, while certainly the major part (probably more than 75%) has escaped over time through small leakages or as sudden releases in connection with breakdowns. Low cost refrigerants such as CFCs and HCFCs were previously not systematically recovered during system condemnation.

Deliberate release of ODS has been banned in most parts of the world (ref. -the Clean Air Act in the United States and Council Regulation (EC) No. 3093/94 in the European Union). As a result, stringent conservation practices have been developed. Similar routines have been transferred, fully or partly, to HFC refrigerants as well.

The effect of the venting ban (and the authorities following up the regulations) may be very significant. In Sweden, for example, HCFC systems with more than 10 kg charge (including all application areas) showed an annual emission rate of 15% of the charge in the early nineties /Nat96/. This figure had dropped to 9% in 1995. Emissions from HFC systems are reported to be somewhat less than this, mainly due to more leak proof designs.

As a world wide average, current CFC and HCFC annual emission rates are likely to be in the range of 10-12% of the charge. 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).

5.7 Available Data on Consumption

5.7.1 General

CFC and HCFC inventory and consumption have been estimated for the entire industrial refrigeration sector as a whole, using a top-down approach, similar to that model used in Chapter 6 in the previous UNEP Technical Options Committee Reports. To indicate separate figures for the sectors covered by Chapters 5 and 6 respectively, it is assumed that cold storage and food processing accounts for 75%, leaving 25% left for other industrial applications. Compared to previous reports, total bank and consumption figures have been adjusted down.

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.

5.7.2 Refrigerant consumption and "bank"

Estimates for halocarbon consumption (CFCs, HCFCs, and HFCs/FCs) and corresponding refrigerant "banks" per 1996, according to a "best guess scenario", are presented in Table 5.1.

Table 5.1 Estimates for halocarbon consumption within cold storage and food processing (1996)

	Consumption, tonnes/year			Refrigerant inventory, tonnes		
	CFCs	HCFCs	HFCs	CFCs	HCFCs	HFCs
Industrialised countries	7700	17600	3400	77000	109000	6800
Article 5(1) countries	1900	1900	-	7500	7500	-
Total	9600	19500	3400	84500	116500	6800

Consumption figures for Article 5(1) countries are not calculated specifically. Consumption is believed to be in the order of 12% of the total world consumption of CFCs, HCFCs and HFCs. Similar figures for CFCs and HCFCs are assumed. The use of HFCs is not supposed to be significant in these countries.

5.7.3 Forecast of use

Future demands are forecasted on the basis of current consumption and bank (Table 5.1) and a "most likely" future development, based on predictions from the enquiry. To allow for anticipated differences in development, separate scenarios have been described for Europe ("European model") and the USA ("American model"). Approx. 60% of the total market in industrialised countries is expected to develop according to the American model and 40% according to the European model. Future development in Article 5(1) countries has been estimated by a separate model. Forecasted demands for halocarbon refrigerants according to the model is presented in Table 5.2.

Table 5.2: Forecast of future demands for halocarbons for cold storage and food processing in tonnes.

	Refrigerant	1998	2000	2005
Industrialised Countries	CFCs	6150	4400	2090
	HCFCs	16790	16160	12470
	HFCs	5040	7320	9130
	Total	27980	27880	23690
Article 5(1) Countries	CFCs	1890	1910	1590
	HCFCs	1950	2060	2650
	HFCs	10	30	110
	Total	3850	4000	4350

As industry runs out of stockpiled CFC, an increasing number of CFC systems will have to be retrofitted or replaced and their charges recycled to balance service demands. It is believed that this will be the situation in the course of two to three years (the model assumes all CFC for service covered by recycled fluid from year 2000).

Experience has shown that industry tends to operate its CFC systems as long as refrigerant is available for service. It is believed, therefore, that retrofit activity will not significantly extend a level which balances CFC demand. This presumption has been taken into account in the model by adapting retrofit activity level (Table 5.3, second column) to estimated CFC demand. The term "retrofit activity level" expresses retrofit activity (quantified by the amount of CFCs available in retrofitted systems) relative to total activity (quantified by the amount of refrigerant charged into new and retrofitted systems).

In practice, more systems than theoretically required have to be retrofitted to avoid local shortage of CFC. This is taken care of in the model by applying a relatively low "recovery efficiency" of 60%.

The potential for CFC recovery as given by the analysis is shown in Table 5.3. Figures for HCFC-22 are also included.

Table 5.3. Estimated potential for CFC and HCFC recovery

Year	CFC retrofit activity level, % of total	Amount CFCs, tonnes		Amount HCFCs, tonnes	
		Potential	Available for reuse (60%)	Potential	Available for reuse (60%)
1998	32	5440	3260	2550	1530
2000	50	8000	4800	2700	1620
2005	30	3990	2990	3150	1890

In 1998 nearly 3000 tonnes of CFCs have to be supplied from stockpiled reserves. By 2000 and 2005 available amounts of recycled CFCs will (per definition) be sufficient to cover remaining service demands. To achieve this, the activity with respect to CFC system retrofit has to increase very considerably in a couple of years.

5.8 References

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6 Industrial Refrigeration

6.1 Introduction

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 and other miscellaneous uses. Refrigeration related to the food industry is covered by Chapter 5. Liquid chillers for industrial air conditioning are discussed in Chapter 7.

Refrigeration capacity spans over a great range, from some 20 kW refrigeration effect to several MW, while temperatures may vary from below -100 °C to well above freezing point. The systems are, to a large extent, custom engineered and erected at site. Unit systems ("chillers") are used for process cooling.

Various types of compressors are used, such as reciprocating compressors, screw compressors, turbo compressors and rotary vane compressors.

All types of refrigerants are used, with HCFCs and ammonia representing the majority of refrigerant volume. CFCs, including R-13B1 for specific low temperature applications, have historically made up some 20% of the total /Mar92/. Hydrocarbons cover a significant market proportion within sectors handling flammable fluids.

Industrial refrigeration systems are normally situated in industrial areas with very limited public access. For this reason toxic or flammable fluids such as ammonia and hydrocarbons may be applied with minimal additional costs.

Some special types of small refrigeration units may be included in the industrial sector, such as compressed air dryers and ultra low temperature freezers, e.g. for medical use. These units represent a quite different capacity range, from about 100 W up to a few kilowatts.

6.2 Current Status

Information about the development since the previous Technical Options Committee Report (1994) has been gathered partly through an enquiry among organisations, companies and individuals dealing with industrial refrigeration.

Availability of CFCs for servicing has been surprisingly good and the majority of the larger CFC systems are still in operation. In 1996 only 15% of industrial end users had achieved a complete CFC phase out in UK /Mar96/. According to the survey mentioned above, a somewhat higher figure of 25% applies. Significant amounts of chemicals have been 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.

It is believed that many larger industrial CFC systems may keep running until their expected time of retirement (year 2010-2015). With respect to the smaller units, technical lifetime is much shorter. Half of these systems are believed to have been either replaced or retrofitted already to a non-CFC refrigerant.

Since 1992-93, CFCs have practically not been applied in new systems in industrialised countries. Replacement fluids have been HCFCs, ammonia and HFCs. A certain return back to hydrocarbons may be registered within industries handling flammables, e.g. the oil and gas industry and the petrochemical industry.

With respect to HCFCs, differing opinions as to their feasibility as replacement fluids for CFCs (for environmental reasons) have led to a dissimilar development between Europe and other main markets such as North America and Japan. The European Union (EU) has announced accelerated de-escalation of HCFC consumption and a complete HCFC phase out is scheduled for 2015. Even stricter national regulations are announced in countries such as Denmark, Germany, Sweden and Switzerland. In Sweden, an HCFC ban for new systems has been in force since January 1, 1998. HCFCs will not be permitted in new, larger systems (mainly industrial) in all EU-countries from the turn of the century, provided that the use of ammonia is not hindered by safety codes or national regulations.

Industrial refrigeration is important to the economy and welfare in Article 5(1) countries, in particular in cold storage and the food industry. With respect to the current situation in these countries, reference is made to Chapter 5, which deals specifically with this sub-sector of industrial refrigeration.

6.3 Description of Options

6.3.1 General

Field experience with new refrigerants and new equipment designs has grown considerably since the last assessment. New options, which are technically mature, include HCFC-123 (no option in Europe due to accelerated HCFC phase-out), HFC-134a, R-404A, R-507A for various applications, HFC-23/R-508A for low temperatures, as well as low charge unit systems (liquid chillers) with ammonia or hydrocarbons. Industrial equipment with R-410A is available from some companies. General market availability is expected in 3-5 years. Water chillers using the water itself as refrigerant in the compression cycle are available from at least three companies (in Germany, Denmark and Israel).

The development with respect to the application of not-in-kind technologies (absorption and adsorption-on refrigeration, evaporative cooling, gas cycles etc.) is modest but not completely absent. As an example, a British company has been reported to be installing a process plant using an air cycle. A certain use of liquid nitrogen and solid carbon dioxide as expendable refrigerants is occurring.

Nevertheless, the vast majority of industrial refrigeration systems will obviously be provided by the conventional compression cycle for many years to come.

6.3.2 Refrigerants for the lower temperature region (below -45°C)

CFCs have been applied for temperatures down to approximately -90°C, for example in ultra-low temperature freezers. Up to approximately -60°C , cascade systems with two different fluids are applied. R-508A and R-170 (ethane) have succeeded CFC-13 and R-503, commonly used in the lower stage, while R-404A, R-507A and HC-290 have taken over for R-502 in the upper stage.

R-13B1 was previously used as one single refrigerant down to -60°C evaporation temperature. No single fluid with a saturation pressure corresponding to that of R-13B1 has been identified. Some refrigerant blends, e.g. R-410A and a mixture of HFC-125/PFC-218/HC-290, are fairly close with respect to refrigeration properties. However, the volumetric capacity is somewhat lower. Pure HFC-125 is used in refrigeration systems with centrifugal compressors.

The lower part of the temperature range of R-13B1 may probably better be covered by cascade systems. In large systems, CO2 may be feasible in the lower stage above approximately -55°C evaporation temperature. The upper temperature range is currently covered by R-404A/R-507A. R-410A is better suited, due to a lower boiling point and may become a more attractive option for applications in the -50°C region as soon as components adapted to the higher system pressure are available. Two-stage compression will be required, while R-404A/R-507A technically may operate in one stage. For efficiency reasons, two stages may be economically favourable irrespective of the type of refrigerant.

Cascading results in increased system costs. On the other hand, the lower temperatures available may yield economic benefits, for example with respect to optimal product yield in condensation of industrial gases (SO_2, Cl_2 etc.)

Only very moderate amounts of refrigerant are consumed for low temperature applications, probably in the order of a few hundred tonnes a year.

6.3.3 Refrigerants for the medium and upper temperature regions (above -45°C) ammonia

Ammonia has historically been one of the leading refrigerants for various sectors of industrial refrigeration (in countries with traditions in using this refrigerant), in spite of its toxic and flammable nature. The main reasons for choosing this refrigerant have been cost and efficiency. During the last decade, its environmental benefits (no ozone depletion, no contribution to global warming) have made it even more attractive for industrial applications (as well as for other sectors).

Over the years, adequate safety codes related to ammonia refrigeration have been developed. Moreover, system design, erection and operation have been - and still are - performed by skilled people. Accidents/incidents are rare, therefore, which is well documented by experience from the numerous ammonia systems in operation. During the nineties, knowledge related to various safety issues has been improved, e.g. ammonia flammability under practical conditions /Lin97/. However, national safety regulations differ considerably, making practical conditions for ammonia application dissimilar between regions and between individual countries.

The reliability and efficiency of conventional ammonia technology is well known. Practical experience with new ammonia technology, including low charge designs, is steadily growing and the results are encouraging. Similar performance, in some cases even better, can be achieved with only a small fraction of refrigerant charge compared to conventional designs. Development areas to be mentioned are evaporator design and regulation for liquid chillers and the use of the low-pressure receiver concept for distributed systems. The new development has made ammonia a viable option over a broader range of applications and may pave the way into new markets.

Ammonia has always held a strong position as industrial refrigerant in northern Europe. Since 1990, its usage has expanded considerably in this region. Currently, it is by far the most important refrigerant for industrial purposes, with a market share above 80% in some countries. Also other parts of the region, with a traditionally lower use of ammonia refrigeration, have experienced a certain increase. On average, ammonia is believed to cover 50-60% of the European industrial refrigeration market. A ban on the use of HCFCs in large industrial systems, provided that ammonia is not ruled out for legal reasons, will be in force in EU from 1 January 2000 and may boost ammonia consumption even further.

The industrial use of ammonia refrigeration is expanding slowly in the USA. The current market share is estimated at approximately 15%. Ammonia usage in Japan has been very limited in the past. However, a growing interest can be noticed. This is illustrated by the fact that all refrigerated sports facilities built for the 1998 Winter Olympics in Nagano were equipment with ammonia as a refrigerant.

Ammonia systems are typically 0-15% more energy efficient than similar systems with CFCs and HCFCs, depending on system types and temperature levels. In some cases, choosing ammonia may imply the use of an indirect refrigeration system. Improved secondary fluids, in particular evaporating/condensing CO_2, will minimise energy penalty from additional temperature difference and pump work. As a result, overall efficiencies may be kept above or comparable to those achieved with refrigerants applicable in direct systems. Pumpable ice slurry is another promising secondary fluid, which may enhance practical feasibility of ammonia in indirect systems.

With respect to initial costs, ammonia is very competitive in large, site-erected systems, while unit systems generally have been more expensive than units with CFCs or HCFCs. Differences have been reduced through the introduction of direct expansion chillers, which have been on the European market for some years.

HCFC-22

HCFC-22 has become the most important replacement fluid for CFCs in new industrial systems outside Europe, where fluid will be available for service for full system lifetime. However, current market share, estimated at 60% of total (including HCFC-123), is supposed to decline significantly after 2000. By 2005, a reduction of 50% is assumed.

Market position in Europe varies much from country to country, between zero (in Sweden in new installations) to more than 50%. A strong decline is anticipated from 2000, along with the aforementioned regulations coming into force within the European Union. Only a small share of 5% is expected to be left by 2005.

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, ammonia may not be a candidate for all types of applications, dependent on national regulations.

HCFC-123 (and other low pressure refrigerants)

HCFC-123 has been the successor of CFC-11 in low pressure centrifugal unit systems ("chillers"). In Europe, only a few units have been installed, however, and the future market is believed to be nearly non-existent due to accelerated HCFC phase out. For more details about HCFC-123, reference is made to Chapter 8.

HFCs

Even though HFCs are considered to be technically mature for industrial applications, their penetration into the industrial market has been slow. HCFCs and ammonia have been able to fill the void after the CFCs to a large extent. At the same time, many industrial end users expressed uncertainty regarding the future of the HFCs /Mar96/. Today, the industry has become more familiar with the HFCs and consumption is increasing.

Current HFC market share is believed to be in the order of 10% in Europe and 20% in the USA. A similar figure to that of the USA may apply for Japan. A steady increase is expected, mainly at the expense of HCFCs. By 2005, more than a doubling of HFC consumption is anticipated (see also Chapter 2).

HFC-134a has replaced CFC-12 in high capacity centrifugal liquid chillers. In other system types, HCFC-22, ammonia, and high pressure HFC blends are preferred due to higher cooling capacity.

Current industrial use of HFC-134a is estimated to be only a few percent of total refrigerant consumption in the sector. Any significant change is not expected.

R-404A and R-507A are very similar in composition and refrigeration properties. They were designed primarily to replace R-502 for low temperature purposes but are technically applicable for any refrigeration purpose. As a result, R-404A and R-507A have become the main HFCs for industrial applications. Technical maturity is proved by practical operation of an increasing number of systems. In spite of minor temperature glides, R-404A and R-507A have proved to be applicable even in flooded systems /Bar96/, and are currently offered by major OEMs for all types of systems.

R-404A and R-507A suffer from relatively large throttling losses in the theoretical reference cycle (ideal vapour compression cycle without superheat and subcooling), partly due to low critical temperatures. For this reason, cycle efficiencies are significantly lower compared to those of ammonia and HCFC-22, particularly at high condensing temperatures. System efficiency should be carefully addressed, therefore, in connection with applications under tropical conditions, e.g. in Article 5(1) countries in the tropics. Air cooled condensers should be avoided as far as possible.

Efficiency may be improved by better adapting system design to refrigerant properties, e.g. by staging and liquid sub-cooling. In most cases, such modifications will be cost effective.

R-407C is regarded as a future replacement for HCFC-22, above all. It has a relatively large temperature glide and is, therefore, applicable only in dry expansion systems and with in tube condensation. Industrial applications will most probably be restricted to compact unit systems. Current consumption is not believed to be significant.

R-410A is well suited for industrial applications, not least for temperatures in the -40 °C range and may become an important refrigerant for the sector. Reference cycle efficiency is fairly good, typically 5-7% below that of HCFC-22 at moderate condensing temperatures (up to 15% below at particularly high temperatures). Due to high volumetric capacity (40 % above that of HCFC-22), compressor efficiency may be better than with HCFC-22 (or with other HFCs). Therefore, resulting performance may be comparable to HCFC-22.

At the moment, availability of components is a limiting factor, due to its higher system pressure (some 60% above that of HCFC-22). So far, experience from field testing is limited.

Hydrocarbons

Hydrocarbons are long-term, proven refrigerants (in use since 1930's) which may fit into any temperature range and their thermodynamic properties are excellent. Historically, their uses have been restricted to applications within the oil and gas industry and other industries handling flammable fluids, where they are still the preferred option. A certain increase in hydrocarbon consumption, which has been registered, has appeared mainly in these sectors.

Hydrocarbons (HCs) are classed as VOCs (Volatile Organic Compounds), which contribute to smog formation but should not result in any restriction on their use in well sealed refrigeration systems.

Commercialised products include HC-290, HC-1270 and HC-290/170 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 R-502. System performance is comparable to and, in some cases even superior to, that of the halocarbons. Several national and European standards permit the use of HCs in virtually all industrial applications and lay down specific safety requirements.

Hydrocarbon chillers for general purposes have recently been introduced in the European market. Efficiency is reported to be very good. So far, however, industrial market shares outside the sectors mentioned above are believed to be insignificant.

Current use of hydrocarbons is believed to be below 5% of the total. A certain increase in consumption is anticipated in the short term and the 5% limit may be reached by 2000.

Carbon dioxide (CO_2)

New CO2 technology represents an interesting option for industrial refrigeration, both as a conventional refrigerant and as a very efficient secondary refrigerant.

In spite of low cycle efficiency as a conventional refrigerant, very high component efficiencies (compressor, evaporator, condenser) and minor piping losses make CO_2 attractive as a low temperature refrigerant in cascade systems, both with respect to cost and energy efficiency /Bre97/. CO_2 technology is readily available.

In Austria, the first ice rink with CO_2 as secondary refrigerant is under construction.

By utilising the transcritical CO_2-cycle, combined needs for cooling and heating, which are commonly found in industry, can be met in a very efficient way. Before commercialisation, components designed for the high system pressure with CO_2 have to be available. Time frame is anticipated to be 5 years or more.

6.4 Retrofits

6.4.1 General

The term "retrofit" is used here to describe both simple conversions and cases where system modifications are required.

As already stated, retrofit activity has been low so far. A significant increase will have to occur in the short term (2-3 years), along with an expected lack of CFCs for service when current sources dry out.

In some countries, such as Sweden and Germany, servicing with CFCs is no longer permitted, which has lead to much faster conversion rates in these countries.

6.4.2 Replacements for CFC-12 and R-502

HCFC-22 may in some cases be used for retrofit of systems with CFC-12 or R-502. The discharge temperature has to be considered in case of retrofitting R-502 systems. With respect to CFC-12 systems, compressor speed has to be reduced, which may affect the oil return.

In spite of this, HCFC-22 has apparently been preferred in a greater number of industrial conversions than relevant drop-in service blends based on HCFC-22. This is because of uncertainties about effects of the temperature glide of the blends, particularly in flooded evaporator systems. Retrofit blends for R-502 with minor temperature glides have been successfully applied in a number of installations.

HFC technology for system retrofit is considered to be fully mature, at least with respect to market leaders like HFC-134a for CFC-12 and R-404A and R-507A for CFC-502. R-407C and other HFC-blends with significant temperature glide are not considered feasible for retrofitting industrial systems, apart from DX-systems in the low capacity range.

Most HFC alternatives have to be used with ester oil, making a thorough flushing of the system necessary to remove the old lubricant. In some cases, a hydrocarbon has been added to improve mineral oil solubility, so that oil change may be omitted. R-413A is a replacement for CFC-12 of this type. However, the amounts of hydrocarbons required may make such blends flammable in the worst case fractionation scenario. This has not caused problems in practice because the total amount of HCs present is usually very low.

HCFC-22 and HCFC blends are more favourable than HFCs with respect to retrofit simplicity and cost. Therefore, up to 70% of retrofits performed so far have involved HCFCs. In some few cases, change over to ammonia or a hydrocarbon has taken place.

Change of refrigerant will normally affect system performance. Theoretically, HCFC retrofit will have a minor effect (increased condenser pressure in some cases must be noted), while a certain efficiency loss can be predicted in relation to a changeover to an HFC. In practice, improvements have been reported also in the latter case, probably resulting from cleaner and better adjusted systems after retrofit.

In future, a trend towards increased use of HFCs for retrofit is foreseen, in the short term particularly much in Europe. As a world-wide average, consumption is supposed be equally divided between HCFCs and HFCs (including HFCs in HCFC blends) by 2000, while a 60/40% distribution in favour of HFCs may apply by 2005.

Ammonia is normally not considered appropriate as a replacement for CFCs in existing equipment, due to lack of material compatibility (copper). This problem is less pronounced for industrial systems, since steel is commonly used as construction material with all types of refrigerant. Open type, industrial compressors for halocarbons can normally be used with ammonia after only minor modifications.

According to the enquiry, ammonia may cover 5% of the current and future European industrial retrofit market. In the USA, ammonia usage for retrofit purposes is believed to be insignificant.

Hydrocarbons may be viable retrofit options in the oil and gas industry and some sectors of the chemical industry. A share of 3% of the European retrofit market is assumed, 5% for the USA. Good compatibility with existing materials and refrigerant oils means a minimum of internal system changes. Further, drop-in cooling capacity and coefficient of performance may result favourably. However, changes to electrical components to eliminate ignition sources is essential to the safe operation of the units.

6.4.3 Replacements for CFC-11

HCFC-123 is the only fluid to replace CFC-11 in existing industrial liquid chillers. The change-over is fairly straightforward with open type compressors, although seals, gaskets etc., have to be replaced. HCFC-123 is not compatible with the stator winding insulation material in semi-hermetic units, and retrofit may not be economically justifiable.

In the United States, some 30% of centrifugal and screw type liquid chillers have been retrofitted so far /ARI98/. It is believed that this low activity, which corresponds well with results from the enquiry, applies to industrial chiller applications as well and on a world-wide level.

6.4.4 Replacements for CFC-13, R-503 and R-13B1

Changeover from CFC-13 or R-503 to HFC-23 or R-508A is, in principle, rather simple since the fluids are very similar. However, ester oil must be used with the chlorine-free alternatives and the requirement for system cleaning is very strict due to low temperatures. HC-170 (ethane) is a well suited alternative to the HFCs, provided that a flammable refrigerant can be applied. It has been applied (in parallel to R-508A) for retrofitting, e.g. ultra-low temperature freezers.

A certain loss in capacity will follow conversion of R-13B1 systems to relevant HFC-blends (described on section 6.3.2). Only blends with a minor temperature glide are applicable for flooded systems. Pure HFC-125 is used in retrofitting refrigeration systems with centrifugal compressors. Increased compressor speed is required to obtain the necessary pressure ratio.

6.5 HCFC Requirements

It will be technically possible to manage without HCFCs in new industrial systems. Ammonia, HFCs or hydrocarbons may cover any type of application.

According to the survey, HCFCs are 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. Ammonia may not be applicable for legal reasons, or not feasible for other reasons. Preference of HCFCs may also be grounded in concern among industrial end users over the long-term future of HFCs.

Introduction of R-410A and a possible revival of CO_2 are believed to become important elements in making new industrial systems fully independent of HCFC-22, also with respect to cost, where ammonia or hydrocarbons are not applicable. Time frame is expected to be 3-5 years relating to the HFC and 5-10 years for CO_2.

There is no "ideal" refrigerant to replace HCFC-22 in existing systems with flooded evaporators. Technically, R-404A or R-507A may be used (not in all cases) but at the expense of a significant increase in energy consumption. It may also be questionable whether many older systems (more than 10-15 years) should be retrofitted to an HFC alternative at all, due to the strong change in internal system chemistry. With respect to HCFC-123, no retrofit option is commercially available. For these reasons, HCFCs have to be available for service throughout system lifetimes.

Since cost is a limiting factor in CFC phase out, lack of HCFCs may prolong dependency of CFCs in Article 5(1) countries.

As a conclusion, HCFCs have to be available for new systems, above all in Article 5(1) countries in the short to mid-term and, for service purposes, in all countries in the long-term (20 years). 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.

6.6 Service Requirements

Annual emissions from industrial systems have previously been in the order of 15% of charge, of which the major proportion has escaped during operation. As a result, more than 2/3 of the fluid consumed has been for replenishment. In most cases, refrigerant was not recovered during system repair and condemnation.

This situation has much changed. Environmental regulations in many countries, e.g. the Clean Air Act in the United States and Council Regulation (EC) No. 3093/94 in the European Union, include a ban on venting ozone depleting substances to the atmosphere. In addition, CFC prices have risen very considerably, making improved maintenance and sound conservation practices economic. Emission rates have clearly gone down and may be 10-12% on average today. It is believed 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.

So far, stockpiled CFC has been available for service. This source will have to dry out shortly, leaving only recycled fluid left for system replenishment. Future requirement for recycled CFC has been assessed, reference next section (a similar assessment with respect to HCFC has been performed as well). Historically, emissions from CFC and HCFC systems are set equal to 15% of charge, while current figures are 10%. A further decline to a lasting value of 8% by 2000 is anticipated.

6.7 Available Data on Consumption

6.7.1 General

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 Chapters 5 and 6 respectively, it is assumed that cold storage and food processing accounts for 75%, leaving 25% left for other industrial applications. Compared to previous reports, total bank and consumption figures have been adjusted down.

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.

6.7.2 Refrigerant consumption and bank

Estimates for halocarbon consumption and corresponding refrigerant "banks" per 1996, according to a "best guess scenario", are presented in Table 6.1.

Table 6.1. Estimated industrial consumption of halocarbons (1996)

	Consumption, tonnes/year			Refrigerant inventory, tonnes		
	CFCs	HCFCs	HFCs	CFCs	HCFCs	HFCs
Industrialised countries	2600	5900	1100	26000	36000	2200
Article 5(1) countries	500	500	-	2500	2500	-
Total	3100	6400	1100	28500	38500	2200

Consumption figures for Article 5(1) countries are not calculated specifically. Consumption is believed to be in the order of 10% of the total world consumption of CFCs, HCFCs and HFCs. Similar figures for CFCs and HCFCs are assumed. The use of HFCs is not supposed to be significant in these countries.

6.7.3 Forecast of use

Forecasted demand for halocarbon refrigerants in industrial refrigeration, according to a "best guess scenario", is summarised in Table 6.2.

Table 6.2. Forecast of demand of halocarbon refrigerants

	Refrigerant	1998	2000	2005
Industrialised Countries	CFCs, tonnes	2050	1470	700
	HCFCs, tonnes	5600	5390	4160
	HFCs, tonnes	1680	2440	3040
	Total, tonnes	9330	9300	7900
Article 5(1) Countries	CFCs, tonnes	520	540	430
	HCFCs, tonnes	550	590	780
	HFCs, tonnes	0	10	40
	Total, tonnes	1070	1140	1250

It is believed that only recycled refrigerant will be available for CFC system service after 2000. To achieve the required amount of CFC, a certain number of systems have to be retrofitted and the refrigerant recovered and recycled. This is taken care of in the model by increasing retrofit activity step-by-step from previous levels of 10-15% of total activity up to a level corresponding to the actual need.

By definition, the term "retrofit activity level" expresses retrofit activity (quantified by the amount of CFCs available in retrofitted systems) relative to total activity (quantified by the amount of refrigerant charged into new and retrofitted systems).

In practice, more systems than theoretically required have to be retrofitted to avoid (local) shortage of CFC. Therefore, a relatively low CFC "recovery efficiency" of 60% has been assumed (this does not mean that only 60% will be recovered but only this percentage will be readily available for servicing industrial systems).

The potential for CFC recovery in connection with system retrofit and retirement, as well as amounts assumed available for system service, according to the model, are indicated in Table 6.3. Figures for HCFC-22 are also included.

Table 6.3. ***Potential for CFC and HCFC recovery***

Year	Retrofit Activity level, % of total	Amount CFCs, tonnes		Amount HCFCs, tonnes	
		Potential	Available for reuse (60%)	Potential	Available for reuse (60%)
1998	32	1810	1090	850	510
2000	50	2670	1600	900	540
2005	30	1330	800	1050	630

6.8 References

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7 Air Conditioning & Heat Pumps (Air-Cooled Systems)

7.1 Introduction & Changes from the 1994 Assessment

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. This broad category often is referred to as unitary equipment. These systems cool, dehumidify and/or heat everything from single rooms to large exhibition halls. Essentially, all 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. Nearly all of these units use HCFC-22 as the working fluid. Air in the space to be cooled, or dehumidified, is drawn over a coil containing evaporating refrigerant. The air gives up the heat it contains to the circulating refrigerant. In heat pumps, the refrigerant flow direction in the heat exchangers 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 1700×10^6 kW of air conditioner and heat pump capacity is installed world-wide.

Refrigerant charge quantities are proportional to capacity. Assuming an average charge of approximately 0.3 kg per kW of capacity, those 1700 million kW of installed capacity represent approximately 423,000 metric-tonnes (1000 kg) of HCFC-22 as determined by the model described in Annex 7.

Changes from the observations in the 1994 Assessment Report can be summarised as follows:

- HFC-134a has not gained acceptance in systems having refrigeration capacities less than approximately 100 kW (7.3.1.1);
- The installed population of this category of products has increased from 214 million to 239 million since the 1994 Assessment (Table 7.1);
- The estimated quantity of refrigerant in the installed population has increased from 364,000 t to 423,000 t (Table 7.1);
- R-410A and R-407C products have been commercialised in Europe, the US and Japan. Japanese manufacturers have stated they plan to complete the conversion to HFC alternatives within 5 to 7 years (7.3.1.1);
- The CO_2 transcritical cycle has been added to the section on alternative cycles. Recent research indicates that the transcritical CO_2 cycle may be applicable to air cooled air conditioners and heat pumps (7.3.2.5);
- HCs have seen limited commercialisation in portable air conditioners and de-humidifiers;
- The HFC blend R32/HFC-134a has been dropped from the current assessment because the commercialisation of this blend appears unlikely;

- A joint ISO/IEC committee has been established to develop safety standards for air conditioners and heat pumps using flammable refrigerants /Grob98/;
- There has been very limited progress toward commercialisation of the "not-in-kind" cycles covered in the 1994 Assessment (7.3.2);
- The refrigerant usage model was updated with an improved system failure model and market forecasts;
- The current HCFC-22 phase-out pattern appears to be tracking the "most likely" scenario shown in Table 7.2. The most likely scenario shown in this assessment is significantly less aggressive than the one used in the 1994 Assessment (7.5);
- If aggressive recycling programs are implemented in both developed and developing countries, between 20 to 50 percent (depending on the phase-out scenario) of the 2015 refrigerant demand could be met with recycled refrigerant;
- Developing countries will have a significant need for the exchange of reclamation and retrofit technologies (7.6).

7.2 Estimated Installed Unit Population and HCFC-22 Bank

Air-cooled air conditioners and heat pumps generally fall into four distinct categories, based primarily on capacity: room air conditioners; duct-free packaged and split systems; ducted systems; and single packaged units or large capacity split systems intended primarily for commercial use (commercial unitary). Estimates of the installed base (number of units) and refrigerant inventories have been made using a computer model that predicts the number units and refrigerant in the installed population /Kel97i/.

7.2.1 Room and packaged terminal air conditioners and heat pumps

Because of their size and relatively low cost, room air conditioners (used in small shops and offices, as well as apartments and other residences) are often the first mechanical refrigeration individual comfort cooling products to appear in developing nations (evaporative air-coolers often precede mechanical refrigeration in areas having low outdoor humidities). Room air conditioners can be mounted in a window, through a wall, or even rolled from room to room. Room air conditioners range in cooling capacity from less than 2.0 kW up to 10.5 kW (having an average size of 2.7 kW). All use hermetic rotary, reciprocating or scroll compressors.

On a world-wide basis, approximately 12.7 million room and packaged terminal air conditioners were sold in 1996; each one containing an average of 0.64 kg of HCFC-22. With service lives of 10 to 15 years, it is estimated that more than 79 million room and packaged terminal air conditioners remain in operation. The total 1996 world-wide inventory of HCFC-22 in room and packaged terminal air conditioners is estimated to be 51,000 metric-tonnes.

7.7.2 Duct-free packaged and split systems

In many parts of the world, the greatest demand is for the duct-free split system. Duct-free split systems include a compressor and 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 inside the conditioned space. There is generally one fan coil unit for each conditioned room. Small duct-free split systems with a single indoor fan coil often are categorised as split room air conditioners and heat pumps. Duct-free split systems can be applied to commercial buildings, schools, apartments and free-standing residences. The duct-free category can be subdivided by cooling capacity into two sub-categories : ductless split PAC (> 4 kW) and ductless split RAC (< 4 kW).

Approximately 89 million duct-free units are installed world-wide. Duct-free split systems, ranging in cooling capacity from 2.0 kW to 20 kW (average size of 3.8kW), have gained greatest acceptance outside North America due to different construction methods and a preponderance of hydronic or non-central heating systems. Smaller capacity duct-free split systems use hermetic rotary compressors while larger models use hermetic scroll or reciprocating compressors. Duct-free split systems have average HCFC-22 charge levels of 0.320 to 0.340 kg per kilowatt of cooling capacity. The total inventory of HCFC-22 in duct-free split systems world-wide is estimated at 112,000 metric-tonnes.

7.2.3 Ducted residential air conditioners and heat pumps

These systems 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 and heat exchanger), located outside the conditioned space supplies refrigerant to a single indoor coil installed within the duct system. Air that is cooled or heated by passing over the coil is distributed throughout the building.

About 55 million ducted split systems are currently in service world-wide -- the majority within North America. Cooling 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. The total estimated inventory of HCFC-22 in ducted systems (< 17.5 kW) is 155,000 metric-tonnes. In 1996, approximately 25% of the ducted residential units produced were reverse cycle systems (heat pumps).

7.2.4 Ducted commercial packaged air conditioners and heat pumps

Many of these 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, schools, hospitals, exhibition halls or other large commercial structures. Other commercial unitary products include indoor packaged units as well as split systems with an outdoor compressor and heat exchanger unit connected by refrigerant piping to one or more indoor fan coils over which air passes to be cooled or heated.

Approximately 16 million commercial unitary air conditioners and heat pumps are installed world-wide. They range in cooling capacity from about 20 kW to as much as 420 kW (average size 23.0 kW). Commercial unitary equipment carries an average HCFC-22 charge of about 0.31 kg per kilowatt of capacity. The estimated total world-wide inventory of HCFC-22 in these systems is 105,000 metric-tonnes. This estimate does not include commercial water chillers that are covered in chapter 8. In 1996, approximately 19 % of the commercial packaged units produced were reverse cycle systems (heat pumps).

7.2.5 Summary of unit population and refrigerant bank

A common attribute of these four equipment categories is their nearly universal use of HCFC-22 as a working fluid. HCFC-22's high density and thermal efficiency have resulted in highly optimised, cost-effective products in these product categories. Table 7.1 summarises the total estimated inventory of HCFC-22 used in these product categories. Table 7.1 is based on data available at the end of 1996.

Table 7.1 Estimated 1996 unit population and HCFC-22 inventories

Product Category	Estimated Unit Population	Estimated HCFC-22 Inventory (tonnes)
Room and Packaged Terminal Air Conditioners and Heat Pumps	79 million	51,000
Duct-free Packaged and Split Systems	89 million	112,000
Ducted Split Systems	55 million	155,000
Commercial Unitary Systems	16 million	105,000
Total	239 million	423,000

7.3 Alternative Refrigerants and Systems

Two areas must be considered in any discussion of new products that do not use HCFC-22 as a working fluid: alternative refrigerants and non-traditional refrigeration cycles. In either case, the future environmental impact of these new technologies must be carefully considered. The primary evaluation criteria for any new refrigerant used in these category of products is shown in Figure 3.1.

Today, hydrofluorcarbon refrigerants have been targeted as greenhouse gases due to their relatively high direct global warming potentials (GWP). However, a more indicative measure of the effect of any technology on global warming is its Total Equivalent Warming Impact, TEWI, see Annex I. TEWI combines the (direct) effect due to the release of refrigerant into the atmosphere as well as the (indirect) effect of the CO_2 produced in generating the energy necessary to run the equipment. For unitary equipment, the indirect effect generally represents over 90 percent of the Total Equivalent Warming Impact /Fis97i/. It is therefore vital that both the direct and indirect global warming impacts of alternative refrigerants be considered. The significant point evidenced from a TEWI analysis of the unitary equipment options is that the energy efficiency of the unit is very important. In the cases where flammable or toxic refrigerants are applied to these units, the incremental costs required to meet applicable safety standards should be compared to the reduction in TEWI that could be achieved by investing the same amount in efficiency improvement technologies. The designer can then select the approach that provides the greatest consumer benefit. For a detailed description of TEWI refer to Annex I.

7.3.1 Alternative refrigerants

HCFC-22 is used almost exclusively as the working fluid in air-cooled vapour-compression air-conditioners and heat pumps. The Montreal Protocol calls for all HCFCs to be phased out by the year 2020 with a small "service tail" allowed until 2030. For Article 5(1) countries' production will be frozen at 2015 levels and a total phase-out will occur in 2040. There are also some local regulations that will phase-out of HCFC-22 earlier than dictated by the protocol. These local regulations will increase the need for a retrofit refrigerant. Therefore, refrigerant and equipment manufacturers world-wide are actively researching zero-ODP refrigerants to replace HCFC-22 in these product categories. Annex I of this report provides technical data for the refrigerant options discussed in this chapter.

7.3.1.1 Primary replacement candidates

There has been significant progress made in developing HCFC-22 alternatives for these categories of products, since the 1994 Assessment. Current trends indicate that two HFC blends R-410A and R-407C are the leading candidates to replace HCFC-22 in these categories of products, with R-410A being the predominate replacement in new products. Unitary equipment using both R-410A and R-407C is already commercially available in some regions of the world. Widespread commercial availability of systems using HFC refrigerants in developed countries is very likely to occur between 1999-2005 (section 7.6).

HFC-134a will likely be commercialised in larger capacity (>100 kW) unitary products. In addition, commercialisation of HC-290 (propane), HC-290/170, HC-1270 and R-744 (CO_2) in this product category is possible in a longer timeframe.

Following is a brief summary of some of the candidate refrigerants being considered for air-cooled systems. It should be noted that the industry is still in the early stages of developing systems that use HCFC-22 alternatives.

R-410A (HFC-32/125)

A 60/40 (mass percentage) composition of this mixture was initially investigated under AREP. Compressor calorimeter results demonstrated an increase in compressor capacity of 40 to 50%, with an efficiency decrease on the order of 8-10%. System tests with soft-optimised systems have shown comparable or greater efficiency than HCFC-22. These system efficiency gains have been attributed to the favourable thermophysical properties of this refrigerant. A 50/50 composition of this refrigerant has received an ASHRAE 34 safety classification of A1/A1 and a number designation of R-410A. R-410A air conditioners (up to 17.5 kW) are currently available in the US and Japan.

Negative attributes of this refrigerant are its high operating pressure and low critical temperature. System pressures with this blend are approximately 50 percent higher than with HCFC-22. System designers can easily address the higher operating pressures through design changes. The low critical temperature may require design changes to address operation at temperatures above the critical point. As a result, the application of this refrigerant in tropical climates should be carefully considered. Work at a major US manufacturer has demonstrated acceptable operation at ambients as high as 55 C.

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

A 30/10/60 composition of this mixture was initially investigated under AREP. Compressor calorimeter results have shown capacities and efficiencies within ±10% of HCFC-22, using HCFC-22 compressors. This blend shows promise as an acceptable OEM and retrofit refrigerant. Flammability concerns resulted in a change in the composition of the original blend tested under the AREP program. A 23/25/52 mass percentage composition of this blend has received an ASHRAE 34 classification of A1/A1 and has received a number designation of R-407C. There are currently R-407C unitary products available in Europe, the US and Japan. R-407C may be one of the most likely interim to long term replacements for HCFC-22 in large capacity (greater than 50 kW) unitary products.

As R-407C is a zeotropic blend, specific attention must be paid to the installation and maintenance, in order to avoid any significant leak which could induce fractionation of the blend.

HC-290 and other hydrocarbons

Very little data has been reported on the use of HC refrigerants in unitary products. Only limited data on HC-290 (propane) pure refrigerant are available from the AREP program. The compressor calorimeter results indicated that capacities with propane are lower than

HCFC-22 (although this can be addressed by increasing compressor displacement), and efficiencies are similar or slightly better than HCFC-22. Manufacturers in the UK have conducted tests on HC-290 and HC-290/HC-170 blends. They have found the performance to be with +/- 5 % of HCFC-22.

The use of hydrocarbons in unitary products that have high charge levels is the subject of considerable analysis and debate in the HVAC community. The obvious concern is product safety. A 1993 workshop /ARI94/ expanded the industry dialogue on the use of flammable refrigerants. The primary issues identified in this workshop were: improved test methods to define refrigerant flammability, a better safety rating system for equipment, quantitative risk assessment and further quantification of the benefits of flammable refrigerants. One paper presented at this conference indicated that it may be possible to design safe systems using flammable refrigerants by thoroughly understanding the risks and developing appropriate mitigation strategies /Grob93/.

International standards that define the system design requirements for using flammable refrigerants in heat pumps and air conditioners are currently being considered. It has been proposed that a joint working group formed from members of ISO TC86/SC1 and IEC SC61D address this issue /Grob98/.

Very little published data is available on the application of hydrocarbon refrigerants in unitary applications. One European manufacturer has introduced a portable air conditioner that uses approximately 225 grams of HC-290 refrigerant. One US unitary equipment manufacturer developed a prototype single-packaged air conditioner using HC-290. This manufacturer reported that the use of HC-290 in this product would increase the cost by 30 percent if product improvements suggested by Underwriters Laboratory were to be incorporated into the design /ARI94/, /Tre94/. It is anticipated that some applications will have lower or higher application costs; depending on the design of the original unit and the changes required to address the safety requirements of the flammable refrigerant. A more recent study has concluded that it may be possible to design cost effective window room air conditioners using proper safety mitigation strategies /Kel97ii/.

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 may 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 need to recover HCs will ultimately be determined by the codes of each country.

<u>HFC-134a</u>

Pure HFC-134a has been examined as a replacement for HCFC-22 in large chillers. This equipment category is addressed in chapter 8. However, HFC-134a should not be ruled out as a potential replacement for HCFC-22 in large (greater than 100 kW) unitary equipment.

HFC-134a is not a *drop-in* replacement for HCFC-22 in unitary equipment. The drop-in testing of HFC-134a into systems designed for HCFC-22 results in approximately a five percent loss in efficiency and a 40 percent loss in capacity. However, it is possible to design unitary equipment using HFC-134a that will have the same system efficiency and capacity as HCFC-22. Significant equipment redesigns are necessary to achieve equivalent efficiency and capacity. Those redesigns include enlarged heat exchangers and refrigerant tubing, larger volumetric displacement compressors, and re-sized compressor motors. Current trends indicate that HFC-134a will be one of the refrigerants used in unitary products with capacities of 50 to 250 kW.

R-744 (CO_2)

Carbon dioxide has been used as a refrigerant since the 1890s /Bha97/. Since it is a naturally occurring compound that is non-ozone depleting, non-flammable, has low toxicity and has an extremely low GWP, it has many of the necessary attributes of the ideal refrigerant. Unfortunately, its extremely high operating pressures, low critical point and poor theoretical performance resulted in the replacement of this refrigerant by the man-made (CFC) refrigerants developed in the 1930s.

This refrigerant has recently received the focus of several research organisations because of its highly desirable environmental properties /Nek98/. There are currently no commercially available CO_2 systems that fit the product categories covered by this section. Prototype systems have been developed and are being evaluated with mixed results (7.3.2.5). Further research is necessary to determine the commercial viability of this refrigerant for air cooled air conditioning and heat pump applications.

7.3.1.2 Lubricants for use with HFC and HC refrigerants

HFCs

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 are currently being pursued by the industry.

1. Polyolester (POE) lubricants (synthetic)
2. Polyvinylether lubricants, PVE (synthetic)
3. Hydrolytically Stable Polyolester (HSPOE) lubricants
4. System designs that can utilise non-miscible mineral oil lubricants.

Of these options, Options 1-3 appear to be the most prevalent. Option 4 may provide an acceptable solution for "close coupled" systems such as window room air conditioners and heat pumps.

HCs

Most commercially available hydrocarbon refrigerants are fully miscible with all common refrigeration oils. However, under some conditions extreme solubility can occur with polyolesters (POE) which may result in a detrimental affect on the operation of the system. The following lubricants are typically recommended:

1. Mineral oil (MO)
2. Alkyl benzene (AB)
3. Poly-alkyl Glycol (PAG)
4. Poly-alpha-olefin (POA)

Slightly higher viscosity grades of MOs may be required in some applications in order to accommodate for the decreased operational viscosity as a result of high solubility. Conventional grades of both AB oils and PAG oils can be applied without this problem due to their limited dilution with the hydrocarbon refrigerants. Mixtures of AB oils can also be used. PAO oils have generally been used for lower temperature applications.

7.3.1.3 Next generation refrigerants

Hydrofluorcarbons (HFC's) have been predominantly chosen as the zero ozone depletion potential (ODP) alternatives for chlorofluorocarbon (CFC) refrigerants. Since there might be other types of zero ODP compounds that could be used as working fluids, several organisations have investigated fluorinated ethers, alcohols, amines, silicon and sulphur compounds. Evaluation criteria included toxicity, non-flammability, stability, atmospheric lifetime, refrigeration performance, and manufacturing feasibility and cost. Although a few of the compounds have predicted refrigeration performance close to HFCs, at this stage of evaluation, none appear to have a balance of refrigerant fluid requirements to challenge HFCs /Biv97/. Should 3rd generation compounds be developed, commercialisation should not be expected for at least 15 to 20 years.

7.3.1.4 Summary

Results so far indicate that HFC blends are the most likely refrigerants to replace HCFC-22 in air-cooled systems. Unitary equipment using HFC refrigerants is already commercially available in some regions of the world. Widespread commercial availability of systems using HFC refrigerants in developed countries is likely to occur between 1999-2005 (see section 7.5).

Hydrocarbon refrigerants may also be suitable replacements for HCFC-22 in some categories of products: air-to-water heat pumps and possibly very low charge level air-to-air systems. When hydrocarbon systems are developed which are as safe (by applicable standards e.x. UL, ISO) and efficient as their HFC counterparts the ultimate decision on their use will be driven by consumer acceptance, economic factors and political considerations.

CO_2 may also be a viable refrigerant option if performance and cost issues can be addressed.

7.3.2 Alternative systems

The desire to reduce emissions of chlorine based refrigerant has led to a resurgence in research, development and utilisation of heat and thermo-mechanical space conditioning systems. The three broad classes of this technology are: *thermo-mechanical* cycles, *absorption and sorption* technology and *desiccant* technology. Section 3.6 provides additional discussion of alternative refrigeration cycles.

Alternative air conditioner and heat pump cycles most often mentioned in the literature are: engine driven, air cycle, Vuilleumier, Stirling, absorption, solid sorption, desiccant, evaporative and passive. More recently, the transcritical CO_2 has attracted the attention of the research community.

7.3.2.1 Engine driven cycles

Internal combustion engines have been used to power refrigeration systems since 1834. Currently, engine-driven systems are available in *ducted-split systems*, *non-ducted split systems* and *packaged* products. These products currently use HCFC-22 or HFC-134a as the refrigerant. It is anticipated that the alternative fluids developed for electric-driven vapour compression systems (section 7.3.1) will also be the refrigerants of choice for these products.

7.3.2.2 Vuilleumier and Stirling cycles

The working fluid of these cycles is usually helium. In the Vuilleumier cycle /Ter91/, the system is driven by heat, usually by a gas fired burner. The gas fired Stirling cycles [sealed and kinematic] are almost identical to the Vuilleumier cycle except that the Vuilleumier burner is replaced with a heat activated Stirling engine. The electric Stirling cycle uses an electric motor in place of heat to drive the cycle. The Vuilleumier cycle has a significant advantage in seasonal performance compared to the electric Stirling cycle machines because of its high heating efficiency. At the time of the last assessment (1995) this cycle was being considered in several air source heat pumps under development /Ter91/.

Both of these cycles face significant design challenges to deal with high component costs and short life expectancy. The maximum efficiency of free-piston Stirling cooler is expected to be approximately 60 percent of the Carnot efficiency /Ber93/. The current state of the art is 32 percent of Carnot efficiency in a domestic refrigerator application. A recent literature search on "Stirling cycle" technology indicates Stirling cycle air conditioners and heat pumps have received very little research attention since the 1994 Assessment. Therefore, Stirling cycle air conditioners and heat pumps are not likely to become commercially available within the next 5-10 years.

7.3.2.3 Absorption and sorption

Sorption heat pumps are a well-established technology for niche applications. Current research is focusing on improved efficiency and reduced first cost. For large systems, triple-effect cycles are being considered. They pose considerable material compatibility challenges and market introduction does not seem to be close at hand.

The low efficiency of single effect equipment makes it impracticable for many applications. The TEWI of single-effect absorption air conditioners is substantially worse than current HCFC-22 air conditioners /FIS91iii/ and future non-ozone depleting refrigerant air conditioners. Therefore, current research is focused on developing cost effective double effect, triple effect and Generator Absorber heat exchange (GAX) cycles. Study of the TEWI of GAX systems indicates that these systems could have lower TEWIs than vapour compression cycles /Fis97i/. It is unknown when GAX heat pumps will become commercially available; however at least two organisations have indicated that commercialisation may occur within the next few years. Larger capacity (250 kW) absorption heat pumps are currently commercially available in Europe.

Research and development of solid sorption (ammonia and activated carbon) systems have also been conducted. However, a recent literature search indicates that very little progress has occurred since the 1994 Assessment. Commercialisation of this technology does not seem likely in the near future (5-10 years).

7.3.2.4 Desiccant cooling cycles

New desiccant materials such as titanium silicate have much higher affinities for water than prior commonly used desiccants such as silica gel. The increased efficiencies of these newer desiccants make it possible to design practicable desiccant air conditioning systems. In this cycle, air is dried to a "super dry" state using these advanced desiccant materials. Because the latent heat of vaporization of the water remains in the air, the air is very dry and very hot when it leaves the desiccant bed. Sensible heat exchange with regeneration air cools the conditioned air but it still remains warm and very dry. Evaporative cooling is then used to cool and re-humidify the conditioned air to a comfortable level. This cycle is under development and limited commercial application is occurring. These systems are physically large and their use has been primarily limited to commercial applications. Desiccant air-conditioning systems require the use of an energy source to regenerate the desiccant. This energy source is likely to come from fossil fuel combustion or solar energy. The current AFEAS study did not estimate the TEWI of this type of systems /Fis97i/.

7.3.2.5 Transcritical CO_2 cycle

There are currently several research projects being conducted on transcritical CO_2 refrigeration cycles. Much of this research has initially been targeted toward automotive and transportation air conditioning applications. More recently, researchers have begun to examine the transcritical CO_2 cycle in the context of residential air conditioning and heat pump applications. The published literature contains a large number of papers describing the performance of these cycles. The researchers have not reached a consensus on the expected performance of transcritical CO_2 air conditioners and heat pumps /Aar96, Aar98, Bul97, Bha97, Pet97/. Some of the research data shows performance comparable to HCFC-22 while other data indicates significant efficiency penalties. If the performance of optimised systems reaches the levels predicted by some researchers, it is possible that transcritical CO_2 air conditioning and heat pump systems could be commercialised within the next 5-10 years.

7.3.3 Impact of alternative refrigerants and cycles

Of the options presented in sections 7.3.1 and 7.3.2 the introduction of HFC refrigerants and possibly hydrocarbon refrigerants into the market place will have the greatest impact on the industry requirements for HCFC-22 (section 7.5) during the next 10-15 years. While alternative cycles are important and could have a long range penetration of this market, the impact of these technologies on the HCFC phase-out will be limited by high first costs, commercialisation timelines and long market development intervals.

7.4 Retrofit

Retrofit of existing systems may be possible using a number of the refrigerant options currently being investigated as retrofit replacements for HCFC-22.

7.4.1 Retrofit issues

The suitability of a specific retrofit refrigerant will be determined by its attributes. Attributes that must be considered are: performance, need for system modifications, impact on system reliability and safety. The performance characteristics of any retrofit refrigerant will be a key factor in its suitability for retrofit applications. To be acceptable the retrofit refrigerant should exhibit similar capacity and efficiency to HCFC-22 (±10 percent). 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 that 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. Incompatibilities between the retrofit refrigerant, lubricant and other materials used in the system can result in high retrofit system failure rates. 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.

7.4.2 Potential candidates

The need and market impact of retrofit techniques and 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 developing countries, because of the limited capital available to manufacture new non-ozone depleting systems. An accelerated phase-out of HCFCs would increase the need for retrofit refrigerants in both developed and developing countries. However, a phase-out schedule with a moderate service tail, coupled with aggressive recycling programs could reduce the need for retrofit refrigerants (7.5).

Development of suitable retrofit refrigerants and techniques should continue, because they will provide high value to developing countries and those that purchase HCFC-22 air-conditioning products prior to the transition to the new refrigerants.

7.4.3 R-407C

At least one promising retrofit candidate is commercially available. The HFC-32/125/134a zeotropic blend, R-407C, may be an acceptable HCFC-22 retrofit refrigerant. Several retrofit field tests have been conducted with promising results.

Some of the changes required when retrofitting R-407C into an existing HCFC-22 system are:

- flushing the existing mineral oil based lubricant from the system;
- charging the system with the appropriate quantity of HFC compatible lubricant (see 7.3.1.2);
- installation of an HFC compatible filter drier;
- charging the system with R-407C.

No other HFC retrofit refrigerants for these categories of products have emerged at this time.

7.4.4 HC-290, HC-290/HC-170 and HC-1270 as retrofit refrigerants

Of significant concern is the use of hydrocarbon refrigerants as retrofit replacements for HCFC-22 in systems not redesigned to mitigate safety risks. There is some evidence that this practice is occurring in both developed and developing countries. It has been reported that HC-290 (propane) has been used as a retrofit refrigerant for HCFC-22 in some Article 5(1) countries. While HC-290, HC-290/HC-170 and HC-1270 provide similar performance (capacity and efficiency) to HCFC-22, the flammable nature of these refrigerants combined with the high charge levels of this category of products, creates a significant safety concern with this practice. Simply replacing HCFC-22 with hydrocarbon refrigerants could be extremely dangerous in most types of unitary products.

While it may be possible to design cost effective HC-290 unitary systems, HC-290 is clearly not recommended as a retrofit refrigerant in unitary applications without extensive system modifications. However, hydrocarbon refrigerants may be offer acceptable retrofit solutions in very low charge level systems if suitable consideration is given to compliance with local and international safety codes.

7.5 HCFC Requirements

After more than 40 years of experience, HCFC-22 has generally been accepted as the most viable refrigerant for unitary 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 HCFC-22 equipment through at least the first decade of the 21st century.

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

1. anticipated demand in the world market for unitary equipment;
2. impact of recycling on the available supplies of HCFC-22;
3. implementation rate of HFC refrigerants and other technologies into unitary equipment; and
4. changes in system design and servicing practices that will reduce the refrigerant charge quantities and refrigerant make-up requirements for unitary equipment.

Section 7.5 will present three scenarios designed to bracket future HCFC-22 requirements for unitary air conditioners and heat pumps.

7.5.1 Usage forecast

Worldwide use of HCFC-22 in 1995 is estimated to have been 243,000 metric-tonnes for all types of refrigeration applications /AFE97/. In 1995, approximately 80,000 metric-tonnes of HCFC-22 were used to manufacture and service the unitary air conditioners and heat pumps covered in this section.

Approximately 50% of these 80,000 metric-tonnes of HCFC-22 were used to service the installed population of unitary air conditioners and heat pumps. The high servicing requirement can be attributed to two factors: the large installed population of unitary products (see Table 7.1) and servicing practices that included limited reclamation.

7.5.2 Usage forecast assumptions

In attempting to project HCFC-22 usage for the period 1996 through 2015 three sets of assumptions were made. Comparison of the impact of each set of assumptions will show the impressive effect that 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 that could replace HCFC-22 in these applications. The only assumption is that some safe and non-ozone depleting refrigerant will replace HCFC-22. The following table shows the three HCFC-22 replacement scenarios assumed for this analysis.

Table 7.2 Phase-out scenarios used for 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	20.0	80.0	10.0	90.0
2015	0	100.0	0	100.0	0	100.0

Data in table excludes service tail

The analysis assumes a reasonably aggressive refrigerant reclamation effort by the world community. The assumptions on the percentage of refrigerant reclamation that will occur during servicing and unit de-commissioning are shown in Table 7.3. The model assumes that approximately 80 percent of the reclaimed refrigerant actually finds its way back into the market as usable refrigerant. Additional details are in the ANNEX Refrigerant Usage Model.

Table 7.3 Reclaim rate assumptions (world-wide average)

Year	Worldwide Recovery/Reclaim Rate (%)
1994 - 2000	50
2001 - 2005	60
2006 - 2010	80
2011 - 2015	90

Table 7.4 lists the leak rates assumed in the analysis for each product category. The leak rates shown in Table 7.4 are defined as the percentage of the original unit charge that is assumed to leak from the system during each year of operation. For product manufactured after 2005 the model assumes leak rates 25% lower than shown in the table.

Table 7.4 Annual leakage rates assumed for each product category

Product Category	Assumed Annual Leakage Rate (%/Year)
Room Air Conditioners	2
Duct-Free Packaged and Split Systems	4
Ducted Systems	5
Commercial Systems	5

The analysis predicts current and future populations of unitary products by using yearly unit shipment data (1964-1996) and assumed market growth rates to predict unit production for subsequent years. The market growth rate assumptions are shown in Table 7.5. The growth rates were estimated by averaging the growth in shipments for the period 1990-1997 and projecting the same growth rate through the year 2015.

Table 7.5 Average market growth-rate by product category (1997-2015)

Product Category	Assumed Annual World Market Growth Rate (%/Year)
Room Air Conditioners	6.0
Duct-Free Packaged and Split Systems	7.5
Ducted Systems	3.7
Commercial Systems	3.7

Once the annual production quantities were combined with assumptions of average product life (Weibull 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.

The product life assumptions for the Commercial and Ducted categories were developed from historical failure data /EPR92/. The product life assumptions for the Window Room Air Conditioners and Ductfree Air Conditioners were assumed to be shorter because these products are more likely to be replaced before they reach the end of their useful service life. The product life assumptions are shown in Table 7.6. The Mean Life is the time required for 67% of the original unit population to be removed from service. In other words, 67% of the ductfree products manufactured in 1998 would be out of service by 2013. A Weibull distribution was used to determine the number of units that fail during each year of the analysis.

Table 7.6 Product life assumptions

Product Category	Mean Life (years)
Room Air Conditioners	10
Duct-Free Packaged and Split Systems	15
Ducted Systems	20
Commercial Systems	20

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.

7.5.3 Worldwide HCFC-22 requirements for unitary products (1996-2015)

Examination of Table 7.7 illustrates the significant impact the rate of insertion of new refrigerants into unitary products can have on the demand for new HCFC-22 production requirements. The results also show the benefits of aggressive recycling programs in both developed and developing countries. In 2015, 20 to 50 percent (depending on the phase-out scenario) of refrigerant demand could be met with recycled refrigerant. The model predicts that the peak demand for HCFC-22 will occur around 2005. This peak could trigger the industry to move from the *most likely* to the *optimistic* phase-out pattern between 2005 to 2010. Failure to implement aggressive recycling programs could also result in an acceleration in the phase-out driven by shortages or price pressure on HCFC-22. Obviously, these projections are based on a mathematical model and could be altered by external factors not considered by the model. However the results are useful in understanding the impact of various assumptions on the HCFC phase-out period.

Table 7.7 ***Predicted HCFC-22 requirements (1994-2015)***

Year	Total HCFC-22 Requirement (tonnes)			Amount from Reclamation (tonnes)			New HCFC-22 Required (tonnes)		
	Pessimistic	Most Likely	Optimistic	Pessimistic	Most Likely	Optimistic	Pessimistic	Most Likely	Optimistic
1996	84,778	84,778	84,778	4,424	5,898	6,488	80,354	78,880	78,290
2000	102,396	100,752	98,042	5,765	7,683	8,447	96,631	93,069	89,595
2005	127,861	114,179	98,599	9,594	12,680	13,785	118,267	101,499	84,814
2010	109,222	88,001	66,675	17,281	22,024	22,929	91,941	65,977	43,746
2015	100,251	73,917	46,789	23,861	28,505	27,406	76,390	45,412	19,383

Usage includes both developed and developing countries.

7.5.4 Differences from 1994 Assessment

Table 7.8 compares the HCFC-22 demand (for this category of products) predicted in the 1999 assessment to that of the 1994 Assessment. One can see that the 1999 assessment shows a significant increase in demand between 2005-2015. This increase is the result of two factors: unitary market growth and a slower phase-out (***most likely*** scenario) than estimated in the 1994 Assessment.

Table 7.8 ***Predicted HCFC-22 demand 1999 vs. 1994 (most likely scenario)***

Year	1999 Assessment (tonnes)	1994 Assessment (tonnes)	Difference (tonnes)
2000	100,752	103,873	-3,121
2005	114,179	89,066	25,113
2010	88,001	57,602	30,399
2015	73,917	39,470	34,447

An examination of Table 7.9 shows the differences in market growth projections between the 1994 and 1999 Assessments.

Table 7.9 *Market growth assumptions 1999 vs. 1994*

Product Category	1999 Assessment (% / year)	1994 Assessment (% / year)	Difference (% / year)
Room Air Conditioners	6.0	4.0	2.0
Ductfree Packaged and Split Systems	7.5	2.5	5.0
Ducted Systems	3.7	2.5	1.2
Commercial Systems	3.7	2.5	1.2

The majority of the increase is driven by increased demand for window room air conditioners and ductfree air conditioners. The growth of these two product categories is being driven by increased market demand in Europe and many developing countries. The prior assessment did not adequately address the projected market growth in developing countries. It is possible that the current economic downturn in Asia could somewhat temper these growth rates during the near term. However, the projected rates are probably valid for the longer period covered by this assessment.

The other difference from the 1994 Assessment is in the predicted phase-out scenario. The current assessment utilises a less aggressive phase-out scenario. Table 7.10 compares the ***most likely*** phase-out scenarios used in the 1999 and 1994 Assessments.

Table 7.10 *Developed countries phase-out scenarios used in 1994 and 1999 assessments*

Year	1999 Assessment	1994 Assessment
1994	100	100
1996	100	97
2000	98	91
2005	76	37
2010	20	0
2015	0	0

The major reason for the change is that the 1994 Assessment did not adequately consider the phase-out period for the developing countries. In 1995 it was assumed that the usage in developing countries represented such a small portion of the total market that it was not considered. Upon examination of the market growth assumptions used in the 1999 assessment, it was apparent that the developing country phase-out had to be considered. Predictions of the phase-out patterns were generated for each geographic region and these were then weighted by the projected market data for each region to arrive at the aggregate phase-out scenario.

7.5.5 How developing countries were addressed in the analysis

The refrigerant usage model was modified to predict the developing countries usage for each year of the analysis. This was accomplished by estimating the percentage of the total world production sold in developing countries for each year of the analysis (Annex 7).

The model then estimated what percentage of the developing countries usage would be supplied by non-ODP product as a function of both year of production and phase-out scenario. These changes enabled the model to make a prediction of the amount of refrigerant required by developing countries for each year of the analysis. Table 7.11 shows the developing country refrigerant requirements for the years 1996 to 2015 for the three phase-out scenarios.

Table 7.11 Developing countries predicted refrigerant usage (1996 to 2015)

Year	Pessimistic (tonnes)	Most Likely (tonnes)	Optimistic (tonnes)
1996	12,007	12,007	12,007
2000	18,724	17,865	17,006
2005	32,773	28,891	25,010
2010	51,034	40,540	30,046
2015	75,149	51,910	28,670

7.6 Article 5(1) Considerations

Historically, the first air conditioning products to enter developing nations are large water or air-cooled chillers, intended for industrial or institutional use, and small room air conditioners. These products will probably utilise HFCs or HCFCs as the refrigerant of choice if they are purchased prior to the phase-out date for HCFCs. The primary concerns for developing countries are: adequate supplies of HCFCs to service existing equipment and equipment manufactured before the HCFC Phase-out date, technology transfer to enable the development of reclamation and recycling programs and technology to enable retrofitting of existing equipment. High excise taxes in many developing countries often discourage early retirement of existing air conditioning and heat pump units. In addition the ratio between labour cost in service and maintenance and the investment cost of new equipment differs significantly from developed country ratios /Eco98/. This phenomenon results in longer product service lives because it is often less expensive to repair or rebuild an existing product than to replace it. A easy retrofit solution will therefore be important if developing countries are to make a timely transition to non-ozone depleting refrigerants.

Another interesting opportunity for developing countries is sharing of information that local enterprises could use to build their own reclamation systems. This would be analogous to when reclamation requirements were implemented in the US market; many of the early reclamation systems were those built by local service personnel from available components. As the market for reclamation systems grew, the availability of off the shelf reclamation systems eliminated the need for field fabricated systems. Information on how to construct safe field fabricated reclamation systems would be of significant benefit to small service enterprises in developing countries. The availability of these systems would serve a secondary role of allowing the service personnel to reclaim refrigerant during servicing. This refrigerant could then be re-introduced into the system at the completion of the repairs. The service person would save the expense of recharging the system with new refrigerant that will likely be increasing in price.

The life expectancy of most unitary equipment is approximately 15 years. The life of equipment in developing countries will be somewhat longer /Eco98/. The developing country concern over the availability of HCFCs to service existing equipment can be handled by promoting retrofit solutions, strong refrigerant recycling programs and a nominal HCFC-22 service tail.

The data in Table 7.7 indicates that a relatively short service tail should be acceptable if coupled with aggressive recycling programs.

The previous sections of this chapter provide an overview of the alternative refrigerants and technologies that are applicable to unitary products in both developed and developing countries. Data on the cost of these refrigerants and the redesigned systems in which they would be applied are just now being evaluated by researchers. Some of these technologies are ideally suited to developing countries. For example, *Evaporative Cooling* technology provides a very low cost alternative to vapour compression refrigeration in developing countries having hot arid climates.

Technologies that are complex and in their early stages of development will probably be too costly or complex for consideration by developing countries. In many developing countries, the servicing of air conditioning systems is mostly provided by small independent businesses. The move away from HCFCs is expected to have a significant impact on both their activities and revenue. Many of these small contractors will not be well equipped to comply with future refrigerant conservation, recovery and recycling regulations. Therefore, there will be a significant need for contractor training in most developing countries. The information clearinghouse of UNEP has developed, in co-operation with refrigeration experts and associations, documents on alternative technologies which are useful for SMEs in developing countries.

Workshops sponsored by the International Institute of Refrigeration provide another excellent source of technical information for developing countries. Past IIR conferences have covered many issues of value to developing countries.

Equipment and operating costs are real barriers to the entry of larger residential and commercial unitary products into a country. If the benefits of air conditioning are to be experienced on a wide scale, then those costs must be kept to a minimum. It is therefore important to develop alternative refrigerants and technologies that are both environmentally safe and cost effective.

Technologies that are environmentally safe but also expensive and complex to implement would be a detriment to rapid conversion in developing countries. Obviously the ideal situation would be to develop an HCFC-22 substitute which costs, looks and performs the same as HCFC-22. None of the technologies currently available meets this ideal criterion.

Annex to Chapter 7: Refrigerant Usage Model

This model was developed to predict the installed population and refrigerant inventory for the world-wide population of unitary air conditioning units. The use of a analytical model was necessary because census data on the installed population of unitary air conditioning units does not exist. The model is based on the following detailed information:

Model Input

ARI and JARI Annual Shipment Data

Annual Leak Rate

- Per Table 7.4
- After 2005 leak rates are assumed to decrease by 25 percent

Manufacturing Losses

- 5 percent of total OEM usage prior to 1992
- 2 percent of total OEM usage 1992 and beyond

Recovery and Reclaim

- Per Table 7.3
- Compliance
    - Pessimistic — 25 percent of values shown in Table 7.3
    - Most Likely — Use data from Table 7.3
    - Optimistic — 10 percent greater than Table 7.3
- Reclaim effectiveness — 80 percent of available charge recovered
- Contaminated refrigerant — 20 percent of total recovered

Each of these factors are combined to determine the actual amount of refrigerant reclaimed. For example for Pessimistic Scenario in year 2000

% recovered refrigerant = (Table 7.3) x Efficiency x Pessimistic Adj x (1- Contaminated) x 100%

% recovered refrigerant = (0.50) x (0.80) x (0.25) x (1 - .20) x 100% = 8.0 %

This is interpreted as: only 8 % of the refrigerant that could have been recovered was actually recovered and recycled to the refrigerant bank.

Service Losses

- Losses are assumed to occur during refrigerant cycle servicing.
- Servicing frequency given by simple linear failure model
- Refrigerant is recovered and reused during servicing using the schedule of Table 7.3
- Reclaim effectiveness — 80 percent of available charge recovered
- Compliance per same schedule as above

Developing Country Market Size

- Current Market Size based on JARN data
- The annual market size is given by linear interpolation of the data in the following table

	1981 (% of World Market)	1996 (% of World Market)	2015 (% of World Market)
Ducted	0	3	5
Ductfree	0	23	60
WRAC	0	45	75
Commercial	0	10	15

Developing Country Market Demand met with non-ODP technologies

	Pessimistic (% non-ODP)	Most Likely (% non-ODP)	Optimistic (% non-ODP)
1996	0	0	0
2015	25	50	75

Market Growth Rates

- Per Table 7.5
- Used to predict total world market
- Split for Developing and Developed per above

Product Life

- Per Table 7.6
- Weibull analysis used to predict failure rate for each year of operation

7.7 References

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8 Air Conditioning (Water Chillers)

8.1 Introduction

Comfort air conditioning in commercial buildings may be provided by two basic types of equipment; unitary air conditioners and water chillers, coupled with an air handling and distribution system. Unitary air conditioners cool and dehumidify by having the air pass directly through a coil containing an evaporating refrigerant. Water chillers cool or heat water, or a water/antifreeze mixture, which is then pumped through a heat exchanger in an air handler or fan-coil unit for cooling and dehumidifying or heating air. Chapter 7 described unitary air conditioners. This chapter discusses water chillers.

The September 1998 ASHRAE Journal gives highlights from a five-volume report on a global market survey of 94 countries by the U.K.'s Building Services Research and Information Association (BSRIA) and the Japan Air Conditioning and Refrigeration News (JARN). The highlights on chillers provide an overview of the situation.

"The world market for centrifugal chillers was US $4 billion in 1997 with the U.S. accounting for 43%. The other main markets are in the Far East. The world market for absorption chillers is more concentrated with nine countries controlling 99%. Four countries – Japan, China, Korea and the U.S. – account for 90%. Reciprocating, screw and scroll chillers are the fastest-growing markets, expanding globally at 4% per year. The big markets reflect the world's biggest economies. These include the five big European markets, the U.S. and the key Asian markets – Japan, China, Taiwan and India."

Water chillers using the vapour-compression cycle are manufactured in capacities from about 7.0 kW to over 35,000 kW. Two types of compressors are used: positive displacement and centrifugal. 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 35,000 kW.

Water chillers are offered in both air cooled and water cooled versions up through about 1500 kW in single units. Above this range, water cooled systems are available. Air cooled units become too large for convenient shipment as factory-assembled systems.

8.2 Volume of Equipment and Refrigerant Usage

HCFC-22 has been used in small chillers employing positive displacement compressors and in large centrifugal chillers. Prior to the CFC phase-out under the Montreal Protocol, CFC-11 and CFC-12 were the traditional refrigerants most commonly used in large centrifugal chillers.

Now, due to the CFC phase-out, CFC-11 and 12 have been essentially replaced in new equipment production by HCFC-123 and HFC-134a, respectively. HFCs, HFC blends (including R-410A and R-407C), ammonia and hydrocarbons are beginning to displace some HCFC-22 unit sales, especially in the EU. In very large chillers, HFC-134a use is now comparable to R-22 use.

Table 8.1 shows estimates of the number of air conditioning water chillers in service world-wide in 1997. The table includes estimates of the total refrigerant charge in service in these chillers for the most commonly used refrigerants: CFC-11, CFC-12, R-500, HCFC-22, HCFC-123, and HFC-134a. The approximate number of new chillers produced in 1997 is also provided.

The following tables concentrate on fluorocarbons, since the refrigerants subject to the Montreal Protocol are fluorocarbons as are the currently dominant replacements for these refrigerants. Other gases, especially ammonia and hydrocarbons, are possible substitutes in some applications but the current numbers are quite small and rather uncertain.

Table 8.1 Air conditioning chillers in service (1997)

Chiller Type and Refrigerant	Approx. no. of Units in Service	Refrigerant in use (kt)	1997 Shipments of New Units
Centrifugal and Screw Chillers:			
❑ CFC-11	88,000	33.0	0**
❑ CFC-12	15,300	6.6	0**
❑ HCFC-22	35,000	14.0	1,500
❑ R-500	5,400	0.9	0*
❑ HCFC-123	28,300	9.8	5,600
❑ HFC-134a	15,500	2.4	3,960
❑ Ammonia	2,100	0.24	285
❑ Hydrocarbons	----------Insufficient	------------------data	-------------available

*Includes CFC-12 in R-500 chillers

**Excludes any chillers produced in the Article 5(1) countries

The Eurovent/CECOMAF statistics for Europe indicate that HCFC-22 is still the dominant refrigerant for chillers. This is attributable to the fact that the European market employs large numbers of small, positive displacement chillers which use HCFC-22. The rather large number of R-407C chillers in the following table shows that the migration from HCFC-22 to R-407C for these machines has begun /Eur97, Tok98a, Lin98/.

Table 8.2 ***EU Chiller Production in 1997***

Refrigerant	Number of Units	Percent of Units
HCFC-22	35687	87.16%
R-407C	2806	6.85%
HFC-134a	2037	4.97%
R-717	285	0.70%
Other	130	0.32%
Total	40945	100.00%
Non-HCFC-22	5258	12.84%

Table 8.3 represents a "best guess" of the average capacity of water chillers employing different refrigerants as built in the USA in 1997 /Mar97/, and in Japan /Sah93/. In the absence of any information to the contrary, the average chiller capacity for a given refrigerant in the rest of the world is assumed to be similar to the weighted average for the U.S.A. and Japan.

Table 8.3 ***Average capacity of air conditioning chillers produced in 1997***

Refrigerant	Average Capacity in kW
HCFC-22 Recips.	15
HCFC-22 Screw	1000
HCFC-123	1500
HFC-134a	1300
R-500	N/A
R-717	770
Hydrocarbons	Not available

Table 8.4 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 8.4 ***Average refrigerant charge in air conditioning chillers in service as a function of capacity in 1997***

Refrigerant	kg/kW
CFC-11	0.25
CFC-12	0.35
HCFC-22 Reciprocating	0.34
HCFC-22 Screw and Centrifugal	0.35
HCFC-123	0.22
HFC-134a	0.35
R-500	0.33
R-717	0.15
Hydrocarbons	Not available

Note: The range for ammonia is variously estimated at 0.04 to 0.25 kg/kW

Table 8.5 presents estimates of the amounts of refrigerants required in 1997 for charging new chillers for operation. Additional amounts are used to make up for leakage and losses during servicing. Leakage occurs because of ageing or failure of seals, fittings, and gaskets, pressure relief valves and operation of purge units (used with low pressure refrigerants). Losses during servicing can occur through accidental spills, failure to remove all of the charge from a system before it is opened for service, or inability to recover and reuse all of the refrigerant removed from a unit.

Table 8.5 Refrigerant usage for new systems produced in 1997

Refrigerant	**New Chiller Use (kt)**
HCFC-123	1.93
HFC-134a	1.29
R-500	0.00
HCFC-22 Cent	0.60
HCFC-22 Screw & Rec.	3.11
CFC-11	0.00
CFC-12	0.00
R-717	0.033
Hydrocarbons	Not available

Please refer to section 12 for discussion on international laws and regulations on refrigerant conservation.

8.3 Options For New Equipment

The Montreal Protocol and subsequent amendments have resulted in phase-out of the CFCs in developed countries and in a high level of activity in the industry to prepare for the ultimate phase-out of the HCFCs. The search for alternates has resulted in a renewed understanding that *ideal refrigerants do not exist* /Cal97/.

The selection of alternate refrigerants requires a balance between the global environment issues of ozone depletion and global warming and local safety issues such as bioactivity and flammability. Even within the single issue of global warming, there is need to account for the direct effects of the release of the chemicals to the atmosphere and the indirect effect that the use of the chemicals has in relation to the chemicals they replace. The indirect effect is due to the emission of carbon dioxide from generation of power to operate the chillers and is dependent on refrigeration cycle efficiency, hours of operation, and fuel mix. For chillers, the indirect effect dominates over the direct effect when low, achievable, leak rates are used in the analysis. See Annex I for discussion of the interplay of the direct and indirect effects and the combined measure of TEWI (Total Equivalent Warming Impact) /Cal93a/, /Cal93b/, and /Cal98/.

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 HCFCs and HFCs to the atmosphere, thus minimising adverse environmental effects. To varying degrees in different countries, each of these practices is being implemented.

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. Of these, the three which are deemed to be most suitable for water chilling are (1) the vapour-compression cycle using ammonia as a working fluid, (2) the absorption cycle, and (3) zeotropic refrigerant mixtures.

8.3.1 Options for new positive displacement compressor chillers

Significant changes in positive displacement chiller refrigerant selections and chiller designs are occurring as a result of ozone depletion concerns. Traditionally, HCFC-22 has been widely used as a working fluid for high pressure positive displacement chillers and CFC-12 has been used as the working fluid for intermediate pressure positive displacement chillers. CFC-12 was phased out in developed countries in 1996 and HCFC-22 is scheduled to be phased out over the next 10 - 20 years.

8.3.1.1 HCFC-22

Due to its low ODP, HCFC-22 has been viewed for several years as a part of the solution to the problems posed by phase-out of CFC-12 and other CFCs. However, the Copenhagen amendments to the Montreal Protocol call for the phase-out of HCFCs with ODPs greater than 0.01 starting in 2004. The phase-out of individual HCFCs is being managed differently in various countries.

Based on efficiency and cost, HCFC-22 is the best presently-available HCFC choice for positive displacement chillers, complemented by HFC-134a. The planned HCFC-22 phase-out has led to intense activity to find and characterise appropriate alternates. Much of this work was under the auspices of the AREP program (the Alternate Refrigerant Evaluation Program) of ARI, the Air-Conditioning and Refrigeration Institute in the U.S.A., with international participation. The refrigerants which were considered include various HFCs, zeotropic and azeotropic blends of these HFCs, ammonia and some HCs. The refrigerants which appear to be most promising in terms of their ability to satisfy the performance and safety criteria are blends of the HFCs. The blends which seem best for use with flooded evaporators, common in chillers larger than 700 kW, are those which are azeotropes or near azeotropes such as R-410A (blend of HFC-32 and HFC-125), which has a much higher pressure than HCFC-22.

Considerable work remains to be done on making design changes required by differences in characteristics between HCFC-22 and the replacements. The challenge is magnified by the need for a fluid which closely approximates the properties of HCFC-22 to service existing systems and the need to find the fluid with the best balance of properties for use in new systems. It appears as though no single refrigerant, or blend of refrigerants, will satisfy both applications.

8.3.1.2 HFC-134a

HFC-134a is being used in positive displacement water chillers as a replacement for CFC-12. 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.

The direct global warming effect of HFC-134a is about 15 percent of that of CFC-12. The theoretical cycle efficiency is about 2% lower than that for CFC-12. However, the excellent heat transfer characteristics of HFC-134a offset the lower cycle efficiency. Thus, the TEWI due to HFC-134a is less than that for CFC-12 in new equipment. Newly-developed chillers are being marketed with flooded evaporators and economiser sub-cooling for better COP and reduced volumetric flow rate (i.e., reduced compressor size).

8.3.1.3 HFC blends

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. Zeotropic mixtures such as R-407C are the most likely candidates for replacement of HCFC-22 in DX systems. However, unfavourable changes in heat transfer necessitate larger, more expensive heat exchangers to maintain performance with zeotropes.

In DX evaporators, some of this difficulty can be offset by using the glide characteristic of zeotropic mixtures to advantage in counter-flow heat exchange. The glide can also be accommodated in the traditional cross-flow air-side heat exchangers of air-cooled chillers. It is only in the flooded evaporators of large chillers that the glide cannot be accommodated.

Mixtures with appreciable glides are not suitable for use in flooded evaporators which 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. Furthermore, flooded evaporators enhance refrigeration cycle efficiency by allowing the water to be chilled closer to the evaporating temperature of the refrigerant.

8.3.1.4 R-410A

Azeotropic mixtures are under consideration as HCFC-22 replacements because they tend to act as a single component refrigerant (i.e., the vapour and liquid composition at a given temperature and pressure are constant). However, no azeotrope has been found which 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, would be required to use these HFC-32/HFC-125 blends in chillers.

8.3.1.5 Ammonia (See also, Annex 8b)

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 compressor stages required to use ammonia in centrifugal chillers limits the practical application to machines with positive displacement compressors.

Application considerations with ammonia are more complex than for many other refrigerants because the ammonia is a strong irritant gas and moderately toxic as well as flammable. Most modern experience and applications are for large refrigerated warehouses. With some development and adaptation, it is certain that ammonia systems could be applied more widely for water chilling including a wider range of air conditioning applications. Wider acceptance would require that public officials could be satisfied that the ammonia systems can be made safe under emergency conditions such as buildings 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).

Since ammonia is toxic and flammable, its current refrigerant applications are primarily limited to large systems that are isolated from the general public. Recommended practice (ASHRAE Std. 15 and ISO/DIS 5149) limits the use of ammonia 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 alarm and venting devices can ensure safety.

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.

Although ammonia enjoys a rather small portion of the market in terms of numbers of chillers, the share of tonnage would be larger because these tend to be large machines. One installation mentioned by several corespondents is at the new airport in Oslo. This is a reversible machine with a cooling capacity of 8000 kW and a refrigerant charge of 2500 kg of ammonia in two sections of 1250 kg each.

The safety provisions for this installation have been summarised by one correspondent /Tok98a/:

" ... necessary safety precautions have been taken to ensure safe operation of the plant with such a high charge of ammonia. First of all, the energy central is situated in a separate building not open to the public, 1 km away from the terminal. The machinery room is gas tight, and has a fail-safe emergency ventilation system. Gas detectors and sprinkler systems are installed and the drain is closed in case of an ammonia leak. The heat pump is also divided into two separate units on the ammonia side, each having a charge of 1,250 kg..."

Many of these protective features (e.g., a separate machinery room, ventilation, and gas detectors) would be required by some standards (e.g., ASHRAE STD-15) for any systems with such a large charge. The one kilometre separation from the terminal is somewhat exceptional but substantial separations between machinery buildings and terminals or offices are common in the layout of large airports.

Further discussion of ammonia is provided in Annex 8b.

8.3.1.6 Hydrocarbons

Although hydrocarbon refrigerants have a long history of application in industrial chillers in petrochemical plants, they have not been used in large numbers in comfort air conditioning chiller applications due to reservations about systems safety.

HCs are used in reciprocating, scroll and screw type chillers, the majority of which are being marketed by companies within Europe. Typical HCs promoted as HCFC-22 replacements include HC-290, HC-1270 and blends of HC-290/HC-170 which exhibit favourable materials compatibility, oil solubility and a thermodynamic efficiency comparable to that of HCFC-22. The cost of HC chillers tends to be higher than that of HCFC equivalents, partly due to the fact that hydrocarbon chillers are a niche market.

The most significant problem with hydrocarbons is flammability which deters their consideration for use in many applications. Some nations such as the UK, Australia, New Zealand and Germany have adopted new refrigeration safety standards to clarify refrigerant use for flammables in most applications, basing charge size limitations on the specific application. 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 working to define safety requirements for use of flammable refrigerants in a wide range of applications which would potentially include air conditioning chillers.

The primary design changes required for HCs include the use of intrinsically-safe or non-sparking electrical circuits and ensuring that the area within which the unit is located is well ventilated and that refrigerant leak detection is employed. For larger machines, this could mean that use of flammable refrigerants in commercial building chillers would require isolation of machinery rooms from the buildings. These aspects can elevate the capital costs (for US unitary products an estimate was given by Keller /Kel97/; comparable values may also apply to chiller installations with similar charges. However, it will be very dependent on safety standards adopted in certain countries).

All service and maintenance technicians must be adequately trained in the use of flammable refrigerants. In addition extra safety precautions are required such as thorough evacuation and safe disposal of all hydrocarbon-containing equipment and containers at the end of the life of the equipment.

8.3.1.7 Carbon dioxide

CO_2 is being investigated by several researchers for a wide range of potential applications using a transcritical cycle (i.e. the pressure from the compressor discharge to the expansion device inlet is maintained above the critical pressure of CO_2 (7.2 MPa at 30°C, compared to HCFC-22 which has a condensing pressure of 1.2 MPa at 30°C).

The transcritical cycle exhibits a significant temperature glide on the high temperature side. Such a glide has potential advantages in a counter-flow heat exchanger and might be attractive for water-cooled chillers or for water heating (see Chapter 11).

Although compressors capable of handling the high pressures of CO_2 are reported to be commercially available for transport air conditioning /Nes98/, there has been no known application to water cooling chillers to date. The high pressure is a particular challenge 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).

8.3.1.8 Water /Dev98c/

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 at 30°C and a suction pressure of 1.6 kPa at 9°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 high triple point limits its use.

The recent applications use water as a refrigerant to produce ice slurries by direct evaporation from a pool of water. These systems carry a cost premium of more than 50% above conventional systems. Some installations have been in use for a few years for air cooling 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 has a 30% lower energy consumption 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.

8.3.2 Options for new centrifugal compressor chillers

Centrifugal compressors are the most efficient technology in their range of applications, from 350 to 35,000 kW capacity (about 100 to 10,000 tonnes). Water chillers employing these compressors are designed for specific refrigerants. The traditional refrigerants were CFC-11, CFC-12, HCFC-22 and R-500. The CFCs were phased out in developed countries at the end of 1995 (and at the end of 1994 in the EU); the HCFCs are scheduled for phase-out starting in 2004, with a complete phase-out of HCFC-22 and HCFC-123 for new equipment in the United States by 2010 and 2020 respectively. The corresponding dates for phase-out of production of refrigerant for service are 2020 and 2030, respectively. Specific dates for phase-out of individual refrigerants in other countries will vary.

CFC-11 and CFC-12 have been replaced by HCFC-123 and HFC-134a, respectively. HCFC-22 had been expected to be used in new equipment for the better part of another decade but it is being phased out of centrifugal production. The relative condensing pressures at 38 °C are 0.145 MPa for HCFC-123, 0.963 MPa for HFC-134a and 1.461 MPa for HCFC-22. The lowest pressure refrigerant (HCFC-123) is usable in centrifugal chillers (from 350 to 10,000 kW); the highest pressure refrigerant (HCFC-22) is usable in the largest chillers (say up to 35,000 kW); and the intermediate pressure refrigerant (HFC-134a) is used from 300 kW to 35,000 kW. Chillers employing all three of these refrigerants have been available for several years with coefficients of performance ranging from 5.4 (0.65 kW/tonne) to 6.4 (0.55 kW/tonne). Manufacturers have made further improvements in COPs. The most efficient products in the market in 1998 have COPs above 7.5 (power consumption less than 0.47 kW/tonne at standard rating conditions).

Direct refrigerant substitution 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. There is no possibility for substituting HCFC-22 into CFC-11 or CFC-12 chillers, for example. In the case of HCFC-123, hermetic motor designs satisfactory for CFC-11 may not be compatible with the chemistry of HCFC-123. This led to development of new motor insulation. Other materials of construction had to be checked and, in some cases, changed. Similarly, the mineral oil lubricants used in CFC-12 systems are insoluble in HFC-134a. New lubricants had to be developed for use with HFC-134a. Additional problems are found in trying to retrofit units operating in the field with alternative refrigerants, as discussed later in Section 8.4.

An early concern with the new generation of refrigerants was potential toxicity. The new refrigerants have undergone the most extensive toxicity tests to which refrigerants have ever been exposed. These tests have been so extensive because the chemicals are used in other applications, such as foam blowing, where routine occupational exposure levels are orders of magnitude higher than the routine exposure levels from refrigerants in closed systems. The toxicity data for these refrigerants can be found in Annex II.

It is reported that HCs have been used in centrifugal chillers in specialised industrial applications but there are no known cases where they have been used in air conditioning chillers due to the large charge associated with these large machines.

8.3.2.1 HCFC-123

HCFC-123 is used in centrifugal chillers from 350 to 10,000 kW. HCFC-123 combines a relatively low environmental impact with the ability to quickly replace CFC-11 in existing chillers of recent manufacture. The refrigerant's low environmental impact is attributable to four factors: (1) a low ODP, (2) a low GWP, (3) the low emissions of current designs for HCFC-123 chillers and (4) the highest known theoretical efficiency of all HCFCs and HFCs. HCFC-123 is a key replacement for CFC-11 due to its relative chemical and physical similarity to CFC-11 which permits it to replace CFC-11 in new and existing chillers without extensive modification of equipment or equipment rooms. There is no other replacement with these characteristics, making HCFC-123 critical to the transition away from CFCs in the chiller sector.

Taken together, these considerations indicate that an accelerated phase-out of HCFC-123 would have small environmental benefits and would be very expensive. If an early phase-out of HCFC-123 significantly slowed down the transition away from CFC-11 and/or led to the adoption of less efficient technologies, as is quite possible, it could actually lead to environmental costs /Cal98/, /Wue97/.

8.3.2.2 HFC-134a

HFC-134a is an energy-efficient refrigerant used in centrifugal chillers from approximately 350 kW to 35,000 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. Some HFC-134a machines are provided with purge units to remove air which enters the machines during service, but this is uncommon.

8.3.2.3 *HFC-236*

Naval centrifugal chillers are built in the range from 440 kW to 2800 kW. Traditionally, CFC-114 has been used in some of these ship-board 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 being converted to HFC-236fa or are being replaced by HFC-134a chillers. Some work was done with HCFC-124 on an experimental basis.

Actually, two isomers of HFC-236 (HFC-236ea and HFC-236fa) have been considered as replacements for CFC-114 in this naval application. HFC-236fa is in commercial production for use as a refrigerant, a fire suppressant and as a specialty gas for semiconductor manufacturing. It has undergone toxicity testing and has a pending 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. HFC-236ea is no longer viewed as a candidate.

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

8.3.2.4 *Water*

The characteristics of water as a refrigerant are discussed in 8.3.1.8 above. Water is seldom if ever used in centrifugal chillers for comfort cooling. The limits on the use of water in chillers were identified by Carrier and Waterfill in 1924 as being the number of compressor stages needed, the large compressor size and the risk of freezing /Cal97/.

8.3.2.5 *Ammonia, carbon dioxide and hydrocarbons*

Ammonia, carbon dioxide and hydrocarbons are not attractive fluids for centrifugal compressors in comfort air conditioning.

The number of compressor stages that would be required for a centrifugal ammonia compressor limits its practical applications to machines with positive displacement compressors /Cal97/.

The pressure problems discussed in 8.3.1.7 have restricted carbon dioxide investigations to small systems employing positive displacement compressors.

Hydrocarbon refrigerants are used in centrifugal chillers in petrochemical plants where a variety of very hazardous materials are routinely used and the staffs are highly trained in safety measures and emergency response. They have not been used in centrifugal chillers for air conditioning due to concerns about system safety with large charges of flammable refrigerants.

8.3.3 Absorption chillers

Absorption is a tried and proven technology that is mass produced and well supported by a cadre of experienced technicians, particularly in Japan. 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 an "absorber" and a "generator" which are complemented by an evaporator and a condenser. The most commonly used working fluids are ammonia with a water absorber and water with a lithium bromide absorber.

Absorption-cycle chillers once dominated the large chiller market. They were later replaced by vapour-compression chillers reflecting technology advances and shifts in the relative cost of gas and electricity. Single-stage chillers powered by hot water or steam still outnumber multistage machines driven by hot water or steam or single- and multistage direct-fired machines.

Because they have low efficiency, direct-fired, single-stage absorption systems can generally not compete with electric vapour-compression systems on an economic basis. Applications were typically limited to sites that could 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 connection charges, such as exist in Japan, also favour the choice of absorption.

During the past decade, 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. Triple-effect absorption systems are being developed to achieve efficiencies even closer to vapour-compression systems. Attainment of cost and performance goals in multi-stage machines remains a challenge.

Furthermore, 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 (the U.S. production was 418 units in 1997 (about 230 thousand tonnes [800 MW]), up from 117 units (65 thousand tonnes [230 MW]) a decade before). In Japan, where electricity prices are much higher, absorption chillers dominate the market.

Absorption chillers appear to be much more popular in Asia than elsewhere. As noted in /ASH98/, Japan, China, Korea, and the U.S. account for 90%. Figures for several Asian countries are summarised in Table 8.6 derived from /JARN96/.

Table 8.6 Absorption chiller sales in the U.S. and several Asian countries /JARN96/ and /ASH98/

Country – Year	**Number of Units**	**Notes**
Japan –1995	6667	(1)
Korea – 1995	1300	(2)
China – 1995	1600	(3)
India – 1996	300	(4)
United States – 1996	579	(5)

Notes:
1. 24 times the number of centrifugals
2. Over three times the number of centrifugals
3. 60% more than the number of centrifugals
4. 50% more than the number of centrifugals
5. In the U.S., centrifugal sales outnumber absorption sales by 20:1

A factor which will limit changeovers from CFC 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 Retrofits

8.4.1 General comments

As shown in Table 8.1, there is still a large stock of chillers now in service which employ CFCs. No substitute refrigerant can be used as a "drop-in" for CFCs with the exception of HFC-134a in some R-500 systems. Now that CFC production for domestic consumption has ceased in developed countries, the functions performed by these chillers will have 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 HCFC or HFC 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 actively involved in any retrofit program.

8.4.2 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. Non-metallic materials have had to be replaced with materials which are compatible with HCFC-123. Materials used in motors of older hermetic chillers generally are not compatible with HCFC-123, putting motor reliability at risk or requiring motor 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. Cycle efficiency will be reduced about 1-2%. An optimised conversion designed for the specific machine will minimise the loss of capacity and efficiency. Furthermore, if the original chiller was somewhat oversized, 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.

8.4.3 HFC-134a for CFC-12 in centrifugal chillers

HFC-134a became available in 1989 to retrofit existing CFC-12 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 now being widely used and compatibility problems are understood and have been 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.

8.4.4 HCFC-124 for CFC-114 in centrifugal chillers

HCFC-124 has been suggested as an alternative to CFC-114 in centrifugal chillers such as those used in Naval applications. HCFC-124 requires operation at higher pressure levels, higher compressor speeds and smaller impeller diameters than CFC-114. HCFC-124 is not suitable for use in existing CFC-114 systems in most cases because the pressure levels will exceed design ratings. Complete compressor replacement is therefore necessary, as a minimum.

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 are being addressed.

8.4.5 Replacements for HCFC-123 in centrifugal chillers

There are currently no satisfactory replacement refrigerants for use in existing equipment designed for HCFC-123. HFC-245fa is being investigated as a potential alternative to HCFC-123. It has similar vapour pressure and appears to have good stability and low toxicity. HFC-245fa may be less aggressive to motor insulation and, thus, may have advantages as a retrofit refrigerant for CFC-11 chillers.

At the time of the 1994 Technical Options Committee report, HFC-245ca looked promising as a low pressure refrigerant. An important concern was that while it is non-flammable in dry air, it can form weakly flammable mixtures in humid air. This has been a factor in its being displaced by HFC-245fa as a candidate, plus the expectation that HFC-245fa will be made in large quantities for use as a foam blowing agent with the attendant economy of scale. Considerable work remains to be done before this refrigerant can be considered to be a viable replacement for CFC-11 or HCFC-123. It does not appear that it will offer efficiency superior to current HCFC-123 chillers in the 1000 to 4400 kW range. It may offer opportunities above 5300 kW.

8.4.6 Replacements for HCFC-22

Based on a very extensive search of alternatives, it is clear that there is no easy replacement for HCFC-22 in chillers with flooded evaporators today, nor is one foreseen.

For equipment now using HCFC-22, zeotropic and azeotropic mixtures of HFCs are being developed. The comments in Section 8.3.1 concerning new equipment explain the problems with zeotropic blends which prevent their use in many existing chillers. In particular, it should be re-emphasised that zeotropic blends will not work with flooded evaporators which are used in the overwhelming percentage of large chillers (essentially all centrifugal chillers and screw chillers over 700 kW use flooded evaporators).

Any further acceleration of the phase-out of HCFC-22 would have serious consequences for the stock of HCFC-22 chillers in service at the time of the phase-out.

8.5 Future Need For CFCs

Production of CFCs ceased in the developed countries by the end of 1996 (in response to the adjustments to the Montreal Protocol made in 1992 in Copenhagen) and the EU ceased production a year earlier. Chiller manufacturers have had non-CFC products available for five to six years and stopped production of CFC chillers in 1993. However, much of the existing stock of installed equipment still needs CFCs for servicing. It is too early 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.

As of the end of the first quarter of 1998, it was estimated that over 70% of the CFC chillers in service in 1990 are still in service using CFCs in the United States /HRA98/. The other 30% have either been replaced or converted to use HCFCs or HFCs. Based on informal inputs, progress does not appear to have been faster in other countries. This rate of conversion is significantly slower than predicted in the 1994 Technical Options Committee Report and raises some concern that a short-fall of refrigerant for servicing these chillers may occur within the next few years. This should be expected in CFC-12 chillers earlier than in CFC-11 chillers because of the large-scale competing uses for CFC-12 (automotive and domestic refrigeration). Further, these competing markets for CFC-12 use relatively small quantities per installation and can out-bid chiller users in a tight market. In that event, CFC-12 chiller users will be forced to retrofit or replace equipment at short notice.

The conversion rate is projected by some analysts to be short of the rate needed to avert a CFC shortage in the years ahead.

8.6 Developing Countries

Chillers 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 have jointly conducted the 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 use of CFCs is permitted in the developing countries until 2009, 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 developing countries are already banning the import or manufacture of equipment using CFC refrigerants.

Asia (India) /Aga97/ and /Dev98b/

Small Packaged Reciprocating Compressor Chillers: About 11,500 units were manufactured in 1997, of which about 95% use HCFC-22 and about 5% use CFC-12. The average capacity is 15 to 20 kW. The production growth rate is about 20% per year. There is a large installed base of CFC-12 machines.

Refrigerant consumption for production is about 50 tonnes of HCFC-22 and about 5 tonnes of CFC-12. About 17 tonnes of CFC-12 are used annually for servicing.

Medium sized Reciprocating Compressor Chillers: About 9000 units were manufactured in 1997, of which about 92.5% use HCFC-22 and about 7.5% use CFC-12. The average capacity is 350 kW.

Refrigerant consumption for production is about 820 tonnes of HCFC-22 and about 11 tonnes of CFC-12. About 6200 tonnes of HCFC-22 and 83 tonnes of CFC-12 are used annually for servicing.

Centrifugal Chillers: There are 4 centrifugal chiller manufacturers in India, all of whom use CFC-11 in at least some of their machines. Current refrigerant use in new production is about 72% CFC-11 and about 18% non-CFCs. There are 1100 machines installed, ranging typically from 1000 to 1750 kW. About 90 to 100 new units were installed in 1997. Some multinational companies are marketing chillers using HCFC-123 and HFC-134a.

Refrigerant consumption for production is about 32 tonnes of CFC-11 and about 12 tonnes (inferred) of non-CFCs. About 64 tonnes of CFC-11 are used annually for servicing. Refrigerant needs for servicing non-CFC chillers are still small since the installed base is small.

Absorption: There are three [LiBr] absorption chiller manufacturers in India. Production started in 1982. There are 700 units installed. Production is currently at about 200 chillers per year. The typical cooling capacity is 1400 to 1750 kW, with a range from about 600 to 2500 kW.

South America - Brazil /Pei98/

Available statistics are in kW of cooling capacity rather than the number of units. For 1996, the kW capacity of new machines was Centrifugal, 73,505 kW; Positive Displacement, 90,844 kW; and Imported (presumably of both types). 155,768 kW. Thus, approximately 50% of the newly installed capacity was imported machines. The installed base of centrifugal chillers is about 1300 units with an average cooling capacity of about 1600 kW.

Africa: /Dev98b/ 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 the 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 water and CFC-11 refrigerants are being used. At least one water machine producing an ice slurry was manufactured in Israel.

8.7 References

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ANNEX 8a Computational Tables

Table 8.x1
This is a computational table provided for reviewers to see the derivation of column 3 of Table 8.1. The first three numerical columns come from the preceding tables. The last numerical column is calculated as shown and input to Table 8.1.

Table 8.x2
This is a computational table for the refrigerant used in new systems, following the protocol described above.

Table 8.x1 Calculation of refrigerant in use - Data used in Table 8.1 column 3

Refrigerant	Average capacity (kW)	Charge (kg/kW)	Number of Machines	Total Charge (ktonnes)
HCFC-123	1500	0.23	28300	9.76
HFC-134a	1300	0.25	7500	2.44
R-500	500	0.33	5400	0.89
HCFC-22 Centrifugal	1000	0.40	35000	14.00
HCFC-22 Screw & Reciprocating	150	0.34	675000	34.43
CFC-11	1500	0.25	88000	33.00
CFC-12	1300	0.33	15300	6.56
Ammonia	770	0.15	2100	0.242

Total charge = (avg. kW)*(kg/kW)*(no. of machines)*

Table 8.x2 Calculation of refrigerant used in new systems in 1997 - Data used in Table 8.4

Refrigerant	Average capacity (kW)	Charge (kg/kW)	Number of machines produced 97	Total Charge (ktonnes)
HCFC-123	1500	0.23	5600	1.93
HFC-134a	1300	0.25	3960	1.29
R-500	500	0.33	0	0.00
HCFC-22 Centrifugal	1000	0.40	1500	0.60
HCFC-22 Screw & Reciprocating	150	0.34	61000	3.11
CFC-11	1500	0.25	0	0.00
CFC-12	1300	0.33	0	0.00
Ammonia	770	0.15	285	0.033

Total charge = (avg. kW)*(kg/kW)*(no. of machines produced)*.

ANNEX 8b Additional Information on Ammonia

The following information was synthesised from /Tok98c/, /Lin98/ and /EUR97/.

Capacity: The capacity range of the ammonia chillers is about 50 kW to 2700 kW [14-770 tonnes]. The average capacity is about 770 kW [based on the most complete manufacturer's data available].

COP [@ 7 °C evaporator leaving and 30 °C condenser entering]: About 3.6 to 5.7

Charge: 0.04 to 0.3 kg/kW tending to decrease with capacity and lower with plate-type heat exchangers than with tube-in-shell. About 0.06 for the average capacity unit of 770 kW from one manufacturer but higher for the typical chiller since the smaller units with the higher charge per unit capacity outnumber the larger ones. A value of 0.15 kg/kW was used in the Annex 8a.

Hardware Technology:

- Compressor: Screw and reciprocating
- Evaporator Heat Exchangers: Plate-type and tube-in-shell
- Condenser Cooling: Evaporative, air and water
- Condenser Heat Exchangers: Plate-type, tube-in-shell, serpentine coil [evaporatively-cooled], and finned tube [air-cooled]

Production volume:

- Eurovent/CECOMAF data: 1996: 240 units for A/C+ process ; 1997: 285 units
- Year to year variability: relatively high in the aggregate and very high for individual manufacturers.
- Air Conditioning vs Process Split: varies between countries and manufacturers from near zero for an individual manufacturer in a given country to almost 80%. It is estimated from samples of manufacturers' shipment data that in Europe the overall spilt may be a high as 50% A/C.
- Extrapolation: European correspondents in the ammonia industry believe that they may have as much as 50% of the global ammonia chiller market, or more. Therefore, lacking better data, it is assumed that the total European production of ammonia chillers can be used as a first order surrogate for the global production of ammonia chillers for air conditioning service.

Units in Service:

The individual manufacturer data, and the Eurovent/CECOMAF data by country, suggest that the year-to-year volumes are highly volatile and that the ammonia chiller production in Scandinavia has grown substantially with the advent of the pressures to phase out CFCs. Thus, as a first order estimate, the number of units in service is estimated to be on the order of 10 times the average production volume in 1996 and 1997 [i.e., about 2100 units in service].

9 Transport Refrigeration

9.1 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 buses and railcars.

Since the 1994 assessment, qualitative changes have resulted in an acceptance of HFCs either as single fluid or as blends in containers, railcars and road transport as CFCs ceased to be used for new equipment and for retrofits in the industry.

Most systems on reefer ships, however, continue to use HCFC-22, even though a few systems were introduced 4 years ago with the non-fluorocarbon option ammonia, predicted by some to be the preferred refrigerant for reefers in the year 2000 and beyond. 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 55% by the millennium.

9.2 Current Status

Since the working environment in all subsections of transport refrigeration is under rough conditions, the emissions on average are higher than other areas. To reduce leakages, better quality systems must be preferred in the future, meaning higher cost to the user but also an increase in quality of the product transported.

Most systems which used CFCs in 1994 have been retrofitted or scrapped to meet environmental legislation, except for Intermodal reefer containers and trucks where the existing fleets using CFCs are still large.

Since all sub-sectors included in transport refrigeration are very dependent on the availability of the product, it has taken a longer time to choose alternatives that meet the criteria for long term solutions. Today, the industry is concentrating on fewer than 10 future refrigerants that are available world-wide.

9.2.1 Reefer ships

The conventional reefer fleet capacity is virtually stagnant. For the forecasted future it is suspected that there will be only modest growth, while the container fleet continues to expand at a much greater rate than the conventional reefer sector. Today there are approximately 1,088 full reefer ships in operation with an average size of 337,000 cbft /Wil98/.

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 percent of all refrigeration systems on fully reefer ships are direct expansion systems, containing a charge from 3 to 5 metric tonnes of refrigerant. The leakage rate is estimated to be on average 35 percent annually of the initial charge (2,000 tonnes in total). 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 than direct systems, from 500 to 1,000 kg. The emission from that category is therefore less than 200 tonnes.

Ships on order for delivery within the next few years will most probably be supplied with long term HCFC-22 alternatives, because many European countries will ban HCFC-22 in new installations. To reduce the initial charge and improve the possibility for a reduced leakage rate, most systems will be delivered with the indirect systems and a secondary refrigerant in the future.

Alternative halocarbon candidates today are R-407C and R-404A but it is estimated that R-410A will be dominant in the marine market from the millennium, as a replacement for HCFC-22 in new systems. Due to increased refrigeration capacity of the product, 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 ozone layer and for the safety of systems /DNV97/.

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 halocarbons. 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 associated with the 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 development of five ships in 1993, shipyards and operators have switched back to HCFC-22 as their preferred refrigerant.

With the introduction of R-410A systems and a competitive price on non-fluorocarbon alternatives, HCFC-22 will vanish from new systems in the beginning of the next decade.

9.2.2 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 refers to "Twenty foot equivalent unit", 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 410,000 units /Car97/ and unfortunately half of them use CFC-12 as a refrigerant. The refrigeration units each contain around 5 kg of refrigerants. Average lifetime of a container is estimated to be 15 years and 50 percent of the units in operation today with CFC-12 are expected to operate to the year 2003 and after. There is therefore a huge potential to retrofit to more environmentally friendly alternatives.

Units made in recent years use HFC-134a (175,000), R-404A (1,000) and 12,000 units with HCFC-22. The total pool of refrigerants is estimated to be 1,000 tonnes of CFC-12, 1,000 tonnes of HFC-134a and 60 tonnes of HCFC-22 /Car97/. Production on new ocean going containers is estimated to 25,000 annually and all of them will use HFC refrigerants in the future.

However, there is a potential for non-fluorocarbon refrigerants 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 flammabilities with reference to IMO (International Maritime Organisation) legislation.

Most refrigeration compressors for Intermodal refrigerated containers on the vapour compression cycle are semi-hermetic compressors with air-cooled condensers. Systems are therefore dependent on a refrigerant with a relatively high critical temperature to match tropical areas. Use of hermetic, scroll compressors is increasing, which could reduce emissions further.

The emission rate for annual refrigeration use is estimated to be 150 tonnes of CFC-12, 100 tonnes of HFC-134a/R-404A and 15 tonnes of HCFC-22.

9.2.3 Refrigerated railcars

There are approximately 80,000 refrigerated railcars in use world-wide today, of which 60 percent are 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 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, /Car97/ but it is reported that there is no production volume today. Total annual emission is estimated to be 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 on non-fluorocarbon refrigerants systems in railcars.

9.2.4 Road transport (trailers, diesel trucks, swap bodies 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 percent in road transport are within this category.

The total world fleet is estimated to be around 1,000,000 vehicles, of which about 30 percent are trailer units, 40 percent are independent truck units and the remainder are smaller units driving from the truck engine /Car97/. The refrigerants CFC-12 and R-502 have been traditionally used and they still account for around 50 percent of the total today, making the CFC-12 and R-502 pool to 4,000 metric tonnes.

Current production uses HFC-134a (200,000 units), R-404A (115,000 units) and 100,.000 units with HCFC-22. This makes a pool of 1,000 tonnes of HCFC-22 and nearly 3,000 tonnes of HFCs.

Because of the onerous operating condition, the after service requirement is 20/25 percent of the pool per year.

A system using synthetic liquid air (SLA) has been developed and could be used combined with a mechanical system. This mechanical system can take over at the point for which it was designed, running at steady state condition. Although SLA can be used for multidrop applications where the power of cryogen will quickly restore the desired temperature, this is likely to consume large quantities of cryogen as a stand-alone solution and may not be practical.

Combined with a mechanical system, the best of both technologies can be exploited, giving extremely good temperature recovery results.

The use of cryogen 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 /Wal98/.

There has been a recent development in Germany and other European countries trialling a test with HC (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 (QRAs) conducted by organisations such as TNO (Netherlands) /TNO95/ and Arthur D Little /Lit95/ which have shown that there is no significant risk in using HCs as a refrigerant.

The third experimental development within this section covers the power for the refrigeration unit, which is generated by photovoltaic panels mounted on the trailer roof. A battery stores excess power for use by the refrigeration system during the hours of darkness.

Most transport refrigeration equipment is powered by diesel engines. These have high-energy demands and maintenance cost, as well as environmental impacts in terms of emissions that contribute to the greenhouse effect and noise.

However, various transport companies/distributors are using LPG as a fuel to operate these engines, as emissions are very much lower, especially in comparison to diesel. The final development of HFCs is that a number of units using R-410A are now available.

9.2.5 Refrigeration and air conditioning on merchant marine

There are more than 30,000 ships of all types (tankers, general cargo, cruise ship, and ferries) in excess of 300 gross tonnes. They all have refrigeration systems for their provision rooms and air conditioning. 95 percent of the fleet use HCFC-22 as a refrigerant, the rest are mainly on CFCs.

It is estimated that the CFC pool has been reduced from 9,000 to 2,000 tonnes since 1994, mainly because of retrofitting to more environmentally accepted refrigerants and scrapping of old ships. Annual emissions may be around 700 tonnes and have been reduced dramatically since 1994.

The total HCFC pool may be around 30,000 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 from 15,000 to 12,000 tonnes annually because of better maintenance and quality of the systems.

Approximately 1,000 new ships in all categories are delivered annually. HCFC-22 is shipowners' and shipyards' first choice, but requests for HFC-134a, R-404A and R-407C are increasing.

In the sector of cruise ships with huge HVAC systems, the majority are delivered with HFC-134a but the last delivery from Europe consisted of chiller equipment using R-410A and it is believed that this fluid will play the HCFC-22 role for new systems in the future for most applications.

9.2.6 Air conditioning in buses and railcars

Buses and Coaches:
There are an estimated 320,000 buses and coaches with air conditioning, of which approximately half are in North America. The refrigerant pool is estimated to be 4,000 tonnes.

Since the 1994 assessment when CFCs dominated the pool, there has been a turnaround today in favour of HCFC-22 (152,000) and HFC-134a (68,000), leaving CFC-12 with 1,000 tonnes only. In other words, the CFC pool has been reduced from 3,000 to 1,000 tonnes /Car 97/.

It is estimated that the biggest growth will be in Europe in the next five years, since air conditioning in buses is not yet fully developed and that HFC-134a will be the preferred refrigerant.

Leakage rates are relatively high, estimated to be 50 percent annually of the initial charge, due to most systems using long lengths of polymeric tubing.

However, late reports from Japan indicate that they manage to reduce the leakage rate on their new models with HFC-134a estimated to 1% annually /JRA98/.

Rail air conditioning systems:

More than 75,000 systems are installed, of which at least 50 percent are in Asia, and mainly in Japan (35,000). These systems mainly operate on HCFC-22, except in India where about 2,000 systems out of 4,000 operate with CFC-12 /Aga98/, given an estimated total pool of about 1,500 tonnes and an annual use for maintenance of 300 tonnes.

In Germany all new high-speed trains will be using air cycle systems for their air conditioning, while new trains in France and Spain have chosen R-407C.

9.3 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. Since

1994, no new systems with CFCs as refrigerant have been made but there are different solutions for future strategy in each sub-section.

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. 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 and R-407C but the numbers so far are minimal.

However, tests with R-410A indicate that this will be the HCFC-22 long-term replacement fluid in the marine sector. Users are awaiting new systems equipment from the OEMs, because of the higher pressure resulting from this fluid. Since the refrigeration capacity and energy efficiency are superior to HCFC-22, it is an interesting product. The majority of refrigerant manufacturers are able to produce the product in the future, hence making R-410A easily available.

Since 1994 no new refrigerated ships have been produced to use ammonia with indirect brine systems, which is disappointing for the future of non-fluorocarbon refrigerants. A promised option for refrigerated ships, however, is the potential comeback of carbon dioxide as the refrigerant, which was used in more than 50 percent of all refrigerated ships as late as the 1960's. It is also tested out in refrigerated containers and might become an important factor of the development in this sector.

The use today of flammable hydrocarbon refrigerants is limited to gas carriers, with a crew that is trained to handle and work with hydrocarbons. However, as mentioned above for trucks, the risk assessments have shown that for those applications there is no significant risk in using HCs as a refrigerant.

9.4 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 has similar pressure and capacity as CFC-12 but these are interim solutions that contain HCFCs;

- HFC-134a demands a cleanliness of the system, which might be difficult to obtain on an old system operating with CFC-12. It is therefore not recommended since also the capacity and performance at low temperature does not compare 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 products are near to being true drop-in alternatives;

- Long term solutions to retrofit from CFC-12 are available today and this is the best environmental solution. In transport, sub-sections such as containers, buses and trucks with more than five years left of their operational service will have environmental and technical advantages if they retrofit to R-407D or R-413A. It should be noted that the latter is classed an A/2 product by ASHRAE;

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 take daily care of the safety consideration and where all the equipment required is intrinsically safe. From a thermodynamic viewpoint the ships done so far have shown advantages over HCFC-22 /Ber98/.

When ships are scrapped it is mainly done in developing countries. The total of refrigerants available could be useful for local markets, if it is recovered and recycled to acceptable standards.

9.5 Environmental aspects

The German interpretation of FCKW -Halon prohibition decree from 28.05.96, which did not allow plants with a charge of more than 1 kg of CFC-12 to operate in Germany, has been clarified following numerous actions conducted by different associations.

The German Federal Office for Environmental Protection has recently provided an official interpretation of the decree, especially the definition of use and upon this interpretation allows a system to use the fluid but not to be serviced with it. A similar definition of use is expected to be adopted by the European Union.

Many countries in Europe restrict or forbid the use of CFCs and in Sweden the use of HCFC-22 in new systems was forbidden from 1 January 1998. It is estimated that the European Union will follow from the year 2001/2002.

9.6 Summary

Options in the transport section will probably 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;
- Direct global warming potential should be as small as possible compared with CO_2;
- However, this should be a secondary issue if containment and efficiency issues are addressed;
- The chosen refrigerants should have the best energy efficiency potential;
- TEWI minimum figures should be aimed for;
- Requirements for competence tests for refrigerant handling will become mandatory;

- Annual preventive maintenance highlighting on leakage and energy efficiency of systems should become routine;
- Update and recording of recycled refrigerants and refrigerant recovery will be mandatory.

The Climate Change summit in Kyoto included halocarbons as greenhouse gases, which should be regulated in the future. However, this is a six-gas basket and since HFCs, accepted as a long term solution in refrigeration, are in the halocarbon 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.

In most European countries it is estimated that HCFC-22 will not be allowed in new systems from the beginning of the next century, since more environmental and efficient fluids are available and can replace HCFC-22 in new systems. There will also be restrictions on future availability for maintenance of existing equipment.

As mentioned above, it is also possible that the use of CFCs will be restricted and/or banned within most European countries from an early date, resulting in a total phase out of CFCs in Europe in the year to come.

Table 9.1 Transport refrigerants requirements (metric tonnes)

	CFCS			HCFC-22			HFCS		
	Pool	Emission	Units	Pool	Emission	Units	Pool	Emission	Units
Reefer Ships	150	50	20	6250	2000	930			
Refrigerated Containers	1000	150	205000	60	15	12000	1000	100	176000
Refrigerated Railcars	1800	20	120000	30	1	2000	450	5	30000
Road Transport	4000	1000	500000	1000	250	100000	3000	700	315000
Air Conditioning Buses	1250	600	100000	1900	950	152000	3000	700	315000
Air Conditioning Railcars	40	10		1500	300	75000			
Merchant Marine & Fishing Vessels	2000	700	1000	30000	12000	28000	500	100	150
Total	10240	2530		40740	15516		7950	1605	

9.7 References

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10 Mobile Air Conditioning

10.1 Introduction and Change From The 1994 Assessment

Of approximately 617 million passenger car and commercial vehicles existing world-wide in 1993 /AAM97/, an estimated 300 million were originally equipped (OE) with CFC-12 air conditioning systems. Given the low cost of CFC-12 and total lack of refrigerant recovery/recycling technology, CFC-12 was emitted to the atmosphere during all phases of the vehicle's lifetime. The major sources of emission resulted from A/C system leakage/permeation and refrigerant venting during service repair operations and vehicle scrappage. Best estimates for such releases were based on the total fleet of CFC-12 vehicles in service (DuPont, 1988) and put the industry use of new CFC-12 at the level of 0.4 kg per A/C-equipped vehicle per year. Taken on a global scale, this amounted to an estimated global release of 120,000 metric tonnes of CFC-12 per year. At a service usage rate of 0.4 kg/A/C-equipped veh/year, and an average refrigerant recharge of 1.18 kg/veh, the estimated industry recharge rate on a per vehicle basis prior to conservationist activities was (1.18kg) / (0.40 kg/yr.), or 1 recharge every 3 years. Assuming a useful A/C system life of 10 years, the lifetime refrigerant usage (and hence, atmospheric release) equated to an industry average of approximately 4 charges/vehicle.

Given the relative global warming impact of gases found in the atmosphere, the release of 120,000 metric tonnes of CFC-12 into the atmosphere is estimated to have the same (referred to as equivalent) effect on global warming as the release of 972 million metric tonnes (m.m.t.) of CO_2. At this level, refrigerant emissions from mobile air conditioning with CFC-12 accounted for approximately 2.72% of the total annual releases of man-made global warming gases to the atmosphere (see Table 1 and Exhibit A).

Table 1 Global sources and absorption of greenhouse gases /EIA95/ (Mtonnes CO_2 -eq)

Gas	**Source Natural**	**Source Man-Made**	**Annual Atmospheric Absorption**	**Annual Atmospheric Increase**
CO_2	550,000	26,057	564,564	11,367 - 12,833
Methane	2310 - 4410	6300 - 9450	9660 - 13,860	735 - 840
N_2O	1860 - 3720	1240 - 2480	4030 - 6200	930 - 1550
Totals (avg.)	**556,149**	**35,792**	**581,439**	**14,131**

Note: Excludes emissions of Montreal Protocol controlled gases estimated at 2,640 Mtonnes of CO_2 equivalent

10.2 Options For New Mobile Air Conditioning Systems

10.2.1 Use Of HFC-134a for new vehicles

All new vehicles produced since 1995 have been equipped with HFC-134a air conditioning systems (with the exception of very limited production of CFC-12 systems in China, India and Korea). Thus, HFC-134a is clearly the globally accepted mobile air conditioning refrigerant.

As new vehicles, equipped with HFC-134a air conditioning systems, enter the world markets there is a significant service concern. With the availability of low cost CFC-12 and the lack of adequate service infrastructure in Article 5(1) countries there is a trend to change these new vehicles systems from HFC-134a to CFC-12 refrigerant. Reports have indicated that this is being done in Africa and South America. Such behaviour represents a disregard for both the environment and the spirit of the Montreal Protocol. Furthermore, CFC-12 is not compatible with new vehicles as HFC-134a A/C systems use a PAG lubricant that becomes chemically unstable when used with CFC and HCFC refrigerants. This can result in compressor lubrication problems and premature failure. PAG lubricant breakdown can also contaminate the refrigerant circuit with sludge that is difficult to remove.

New vehicles are expected to continue to be equipped with HFC-134a air conditioning systems until an alternative is identified, developed, and commercialised that offers an economically viable environmental advantage with respect to global climate change concerns addressed in the recent Kyoto Protocol agreement. Efforts to identify alternatives are underway and are addressed briefly in this report.

Industry consensus was reached at the Phoenix Alternate Refrigerant Forum (Section 10.2.3) as to the global climate impact of mobile air conditioning HFC-134a emissions. This will provide valuable input for industry discussions regarding strategies to mitigate the threat of global warming.

10.2.2 Other options

Mobile A/C systems impact Global Warming in two ways; directly as a result of emission of refrigerant to the atmosphere, e.g. from system leakage and servicing and indirectly from the release of CO_2 from burning fuel to power the A/C system and to carry its weight. The combined effect of these direct and indirect impacts is called the Total Equivalent Warming Impact, or TEWI. Thus defined, the TEWI concept encompasses the total useful life cycle of the system, excluding energy considerations associated with manufacture and scrappage of the system.

To date, two candidate future systems are under study as potential replacements for HFC-134a, these being transcritical carbon dioxide and hydrocarbons.

Transcritical Carbon Dioxide

CO_2 systems, which were once used on ocean-going vessels, were abandoned by the mid-1900's in favour of the more efficient, better performing and lower pressure chlorofluorocarbons (CFC's). CFC's have, in turn, been replaced by the more environmentally friendly hydrofluorocarbons (HFCs). The CO_2 system and its applicability to mobile air conditioning have been under study by a European Union project known as the RACE Project (Refrigeration and Automotive Climate Systems under Environmental Aspects). The results of this effort, initiated in 1994, have recently been released in the form of a an executive summary /RAC98/ and a paper presented at a recent conference /Gen98/ on the use of naturally occurring materials (e.g. CO_2, ammonia and hydrocarbons) as refrigerants. Four additional presentations were delivered at this conference on the use of CO_2 as a mobile air conditioning refrigerant /Hir98,Wer98,Haf98,Yin98/. The consensus of the Race Project paper is that, although many questions remain concerning safety, quality, efficiency, maintenance and commercialisation, the transcritical CO_2 system appears to be a promising technology for mobile air conditioning.

Flammable Refrigerants

The use of flammable hydrocarbon refrigerants in future vehicles has been proposed for reasons similar to those for CO_2, i.e. they are materials that occur naturally in the earth's biosphere, they are non-ozone depleting and have very low global warming potentials. While they are excellent refrigerants, they carry the burdens of flammability and potential explosion, rendering them a significant potential safety hazard for use in mobile A/C. Because of these concerns, the use of flammable refrigerants in mobile A/C has not received much support. Despite this, some vehicle manufacturers have initiated engineering efforts to enhance the safety of flammable refrigerants, as evidenced by recent patent activity on the subject /NipXX/, /MerXX/. A recent paper by a major A/C system supplier suggests that hydrocarbons should be considered a candidate if safety concerns are adequately addressed through joint co-operation of vehicle and A/C system manufacturers /Hir98/.

The concerns about flammability can be significantly reduced, if not completely eliminated, through the use of a secondary coolant loop, wherein the flammable refrigerant is contained within the engine compartment and a secondary cooling fluid (e.g., water-glycol) transfers heat from the passenger compartment to the refrigerant. This type of system would prevent the refrigerant from entering the passenger compartment. It should be emphasised that this type of system would be unique and would have to be designed into the vehicle to assure safety, durability and performance. Such indirect systems may require 5-10% additional energy to operate.

10.2.3 Phoenix Alternate Refrigerant Forum

To begin to address the issue of climate change, members of this TOC arranged an international industry stakeholders' meeting in Phoenix, Arizona (USA), held July 15 -18, 1998 to discuss climate change and new technologies and to evaluate demonstration vehicles with alternate systems /Sun98/. The Forum was attended by the major stakeholders in the mobile air conditioning industry from Australia, Europe, Japan and the United States. Participants included 15 global vehicle manufacturers, representing over two thirds of the world's passenger car and commercial vehicle production, major A/C system suppliers, A/C component suppliers and representatives from the US Environmental Protection Agency and Oak Ridge National Laboratories. Four experimental CO_2 systems, one experimental hydrocarbon system and nine production HFC-134a systems were evaluated for passenger comfort.

The following summarises the major results of the forum:

- Participants agreed on the global warming impact of both current and future HFC-134a mobile A/C systems. Scenarios for determining current and future impact can be found in reference /Bak98/;

- Participants agreed on the need to measure total system energy consumption of alternate systems to assess their impact on fuel economy and TEWI;

- The ability of current technology hydrocarbon systems to provide adequate comfort performance is yet to be demonstrated;

- One of the CO_2-equipped vehicles showed equivalent cooling performance compared to production HFC-134a systems. The focus to date has been on building prototype systems capable of providing acceptable A/C comfort performance. Less attention has been given to materials compatibility, durability, reliability, safety (system pressures during operation and servicing), energy efficiency, cost, etc. Agreement was reached that these issues need to be dealt with prior to a decision to commercialise CO_2 systems. One notable need is to develop an entirely new line of A/C hoses to handle the higher pressures of CO_2 systems. Significant system development remains to be done prior to commercialisation;

- From the European RACE Project summary in 1997 /RAC98/, CO_2 systems were projected to cost 20% more, and weigh 2.5 kg more, than HFC-134a systems;

- The group agreed on the need for continued discussions on the issues covered at the Phoenix Forum and asked the Society of Automotive Engineers (SAE) Interior Climate Control Committee to provide such a forum.

The details and results of the Phoenix Alternative Refrigerant Forum were presented at the 1998 Earth Technologies Forum in Washington, D.C. in October, 1998 /Bak98, Atk98/.

10.3 Options For Existing CFC-12 Vehicles

Because no new vehicles have been produced with CFC-12 air conditioning since 1994 (exceptions noted above), the existing CFC-12 fleet is expected to phase out of existence by the year 2008. Efforts to accelerate complete phase out would, of course, be environmentally beneficial.

The mobile A/C service industry in the United States has a great deal of experience with on-site recycling of refrigerant during system service. Refrigerant recycling has been proven to be of value, both economically and environmentally. Recycling standards developed by the SAE are being converted to the proper format for adoption by ISO to facilitate recycling on a global basis. Such standards have been used by the United States in support of their national refrigerant management program.

Experience with multiple refrigerants (CFC-12, HFC-134a, and several retrofit refrigerant blends) has shown that, with refrigerant recycling and reuse, it is very important to prevent refrigerant cross-contamination from occurring in mobile A/C systems. Mixing of refrigerants can lead to high compressor discharge pressures, loss of cooling, deterioration of A/C system materials and possible system failure. Such effects depend on the refrigerants involved and the extent of cross-contamination. The U.S. industry recognised this concern before HFC-134a entered production and developed a standard unique service fitting to minimise the possibility of refrigerant contamination. The U.S. EPA has, at the request of the mobile A/C industry, included the requirement for each alternate refrigerant to have its own unique service fitting. Unfortunately, the implementation of unique service fittings for each refrigerant is left to the service technicians and the addition of the wrong refrigerant, and the lack of the unique service fitting, can occur. The industry is attempting to further control contamination through the use of refrigerant identifiers that analyse the refrigerant in the vehicle's system prior to recovering it for recycling. SAE standards for refrigerant identification equipment are available for global use.

Country Refrigerant Management programs should strongly consider the requirement for unique service fittings in those countries where alternate refrigerants are introduced.

Retrofitting of the CFC-12 fleet has occurred but not nearly to the extent that was predicted previously. This is likely due to stockpiling that occurred prior to the ban on CFC production, CFC-12 recycling and smuggling of CFC-12 into developed countries, especially those with a high tariff on CFC-12. HFC-134a is the only retrofit refrigerant recommended and supported by vehicle manufacturers. Refrigerant production in Article 5(1) countries, stockpiling, retrofitting and natural ageing of the CFC-12 fleet will likely allow the transition away from CFC-12 to be reasonably non-disruptive for the industry and consumers.

10.3.1 Vehicle service profile

The requirement that all refrigerants be recovered at service rather than venting them to the atmosphere has greatly reduced emissions to the atmosphere and, consequently, the need for new refrigerant. Based upon historical data, collected by the Mobile Air Conditioning Society worldwide (MACS), service procedures mandated as a result of the Montreal Protocol have dramatically changed the mobile air-conditioning industry. The practice of simply adding refrigerant to leaky systems is disappearing in favour of leak repair, proper charging and responsible refrigerant handling. This policy of repairing leaking systems should be encouraged in "Country Refrigerant Management Programs"

The U.S. Clean Air Act requires the recovery and recycling of refrigerant during service of mobile A/C systems. Comparing vehicle service profiles since 1990 indicates that A/C system design changes and technician service procedures have reduced the amount of refrigerant required to service the fleet. In addition, the higher cost due to the U.S. tax on new CFC-12 and the elimination of new supplies have made it cost-effective to repair a leaky system rather than simply add refrigerant. The non-taxed reuse of recovered and recycled refrigerant allows the service facility to recover the cost of recovery/recycling equipment.

The typical mobile A/C system service profile in the U.S. has changed since the implementation of the prohibition of venting refrigerants.

The following U.S. service activity information has been obtained from MACS Field Service Survey Reports covering the period of 1990 to 1997 /MAC97/.

- System refrigerant hose replacements due to leakage have been reduced by nearly 50% due to improved designs made by the world automobile manufacturers. In 1993, the replacement of refrigerant hose assemblies was reported on 21.1% of serviced vehicles. In 1997, the replacement of hose assemblies occurred on 11.1% of the serviced fleet;

- In prior MACS surveys, the percentage of vehicles arriving for service with recoverable and reusable refrigerant was in the range of 60% to 70%. The most recent survey for 1997 indicated that more than 80% of vehicles had recoverable refrigerant;

- In 1990 and 1991, 12.5% of all vehicles serviced were simply recharged and returned for additional service within one year. In 1995, only 5.3% of the serviced fleet returned within one year, indicating the repair of a larger percentage of system leaks;

- In 1991, the average refrigerant required to charge a repaired CFC-12 system was 1.34 kg. This refrigerant charge quantity was reduced by system design changes in the 1980's. From these changes, the average repair refrigerant CFC-12 charge amount in 1997 was reduced by 35% to 0.87 kg per vehicle serviced;

- 77% of the vehicles serviced in the 1997 MACS survey were checked for refrigerant contamination using refrigerant identification equipment. Contamination can either be cross-contamination with another refrigerant or excess air resulting from improper use of recovery/recycling equipment. Results indicate that 2.1% of vehicles requiring service had a refrigerant system contaminated with another refrigerant, air, or both;

- These same service and maintenance trends also apply to HFC-134a mobile A/C systems and show that the industry is making significant progress in containing the refrigerant.

10.3.2 Retrofit procedures

With an adequate supply of CFC-12, the service industry has only recently started to retrofit the CFC-12 fleet. Release of retrofit information by the auto manufacturers for their CFC-12 equipped vehicles has helped the service industry perform successful system retrofits to HFC-134a.

A typical time to consider retrofitting is when a major component fails and the system requires service. Replacement components should be of comparable performance levels if the cooling performance after retrofit is expected to be comparable to the original system. There are two basic retrofit procedures:

- Type I: This follows the vehicle manufacturer's recommended procedure which may include the addition or replacement of an A/C component(s). The intent is to provide a procedure that maintains system durability and cooling performance;

- Type II: This is the minimal system change that only includes installing new service fittings, a new identification label and the possible addition of a synthetic lubricant. Unless specified by the vehicle manufacture as their method of choice (i.e., Type I), this procedure may result in reduced cooling performance and possible compressor failure.

The 1997 MACS survey indicated that the professional service industry retrofitted 17.3% of the CFC-12 vehicles arriving for service. Assuming that approximately 20% of the CFC-12 fleet requires service each year, this means that about 3.5% of the total CFC-12 fleet was retrofitted in 1997. Sixty-five percent of retrofitted vehicles followed the factory recommended Type I procedure. In addition, the decision to retrofit the system was based upon having experienced a major system failure. Having a failed compressor was the major reason for considering retrofitting. The 1997 MACS survey indicated that 55% of the systems having a failed compressor were retrofitted. The greatest number of vehicles retrofitted was those less than 8 years of age even though older ones were also retrofitted.

The cost of repair versus the value of the vehicle and its future usefulness seems to be the determining factor for both A/C repair and retrofit.

The incremental cost to retrofit a CFC-12 system, over and above the cost of repairing the original failure that brought the vehicle in for service, was $117 for a Type I and $62 for a Type II retrofit. These retrofit costs (in US $) were originally estimated in the 1994 Technical Options Committee report at US $122.50 for Type I and US $77.50 for Type II.

It should be noted that some countries (e.g., Germany in 1998) have taken an aggressive approach to encouraging retrofitting by making recharging with CFC12 illegal, thus forcing retrofitting or voluntary obsolescence of the system.

10.3.3 Retrofit refrigerants

The international vehicle manufacturers have, after extensive testing, recognised only HFC-134a for use in new vehicles and for retrofitting CFC-12 mobile A/C systems. Mobile A/C systems designed to operate on CFC-12 were never intended to operate with another refrigerant. As a result, there are many considerations when retrofitting to a different refrigerant and lubricant, including materials compatibility, refrigerant control calibration and lubrication of the compressor, all of which require extensive laboratory and vehicle testing to assure system durability.

Aftermarket suppliers have introduced several blend refrigerants into the mobile A/C service sector. A small portion of the retrofitting market has been captured by these blend refrigerants, either for cost reasons or the absence of retrofit recommendations from the car maker. In the United States, the US EPA has deemed many of these blends as acceptable replacements for CFC-12 but it is important to note that such allowance is granted after review for safety and environmental concerns, not suitability for use as a refrigerant in the A/C system. With the exception of HFC-134a, which is a single component refrigerant, all other alternate refrigerants are blended refrigerants with most containing Class II ozone-depleting substances. At least one of these, available in the international market, contains PFC-218, a powerful global warming gas. There is great interest in many countries for dramatically accelerating the phase-out of HCFCs. Thus, the applicability of blend refrigerants containing those substances may be limited.

Because it is impossible for the blend supplier to test his refrigerant and lubricant with all of the thousands of makes and models of CFC-12 vehicles sold world-wide, the compatibility of the refrigerant and its lubricant with system components remains uncertain. Prospective users of a blend refrigerant should consult with the blend's manufacturer to obtain all test results. Certain blend components may be incompatible with commonly used materials. For example, alternate blend refrigerants containing HCFC-22 have damaged certain polymer materials used in the system, causing operating problems in both A/C systems and service equipment. Mobile A/C systems that use pressure control devices and expansion valves for refrigerant flow may also require re-calibration to maintain the expected performance when retrofitted from CFC-12 to an alternate refrigerant.

In addition, blend refrigerants tend to change composition when used in the system due to the selective loss of higher pressure components during refrigerant leakage and permeation of A/C hoses. They can also change composition within the system (fractionate) during operation due to their differences in volatility, i.e., boiling points. Fractionation and leakage from seals and hose assemblies may result in reduced performance, sometimes within a short period of time.

Because of changes in blend refrigerant composition with time and usage, the blends, unlike HFC-134a, cannot currently be recycled on-site for direct reuse. This requires that the blend refrigerant be removed from the system and sent off-site for processing or destruction. This added complication could contribute to intentional venting of the refrigerant to the atmosphere to avoid processing costs. Efforts are underway by Underwriters Laboratories to develop a blend reuse standard (UL Draft 2964) for equipment that would recover the blend refrigerant from the A/C system and return the used refrigerant to the same vehicle. Additional new blend refrigerant will likely also have to be added to make up for losses during system operation and servicing. If, after following this procedure, the A/C system does not provide acceptable cooling, the service shop would have to recover the refrigerant for off-site reclamation and recharge the system with new blend refrigerant.

Service fittings for CFC-12 have been specified in SAE J639 since 1953. In 1991, automotive engineers added specifications for unique service fittings for HFC-134a to this standard. These fittings identify that the system contains a specific and unique refrigerant. In the U.S., the EPA requires each retrofit refrigerant to have its own unique service fittings. In response to this, blend refrigerant suppliers have developed their unique fittings for their refrigerants. The use of any refrigerant, without its own unique service fittings increases the chances for A/C system and service equipment contamination.

Engineering standards and guidelines were developed by the world's automotive engineers in a series of SAE documents that specify testing procedures and acceptance criteria for refrigerants and materials used in mobile A/C systems. SAE J1657 "Selection Criteria for Retrofit Refrigerants to Replace R12 in Mobile Air Conditioning Systems", provides these specific requirements. Suppliers of retrofit refrigerants are encouraged to certify their refrigerant to the requirements in these documents (Annex I).

10.3.4 Hydrocarbons for retrofit

Hydrocarbons have been used in some countries (e.g., Australia) as a retrofit refrigerant for CFC-12 systems. The use of a flammable refrigerant in CFC-12 mobile A/C systems, which were not specifically designed to safely handle such refrigerants, is an extremely dangerous practice due to the risk of passenger injury caused by fire and/or explosion. In the United States, given the clear potential for hazard and absence of proof that flammables can be used safely, the US EPA has banned their use in existing CFC-12 mobile A/C systems. The use of flammable refrigerants in HFC-134a mobile A/C systems has also been banned in some states in Australia and the United States.

Supporters of flammable refrigerants have acknowledged safety concerns and have recommended A/C system modifications prior to using flammable refrigerants /Mac97/. These considerations should be taken into account in any effort to design new systems to use flammable refrigerants.

10.4 Lessons Learned For Use In Article 5(1) Countries

Mandatory refrigerant recovery and on-site recycling will substantially reduce emissions to the atmosphere. Country refrigerant management programs, funded under the Montreal Protocol Multilateral Fund, include recovery and recycling of refrigerant during service of mobile A/C systems. These programs provide technician training and implementation of recovery/recycling equipment at A/C service facilities.

Technician training (certification) on service procedures and refrigerant recovery/recycling will reduce the requirements for large quantities of new refrigerant.

Most CFC-12 mobile A/C systems can be retrofitted at reasonable cost to use non-ozone depleting HFC-134a. Although not recommended by car makers, refrigerant blends may, in some cases, provide an acceptable option for system retrofit. Based on the ability to successfully retrofit to HFC-134a, the use of blend refrigerants that contain Class II ozone-depleting chemicals is not a benefit for the environment.

To prevent refrigerant release to the atmosphere, the use of any refrigerant in the automotive service industry requires recovery/recycling equipment. The addition of other alternate refrigerants (including blends) creates the need for separate equipment for each refrigerant. This increases the possibility of system operating problems as well as contamination of mobile A/C systems and service equipment.

The use of unique fittings and labels for each refrigerant can prevent refrigerant cross-contamination.

10.5 Conclusions and Recommendations

- Regulations should be established in all countries to discourage intentional venting of refrigerants to the atmosphere and to encourage training of service technicians;

- Those Article 5(1) countries still manufacturing vehicles with CFC-12 A/C systems should be encouraged to convert to HFC-134a as early as possible. The successful conversion to HFC-134a in the rest of the world should provide a "role model" for conversion and eliminate concerns and uncertainties that may have been a roadblock in the past. Retrofitting has proven to be simple and effective;

- Currently available service technologies should be supported to enable Article 5(1) countries to convert early from CFC-12 to HFC-134a in new and existing vehicles. The Society of Automotive Engineers (SAE) has developed refrigerant recycling/recovery and service procedures standards and recommended practices for use by the industry to enable better environmental handling of refrigerants. These SAE documents (Annex I) can be used directly or converted into ISO format for adoption and then combined with specific national requirements to implement the appropriate technologies;

- It should be emphasised that no "drop-in" refrigerant exists that can replace CFC-12 without requiring system modifications. Further, the only refrigerant endorsed by vehicle manufacturers world-wide for retrofit is HFC-134a;

- Unless unique service fittings and labels are used, all alternate refrigerants pose the risk of cross-contamination and possible damage to systems and service equipment;

- Country "Refrigerant Management Programs" should consider the requirements for unique service fittings to minimise A/C system and service equipment contamination;

- Work to continue development of other technical options for new vehicles (e.g., CO_2 and hydrocarbons) should be encouraged.

10.5.2 Emission reduction

The ongoing goal is to minimise refrigerant emissions to the atmosphere. This involves the active participation of A/C system manufacturers, the service industry and governmental regulatory bodies. System manufacturers should improve original equipment designs to minimise both the refrigerant charge and refrigerant emissions, while maximising total system energy efficiency. The service industry has developed appropriate equipment, procedures and practices (SAE and ISO documents) to minimise emissions during service and these should be used world-wide. Regulatory agencies (world-wide) should mandate recovery/recycling and reuse of refrigerants during A/C system service and at vehicle scrappage. Commercially available equipment exists for effective on-site recycling of CFC-12 and HFC-134a for mobile A/C systems and efforts are underway to develop equipment to allow the on-site reuse of blend refrigerants. On-site recycling is preferable to recovery followed by off-site reclamation; using currently available on-site recycling equipment avoids the cost of the infrastructure required to support off-site reclamation.

10.6 References

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/Yin98/ J. Yin, et al (Univ. of Illinois), Experimental and Model Comparison of Transcritical CO2 Versus R134a and R-410 System Performance, presented at the IIR Natural Working Fluids '98 Conference, June 2-5, 1998, Oslo, Norway.

Exhibit A   Mobile A/C Annual Industry Emissions of CFC-12

Total Emissions	972 Mtonnes $CO_2\{eq\}$*
Relative Emissions	972 (100%) / 35,792 = ~ 2.72 % of Total Global Man-Made Greenhouse Gas Emissions

*based on a GWP of 8100 for CFC-12, 300 million A/C-equipped vehicles world-wide and a service use rate of 0.40 kg R-12 / vehicle / year /UNE94/

In response to concerns over the Earth's ozone layer (Montreal Protocol), global vehicle manufacturers had, by late 1994, converted all new vehicles from CFC-12 to HFC-134a, thus eliminating any impact from new vehicles on the Earth's ozone layer. The conversion to HFC-134a was very successful. The co-operative efforts of vehicle and A/C system manufacturers, the service industry, environmentalists and government agencies all contributed to a major change that was essentially transparent to the consumer. Improved A/C system refrigerant containment, principally via improved A/C hoses, hose couplings and fittings, combined with environmental consciousness and recovery and/or recycling at vehicle assembly and service have dramatically reduced both refrigerant emissions and the need for new refrigerant at service (see Section 10.3.3). Society of Automotive Engineers (SAE) standards covering all aspects of refrigerant containment (including hose assemblies), A/C system servicing and A/C system retrofit have been developed and are available for global use (see Annex I).

Although the eventual replacement/retrofit of the CFC-12 fleet to HFC-134a will completely remove mobile A/C from the ozone layer issue, concerns over the role of mobile A/C in Global Climate Change remain. When the global CFC-12 fleet is eventually replaced by new HFC-134a vehicles (around 2008), the estimated refrigerant required per vehicle lifetime (to replace fugitive emissions) is estimated to range from 1.26 - 1.92 charges depending upon the availability of refrigerant recovery at vehicle scrappage (see Exhibit B). This dramatic reduction of emissions, coupled with the lesser global warming impact of HFC-134a versus CFC-12, will result in approximately a 92% reduction in the overall annual impact of mobile air conditioning refrigerant emissions on Global Climate change.Thus, the conversion will reduce the impact of mobile A/C on total man-made global warming gas emissions from 2.72% with CFC-12 to 0.22% with HFC-134a.

Exhibit B   Current Mobile A/C Industry Charge Loss

Assumptions:
2 recharges / 12 year vehicle lifetime (Recharge at 5 years and 9 years)
Systems recharged at 40% charge loss
6% loss during recycling/recovery
0.91 kg (2 lbs.) OE refrigerant charge

Lifetime Charge Loss = Original Charge plus Service Recharges minus Recovered Charge.

Lifetime Charge Loss = Original Charge + 46%(2)(Original Charge) - 94% of the Amount Remaining at Vehicle Scrap.

Scenarios

I. *With Recycling at Service and Recovery at Vehicle Scrap*

Lifetime Charge Loss = 0.91 kg + 0.46(2 x 0.91 kg) - 0.94 (0.70 x 0.91kg)
= 1.148 kg with Recovery at Scrap = **1.26 OE Charges / Lifetime**

= 0.096 kg / vehicle / year = Industry loss on a per-vehicle basis

II. *With Recycling at Service - No Recovery at Vehicle Scrap*

Lifetime Charge Loss = 0.91 kg + 0.46(2 x 0.91 kg) - 0
= 1.747 kg without Recovery at Scrap = **1.92 OE Charges / Lifetime**

= 0.146 kg / vehicle / year = Industry loss on a per-vehicle basis

Annex - SAE Documents

Since the first SAE document J513 in January 1936, which conforms to ANSI B70-1974, SAE refrigeration flare fittings have been an industry standard. In April, 1953, SAE J639 provided standards for the system service access fittings currently used by the automotive and commercial industry. To prevent mis-connections, SAE J639 was revised in the 70's to provide different size system service connections on CFC-12 mobile A/C systems. Different high and low refrigeration service access fittings are not used in the commercial industry.

When the mobile industry changed refrigerants from CFC-12 to HFC-134a, new unique quick couple service fittings were developed to reduce venting and possible mixing of refrigerants during service of mobile A/C systems. The mobile air conditioning industry established replacement refrigerant criteria, resulting in new SAE documents.

The industry/EPA field study of mobile A/C systems identified what level of contamination could be expected from used CFC-12 refrigerant and established equipment requirements and the purity levels for recycled refrigerant. Based on that study, SAE and industry have identified that only refrigerant removed from a mobile A/C, recycled on-site and directly used in a mobile A/C system can be accepted. All used refrigerant from other sources must be sent off-site for processing and must meet the specific ARI recycled purity specification.

ISO ACTIVITY

Documents identified [ISO] have been submitted to the ISO/TC22/ WG8 for consideration as possible future ISO documents.

SUMMARY OF SAE DOCUMENTS

At the request of the U.S. Environmental Protection Agency, SAE Interior Climate Control Standards Committee established working groups to address the needs of the auto industry regarding these environmental concerns. This summary includes SAE documents that have been developed to cover emission, contamination and handling of refrigerants used in the mobile air conditioning industry.

INDUSTRY CRITERIA AND GUIDELINES

SAE J2219 "Mobile Air Conditioning Industry and Guidelines". This document was originally published in 1991 and revised in 1994. The purpose of this SAE Information Report is to provide information on refrigerant issues of concerns to the mobile air-conditioning industry.

SERVICE ACTIVITIES

SAE J639 "Safety and Containment of Refrigerant for Mechanical Vapour Compression Systems used for Mobile Air Conditioning Systems". This document covers system access service fittings, pressure relief valves and system label requirements.

[ISO] SAE J1629 "Cautionary Statements for Handling HFC-134a During Mobile Air Conditioning Service".

SAE J2196 "Service Hose for Automotive Air Conditioning". This defines service equipment (gauge lines) hose emission rates and hose construction requirements.

SAE J2197 "HFC-134a Service Hose Fittings for Automotive Air Conditioning Service Equipment". To prevent mixing of HFC-134a, with other refrigerants, a new ½ inch Acme thread fitting for containers was developed by the "Compressed Gas Association". (CGA) This ½ inch Acme thread is also required on HFC-134a automotive service equipment.

SAE J2297 "Stability And Compatibility Criteria Of Fluorescent Refrigerant Leak Detection Dyes For Mobile R-134a Air Conditioning Systems". This provides requirements for material compatibility of trace dye material with mobile A/C systems.

SAE J2298 " Use Of Refrigerant Leak Detection Dyes For Service Of Mobile Air Conditioning Systems". This covers the procedures, including safety requirements, when using trace dye to determine if the A/c systems has a refrigerant leak.

SAE J2299 "Performance Requirements For Leak Detection Dye Injection Equipment". This document establishes the requirements for the equipment required to install trace dye material into the refrigerant circuit of a mobile A/C system.

TECHNICIAN SERVICE PROCEDURES

[ISO] SAE J1628 "Technician Procedure for Using Electronic Refrigerant Leak Detectors for Service of Mobile Air Conditioning Systems". This document provides guidelines for the technician when using an electronic leak detector in determining a system refrigerant leak.

[ISO] DIS 13191 SAE J1989 "Recommended Service Procedure for Containment of R12". This document covers the technician refrigerant recovery procedure when servicing R12 mobile A/C systems and identification of excess NCGs.

SAE J2211 "Recommended Service Procedure for Containment of HFC-134a". This document covers the technician refrigerant recovery procedure when servicing HFC-134a mobile A/C systems and identification of excess NCGs.

SERVICE EQUIPMENT

[ISO] SAE J1627 "Rating Criteria for Electronic Leak Detectors". This document establishes the criteria for electronic leak detectors to identify refrigerant leaks.

SAE J1732 "HFC-134a Extraction Equipment for Mobile Automotive Air Conditioning Systems"

Establishes equipment specifications for recovery of HFC-134a to be processed in SAE J2210 recycling equipment or to be sent off-site facilities to meet ARI 700 purity requirements.

SAE J1770 "Automotive Refrigerant Recovery/Recycling Equipment intended for Use with both R12 and R134a". This document establishes the requirements for a single cabinet (enclosure) having recovery/recycle equipment for both R12 and R134a with a common refrigerant circuit. It establishes the specifications that will assure that the equipment will not cross contaminate refrigerant under normal operating conditions.

SAE J1771 "Criteria For Refrigerant Identification Equipment For Use With Mobile Air Conditioning Systems". Establishes specifications for refrigerant identification equipment used to identify refrigerant purity. This was developed due to the refrigerant contamination problems occurring in mobile A/C systems and refrigerant supplies.

[ISO] DIS 13192 SAE J1990 "Extraction and Recycle Equipment for Mobile Automotive Air Conditioning Systems". This covers equipment certification for recycling CFC-12 to meet the standard of purity.

[ISO] DIS 13193 SAE J1991 "Standard of Purity for use in Mobile Air Conditioning Systems". This identifies the purity level of recycled R12 refrigerant after a contaminated sample has been processed in SAE J1990.

SAE J2209 "CFC-12 Extraction Equipment for Mobile Air Conditioning Systems". This covers equipment certification for removal of CFC-12 from mobile A/C systems that shall be sent off-site for process to meet ARI 700 purity level.

SAE J2210 "HFC-134a Recycling Equipment for Mobile Air Conditioning Systems". This covers equipment certification for recycling of HFC-134a to meet the standard of purity.

SAE J2099 "Standard of Purity for Recycled HFC-134a for use in Mobile Air Conditioning Systems". This identifies the purity level of recycled refrigerant after a contaminated sample has been processed in SAE J2210.

SAE J2296 "Retest Of Refrigerant Cylinder". Refrigerant containers used with recovery and recovery/recycle equipment must be inspected every 5 years to assure their safe use. This document covers the re-testing of these containers.

The mobile Air Conditioning industry has established performance certification requirements for recycle and extraction equipment and purity requirements for recycle equipment. Use of certified ARI-740 equipment, which does not have purity standards requirements, cannot be used in the mobile air conditioning industry since it does not comply with SAE or Section 609 of The Clean Air Act requirements.

SYSTEM COMPONENTS

SAE J51 "Automotive Air Conditioning Hose. This document covers emission rates for R12 refrigerant hoses use on mobile air conditioning systems.

SAE J2064 "R134a Refrigerant Automotive Air Conditioning Hose". This document covers emission rates and coupling integrity for HFC-134a refrigerant hoses used on mobile A/C systems.

ALTERNATE REFRIGERANT REQUIREMENTS

Four documents were developed at the request of EPA to provide engineering guidelines for an alternate refrigerant being considered for mobile A/C systems.

[ISO] SAE J1657 "Selection Criteria for Retrofit Refrigerants to Replace R12 in Mobile Air Conditioning Systems". This includes flammability, ozone depletion, toxicity and other refrigerant and lubricant compatibility requirements to be usable in mobile A/C systems.

[ISO] SAE J1658 "Alternate Refrigerant Consistency Criteria for Use in Mobile Air Conditioning Systems. Blend refrigerants consist of more than one substance, this document identifies the proper handling procedure, vapour or liquid phase and identifies when the remaining container contents can not be used due to improper blend consistency.

[ISO] SAE J1659 "Vehicle Testing Requirements for Replacement Refrigerants for use in R12 Mobile Air Conditioning Systems". This requires certain vehicle tests which must be conducted to establish any system performance changes due to the alternate refrigerant.

[ISO] SAE J1662 "Material Compatibility With Alternate Refrigerants". Seals, hoses and "O" rings used in CFC-12 systems may not be compatible with some alternate refrigerants and could break down causing system failures. This document covers test procedures for establishing material compatibility.

RETROFIT DOCUMENTS

Two documents cover the retrofit procedures for conversion of CFC-12 mobile air conditioning systems to HFC-134a.

[ISO] SAE J1660 "Fittings and Labels for Retrofit or R12 Mobile Air Conditioning Systems to R134a". This document covers modification of service fittings and labels for retrofitted vehicles in preventing future system damage and contamination of the refrigerant supplies.

[ISO] SAE J1661 "Procedure for Retrofitting R12 Mobile Air Conditioning Systems to R134a". This covers the retrofit modification and system processing procedure to reduce the remaining system R12 residue to less than 2%, which is required to reduce future contamination of the R134a refrigerant supply when the vehicle is serviced.

11 Heat Pumps (Heating Only and Heat Recovery)

11.1 Introduction and Significant Observations

Energy conservation is one of the main strategies to enlighten the environmental problems arising from the continuously world-wide growing energy demand. 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 in residential and commercial buildings as well as industrial applications. Because heat pumps require less primary energy than conventional heating systems, they are considered an important technology for reducing emissions of gases that harm the environment, such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x). The overall environmental impact of electric heat pumps depends to a large extent on the efficiency and on the energy mix used for power generation.

In many processes with a heat demand, the medium to be heated has a temperature glide. The heat exchange process could benefit from a temperature glide also of the refrigerant, to better match the temperature profile of the medium to be heated and thus minimalise the heat exchange losses. One example is heating of tap water, which will normally be from 5-10°C and up to 60 - 80°C. Another application area where one can benefit from a temperature glide is heating of process water in industrial processes and in hydronic heat distribution systems.

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. Refrigerants currently used in heat pumps are CFCs, HCFCs, HFCs, ammonia and hydrocarbons (HCs). The ideal refrigerant does not exist and all these options have drawbacks. CFCs and HCFCs contribute to the depletion of the earth's ozone layer (ODP) and, together with HFCs, they also contribute to the greenhouse effect (GWP). Hence, loss of these refrigerants during operation, maintenance and scrapping will partly counteract the reduction in specific CO_2 emissions. Ammonia and HCs are environmentally friendly but represent a local risk, since ammonia is toxic and HCs are flammable.

This chapter discusses 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, "Air Conditioning & Heat Pumps (Air-cooled Systems)".

The most significant observations in the heat pump (heating only and heat recovery) market since the 1994 assessment are:

- 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;

- In developed countries HCFC-22 is still used as one of the main refrigerants in heat pumps. In developing countries (China) CFC-12 still hold a large portion of the refrigerants, together with HCFC-22. Several European countries have regulations on HCFCs in order to phase them out more rapidly than has already been agreed under the Montreal Protocol;
- Developed country manufacturers have introduced HFC alternatives to replace their HCFC heat pump models. HFC-134a and R-404A has been on the market for 5 years and the first models with R-407C as refrigerants entered the market in 1996/97. Full market penetration is expected within few years. R-410A is available as a refrigerant and the first models with R-410A are expected to be available in 1998/99;
- For heat pumps working with higher temperatures HFC-134a is the preferred refrigerant, especially in medium and large capacity units;
- Ammonia is applied in medium/large capacity heat pumps in commercial buildings, especially in Scandinavian countries, and has proved to be a reliable, energy efficient and safe option, taken the necessary safety measures;
- A number of North European manufacturers (Denmark, Germany, Sweden, Austria, and United Kingdom) are producing small air/water or water/water units for residential and commercial usage with hydrocarbons as refrigerants. The units are limited in size, and are designed for low refrigerant charge;
- Due to increased cooling demand in modern and well equipped commercial buildings in northern climates which traditionally only required heating, integrated heat pumps and cooling systems for simultaneously heating and cooling is a trend that is expected to expand in the next few years;
- Several research institutes in US, Europe and Japan are reporting promising theoretical and experimental results with the transcritical CO_2-process in heat pumps, for tap water and process water heating and for drying. Because of a very good temperature match on the heat rejection side due to the CO_2 temperature glide, the process gains excellent coefficient of performance;
- Though ambient air and seawater are still the most common heat sources in heat pumps, geothermal heat pumps are becoming increasingly popular both in the US and in Northern Europe;
- The estimated refrigerant volume is approximately 10,600 tonnes, with 45% CFCs, 42% HCFCs, 11% HFCs and 2% Ammonia (1998). Assessments indicate that the total annual refrigerant demand for heat pumps will be about 2,000 tonnes in the year 2005, of which 70-80% are HFCs and the rest HCFCs, ammonia and hydrocarbons;
- Assuming that 40% of the refrigerant from scrapped and retrofitted heat pump equipment can be recovered, approximately 1,400 tonnes of CFC and 1,800 tonnes of HCFC will be made available for reuse between the year 1998 and 2005. This would still be only 50% of the expected demand for CFCs and HCFCs for servicing of existing heat pump installations during the same period.

11.2 Current Status

11.2.1 Geographical distribution of heating only heat pumps

Due to climate, standard of living, as well as other reasons, the majority of heating-only heat pumps in buildings are located in the North of Western Europe. Though most heat pump installations in Japan, USA and Canada are reversible air-conditioners, there are also a considerable number of heating only heat pumps in these countries. Heat pumps for heating only and heat recovery are scarcely applied in Article 5(1) countries. The reason is that many developing countries are located around the Equator, hence having a very limited space heating demand. Also, since capital is limited in these regions, the CFC-using equipment, to the degree it exists, is more likely to have a refrigeration function (food conservation). Therefore, it is assumed that the number of heat pumps and the annual CFC consumption for developing countries both are negligible.

The Russian Federation, China, and most of the Eastern Europe have average household energy consumption far below that of the Western World. The application of heat pumps in China increases quickly, mostly heat pump units that supply hot water in the winter and cool water in summer /HPC98/. Economic reforms and emerging democracies may eventually yield 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, including that for heating, should preferably not be based on direct combustion of oil or coal. This could spur the demand for heat pump systems, resulting in a world growing market. All this is connected to a high degree of uncertainty and is highly dependent on political decision making and economic growth.

11.2.2 Types and volume of equipment

Heating-only heat pumps are used for space and water heating in residential, commercial/-institutional, industrial buildings, and in district heating and cooling plants. In industry 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. 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. The corresponding figures for industrial heat pumps are 8,500 units, and a total heating capacity of 3,000 MW /HPC94a, Gil93, HPC98/.

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, etc. Industrial heat pumps have much longer annual operating hours, typically between 6,000 to 8,000 hours. The majority of industrial heat pumps operate in the chemical and food processing industries.

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.

11.2.2.1 Residential and commercial/institutional applications

Heating-only heat pumps in buildings 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 small to medium capacity heat pumps in buildings are standardised, factory made units. Large heat pump installations are usually custom made and assembled at the site. Refrigerant charges range between 0.1 and 1.5 kg per kW thermal output, with 1.0 and 0.5 kg/kW as estimated averages for the existing heat pump stock produced before and after 1994, respectively /UNE91, Ste98/. The trend is towards compact heat pumps with smaller refrigerant charge, and there are units on the market with less than 0.05 kg/kW.

Heat pump water heaters, which are heating tap water for sanitary purposes have captured 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 increasingly more popular. Approximately 570,000 units are currently installed in Europe /HPC93a, HPC98/. The potential US domestic market for residential heat pump water heaters is expected to grow in the near future, due to an increased competition between gas utilities and electric utilities in a deregulated energy market /HPC98/.

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

Evaporation temperatures typically range from –10°C to +10°C, with condensation between 40°C and up till 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 US, hydronic heat distribution systems are used both in homes and in larger buildings. The use of hydronic has decreased during the past 20 years. However, the trend in Europe is increased use of hydronic systems in new buildings, especially in commercial sector. Low temperature radiant heating systems permitting distribution temperature of 30-60°C is usual, 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 heat source have become more popular the recent years. It is the fastest growing heat pump application in both the US market and the North 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 very high efficiencies, have made ground source heat pumps competitive compared to other heat sources.

The majority of heating-only heat pumps currently in operation are electric closed-cycle compression type units, using a CFC, HCFC, HFC, ammonia or HCs as refrigerants. The number of engine driven systems is small, but growing. In Japan approximately 30,000 new systems are installed every year /HPC98/. Advanced gas-fired absorption heat pumps was introduced to the market into the early 90ies. The market share is still negligible compared to vapour compression systems.

A large part of the heat pumps on the residential market are small reversible air conditioning units, using outdoor air or exhaust ventilation air as heat source. These units are dominating the market in Japan, Canada and the US, and also hold a large portion of the heat pump market in other countries with a considerable cooling demand. More information about these kind of units can be found in section 7, Air Conditioning and Heat Pumps (air cooled systems)

11.2.2.2 Industrial applications

Industrial heat pumps are generally large in thermal capacity ranging from about 100 kW to several MWs, and the systems are usually custom designed. Heat pumps for batch drying tend to have lower capacities. Evaporation temperatures are generally higher than with residential and commercial/institutional applications and condensation temperatures are typically in the 80°C to 150°C range.

Industrial heat pumps have a much higher Coefficient of Performance (COP) than space heating heat pumps. This is mainly due to the small temperature lifts, large size, efficient design and stable operating conditions.

The type of heat pump applied depends heavily on the process, the heat source and the operating temperatures. Electric driven heat pumps are still the most commonly used. The most common types of industrial heat pumps are:

- Mechanical vapour recompression (MVR) is a technique to increase pressure and temperature on gaseous waste heat and thereby reuse it. MVR systems, or open (semi-open) heat pumps, are extensively used in industrial processes for evaporation or distillation. In the most common type of MVR systems (semi-open, sometimes called direct system), the process steam is compressed directly, and then condensed in a heat exchanger in order to meet a heating demand. 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).

- Electric closed-cycle compression heat pumps are the most commonly used type of heat pumps world-wide. Traditionally, these heat pumps have been using CFCs, HCFCs, and ammonia, but in the recent years HFCs and hydrocarbons have been introduced. These refrigerants are used yet on a small scale. 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/.

- Absorption heat pumps (section 11.3.2.2) are to a small extent installed in industrial applications and in refuse incineration plants to recover heat from the flue gas cleaning process. These installations range from 5 to several ten's of MW capacity. Some installations operate on ground source heat as heat source and supply heat to a district-heating network. Most absorption heat pumps use water and lithium bromide as the working pair, and are capable to deliver heat up to 100°C.

- Heat transformers (section 11.3.2.3) are used to produce useful high-temperature heat from medium-temperature industrial waste heat. Current systems use water and lithium bromide as the working pair. The maximum delivery temperature is 150°C. World wide, less than 25 units are installed.

11.3 Alternative Refrigerants and Technologies

11.3.1 Refrigerants used today and alternative refrigerants

As a general requirement, heat pumps using refrigerants other than CFCs and HCFCs should have at least the same reliability and be as cost effective as (H)CFC systems. Moreover, the energy efficiency of the new systems should be the same or higher. In addition to developing alternative and environmentally acceptable refrigerants, it is important to modify or redesign heat pumps in order to achieve these goals. In general, the energy efficiency of a heat pump depends more on the working cycle and system design than on the refrigerant used.

Traditionally, the most common refrigerants for closed cycle compression heat pumps have been CFC-12, R-502, CFC-11 (heat recovery from centrifugal chillers), CFC-114 and R-500, and HCFC-22, which are all CFCs and HCFCs regulated by the Montreal Protocol. In developed countries HCFC-22 is still used as one of the main refrigerants in heat pumps. In developing countries (China) CFC-12 still hold a large portion of the refrigerants, together with HCFC-22.

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 5 years, the first models with R-407C as refrigerants entered the market in 1996/97 and units with R-410A are expected to appear in 1998/99. Full market penetration is expected within few years. 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 environmentally safe alternatives to CFCs and HCFCs in heat pump systems. The most promising potential refrigerants in this group are ammonia, hydrocarbons (e.g. propane, propylene, and blends of hydrocarbons), carbon dioxide and water (MVRs). Annex 22, *"Compression Systems with Natural Working Fluids"* under the IEA Implementing Agreement on Heat Pumping Technologies (1995-98), amongst others provides state-of-the-art information on compression heat pumps with ammonia, hydrocarbons, CO_2 and water, and establish guidelines for design and safety recommendations for new heat pump installations. An extension of the program is foreseen.

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

Especially in North European countries, ammonia is applied in medium/large heat pump units in commercial buildings and in district heating systems, with capacities ranging from 2-300 kW and upward.

Estimates of the consumption of CFCs (mainly CFC-12) and HCFCs (mainly HCFC-22) in heating-only heat pumps in 1998 are indicated in Table 11.1. These figures include charging of new heat pumps as well as recharging and retrofitting of existing installations. The data are extrapolated from the 1994 statistics /UNE91, HPC94a/, and later developments. The table also gives an estimate of the total refrigerant volume in existing heat pump installations in 1998. Due to many uncertainties in the calculations, all data are to be regarded indicative.

Table 11.1 Estimated annual consumption and total volume of CFCs and HCFCs in heating-only heat pumps (1998).

Refrigerants	Consumption, 1998 [tonnes/year]	Total Volume, 1998 [tonnes]
CFCs	480	4800
HCFCs	700	4500
HFCs	560	1150
Ammonia	50	140

11.3.1.1 HFC-134a

HFC-134a is quite similar to CFC-12 and R-500 in terms of thermodynamic and physical properties, and is regarded as the main successor of CFC-12 in medium temperature heat pump systems. The condensation temperature at 25 bar is approximately 77°C. 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 almost the same as for CFC-12 /Hau93/. Extensive liquid sub-cooling is recommended to improve system energy efficiency. The volumetric refrigeration capacity of HFC-134a is typically 2-3% lower than with CFC-12 at 0°C evaporation temperature /Hau93/, hence a slightly higher compressor capacity is needed.

11.3.1.2 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, e.g. in the United States, Scandinavia and China /Nil91, UNE91, UNE94/.

Due to its flammability, when designing new heat pump plants with HFC-152a, adequate safety precautions should be taken to ensure safe operation and maintenance.

Several pure HFC and HFE alternatives have been investigated, for instance to replace CFC-114 in high temperature heat pumps. In the USA and Japan, a number of partially fluorinated propane's plus two- and three-carbon ethers have been synthesised. Several of these compounds show potential as substitutes, and their properties suggest that as pure fluids and blends they could be applied for most heat pump applications/HPC94b, WFL93, TSU87, Sin97, Sus97, Wat97/. Measurements of basic properties have been carried out to develop correlation's for thermodynamic properties and to simulate cycle performance. Extensive work is needed before any of the alternatives reach commercialisation.

11.3.1.3 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 that they replace, and systems have had to be optimised in order to bring the performance in line with HCFC systems through enhanced surface heat exchangers, effective control systems, improved compressor design, etc.

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 (0.9K at 1.013 bar), 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 rather large glide, 7.2K at 1.013 bar, while the saturation pressure and volumetric heating capacity is about the same as for HCFC-22. The discharge temperature is somewhat lower that for HCFC-22, as is also the Carnot efficiency.

R-410A is a binary blend that can replace HCFC22. The blend has practically zero temperature glide. Its normal boiling point is approximately 10°C lower than HCFC-22, resulting in a 50 % pressure increase. The volumetric heating capacity is approximately 50% higher than for HCFC-22 /BIT97/.

11.3.1.4 Ammonia

Ammonia has excellent thermodynamic properties, and has been used as refrigerants in industrial purposes for many years. 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, thus reducing the required compressor capacity. 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 gaining popularity 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 2,000 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 still 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, industry, as well as in fish farming plants.

Due to ammonia being toxic, system safety requires the machine room to be designed according to prevailing standards. Safety design measures can include proper placing and/or gas tight enclosure of the heat pump, application of low-charge systems, use of indirect heat distribution systems (brine systems), fail-safe ventilation systems, gas detectors (alarm system), water spray systems, etc.

Although ammonia is an excellent high-temperature refrigerant, it has not been applied in industrial heat pumps operating above 80°C, mainly due to the lack of high-pressure compressors with a reasonable efficiency. A prototype ammonia heat pump for drying has been developed in Norway, operating at a maximum condensing temperature of 100°C /Jon97/.

11.3.1.5 Hydrocarbons

Hydrocarbons (HCs) are flammable, proven refrigerants which have been used in large refrigeration plants for many years, notably in petrochemical industry. Hydrocarbons are non-ODP and low-GWP refrigerants. Today hydrocarbons emerge 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 propane/iso-butane and ethane/propane. Several North European manufacturers of heat pumps are using HC-290 or HC-1270 as refrigerants in small residential and commercial water-to-water and air-to-water heat pumps. A number of prototype heat pumps with HC-290 and other hydrocarbons have been installed /HPC93b, NLA94, FIZ98/.

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 CFC-12 /Ber93/. Maximum condensing temperature with standard 25-bar equipment is about 68°C.

Hydrocarbons are soluble with all lubricants, and compatible with materials such as metals and elastomers that are traditionally used in refrigeration equipment. Standard refrigeration practise as for HCFCs and CFCs can be used without major system detriment to system integrity.

When designing new heat pump systems with propane or other flammable refrigerants, adequate safety precautions should 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 systems, fail-safe ventilation systems and gas detector activating alarm systems. Several standards that regulate the use of hydrocarbons in heat pumps, given the proper safety precautions, exist or are on their way in Europe, Australia and New Zealand (KYS96, DIN 7003, UVV-VBG 20, BS 4434, prEN 378). A draft of IEC-335-2-40 is presently being worked on to accommodate flammable refrigerants.

11.3.1.6 CO_2 used in transcritical process

CO_2 was used as a refrigerant before the CFCs entered the market 60 – 70 years ago, and has excellent thermophysical properties, leading to good heat transfer, efficient compression and compact system design due to high capacity. Besides being non-ODP and non-GWP, carbon dioxide (CO_2) offers a number of advantages. CO_2 is non-flammable, has low toxicity, and is compatible to normal lubricants and common machine construction materials.

At 0°C the volumetric refrigerating capacity of CO_2 is between five and eight times higher than for other refrigerants, consequently reducing the compressor volume. The pressure ratio is also greatly reduced compared to conventional refrigerants, thus giving the CO_2 compressor very high efficiencies. The relatively low molar mass of CO_2 reduces the mass flow and the required dimensions of compressor, valves and piping. Due to the limited volume of the system, the high pressure (above 100 bar) does not constitute a larger danger in the case of rupture, compared to HCFC-22 baseline systems /Pet97/.

The ability of the transcritical CO_2 process to absorb heat at constant temperature and reject heat at gliding temperature above supercritical pressure, makes it well suited for heat pump applications with ambient heat as the heat source and a considerable temperature glide (30-50°C) on the heat distribution side. Examples of such applications are heat pump water heaters and large heat pumps in district heating systems /Nek98/.

Several research institutes are carrying out theoretical and experimental studies on transcritical CO_2 processes in different heat pump applications, such as heat pump water heaters, residential heat pumps and heat pump dryers /Nek98/. Laboratory prototype utilised for tap water heating, shows an considerably energy consumption reduction with as much as 30% compared to standard heat pump water heaters using CFC-12 or HFC-134a /Nek92, Sai97, Nek97/. The high process efficiency is partly due to good adaptation of the process to the application, and partly due to a very efficient compression and good heat transfer characteristics for CO_2. 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.

CO_2 heat pump water heaters are expected to be the first CO_2 heat pump application to be commercialised, and will most likely enter the market in the early 2000s.

11.3.1.7 Water

Water is an excellent refrigerant for high-temperature industrial heat pumps due to its favourable thermodynamic properties and the fact that it is neither flammable nor toxic. Water has mainly been applied as a working fluid in open and semi-open MVR systems in industrial evaporation processes. Operating temperatures are in the range 80° to 150°C. A closed-cycle prototype heat pump has reached an output temperature of 300°C (85 bar) /HPC89/. 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.

11.3.2 Alternative technologies

11.3.2.1 Absorption heat pumps (Type I)

Absorption heat pumps for space heating are mostly gas-fired, whereas industrial systems are in most cases driven by steam or waste heat. Most of the systems use water and lithium bromide as the working pair, and can achieve about 100°C output temperature. Industrial absorption heat pumps are, for economic reasons, mainly used in large sizes (MW).

Absorption heat pumps for heating of residential buildings start entering the market. An Austrian firm has developed a heat pump for retrofit applications. It is expected that within 2 years small, residential systems for new houses will enter the market in Japan and Europe. In industry absorption heat pumps are applied on a negligible scale only. In Sweden and Denmark a number of installations are in operation, which supply heat to district heating networks. They recover heat from flue gas cleaning systems in refuse incineration plants or use geothermal heat as heat source (Denmark/Germany).

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. Advanced 250 kW GAX absorption heat pump for space heating and cooling entered the market in 1993, with ammonia/water as the working pair. Systems have been installed in institutional buildings in Netherlands and are planned in Germany. The systems have demonstrated good performance, low maintenance and high seasonal PER.

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.

A new working fluid for high temperatures (max. 260°C) is now available on the market. This fluid makes it possible to use cheaper construction materials as the corrosion rate is negligible /HPC94a/. No demonstration projects or applications have been reported in literature.

11.3.2.2 Heat transformers (Type II)

Heat transformers are used in some industries to upgrade waste heat to a useful temperature level. These systems use water and lithium bromide as the working pair. Current systems have a maximum delivery temperature and temperature lift of 145°C and 50°C, respectively. 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/.

11.4 Existing Heat Pump Installations - Retrofits

11.4.1 General

Heat pump systems have a typical average lifetime of 15 for small units and up to 25 years for larger units. A large number of existing installations using CFCs and HCFCs are expected to operate beyond the date of CFC and HCFC phase-out. Hence, measures have to be taken to ensure full lifetime operation. In practice, two options are available. Refrigerants can be *re-used/recovered* or heat pumps can be *retrofitted* with alternative refrigerants. In general, the number of retrofitted heat pumps have been lower than it was expected to be in the 1994 Assessment.

11.4.2 Re-use and recovery of refrigerants

It has not been technically feasible, or economically justifiable to retrofit or dismantle all heating-only heat pumps using CFCs by 1995/96. Reuse and recovery of refrigerants still plays an important role. Provided that a proper quality of recovered refrigerants is secured, existing heat pumps may be allowed to continue operating with the refrigerant they have been designed for. Main challenges will be to avoid leakage and update existing equipment, and ensure high quality standards for the recycling process.

11.4.3 Retrofitting

Retrofitting means replacement of CFC refrigerants in existing equipment, including minor or major modifications or redesign of plants. The degree of plant modification depends on factors such as the alternative refrigerant, lubricant, system design, size, material compatibility etc. Old, leaking installations in poor technical condition should preferably be scrapped and replaced by new equipment. Relatively new heat pump systems should be sealed before any retrofitting is carried out.

Technically, most equipment can be retrofitted with new refrigerants. In general retrofitting involves a thorough and systematic evaluation of safety, reliability, capacity requirements and energy efficiency. Other aspects, such as equipment, refrigerant and labour costs, as well as availability of refrigerants are taken into consideration when selecting retrofit refrigerants.

Typical modifications include change of lubricant, adjustment or change of expansion device, change of desiccant material, replacement of non-compatible sealing materials (elastomers in O-rings, gaskets, etc.), and compressor modifications/replacement. For details on retrofitting procedures for heat pumps using CFC-11, CFC-12, R-500, R-502 and HCFC-22 reference is made to compressor or heat pump manufacturers manuals, and to the refrigerant suppliers.

Table 11.2 provides an overview of today's refrigerant alternatives for retrofitting heat pumps.

Table 11.2 Alternatives for retrofitting of heating-only heat pumps.

Refrigerant	Alternative Refrigerants for Retrofitting	
	Short Term	Medium/Long Term
CFC-11	HCFC-123	
CFC-12 and R-500	HCFC blends: R-401A R-401B R-409A	HFC-134a Hydrocarbons
CFC-114	HCFC-124 (HCFC-123)	
R-502	HCFC blends: R-402A R-402B R-408A HCFC-22	HFC blends: R-404A Hydrocarbons
HCFC-22		HFC blends: R-407C (R-404A) Hydrocarbons

11.4.3.1 CFC-11 alternatives

Examples of CFC-11 heat pump retrofits are not widely available. HCFC-123 is a possible retrofit, it is applied in retrofits in US, but is not done in Europe. The trend seems to be replacement of the 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 small units.

11.4.3.2 CFC-12 and R-500 alternatives

A large number of CFC-12 and R-500 heat pump plants has been retrofitted to HFC-134a. The retrofit requires cleaning, vacuuming and oil change, since mineral oil is not compatible with HFCs. There are currently available HCFC blends for replacing CFC-12 and R-500. Hydrocarbons are also an alternative.

a) HFC-134a

When retrofitting from CFC-12 to HFC-134a, the mineral oil is replaced with a polyol ester lubricant. Proper cleaning of the heat pump system is crucial before recharging with HFC-134a, since residual mineral oil, sludge deposits and moisture may cause serious operational problems. Standardised cleaning methods have been developed, and a number of small, medium and large capacity heat pumps have already been successfully retrofitted.

Users are reporting only minor, or none problems at all with their plants after retrofitting. Experience and measurements from retrofits in Scandinavia have shown that the capacities and COPs are unchanged or sometimes even better after a retrofit from CFC-12 to HFC-134a. Generally, the capacities and the COPs are better after any retrofit than an idealised theoretical comparison would show, due to the service and the cleaning that the system undergoes during a well done retrofit /Her96/.

b) HCFC-Blends

The HCFC blends can use both mineral oil and alkylbenzene lubricants, which make the cleaning process much less critical compared to retrofitting to HFC-134a. Manufacturers in most cases recommend alkylbenzene, to ensure adequate lubrications and oil return to the compressor. The HFCF-blends are near-azeotropic, and only minor system modifications are needed.

Common ternary blends for retrofitting of heat pumps using CFC-12 and R-500 are *R-401A*, *R-401B* and *R-409A*. Volumetric refrigeration capacity and theoretical energy efficiency is approximately the same as for CFC-12, but the blends have a temperature glide of approximately 2 - 4°C.

c) Hydrocarbons

There have been discussions about using hydrocarbons 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, since the blend matches the characteristics of CFC-12 better. Hydrocarbons are soluble with all lubricants and compatible with materials that are traditionally used in refrigeration equipment, and retrofits do not require any lubricant change.

Due to the flammability, application of hydrocarbons in retrofit applications may be limited by local ordinances and safety codes and it is necessary to ensure all retrofits conform to relevant safety standards. Typical safety measures include addition of tracer gases, proper placement and/or gas tight enclosure of the heat pump, fail-safe ventilation systems and gas detector activating alarm systems. Several standards that regulate the use of hydrocarbons in heat pumps, given the proper safety precautions, exist or are on their way in Europe, Australia and New Zealand (KYS96, DIN 7003, UVV-VBG 20, BS 4434, prEN 378, IEC-335-2-40 (draft)).

Though it is thermodynamically and physically feasible, retrofits from CFC-12 to hydrocarbons in heat pumps are not commonly carried out.

11.4.3.3 CFC-114 alternatives

CFC-114 was used in high-temperature heat pumps for industrial purposes, for instance for process water heating (80-120°C). Examples of CFC-114 heat pump retrofits are not widely available, and CFC-114 equipment is often replaced by equipment with new, ODS-free refrigerants or other, more traditional heating systems (oil boilers, electric resistance boilers, gas boilers).

HCFC-124 is a possible alternative for retrofitting heat pumps using CFC-114. HCFC-124 requires higher operation pressure levels than CFC-114, and is in many cases not suitable for retrofitting heat pumps since the pressure levels will exceed design ratings. Moreover, the volumetric refrigeration capacity of HCFC-124 is 40-45% higher than that of CFC-114, and complete compressor and motor replacement is necessary in order to maintain required heating capacity.

11.4.3.4 R-502 alternatives

Current alternatives for retrofitting heat pumps using R-502, are HFC-blends, HCFC-22 and HCFC-blends.

a) HFC-blends

HFC blends for retrofitting heat pumps using R-502 have been commercially available as of 1993/94. The retrofitting procedure for HFC-blends is similar to HFC-134a retrofitting, with a change of lubricant from mineral oil to a polyolester lubricant. The most frequently used retrofit blend in heat pumps is R-404A. R-404A is a near-azeotrope with a temperature glide of 0.3 – 0.4°C, and a volumetric cooling capacity that is about 15% higher than that of R-502. R-404A may result in capacity decrease and increase in energy consumption, giving COPs about 10 – 20% lower than R-502 dependent of the system design and of the temperatures.

b) HCFC-22 and HCFC-blends

The HCFCs can use both mineral oil and alkylbenzene lubricants, which make the cleaning process much less critical compared to retrofitting to HFCs. The volumetric capacity of HCFC-22 is slightly higher than that of R-502, and the system pressure is almost the same. Hence, 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 have been developed as short term alternatives to retrofit R-502 units. Common near-azeotropic retrofit blends are *R-402A*, *R-402B*, and *R-408A*. The retrofit procedure is simple and inexpensive.

c) Hydrocarbons

R-290, a blend of R-290/R-170 and R-1270 are possible retrofit candidates for R-502. The volumetric refrigeration capacity of propane is almost the same as with R-502, and no compressor modifications are needed. Hydrocarbons are soluble with all lubricants and compatible with materials that are traditionally used in refrigeration equipment, and retrofits do not require any lubricant change.

Due to the flammability, application of hydrocarbons in retrofit applications may be limited by local ordinances and safety codes and it is necessary to ensure all retrofits conform to relevant safety standards. Typical safety measures include addition of tracer gases, proper placement and/or gas tight enclosure of the heat pump, fail-safe ventilation systems and gas detector activating alarm systems. Several standards that regulate the use of hydrocarbons in heat pumps, given the proper safety precautions, exist or are on their way in Europe, Australia and New Zealand (KYS96, DIN 7003, UVV-VBG 20, BS 4434, prEN 378, IEC-335-2-40 (draft)).

As for CFC-12, retrofits from R-502 to hydrocarbons are not commonly done in heat pumps.

11.4.3.5 HCFC-22 alternatives

Current alternatives for retrofitting heat pumps using HCFC-22, are HFC blends and hydrocarbons.

a) HFC-blends

A number of *HFC blends* which can replace HCFC-22 (and R-502) in existing heat pump installations have been investigated, and has been commercially available from 1993/94. Although R-407C (HFC-32/125/134a) has a large temperature glide (5 – 7 °C) which may lead to liquid slugging in the compressor when using thermostatic expansion valve, it is the most promising and preferred of the candidates for retrofitting. The saturation pressure and volumetric cooling capacity is about the same as for HCFC-22. The discharge temperatures are lower with R-407C than with R-22, as is the COP of the systems /Her96/.

R-407C has retrofitting procedures similar to HFC-134a retrofitting, which include change of lubricant. The mineral oil is replaced with a polyolester lubricant. As for an HFC-134a retrofit, proper cleaning of the heat pump system is crucial before recharging with R-407C, since residual mineral oil, sludge deposits and moisture may cause serious operational problems.

b) Hydrocarbons

R-290, a blend of R-290/R-170 and R-1270 are possible retrofit candidates for HCFC-22. The volumetric refrigeration capacity of propane is almost the same as with HCFC-22, and no compressor modifications are needed. The maximum achievable condensing temperature when using standard 25 bars equipment increases from about 61°C to 68°C. Hydrocarbons are soluble with all lubricants and compatible with materials that are traditionally used in refrigeration equipment, and retrofits do not require any lubricant change.

Due to the flammability, application of hydrocarbons in retrofit applications may be limited by local ordinances and safety codes and it is necessary to ensure all retrofits conform to relevant safety standards. Typical safety measures include addition of tracer gases, proper placement and/or gas tight enclosure of the heat pump, fail-safe ventilation systems and gas detector activating alarm systems. Several standards that regulate the use of hydrocarbons in heat pumps, given the proper safety precautions, exist or are on their way in Europe, Australia and New Zealand (KYS96, DIN 7003, UVV-VBG 20, BS 4434, prEN 378, IEC-335-2-40 (draft)).

In Germany heat pumps using HCFC-22 have been successfully converted to propane /HPC93c/.

11.5 Forecast of Refrigerant Use

CFC production has stopped, and future refrigerant supply for heating-only heat pumps will come from recycled/recovered CFCs from scrapped and retrofitted heat pumps, stocked CFCs by end-users, as well as HCFCs, HFCs, ammonia and hydrocarbons in retrofitted plants.

Estimates for the refrigerant volume in existing heat pump stock has been made by using the heat capacity of the existing heat pump stock in 1998, multiplied with an average estimate for refrigerant charge. 1.0 and 0.5 kg/kW has been used as average refrigerant charge for heat pumps produced before and after 1994, respectively /UNE91, Ste98/. The trend is towards compact heat pumps with smaller refrigerant charge, and there are units on the market with less than 0.05 kg/kW. This is not reflected in the model. An average lifetime of the heat pumps are estimated to 15 years, meaning that 6-7 % will be scrapped yearly.

Estimates for the distribution of refrigerant used in the installation of new heat pumps are as follows /UNE94b, Egg95, HPC94a/:

	CFC	HCFC	HFC	Ammonia
Before 1994:	60%	40%		
1995 - 1996		75%	20%	5%
1997 - 2000		35%	60%	5%
2001 -		5%	90%	5%

The estimated refrigerant volume in 1998 is approximately 10,600 tonnes, with 45% CFCs, 42% HCFCs, 11% HFCs and 2% Ammonia. Heat pumps for heating only purposes have a negligible impact on the world-wide total refrigerant consumption volume (<1%).

The following estimate of world-wide annual refrigerant demand can be made, Table 11.3. Since CFC is prohibited in new installations from 1995, it is assumed that CFC demand only cover leakage, with a leakage rate of 10 % annually of the existing heat pump stock.

Table 11.3 Estimated heat pump refrigerant demand [tonnes]. Ammonia demand is to be read as HFC equivalents.

Year	Type of Refrigerant				
	CFCs	HCFCs	HFCs	Ammonia	Total
1998	480	710	560	50	1,800
1999	440	705	630	55	1,830
2000	400	700	700	60	1,860
2001	350	400	1,060	70	1,880
2002	310	350	1,180	80	1,920
2003	265	300	1,300	85	1,950
2004	220	230	1,440	90	1,980
2005	180	160	1,580	100	2,020

Estimated CFC and HCFC demand for heating only heat pumps in 1998 is 480 and 710 tonnes, respectively. The assessments indicate that the total annual refrigerant demand for heat pumps will be about 2,000 tonnes in the year 2005, of which 70-80% are HFCs and the rest HCFCs, ammonia and hydrocarbons.

An important factor is the *availability* of high quality recovered refrigerants for service purposes. Due to various reasons, only a fraction of the potential for recovery can be utilised as refrigerant, and the rest of the returned CFC is destroyed due to contamination /NRR98/. Assuming that 40% of the refrigerant in scrapped and retrofitted heat pump equipment can be recovered, approximately 1,400 tonnes of CFC and 1,800 tonnes of HCFC can be made available for reuse between the year 1998 and 2005. This would still be only 50% of the expected demand for CFCs and HCFCs for servicing of existing heat pump installations during the same period.

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12 Refrigerant Conservation

12.1 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 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 three 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 come from the field, where refrigerant is beginning to be regarded as too expensive to be wasted.

12.1.1 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. Six types are identified in /Clo98/ :

- **Fugitive emissions** are emissions whose source cannot be precisely located.
- **Tightness degradation** is due to temperature variations, pressure cycling, and vibrations that can lead to unexpected and significant increases of leak flow rates.
- **Component failures** mostly originate from poor construction or faulty assembly.
- **Losses due to refrigerant handling** occur mainly when charging the system, and opening the system without previously recovering the refrigerant.
- **Losses due to accidents** are unpredictable and occur from accidents, fires, explosions, sabotage, and theft.
- **Losses at equipment** disposal are due to venting, rather than recovering, refrigerant at the end of the systems life.

12.1.2 Reduction of emissions through leak tightness

Experience in different countries has shown that air-conditioning and refrigeration equipment manufactured over the past few years has been designed to be tighter than air-conditioning and refrigeration equipment manufactured earlier, and that existing appliances have often been modified with new devices, such as high-efficiency purge devices for low-pressure chillers, that have significantly lowered their refrigerant emissions. Manufacturers have made these design changes, and owners have invested in them, in response to growing environmental and economic concerns associated with refrigerant emissions.

Comfort cooling chillers

Research performed by the US EPA indicates that the reduction in leak rates in the USA has been most dramatic in comfort cooling chillers, where leak rates have been lowered from between 10 and 15 percent per year to less than five percent per year in many cases. Design changes that have contributed to this reduction include the installation of high-efficiency purge devices on low-pressure chillers, the installation of microprocessor-based monitoring systems that can alert system operators to warning signs of leakage (such as excessive purge run time), the use of leak-tight brazed rather than leak-prone flared connections, and the use of isolation valves, which permit technicians to make repairs without evacuating and opening the entire refrigerant circuit. The first two conservation measures can be implemented for existing as well as new equipment; the last two apply primarily to new equipment. Manufacturers, servicemen, and users of chillers state that, as a result of these modifications, chillers built since 1992 typically leak less than five percent per year, with many new chillers leaking around two percent per year, and some leaking less than one percent. Only one type of new equipment has been reported to have a leak rate above five percent; that is high-pressure chillers with open-drive compressors, which have been found to have leak rates ranging from four to seven percent. Older chillers that have been modified with emissions-reduction technologies are reported to leak between one and 10 percent per year. Where industry sources have not distinguished between modified and unmodified older equipment, leak rates have been reported to average four percent per year, indicating that most of the chiller fleet has either been modified to leak less or is significantly better maintained than it was five years ago /EPA98/.

Chillers end-users have been very active. The annual loss rates recorded by a French association of chiller operators, called Climafort, are summarised in Table 12.1. These data show that the containment policy that these operators have implemented since 1992 brought positive results.

Rapidly, the loss rates of R-11 chillers (semi-hermetic compressors, average age of 24 years) became lower than those of R-12 chillers (open compressors, average age of 20 years). These rates decreased by more than 60% for R-11 and by 40% for R-12 despite the age of the chillers.

Table 12.1 ***Refrigerant losses from Climafort Chillers in /Clo98/***

Loss rates (% charge/yr)	1987	1988	1989	1990	1991	1992	1993	1994
R11	15	23	16	19	20	15	8	7
R-12	33	24	36	27	23	30	10	17

Commercial refrigeration

In general, leak rates are higher in the commercial refrigeration sector than in the chiller sector. In large part, this is attributable to the facts that (1) equipment in the commercial refrigeration sector is largely assembled in the field rather than in the factory and (2) commercial refrigeration equipment generally uses a long single refrigerant loop for cooling rather than a short primary refrigerant loop with a secondary loop. Also, the need to operate system continuously to protect product from spoilage makes it more difficult to perform leak repair and related maintenance of commercial refrigeration equipment. Nevertheless, data from manufacturers and owners of commercial refrigeration equipment indicates that leak rates considerably lower than those being achieved a few years ago can be achieved cost effectively with this equipment. One large German manufacturer of commercial refrigeration equipment, for instance, reports an average of 10% annual leakage rate for their new equipment /Rin98/.

A study sponsored by US EPA's Office of Research and Development (ORD) analysed two detailed bodies of data on leakage from commercial refrigeration equipment, one collected by a Midwestern chain of 110 stores and the other gathered by the South Coast Air Quality Management District (SCAQMD) in California, which requires monitoring and reporting of leak rates from large refrigeration systems. The Midwestern chain achieved an average leak rate of 15 percent by establishing written procedures for equipment installation (including a requirement that expansion valves be brazed or "sweated"), a refrigerant monitoring system, and an equipment inspection protocol. This rate was achieved in 1992, even before EPA's leak repair requirements were in effect. The data collected by SCAQMD was based on 440 recharging and leak testing events from 56 different stores representing 20 different businesses. The average leak rate achieved by the stores was eight percent of total charge per year. The EPA ORD report also investigated the cost-effectiveness of different strategies and technologies for reducing leak rates, finding that many of these approaches could lower leak rates significantly and thereby pay for themselves. Using a combination of these approaches, a number of supermarket chains have significantly reduced both overall refrigerant consumption and leakage from equipment over the previous two to eight years. Some of the most effective approaches included vibration elimination devices, use of high-quality brazed rather than mechanical connections, low emission condensers, stationary refrigerant monitors, refrigerant tracking and improved preventive maintenance. A few of the approaches, such as installation of low-emission condensers, were more applicable to new than to existing equipment; however, many of the approaches, such as refrigerant monitors, refrigerant tracking systems, and improved preventive maintenance, were applicable to both existing and new equipment. These approaches were expected to reduce leak rates from equipment by between five and forty percent of the charge per year /EPA98/.

12.1.3 Reduction of emissions through recovery

The case of France where results on reclaim 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 raised to 300 tonnes and the number of refrigeration companies concerned doubled from 200 to 400 out of 2500. Since, the quantities have increased. This excludes recovery for reuse on site which is still much more difficult to quantify. In this example government incentives were necessary to reach full development of recovery. It also shows that making recovery a habit requires some time.

For Denmark, figures are available since the introduction of the mandatory refrigerant reclaimment in 1990 /KMO98/.

Reclaimed (metric tonnes)	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
France	120	150	260	250	300	420	500	550
Denmark					40	48	44	31

12.2 Suggested Government Options in Encouraging Refrigerant Conservation

In addition to phasing out production of ODS under the Montreal Protocol, governments can help to reduce ozone-depletion by strongly encouraging containment. One basic approach is simply to make refrigerant recovery compulsory. In addition to direct regulation, governments can encourage refrigerant containment in a number of ways including research and development, information dissemination, and financial incentives. A brief description of each approach and its advantages and disadvantages follows. They are valid, with appropriate adaptations, for both developed and Article 5(1) countries.

12.2.1 Research and development

Research and development typically involves research on sources of emissions and technologies to address these. Governments may establish their own laboratories and/or fund industry research efforts. Projects for research and development may include surveys or measurements to identify the most emissive types of systems, components, and phases of the system life cycle (i.e., manufacturing, service, use, or disposal), as well as investigation of charge minimisation measures, high efficiency recycling and recovery equipment, improved service practices, and technologies and maintenance practices to increase system tightness.

R &D can reveal effective containment methods and technologies and is an unobtrusive method of encouraging containment. However, the existence of an effective containment method or technology does not alone ensure that it will be used, and R&D is likely to be most effective when there are legal or financial incentives to implement findings.

12.2.2 Information dissemination

Information dissemination can encourage refrigerant conservation by emphasising both why and how to contain. It may include providing materials and/or training on the role of ODS, the effects of ozone depletion, and technologies and techniques for reducing emissions. Information dissemination may be targeted both at industry and the general public, and may be especially effective in changing the behaviour of more isolated segments of the industry, for whom ignorance of proper techniques has hampered containment.

Information dissemination may increase general knowledge of both how and why to contain, improving containment where ignorance is the primary problem. However, information dissemination is likely to be most effective with legal or financial incentives to implement it. Moreover, populations that are isolated from the industry may also be difficult for government to reach.

12.2.3 Financial incentives

Financial Incentives can encourage containment by making emissions more costly for users. Financial incentives may include sales taxes on refrigerants, deposit-refund schemes, and tax breaks for investing in recovery/recycling equipment or other refrigerant containment technologies. Unlike direct "command and control" regulation, financial incentives encourage containment without prescribing specific methods. Thus, they allow the market to find the most cost-effective containment measures and they encourage innovation.

Sales Taxes or excise taxes encourage conservation of refrigerants by making it more expensive to replace them. A gradually rising excise tax on CFCs in the U.S. has been effective in increasing containment of CFC refrigerants. For instance, the tax has made it less expensive to recycle CFC-12 in motor vehicle air-conditioners than to buy new refrigerant, addressing a significant source of emissions.

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 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.

Tax breaks for investing in refrigerant containment equipment and technologies have been adopted by some states in the U.S. To the extent that they are tied to particular technologies, tax breaks 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, because, left unchecked, such a market will eventually undermine the incentives.

Financial Incentives may be easier than direct regulations to develop and enforce, and more flexible than direct regulation as they 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, as is occurring for HCFCs and HFCs in many developed countries, and for CFCs in many Article 5(1) countries. (While higher refrigerant prices tend to encourage conservation, lower prices tend to discourage it. This is particularly the case if refrigerant prices are so low that it is more economical for field engineers to vent refrigerant than to spend the time necessary to recover 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 grey or black market in refrigerants (e.g., illegal imports) is allowed to operate. Moreover, by themselves, financial incentives cannot compel conservation. Finally, in case of market failures, such as inadequate information on recycling techniques and technologies, the effectiveness of financial incentives may be hampered.

12.2.4 Direct regulation

Direct regulation is the most traditional governmental approach to encouraging conservation and reducing pollution. For purposes of refrigerant containment, direct regulation may include establishing required service and disposal practices for air-conditioning and refrigerating equipment, containment standards and/or certification programs for air-conditioning and refrigerating equipment and recovery/recycling equipment, and required training and/or operator certification programs. To the extent possible, standards should be performance based rather than technology based tc 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.

12.2.5 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.

In the European Council (E.C.) Regulation no. 3093/94 on substances that deplete the ozone layer /EC94/, the European Commission requires that all precautionary measures practicable shall be taken to prevent leakage of CFCs and HCFCs and the Member States may define the minimum qualification requirements for the servicing personnel involved. In the future, this regulation should be updated and an annual leak tightness inspection could be 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 any installation containing more than 2 kg of charge. Recovery must be performed by experienced operators and registered companies. This decree is being updated to meet the requirements of the E.C. Regulation no. 3093/94 and will make an annual leak tightness inspection mandatory, except for domestic appliances and automotive air conditioning. The application documents of the decree will specify the conditions for this leak tightness inspection.

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 frequency of leak tightness inspection is also specified: once a year for charges under three kilograms, once every three 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. The leak tightness tests are performed by certified operators equipped with leak detectors of 5 p.p.m. sensitivity. Before commissioning new installations or changing refrigerant, leak tightness test must be performed at maximum working pressure of the equipment.

The United Kingdom Environmental Protection Act of 1990 mandates several measures for CFCs, HCFCs and HFCs conservation. 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 under sections 608 and 609 of the Clean Air Act Amendments /CAA95/. These regulations include both Recovery, Recycling and Reclamation requirements and Maximum Allowable Leak Rates :

- Before repairing or disposing of air conditioning and refrigeration equipment, technicians must recover the refrigerant. The percentage of refrigerant that must be recovered or the level of evacuation that must be achieved varies depending upon the type of equipment. Small appliances (primarily household refrigerators and freezers and room air-conditioners) must have 80 or 90 percent of the refrigerant recovered, depending upon whether or not the compressor of the small appliance is operating. Larger equipment containing high-pressure refrigerants (including R-114 and higher saturation pressure refrigerants) must be evacuated to levels between 51 and 101 kPa (7.4 and 14.7 psia). Larger equipment containing low-pressure refrigerants must be evacuated to between 3.45 and 17.2 kPa (0.5 and 2.5 psia). Some types of releases are excepted from the prohibition on venting, including releases from mechanical purging of non-condensables, releases of mixtures of nitrogen and refrigerant used in leak testing, and small releases associated with efforts to charge or recover refrigerant.

- Owners of equipment containing charges of more than 50 pounds are required to repair leaks in their equipment when the leak rate exceeds the applicable maximum allowable rate. These maximum allowable rates are 35% of the charge for commercial and refrigeration 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. Owners are required to repair leaks within 30 days of discovery. This requirement is waived if, within 30 days of discovery, owners develop a one-year retrofit or retirement plan for the leaking equipment. The US EPA is currently developing an amendment to the regulation that would lower the maximum allowable rates for all types of equipment.

12.3 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. ASTM E 479, one of the manufacturer's reference document, determines the maximum allowable leakage flow for a cooling system based on the period during which the system must operate without refrigerant recharge (5 years for a hermetically sealed system and 3 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. Values of allowable leakage flows could be changed to take account of environment.

12.3.1 Design

Every attempt should be made to design tight systems which will not leak during the service life as well as to minimise the service requirements that lead to opening the system. The potential for leakage is first affected by the design of the system. Manufacturers select the materials, the joining techniques, and the service apertures, and design the replacement parts. In addition, the manufacturer provides the recommended installation and service procedures. They 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.

12.3.2 Charge minimising

The lower the charge of refrigerant in a system, the lower the emission in case of rupture of the system. Because little attention has historically been given to the charge in installations, its quantity is not often known, except for small manufactory-built equipment. Receivers are frequently vessels that enclose 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 serious 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, ...) to be provided.

12.3.3 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-condensables 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.

12.3.4 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 up cooling systems with refrigerant. It is necessary to make end-users understand that the price they used to pay for refrigerant must be spared and spent on improved maintenance. It is to be noted that such a step has already been taken in some cases, especially in countries such as the U.S. where 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). As noted above, some countries have adopted training and testing (certification) requirements for technicians who work with refrigerants; in others, private groups have adopted voluntary certification programs.

Refrigerating systems must be tested regularly to ensure that they are well sealed, properly charged, and operating properly. During maintenance and scrapping of the system, refrigerant should no longer be released; instead, it should be isolated in the system or recovered. Special care is required to properly handle and clean used refrigerants. The equipment should be checked in order to detect leaks in time and thus to prevent loss of the entire charge. Use of disposable cylinders for refrigerants should be forbidden as their remaining heel is not recovered after use and contributes to the emission of refrigerant to the atmosphere.

The operator must study the service records to determine history of leakage or malfunction. He should look for evidence that the equipment has been retrofitted to a different refrigerant or lubricant. The operator will also need to check the refrigerant saturation pressure at the measured temperature or analyse the refrigerant to assure it is the nameplated type. He will want to determine the best location from which to recover the refrigerant and assure he has the proper recovery equipment and recovery cylinders. The operator should also thoroughly check for leaks and measure performance parameters to determine the operating condition of the cooling system.

The existence of a maintenance document enables the user to monitor additions and removals of refrigerant with recovery. After a number of years, this information could be used for statistical comparison. Records of refrigerant quantities can indicate whether recharging operations are actually associated with searches for and repairs of leaks. Maintenance documents have been made mandatory by a number of countries, as it enables authorities to check the actual consumption of refrigerants.

12.4 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. It takes place both
- at the end of construction by the manufacturers, or at the end of assembly on the field, and
- regularly during operation of equipment.

There are three general types of leak detection. 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. Local methods pinpoint the location of the leak and are the usual methods used during servicing. Automated performances monitoring systems indicate that a leak exists by alerting operators to changes in equipment performances.

12.4.1 Global methods

This method may be described as applicable any time the system has been emptied of its whole refrigerant charge. Two methods are used: one controls the cooling system, the other measures presence of refrigerant in the air around it. Whereas the first one can only be used prior to charging the system, the latter can be used for continuous monitoring during operation.

System checking:
- The system is pressurised using nitrogen or helium and isolate. A pressure drop within a specified time indicates leakage.
- The system is evacuated and the vacuum level is measured over a specified time to assure tightness. A pressure rise indicates leakage.

Continuous monitoring during operation :
Electronic leak detectors, installed in machinery rooms, may prove efficient provided that (1) they are sensitive enough to dilution of refrigerant in the air, and (2) that air is circulated properly in the room.

12.4.2 Local detection

The different local detection methods vary widely in their sensitivity. Sensitivity levels to non-chlorinated refrigerants may be lower for certain methods. This sensitivity is usually given in p.p.m./volume but for sake of clarity, they are often given in mass flow rates (g/year).

- Visual checks locate large leaks (100 g/year or more) by seeking tell-tale traces of oil at joints.
- Soapy water detection ("bubble testing") is simple, inexpensive and pinpoints leaks (50 g/year or more) when the operator is trained.

- Tracer dyes (colour or ultraviolet) added to the oil-refrigerant mixture shows the location of the leak. The tracer must be compatible with the various materials used in the refrigeration circuit.
- Electronic detectors using coronna discharge, hot wire anemometer, or similar techniques can detect from 5 g/year to 100 g/year according to their sensitivity.
- Ultrasonic detectors register the noise of the leak. They avoid the use of a HCFC or HFC tracer when checking the tightness of a new installation yet provide the location of the leak.

12.4.3 Automated performance monitoring systems

Monitoring input of parameters such as temperatures and pressures meaningful to the coolant cycle, helps to monitor any change in the equipment. This monitoring provides information useful for carrying out diagnostics on the condition of the heat exchanger surfaces, proper refrigerant pumping, and shortage of refrigerant charge. Automated diagnostic programs are now being developed to produce pre-alarm messages as soon as a drift is observed. These developments are in their early stages, but their generalisation would give better control over refrigerant leaks. Equipment room monitors for HCFC-123 low pressure systems are currently used. On low pressure systems, it is also possible to control the tightness of the equipment by monitoring purge unit run time, which can indicate leaks.

12.5 Refrigerant recovery

Refrigerant recovery equipment has been developed and is available with a wide range of features and prices. Some specific explosion proof equipment also exist for recovery of flammables. Testing standards have been developed to measure equipment performance for automotive /SAE/ and non-automotive /ISO/ applications. Refrigerant conservation requires defining the efficiency or completeness of the recovery. Many countries have adopted final recovery vacuum requirements of 0,3 or 0,6 atm absolute depending on the size of the cooling system and saturation pressure of the refrigerant. This provides for recovering 92 to 97 percent of the refrigerant. Some equipment may go further, but the final phase will take longer. Due to the ratio of the densities of liquid and saturated gas, the recovery in liquid phase can be 30 to 40 times faster than in vapour phase. When all conditions have been combined for a quick transfer of the liquid, it is possible to achieve average flows of 50 to 500 kg/h which may be necessary to economically recover refrigerant from larger systems. The residual vapour remaining after liquid recovery will generally represent 20 percent of the total refrigerant charge. 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 which may limit the practical usage to systems containing up to 5 kg refrigerant (the most numerous ones). For larger systems and in order to reach the vacuum levels that are required in some countries, vapour recovery will be used after liquid recovery /Clo94/.

It is difficult for technicians to compare different equipment. In order to make the comparison easier, and also, in countries which certify equipment, to establish a consistent test method, standards for measuring recovery and recycling performances have been designed /Clo93/. ISO 11650, the international standard, or ARI 740-95 (U.S.) or NF E 35-421 (France) can be used, and are based on the same elements.

The measured performances are the following ones:
- Vapour refrigerant recovery rate (kg/h)
- Liquid refrigerant recovery rate (kg/h)
- Final recovery vacuum (bar)
- Recycle rate (kg/h)
- Purge loss due to air purge, clearing unit, and oil removal are limited to less than 3% by weight.
- Trapped refrigerant in % by weight and in kg. Indicates the potential for mixing in recovery or recycling units rated for multiple refrigerants.

The need to handle refrigeration containment has led the industry to develop a specific terminology which is used in this section. The following definitions are extracted from ISO standard 11650 /ISO/:

- recover: to remove refrigerant in any condition from a system and store it in an external container.
- recycle: to reduce contaminants in used refrigerants by separating oil, removing non-condensables, and using devices such as filter-dryers to reduce moisture, acidity, and particulate matter.
- reclaim: to process used refrigerant to new product specifications. 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.
- dispose: to destroy used refrigerant in an environmentally responsible manner.

12.5.1 The recovery cylinder

Cylinders used for recovered refrigerants must comply with local and national requirements for pressure vessels, which can be very different in each country (including re-testing at regular intervals such as every five years or if some unusual tank condition is noticed). They may be delivered with an internal vacuum or with a holding charge and should be prepared according to the cylinder and equipment manufacturer's instructions.

Labelling - Recovery cylinders and the refrigerants contained in them must be clearly identified to prevent possible mixing of refrigerants and for the safety of the transporter. In addition, some countries require environmental warning labels.

Filling - Due to the uncertainties about the density of the recovered product because of the presence of oil and ambient temperature variations, recovery cylinders should only be filled with liquid up to 80 percent of their volume. A scale or other weight sensitive device, a liquid level switch, or a double valve have all been used for this purpose.

Cleaning - To avoid mixtures, recovery cylinders should be dedicated to the same refrigerant or cleaned after each operation, as reclaimers do.

12.5.2 Hoses and connections

Excessively small diameters or restrictions cause pressure drops that can easily double recovery times. Enlarging the hose diameter from 1/4 inch to 3/8 inch increases the flow by more than 40 %. Connecting to both high and low pressure circuits of the cooling system will reduce the recovery time. The refrigerant hose should be equipped with a valve to prevent refrigerant emissions and intake of air. Hose materials and construction should minimise refrigerant permeation and be suitable for the refrigerant and lubricant type. Connections on existing systems are frequently lacking because recovery was never considered in design, except for large systems. Often, the only available connections are for the "manifold" fitted with pressure gauges. In order to carry out the liquid recovery, it may be necessary to create access in the circuit wherever this liquid accumulates. During maintenance, it is useful to make permanent, leak tight access to facilitate recovery because this operation will be probably repeated later. Since liquid recovery is very fast, the necessary time and expense to create a sufficiently large access may be justified for larger systems.

12.5.3 Liquid recovery

Recovery of the liquid is the quickest, and should be the priority when recovering quantities above 50 kg as time-loss is a decisive argument against carrying out recovery. Among the several techniques available, the use of compressors and pump are now leading.

Recovery by nitrogen overpressure was frequently used for low-vapour-pressure refrigerants such as CFC-11. It cannot be recommended as it cannot recover the vapour and generates a 10% to 20% loss.

Use of a relative vacuum in recovery cylinders can recover liquid if there is direct access to the liquid. It can also help to extract residual vapour, but only small quantities. Another way of reducing pressure is to cool the recovery cylinder, for instance by storing it in a cold room (beware that nature of standard cylinders construction materials is limited to minus 20°C). It is also possible to heat the refrigerant in the system. Some recovery units consisting of an electric heater and a pump heat the water contained in the evaporator of chillers and pressurise the liquid refrigerant to make it flow into a recovery cylinder. Transfers by pressure difference can be prolonged using the difference of level between the system and the cylinder.

Recovery by centrifugal or pneumatic pump is frequently used for large volume as they are simple and efficient. Pneumatic pumps have, however, the ability to recover either the vapour or the liquid whereas prolonged operation of a centrifugal pump in vapour will deteriorate it. Liquid pumps must be equipped with safety valves as there is a risk of explosion if a valve is closed at the pump discharge, which pneumatic pumps do not require.

Recovery by pressurisation may be made either by the system compressor or by external equipment. Liquid can be recovered by units running with usual refrigerating compressors according to two different methods:

- Evaporate, compress, and then recondense the liquid before discharging it into the cylinder. This is actually vapour recovery, and consequently slow.
- "Push" the liquid by using the compressor to maintain a pressure difference between the system and the recovery cylinder. Some recovery units have complex designs that may be suitable for systems with only one access point to the refrigerant and one valve on the recovery cylinder. The "push-pull method" may be used with any compression unit but requires two access points to the liquid in the system and two ports on the cylinder.

12.5.4 Vapour recovery

This operation is necessary, since the only way of checking that all liquid has been evaporated is to lower the pressure in the system below the saturation vapour pressure of the refrigerant. Moreover, a number of countries require recovery into a vacuum. Extraction time of vapour is often considered to be too long, and may be due to residual liquid that remains in difficult-to-access low points. However, recovering vapour is the only way of guaranteeing an efficient final emptying operation. Besides using the relative vacuum of the cylinders or the heat transfer, which is not very efficient, technicians may use the following devices.

Pneumatic pumps can recover vapour refrigerant with volume flow rates in the same range as compression systems. Very low intake pressures of the order of 0.1 atm absolute pressure can also be obtained.

Despite conventional primary vacuum pumps discharge into the open air, some special vacuum pumps can recover the residual CFC-11, when they are equipped with a well-designed condenser. A new design of equipment - two stage vacuum pump plus compressor units - provide an economical solution for recovering the last fraction of refrigerant left in a system and may be done in idle time provided the recovery cylinder is large enough.

Recovery by compressor is the most used solution. Most compression recovery units are suitable for recovering vapour, even for low pressure values down to 1.5 psia (0.1 atm abs). Depending on the type of compressor they are equipped with - hermetic units, open units, dry piston or diaphragm compressors - recovery systems will have different costs and different maintenance requirements.

Recovery equipment used for recovering hydrocarbons should be constructed to prevent ignition of flammable concentrations of leaked refrigerants (e.g., all sparking electrical components should be sealed).

12.6 Recycling and Reclamation

12.6.1 Recycling

Recycling is one of three available options for dealing with recovered refrigerants. The other two are direct reuse and reclaiming. Unlike reclaiming, recycling does not involve analysis of each batch of used refrigerant and therefore does not quantify contaminants nor identify mixed refrigerants /Kau92/.

Unlike direct reuse, 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 /ARI740/.

Although some current recycling units are capable of processing the contaminated refrigerant sample to levels close or equal to new /ARI 700/ or reclaimed refrigerant, some restrictions have been placed on the use of recycled refrigerant because it is not supposed to be analysed before each use. This has even led to legal restrictions on recycled refrigerant, as in France where it cannot be used in another system than in the one it came from. In the U.S., a broad based industry group has put together a document /ARI94/ which defines recommended procedures as well as contaminant levels for recycled refrigerants used in cooling systems for the same owner.

A variety of recycling equipment is available over a wide price range. Right now, the automotive air-conditioning industry is the only application which prefers the practice of recycling. Acceptance in other sectors depends on national regulation, recommendation of the cooling system manufacturers, existence of another solution such as a reclaim station, variety and type of systems and the preference of the service contractor. Recycling with limited analysis capability may be the preference of certain developing countries where access to qualified laboratories is limited and shipping costs are prohibitive. In most cases, there are no inexpensive field instruments to measure the contaminant levels after processing. Drawing a laboratory sample and obtaining an analysis may cost US $40 for a single contaminant and US $125 for a complete analysis.

12.6.2 Mixed refrigerants

Every effort should be taken to avoid the mixing of refrigerants. This includes ensuring that the refrigerant present in the system is correctly identified before charge adjustment (topping up) is carried out; and ensuring that, when refrigerant is recovered, it is recovered into the correct recovery cylinder (either one that is totally empty, and under vacuum, or into one already containing the same refrigerant). Correct identification of the refrigerant in systems and containers is essential.

Mixed refrigerants are a concern because of the:
- Impact on performance and operation that may affect the cooling system capacity and efficiency.
- Effect on materials compatibility, lubrication, equipment life, and warranty costs.
- Increased service and repair requirements and higher operating costs.
- Increased pressures that may lead to refrigerant releases (through purge or relief devices) or safety hazards.
- Reintroduction of used refrigerants into the commerce stream.
- Inability or high cost of separating refrigerants.
- High cost of disposal and loss of refrigerant for future service.

This condition of mixture can be caused by chemical reactions such as in a hermetic compressor motor burnout. It is more likely caused by service practices such as failing to recognise which refrigerant is contained in a system, recovering refrigerant in a cylinder that already contains another refrigerant, or consolidating refrigerant in larger batches. Mixtures can also happen when using one recovery or recycling equipment for different refrigerants without vacuuming it /Manz91/.

The following steps can be taken to minimise the probability of mixing refrigerants:
- Properly cleaned recovery units, hoses, and cylinders or dedicate them to a specific refrigerant.
- Test suspect refrigerant before consolidating into larger batches and before attempting to recycle or reuse.
- Keep appropriate records of refrigerant inventory.
- Label systems with the identity of their refrigerants, especially upon retrofit.
- 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 CFC-12, HCFC-22 and HFC-134a refrigerants at purity levels of 97 % or better are now available.

Recycling equipment can neither detect nor separate mixed refrigerants. Except for automotive air-conditioning, there is consequently much discussion, going on about where and under which conditions recycled refrigerant may be used.

In automotive applications where only CFC-12 and HFC-134a are being used, 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 CFC-12 and HFC-134a cooling systems and must be properly labelled /SAE1990/.

12.6.3 Reclamation

Reclaimed refrigerant refers to refrigerant which has been processed and verified by analysis to meet new product specifications such as given in ARI 700-93 /ARI700/.

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 which would lead to further refrigerant emission. As reclaimed refrigerant meets new product specifications, it often has the support of equipment manufacturers. Under the guarantee period, these new product specifications support the guarantee conditions given by the manufacturer. Reclaimers will typically have the ability to analyse incoming refrigerant, to process the refrigerant as required, and to clean and fill the recovery cylinders. Analysis of outcoming refrigerant will make it possible to assess the refrigerant specifications. Reclaimers will also typically provide shipping and labelling instructions and furnish or recommend cylinders. Reclaiming has the advantage to make it easily possible to measure amounts of refrigerant which have actually been recovered. It requires anyhow a costly infrastructure, which may only prove interesting when potential for return of recovered refrigerant is large enough.

12.6.4 Destruction

Two installation types are available to destroy CFCs.

- Public or commercial installations have the advantage of being accessible in return for payment. They are often "generalist" and, therefore, capable of treating several families of chemical products.
- Other installations, designed for the internal needs of CFC manufacturers, are not always adapted to the needs of outside groups.

Destruction plants exist in Europe, Japan and North-America. Running costs announced by Japan for a plasma destruction system is about 5 US $ / kg /Hot94/.

It is probable that total destruction will be fairly low in the refrigeration industry, since the demand for CFCs will remain high. However, some countries have reported a rising volume of destroyed refrigerant, reflecting rising rates of refrigerant cross-contamination. (Such rising rates of cross-contamination in turn reflect the increasing number of refrigerants on the market). While distillation permits separation of mixed refrigerants, such distillation is expensive, and most mixtures are therefore destroyed. In addition, local regulations forbidding use and export of CFCs may create a need for destruction facilities.

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. The number of usable incinerators is limited mainly by their resistance to hydrofluoric acid. CFCs, and more particularly halons, burn very poorly. In order to be incinerated, they must be mixed with fuels in specific proportions /DES92/.

Appropriate destruction requires that materials making up the installation are resistant to products to be destroyed and to the effluents, destruction is complete, residual products can be eliminated, and a destruction efficiency threshold (D.E.) is defined. The threshold considered as being realistic is 99.99% on a mass basis. In other words, a maximum of 1 ten thousandth of the initial product is rejected into the atmosphere. Note that most countries in which there are incinerator installations have regulations and standards that define requirements about the limitation of liquid or gaseous emissions.

Five existing technologies appear to be suitable: incineration with liquid injection, cracking, smoke oxidation, incineration in rotary furnaces, and incineration in cement kilns. Two of these technologies are widely used and have been specially tested for the destruction of CFCs and have the required D.E. of 99.99%. These are liquid injection and rotary furnace incinerators. However, installations equipped with this type of incinerator do not necessarily resist combustion products. They must also be equipped with scrubbers to eliminate acids. The cracking technique also affects the destruction efficiency (D.E.). A cracking reaction vessel was specially designed for destruction of CFCs. This type of reaction vessel has been used since 1983. The principle can be used to build units capable of treating 1.8 million to 3.5 million lbs/year (800 to 1600 tonnes/year).

In addition to these destruction techniques, it is also possible to destroy CFCs in industrial processes. This is the case for the aluminium degassing process in second melting. In order to eliminate hydrogen inclusions that make metal brittle, CFC-12 is a replacement product for hexachlorethane and has the advantage of low toxicity. In this process, CFC molecules are destroyed at a very high temperature in the molten aluminium bath.

12.7 Refrigerant Conservation in Article 5(1) Countries

Although the wide range of conditions in Article 5(1) countries makes generalisation difficult, a few characteristics emerge across the refrigeration infrastructures of Article 5(1) countries that distinguish them from the refrigeration infrastructures of developed countries. These characteristics argue for adopting 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. Because CFCs are not scheduled to be phased out until 2006 in most Article 5(1) countries, they remain relatively inexpensive in most such countries. In fact, in some, CFC refrigerants are reportedly less expensive than ever. 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 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 has not been routine in the past. Moreover, significant incentives are still necessary for refrigerant conservation because of 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 "Reclaim Centre" for one country only. To ensure that refrigerant is adequately cleaned before being reused, developing countries may either devote resources to developing a reclamation infrastructure or emphasise on-site refrigerant recycling. If they choose the latter, screening tests may be used to target severely contaminated refrigerant for destruction. Because of the decentralised nature of on-site recycling, its success (in terms of both the quantity and quality of the refrigerant recycled) is more difficult to evaluate than that of reclamation. Where reclamation facilities are not available, destruction in existing incinerators may be an alternative.

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

- Unreliable power and parts supplies. In many Article 5(1) countries, frequent voltage fluctuations increase the incidence of compressor burnouts, which aggravates 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, 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) that are in a shop for service.

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, however, 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 recaptured. This emphasises the fact that for any refrigerant, the first step to take is improving leak tightness of systems.

There is no shortage of leak detection devices, conservation methods, or recovery/recycling equipment available from developed countries /UNE94, UNP94/. However, provision of such equipment will not, in itself, guarantee that refrigerant conservation occur 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 A5 countries consuming low volumes of ODS in critical refrigerant sectors include these different aspects /UNE98/.

Under the Multilateral Fund's assistance, UNDP and UNEP in co-operation with GTZ Proklima are implementing Refrigerant Management Plans (RMP) in fourteen Eastern and South-Eastern African countries. The objective of the RMP is to design and implement an overall and integrated strategy for cost-effective phase-out of CFCs in the refrigerant maintenance sector. The countries for which the Refrigerant Management Plans have been developed are Botswana, Ethiopia, Lesotho, Kenya, Malawi, Mauritius, Mozambique, Namibia, Seychelles, Swaziland, Tanzania, Uganda, Zambia and Zimbabwe.

The RMP is a key component for the reduction of all ODS because significant portion of all ODS used are consumed in refrigeration and air-conditioning sector. The RMP's role is essential to aid ODS 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 in containment of refrigerants and retrofitting equipment, introducing new technologies and establishing recovery and recycling programmes for ODS.

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 on refrigerant conservation through recovery/ recycling/reclaim and leak reduction.

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Annex I -Total Equivalent Warming Impact (TEWI): An Overview

Introduction

Air-conditioning and refrigeration equipment may contribute to global warming in two ways. First, the equipment consumes energy, and energy is usually generated through the combustion of fossil fuels, which results in the emission of carbon dioxide. Carbon dioxide is the most common man-made greenhouse gas. Second, the equipment usually releases some refrigerant (and in the case of refrigerators containing foam insulation, blowing agent) when it is manufactured, used, serviced, and disposed of. Like carbon dioxide, many refrigerants and blowing agents are greenhouse gases.

When comparing the global warming impacts of different air-conditioning and refrigeration technologies, it is reasonable to consider both the "indirect" impacts of carbon dioxide emissions resulting from the equipment's energy consumption and the "direct" impacts of refrigerant emissions resulting from the equipment's manufacture, use, service, and disposal. In an effort to facilitate such comparisons, analysts have developed an index known as Total Equivalent Warming Impact, or TEWI.

The TEWI Calculation

TEWI integrates the global warming impacts of equipment's energy consumption and refrigerant emissions into a single number, usually expressed in terms of CO_2 mass equivalents. The calculated TEWI for any given piece of air-conditioning and refrigeration equipment is based on estimates for (1) the quantity of energy[1] consumed by the equipment over its lifetime, (2) the mass of carbon dioxide produced per unit of energy consumed, (3) the quantity of refrigerant released from the equipment over its lifetime, and (4) the global warming potential of that refrigerant, expressed in terms of CO_2 mass equivalents per unit mass of refrigerant.[2]

This relationship is frequently expressed in the following equation:

$$TEWI = M_{losses} \times GWP_{refrigerant} + (a \times N_{lifetime} \times E_{annual})$$

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[1]Note that this energy may be electrical, as in a typical household refrigerator, mechanical, as in a motor vehicle air-conditioner or engine-driven chiller, or thermal, as in an absorption chiller.

[2] Several publications have outlined the factors to be considered in calculating TEWI. These include, to name just a few, "Energy and Global Warming Impacts of CFC Alternative Techonologies, SK. Fischer et al., AFEAS, Washington, D.C., U.S.A., 1991; "Guideline method of calculating TEWI," British Refrigeration Association, Medmenham, 1996; and "Refrigeration and the greenhouse effect: GWP, TEWI or COP?" IIR informatory note no. 11, January 1995.

where

M_{losses} = the quantity of refrigerant lost by equipment over its lifetime to the atmosphere, in kg
$GWP_{refrigerant}$ = the global warming potential of the refrigerant, in kg CO_2/kg refrigerant
a = the mass of carbon dioxide produced per unit of energy delivered, in kg CO_2/kWh delivered
$N_{lifetime}$ = the functioning lifetime of equipment, in years, and
E_{annual} = the annual energy use of the equipment, in kWh/year.

Applying TEWI

TEWI is a the best available gauge of equipment's impact on global warming, accounting for both the direct impact of refrigerant emissions and the indirect impact of energy use. However, in reading and applying TEWI analyses, policy makers should be aware that the calculated TEWI for any given air-conditioning and refrigeration technology may vary significantly depending upon (1) the extent to which the design is optimised for energy-efficiency, refrigerant containment, and/or safety (which, in turn, is closely related to the costs of the design), and (2) site-specific values for the factors in the TEWI calculation. In addition to these variabilities, many of the factors are subject to some uncertainty. These variabilities and uncertainties affect the applicability and validity of TEWI analyses.

This overview is intended to enable policy makers to read TEWI analyses thoughtfully and critically, bearing these variabilities and uncertainties in mind. Following is a discussion of the variabilities and uncertainties and the factors behind them.

Variabilities and Uncertainties in the TEWI Calculation

System Design and Cost

In general, the energy efficiency or refrigerant containment (and therefore TEWI) of any technology can be improved, but only at increased capital cost. Capital cost and TEWI are also related to operating costs, including energy and maintenance costs. To ensure that technologies, rather than levels of investment, are being compared, TEWI analyses should compare designs of similar life-cycle costs, where life-cycle costs include capital, operating, maintenance, and disposal costs.[3] In addition, where significant design modifications (e.g., secondary loops) are required to bring one technology (e.g., one using ammonia or hydrocarbons) into conformance with safety standards, TEWI analyses should compare designs of similar safety. However, selecting designs of "similar cost" or "similar safety" for comparison is difficult when one or more of the technologies is at the research

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[3]For further discussion of this topic, see "The Impact of the Montreal and the Kyoto Protocol on New Developments in Refrigeration and A/C," Lambert Kuijpers, Preprints: Emerging Trends in Refrigeration and Air Conditioning, IIR Conference, March 18-20, 1998, New Delhi, India, pp. IK-8 and 9.

stage. For this reason, TEWI analyses involving emerging technologies are subject to significant uncertainty.

Site-Specific Factors

Most of the factors in TEWI also vary depending upon the location of the equipment. First, the quantity of energy consumed by the equipment depends upon the equipment's energy efficiency, annual hours of operation, and lifetime. Even for a single equipment design, energy efficiency and equipment lifetime can vary significantly based on how well the equipment is maintained, and annual hours of operation can vary widely depending upon the climate of the equipment's location. Second, the mass of carbon dioxide produced per unit of energy consumed depends upon the fuel mix used to produce power in the equipment's location, which again, can vary widely. Third, refrigerant loss rates depend upon manufacturing, installation, maintenance, and disposal practices; poor practices at any one of these life cycle stages can increase lifetime losses several times over.

GWPs

The global warming potential of any refrigerant varies depending upon the time horizon over which the refrigerant's global warming impact is compared to that of CO_2 ; the 20-year GWPs for common HFCs are about three times higher than the 100-year GWPs for these refrigerants, which in turn are about three times higher than the refrigerants' 500-year GWPs (the factor of three only applies to a certain number of commonly used refrigerants). The world technical experts appear to have settled on the 100-year GWP as the most appropriate value. GWPs are also subject to uncertainties of up to $\pm$ 35 percent, according to the 1994 Scientific Assessment of Ozone Depletion.

Almost all of these uncertainties and variabilities are aggravated by the fact that TEWI is generally used to evaluate equipment that would be used in the future. Over the 10- to 30-year lifetimes of air-conditioning and refrigeration equipment, equipment efficiency, refrigerant emissions rates, and even fuel mix may change significantly.

Applicability of TEWI

Despite the above variabilities and uncertainties, TEWI can be a useful tool for evaluating the global warming impact of equipment, so long as the TEWI analysis (1) compares equipment designs of comparable cost and safety, (2) ensures that the site-specific values used (for operating hours, CO_2 and refrigerant emissions rates, etc.) are fully representative of those in the region(s) to which the analysis is to be applied, (3) identifies the assumptions behind the calculations, and (4) discusses the potential impacts of variabilities and uncertainties on the results. **The last two requirements are particularly important; decision-makers should be wary of TEWI analyses that omit this vital information.**

TEWI results are likely to be most reliable when they are developed for and applied to equipment over a relatively small area and time span, and when the equipment studied has a TEWI that is relatively insensitive to installation, maintenance, and disposal practices (e.g., hermetically sealed systems with high power consumption and low service rates, or, on the other hand, inherently emissive systems). In these situations, the results of TEWI analyses are likely to be robust. Nevertheless, decision makers need to be aware of the uncertainties involved in the TEWI calculation so that they can consider them in assessing the significance of small differences between the calculated TEWIs of competing technologies; these differences may not in themselves justify choosing one technology over another if they are below the level of statistical significance.

Care must be taken when the results of the TEWI analysis are to be applied to larger areas and longer time spans, because variabilities in operating hours (climate), CO_2 emissions rates (fuel mix), and refrigerant emissions rates (maintenance practices) can become considerable. Even within Europe, for example, chiller operating hours vary widely between Norway and Greece, and CO_2 emissions rates range from 0 kg/kWh in Norway to .98 kg/kWh in Greece.[4] Thus, energy efficiency will be much more important in TEWI calculations (and decisions based on them) in Greece than in Norway. In France, surveys indicate that leak rates from building chillers have been cut in half over the past 10 years, demonstrating that the relative importance of the "direct" and "indirect" components of TEWI can change dramatically within the lifetime of equipment at a single location.[5] These examples highlight the risk of over-generalising from the results of TEWI analyses that are based on estimates from only one location or a small set of locations.

Conclusion

TEWI is a useful tool for comparing the global warming impacts of air-conditioning and refrigeration technologies under similar, well-defined circumstances. A good TEWI analysis details the sensitivity of calculated TEWIs to the level of investment in equipment and to site-specific factors. Of course, TEWI itself is only one of a number of environmental, engineering, and economic factors that must be considered when evaluating and selecting air-conditioning and refrigeration equipment. Other considerations, such as private life-cycle costs, safety, and environmental life-cycle impacts (the full environmental

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[4] "Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies," J.R. Sand, S.K. Fischer, and V.D. Baxter, AFEAS, Washington, D.C., U.S.A., 1997, p. 125.

[5] Zero Fuite , Denis Clodic, Pyc Ed. 1997, and Zero Leaks, Denis Clodic, ASHRAE, 1998.

impacts of manufacturing, using, and disposing of the refrigerant/equipment), are relevant to equipment choices but are outside the scope of TEWI.

Annex II - Heat Transfer Fluids For Secondary Loops

Safety for Heat Transfer Fluids has to take into account the same criteria (flammability and toxicity) as used for refrigerants, and additional ones.
Where it concerns toxicity the studies for Heat Transfer Fluids are not the same as for gases, since at least three new items have to be taken into account :
- direct ingestion
- food compatibility
- water and soil contamination.

Furthermore, the flash point shall be above 65°C.

Trade Name	Fluid Type	Chemical Formula	Molecular Weight	Normal Boiling Point °C	Freezing Point °C	Flash Point °C	Toxicity	Flamma-bility range
Dowtherm J	ASF		134	–	-86	58	Low	
Dowtherm Q	ASF		190		<-34	120	Low	
Marlotherm L	ASF				<-55	280	Low	
Jarytherm BT06	ASF		200	290	-30	140	None	
Jarytherm CF	ASF		130	181	<-70	68	Low	
Santotherm 60	ASF				<-50	310	Low	
Gilotherm ADX10	ASF				<-50	>250	Yes	
Gilotherm D12	NASF				<-70	190	None	
Santotherm 44	NASF				<-40	>250	None	
Syltherm 800	SSO				<-40	400	None	
Syltherm XLT	SSO		317	300	-111	47/54	None	Yes
Calcium Chloride	B				-51		None	None
Ethylène Glycol	B				-20	198	None	
Propylène Glycol	B				-50	187	None	
d-limonène	O				<-73	>150	?	
Hycool	B			>100	-20 to -60	None	None	None
Pekasol	B	mixture	n/k	100	<-56	None	None	None
Temper	B			109	-20/-60	None	None	None
Tyfoxit	B			100	<-50	None	Yes	None
Thermogen VP 1869	B			117-125	<-80			
Mixigel	B			106	-63	-	None	
HFE7100		$C_4F_9OCH_3$	250	60	-130	None	None	None
HFC-4310mee		$CF_3CF_2(CHF)_2CF_3$	252	53.7	-84	None	None*	None
Carbon dioxide		CO_2	44	-78				
Water		H_20	18	100	0	None	None	None

ASF = Aromatic Synthetic Fluid; B = Brine ; NASF = Non Aromatic Synthetic Fluid ; O = Others; SSO = Synthetic silicon oil
* It is recommended to read the MSDS provided by manufacturer before use.

This table has been written with usual data given by heat transfer fluid manufacturers.

Annex III -Refrigerant Data

Data Summary

Table 1 provides summary data for refrigerants, both single compounds and blends, addressed in this report as well as those known to have been 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 the ARTI Refrigerant Database /Cal98/, which provides further information on the refrigerants included and addresses additional refrigerants. This database identifies the source for the data presented in the table as well as, for some refrigerants, additional data where conflicting values have been identified 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 /McL98/ 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 /ASH97/
- chemical formula, in accordance with the IUPAC convention /IUP79/ or, for blends, the blend composition in accordance with ASHRAE Standard 34 /ASH97/
- 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 /ASH97/
- heat of combustion (HOC) in MJ/kg calculated assuming complete reaction to the most stable products in their vapour state, namely CO_2, HF (or F_2 if insufficient H), Cl_2, N_2, and H_2O: Negative values indicate endothermic reactions while positive values indicate exothermic reactions
- safety classification, if assigned, in accordance with ASHRAE Standard 34 /ASH97/ 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

"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
- ozone depletion potential (ODP) relative to R-11 based on the modelled values adopted in the Scientific Assessment /WMO95/ or, for blends, the mass-weighted average based on the IUPAC atomic weights /IUP97/ of the component ODPs *[these values may be updated before publication of the TOC report if revisions are made and published in time in the 1999 Scientific Assessment update]*
- global warming potential (GWP) relative to CO_2 for 100-year integration based on the values adopted in the IPCC Assessment /IPC96/ or, for blends, the mass-weighted average based on the IUPAC atomic weights /Cop97/ of the component ODPs
- 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

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refrigerant number	chemical formula - common name	physical data: molecular mass	physical data: NBP (°C)	physical data: Tc (°C)	physical data: Pc (MPa)	safety data: TLV-TWA (PPM)	safety data: LFL (%)	safety data: HOC MJ/kg	safety data: Std 34 safety group	environmental data: atmospheric life (yr)	environmental data: ODP	environmental data: GWP 100 yr	st at us
CFC-11	CCl3F	137.37	23.7	198.0	4.41	C1000	none	0.9	A1	50	1.000	3800	M
BCFC-12B1	CBrClF2 - halon 1211	165.36	-4.0	154.0	4.10	1000	none			20	5.100		M
CFC-12	CCl2F2	120.91	-29.8	112.0	4.14	1000	none	-0.8	A1	102	0.820	8100	M
BFC-13B1	CBrF3 - halon 1301	148.91	-57.7	67.1	3.96	1000	none		A1	65	12.000	5400	M
CFC-13	CClF3	104.46	-81.3	29.2	3.92	1000	none	-3.0	A1	640	1.000	11700	M
FIC-13I1	CF3I	195.91	-22.5	122.0			none			<0.1		<1	
FC-14	CF4 - carbon tetrafluoride	88.00	-128.1	-45.6	3.75		none		A1	50000	0.000	6500	K
HCFC-21	CHCl2F	102.92	8.9	178.3	5.18	10	none		B1		0.010		M
HCFC-22	CHClF2	86.47	-40.8	96.2	4.99	1000	none	2.2	A1	12.1	0.040	1500	M
HFC-23	CHF3 - fluoroform	70.01	-82.1	25.9	4.84	1000	none	-12.5	A1	264	0.000	11700	K
HCC-30	CH2Cl2 - methylene chloride	84.93	40.2	237.0	6.08	50	14.6		B2	0.46	0.000	9	
HCFC-31	CH2ClF	68.48	-9.1			0.1					0.010		M
HFC-32	CH2F2 - methylene fluoride	52.02	-51.7	78.1	5.78	1000	13.3	9.4	A2	5.6	0.000	650	K
HCC-40	CH3Cl - methyl chloride	50.49	-24.2	143.1	6.67	50	8.1		B2	1.5	0.020	8	
HFC-41	CH3F - methyl fluoride	34.03	-78.1	44.1	5.90					3.7	0.000	150	K
HC-50	CH4 - methane	16.04	-161.5	-82.5	4.64	1000	5		A3	12.2	0.000	21	
CFC-113	CCl2FCClF2	187.37	47.6	214.1	3.39	1000	none	0.1	A1	85	0.900	4800	M
CFC-114	CClF2CClF2	170.92	3.6	145.7	3.26	1000	none	-3.1	A1	300	0.850	9200	M
CFC-115	CClF2CF3	154.47	-38.9	80.0	3.12	1000	none	-2.1	A1	1700	0.400	9300	M
FC-116	CF3CF3 - perfluoroethane	138.01	-78.2	19.9	3.04	1000	none		A1	10000	0.000	9200	K
HCFC-123	CHCl2CF3	152.93	27.8	183.8	3.66	50	none	2.1	B1	1.4	0.014	90	M
HCFC-124	CHClFCF3	136.48	-12.0	122.3	3.62	1000	none	0.9	A1	6.1	0.030	470	M
HFC-125	CHF2CF3	120.02	-48.1	66.2	3.63	1000	none	-1.5	A1	32.6	0.000	2800	K
HFE-E125	CHF2-O-CF3	136.02	-42.0	81.3	3.35					82	0.000		
HFC-134	CHF2CHF2	102.03	-23.0	119.0	4.62	1000	none	4.3		10.6	0.000	1000	K
HFC-134a	CH2FCF3	102.03	-26.1	101.1	4.06	1000	none	4.2	A1	14.6	0.000	1300	K

refrigerant number	chemical formula - common name	physical data: molecular mass	physical data: NBP (°C)	physical data: Tc (°C)	physical data: Pc (MPa)	safety data: TLV-TWA (PPM)	safety data: LFL (%)	safety data: HOC MJ/kg	safety data: Std 34 safety group	environmental data: atmospheric life (yr)	environmental data: ODP	environmental data: GWP 100 yr	status
HFE-E134	CHF2-O-CHF2	118.03	6.2	160.8	4.23		none			8	0.000		
HCFC-141b	CH3CCl2F	116.95	32.0	204.2	4.25	500	6.4	8.6		9.4	0.100	600	M
HCFC-142b	CH3CClF2	100.49	-9.0	137.1	4.12	1000	6.9	9.8	A2	18.4	0.050	1800	M
HFC-143	CH2FCHF2	84.04	5.0	156.7	4.52		5.8	10.9		3.8	0.020	300	K
HFC-143a	CH3CF3	84.04	-47.2	72.9	3.78	1000	7.1	10.3	A2	48.3	0.000	3800	K
HFE-E143a	CH3-O-CF3	100.04	-24.1	104.9	3.59					5.1	0.000	450	
HFC-152a	CH3CHF2	66.05	-24.0	113.3	4.52	1000	3.1	17.4	A2	1.5	0.000	140	K
HCC-160	CH3CH2Cl - ethyl chloride	64.51	13.1	187.2	5.24	100	3.8	20.6		<1	0.000		
HFC-161	CH3CH2F - ethyl fluoride	48.06	-37.1	102.2	4.70		3.8			<1	0.000	low	K
HC-170	CH3CH3 - ethane	30.07	-88.6	32.2	4.87	1000	3.2		A3		0.000	-20	
HE-E170	CH3-O-CH3 - dimethyl ether	46.07	24.8	128.8	5.32	1000	3.4				0.000	-20	
FC-218	CF3CF2CF3 - perfluoropropane	188.02	-36.6	71.9	2.68	1000	none		A1	2600	0.000	7000	K
HFC-227ea	CF3CHFCF3	170.03	-15.6	102.8	2.98	1000	none	3.3		36.5	0.000	2900	K

refrigerant number	chemical formula - common name	physical data: molecular mass	physical data: NBP (°C)	physical data: Tc (°C)	physical data: Pc (MPa)	safety data: TLV-TWA (PPM)	safety data: LFL (%)	safety data: HOC MJ/kg	safety data: Std 34 safety group	environmental data: atmospheric life (yr)	environmental data: ODP	environmental data: GWP 100 yr	status
HFC-236ea	CHF2CHFCF3	152.04	6.2	139.3	3.50		none	5.4		7.8	0.000		K
HFC-236fa	CF3CH2CF3	152.04	-1.4	124.9	3.20	1000	none			209	0.000	6300	K
HFC-245ca	CH2FCF2CHF2	134.05	25.1	174.4	3.94		7.1	8.4		6.6	0.000	560	K
HFC-245cb	CH3CF2CF3	134.05	-18.0	107.2	3.26					1.8	0.000		K
HFC-245fa	CHF2CH2CF3	134.05	15.1	154.1	4.43	500 p	none	6.1	A1p r	8.8	0.000	820	K
HFE-E245fa1	CHF2-O-CH2-CF3	150.05	29.2	170.9	3.42					6.1	0.000	640	
HFC-254cb	CH3-CF2-CHF2	116.06	-0.8	146.2	3.75					1.6	0.000		K
HC-C270	-CH2-CH2-CH2- - cyclopropane	42.08	-33.5	125.2	5.58		2.4				0.000		
HC-290	CH3CH2CH3 - propane	44.10	-42.1	96.7	4.25	2500	2.3	50.3	A3		0.000	~20	
FC-C318	-CF2-CF2-CF2-CF2-	200.03	-6.0	115.2	2.78	1000	none		A1 d	3200	0.000	8700	K
HFE-E329mcc2	CHF2-CF2-O-CF2-CF3	236.04	22.0	139.5	2.26						0.000		
HFC-338mcc	CH2FCF2CF2CF3	202.05	27.8	158.8	2.73						0.000		K
HFC-338mee	CF3CHFCHFCF3	202.05	26.0	148.5	2.48		none				0.000		K
HFE-E347mcc3	CH3-O-CF2-CF2-CF3	200.05	34.2	164.6	2.48		none			6.4	0.000	485	
HFE-E347mmy1	CF3-CF(OCH3)-CF3	200.05	29.4	160.2	2.55					4.9	0.000	368	
HFC-365mfc	CH3CF2CH2CF3	148.07	40.2	187.7	2.75		3.5			11	0.000	850	K
R-400(50/50)	R-12/114 (50/50)	141.63	-20.8	128.9	3.92		none		A1/A1		0.835	8650	M
R-400(60/40)	R-12/114 (60/40)	136.94	-23.2	125.4	3.99		none		A1/A1		0.832	8540	M
R-401A	R-22/152a/124 (53/13/34)	94.44	-34.4	105.3	4.61	1000	none		A1/A1		0.031	970	M
R-401B	R-22/152a/124 (61/11/28)	92.84	-35.7	103.5	4.68	1000	none	-2.7	A1/A1		0.033	1060	M
R-401C	R-22/152a/124 (33/15/52)	101.03	-30.5	109.9	4.40		none		A1/A1		0.029	760	M
	R-22/152a/124 (31/24/45)	95.09	-29.6	110.4	4.43						0.026	710	M
R-402A	R-125/290/22 (60/2/38)	101.55	-49.2	76.0	4.23		none	-1.4	A1/A1		0.015	2250	M
R-402B	R-125/290/22 (38/2/60)	94.71	-47.2	83.0	4.53		none	-1.6	A1/A1		0.024	1960	M
R-403A	R-290/22/218 (5/75/20)	91.99	-44.0	91.2	4.69	1000	none		A1/A1		0.030	2530	M
R-403B	R-290/22/218 (5/56/39)	103.26	-43.8	88.7	4.40	1000	none		A1/A1		0.022	3570	M

refrigerant number	chemical formula - common name	physical data: molecular mass	NBP (°C)	Tc (°C)	Pc (MPa)	safety data: TLV-TWA (PPM)	LFL (%)	HOC MJ/kg	Std 34 safety group	environmental data: atmospheric life (yr)	ODP	GWP 100 yr	status
R-404A	R-125/143a/134a (44/52/4)	97.60	-46.6	72.1	3.74	1000	none	-6.6	A1/A1		0.000	3260	K
R-405A	R-22/152a/142b/C318 (45.0/7.0/5.5/42.5)	111.91	-32.9	106.0	4.29	1000	none		A1/A1 d		0.021	4480	M
R-406A	R-22/600a/142b (55/4/41)	89.86	-32.7	116.5	4.88		wff		A1/A2		0.043	1560	M
	R-22/600a/142b (65/4/31)	88.57	-35.0	112.2	4.95		wff				0.042	1530	M
R-407A	R-32/125/134a (20/40/40)	90.11	-45.2	81.9	4.49	1000	none	-3.6	A1/A1		0.000	1770	K
R-407B	R-32/125/134a (10/70/20)	102.94	-46.8	74.4	4.08	1000	none	-1.8	A1/A1		0.000	2290	K
R-407C	R-32/125/134a (23/25/52)	86.20	-43.8	87.3	4.63	1000	none	-4.9	A1/A1		0.000	1530	K
R-407D	R-32/125/134a (15/15/70)	90.96	-39.4	91.6	4.48	1000	none	-4.3	A1/A1		0.000	1430	K
R-407E	R-32/125/134a (25/15/60)	83.78	-42.8	88.8	4.73	1000	none	-4.8			0.000	1360	K
	R-32/125/134a (30/10/60)	80.13	-43.4	89.1	4.87		wff				0.000	1260	K
R-408A	R-125/143a/22 (7/46/47)	87.01	-45.5	83.3	4.42		none	5.7	A1/A1		0.019	2650	M
R-409A	R-22/124/142b (60/25/15)	97.43	-35.4	106.9	4.69	1000	none	3.0	A1/A1		0.039	1290	M
R-409B	R-22/124/142b (65/25/10)	96.67	-36.5	104.4	4.71		none		A1/A1		0.039	1270	M

		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-410A	R-32/125 (50/50)	72.58	-51.6	72.5	4.95	1000	none	-4.4	A1/A1		0.000	1730	K
R-410B	R-32/125 (45/55)	75.57	-51.5	71.0	4.78		none		A1/A1		0.000	1830	K
	R-32/125 (32/68)	84.63	-51.1	67.7	4.40						0.000	2110	K
	R-32/125 (48/52)	73.75	-51.6	69.9	4.73		none				0.000	1770	K
R-411A	R-1270/22/152a (1.5/87.5/11.0)	82.36	-39.7	99.1	4.95	1000	wff		A1/A2		0.035	1330	M
R-411B	R-1270/22/152a (3/94/3)	83.07	-41.6	96.0	4.95	1000	wff	6.5	A1/A2		0.038	1410	M
R-411C	R-1270/22/152a (3.0/95.5/1.5)	83.44	-41.8	95.5	4.95		none				0.038	1440	M
R-412A	R-22/218/142b (70/5/25)	92.17	-36.4	107.5	4.88	1000	wff		A1/A2		0.041	1850	M
R-413A	R-218/134a/600a (9/88/3)	103.95	-29.3	101.4	4.24		wff				0.000	1770	K
R-414A	R-22/124/600a/142b (51/28.5/4/16.5)	96.93	-34.0	110.7	4.70	1000		3.6			0.037	1200	M
R-414B	R-22/124/600a/142b (50/39/1.5/9.5)	101.59	-34.4	108.0	4.59		none				0.036	1100	M
	R-23/22/152a (5/80/15)	81.72	-47.0	97.2	5.04	1000	wff				0.032	1810	M
	R-23/22/152a (5/65/30)	78.29	-44.8	100.8	4.95						0.026	1600	M
	R-23/22/152a (5/90/5)	84.18	-48.4	94.4	5.10	1000	none				0.036	1940	M
R-416A	R-134a/124/600 (59.0/39.5/1.5)	111.92	-23.4	108.2	4.02			7.8			0.012	950	M
	R-22/12/142b (25/15/60)	98.99	-26.6	129.4	5.10	1000	wff				0.163	2670	M
	R-22/124/600 (50/47/3)	102.64	-34.8	102.6	4.56	900	none				0.034	970	M
	R-22/134a/21 (65/15/20)	91.49	-35.9	111.0	5.10						0.034	1500	M
	R-22/142b (40/60)	94.37	-27.9	123.1	4.72		wff				0.046	1680	M
	R-22/142b/21 (65/20/15)	91.20	-34.5	116.0	5.07						0.042	1600	M
	R-22/227ea/600a/142b (41/40/4/15)	107.82	-32.4	108.2	4.37						0.024	2050	M
	R-23/125/143a (20/36/44)	90.16	-64.8	67.3	4.03						0.000	5020	K
	R-23/32/134a (4.5/21.5/74)	83.14	-42.2	89.0	4.90		none				0.000	1630	K
	R-32/125/143a (10/45/45)	90.69	-48.4	72.0	4.05		none				0.000	3040	K
	R-32/125/143a/134a (10/33/36/21)	90.80	-49.4	77.5	4.01		none				0.000	2630	K
	R-32/134a (25/75)	82.26	-40.3	93.7	4.83		wff				0.000	1140	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-32/134a (30/70)	79.19	-41.8	92.4	4.94	1000	wff				0.000	1110	K
	R-32/134a (33.8/66.2)	77.03	-42.8	91.4	5.02						0.000	1080	K
	R-125/143a/290/22 (42/6/2/50)	95.70	-47.7	81.0	4.45	1000	none				0.020	2150	M
	R-134a/142b (80/20)	101.71	-24.1	107.5	4.12						0.010	1400	M
	R-134a/152a (20/80)	71.06	-24.1	384.2	4.40						0.000	370	K
	R-152a/227ea (25/75)	122.01	-20.7	107.8	2.83		none				0.000	2210	K
	R-170/290 (6/94)	42.90	-50.0	91.2	4.29		1.9				0.000	-21	
	R-218/134a/600 (32.7/62.8/4.5)	115.36	-31.4	99.8	4.15						0.000	3110	K
	R-290/22/124 (3/40/57)	105.45	-37.0	112.5	4.46	500	none				0.033	870	M
	R-290/600a (50/50)	50.15	-32.8	114.8	4.04		2				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	6010	M
R-501	R-22/12 (75.0/25.0)	93.10	-40.5	96.2	4.76		none		A1		0.235	3150	M
R-502	R-22/115 (48.8/51.2)	111.63	-45.3	80.7	4.02	1000	none		A1		0.224	5490	M

		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-503	R-23/13 (40.1/59.9)	87.25	-87.5	18.4	4.27	1000	none				0.599	11700	M
R-504	R-32/115 (48.2/51.8)	79.25	-57.7	62.1	4.44		none				0.207	5130	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 (50/50)	98.86	-47.1	70.9	3.79		none	-5.5	A1		0.000	3300	K
R-508A	R-23/116 (39/61)	100.10	-87.4	11.0	3.70	1000	none		A1		0.000	10200	K
R-508B	R-23/116 (46/54)	95.39	-87.4	14.0	3.93	1000	none		A1/A1		0.000	10400	K
R-509A	R-22/218 (44/56)	123.96	-40.4	87.2	4.03	1000	none		A1		0.018	4580	M
	R-134a/152a (85/15)	94.32	-25.4	102.9	4.08						0.000	1130	K
	R-152a/600a (70/30)	63.45	-26.5	120.3	4.93						0.000	100	K
	R-218/152a (83.5/16.5)	144.11	-34.8	86.8	3.38						0.000	5870	K
R-600	CH3-CH2-CH2-CH3 - butane	58.12	-0.5	152.0	3.80	800	1.9	49.5	A3		0.000	~20	
R-600a	CH(CH3)2-CH3 - isobutane	58.12	-11.6	134.7	3.64	800	1.8	49.4	A3		0.000	~20	
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	5.1		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		
	NCH3(CF3)2	167.05	10.4	142.6	2.92						0.000		
	NCHF2(CF3)2	203.03	7.5	131.8	2.73					2.2	0.000		
R-704	He - helium	4.00	-268.9	-267.9	0.23		none		A1		0.000		
R-717	NH3 - ammonia	17.03	-33.3	132.3	11.33	25	14.8	22.5	B2		0.000	<1	
R-718	H2O - water	18.02	100.0	374.2	22.10		none		A1		0.000	<1	
R-729	air	28.97	-194.4	-140.7	3.77		none				0.000		1
R-744	CO2 - carbon dioxide	44.01	-78.4	31.1	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						

refrigerant number	chemical formula - common name	physical data: molecular mass	NBP (°C)	Tc (°C)	Pc (MPa)	safety data: TLV-TWA (PPM)	LFL (%)	HOC MJ/kg	Std 34 safety group	environmental data: atmospheric life (yr)	ODP	GWP 100 yr	status
HC-1150	CH2=CH2 - ethylene	28.05	-109.4	9.3	5.11	1000	2.7		A3		0.000		
FC-1216	CF2=CFCF3	150.02	-29.4	94.9	2.90		none			5.8 d	0.000	2	K
HC-1270	CH3CH=CH2 - propylene	42.08	-47.7	92.4	4.67	375	2.0		B3 r		0.000		

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").

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

Shaded areas denote substances or blends containing substances that are controlled under the Montreal Protocol.

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Annex IV - 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
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)
TOC	Technical Options Committee
VOC	Volatile Organic Compound

Annex V - Participants / Resource Persons

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