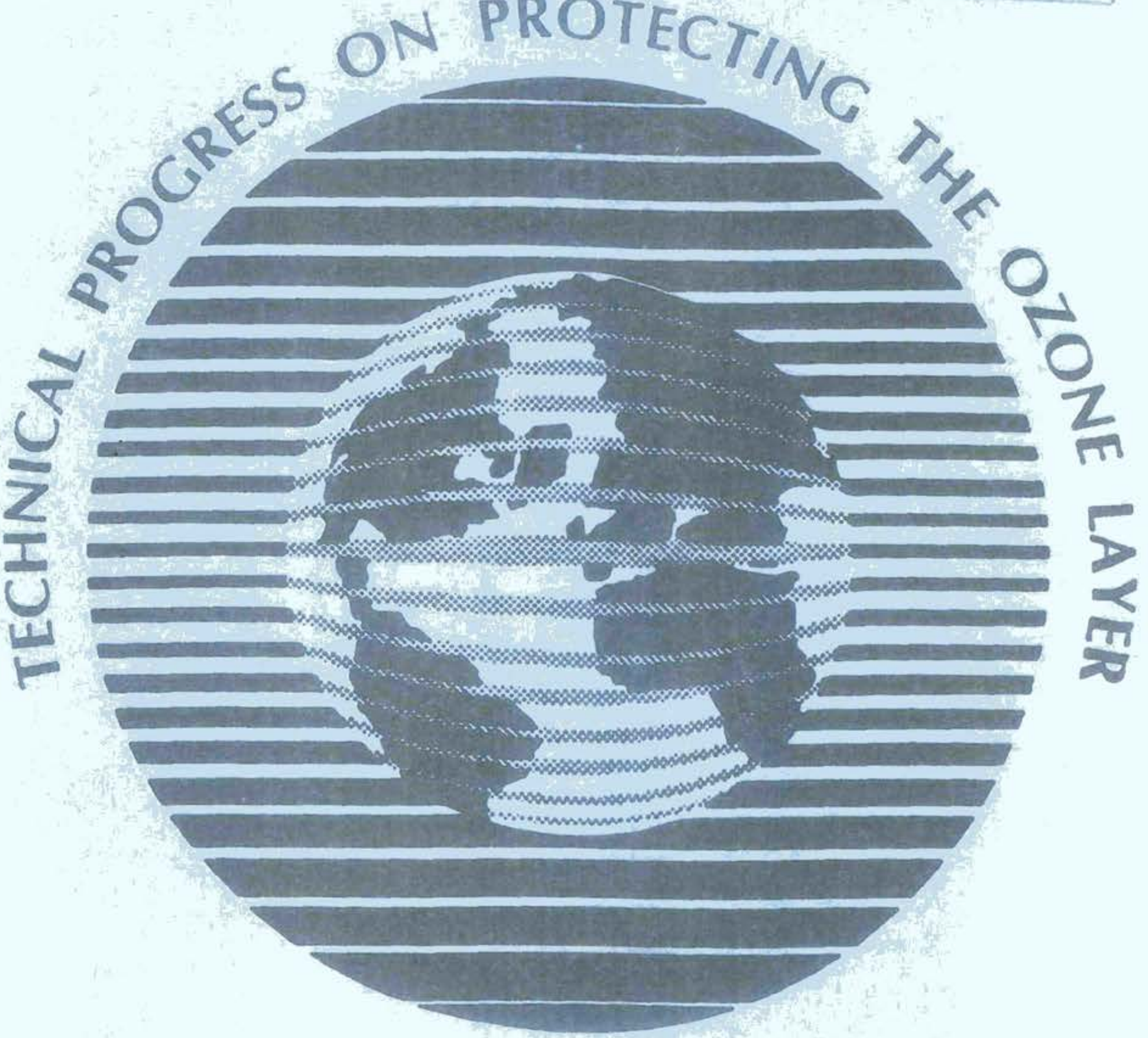
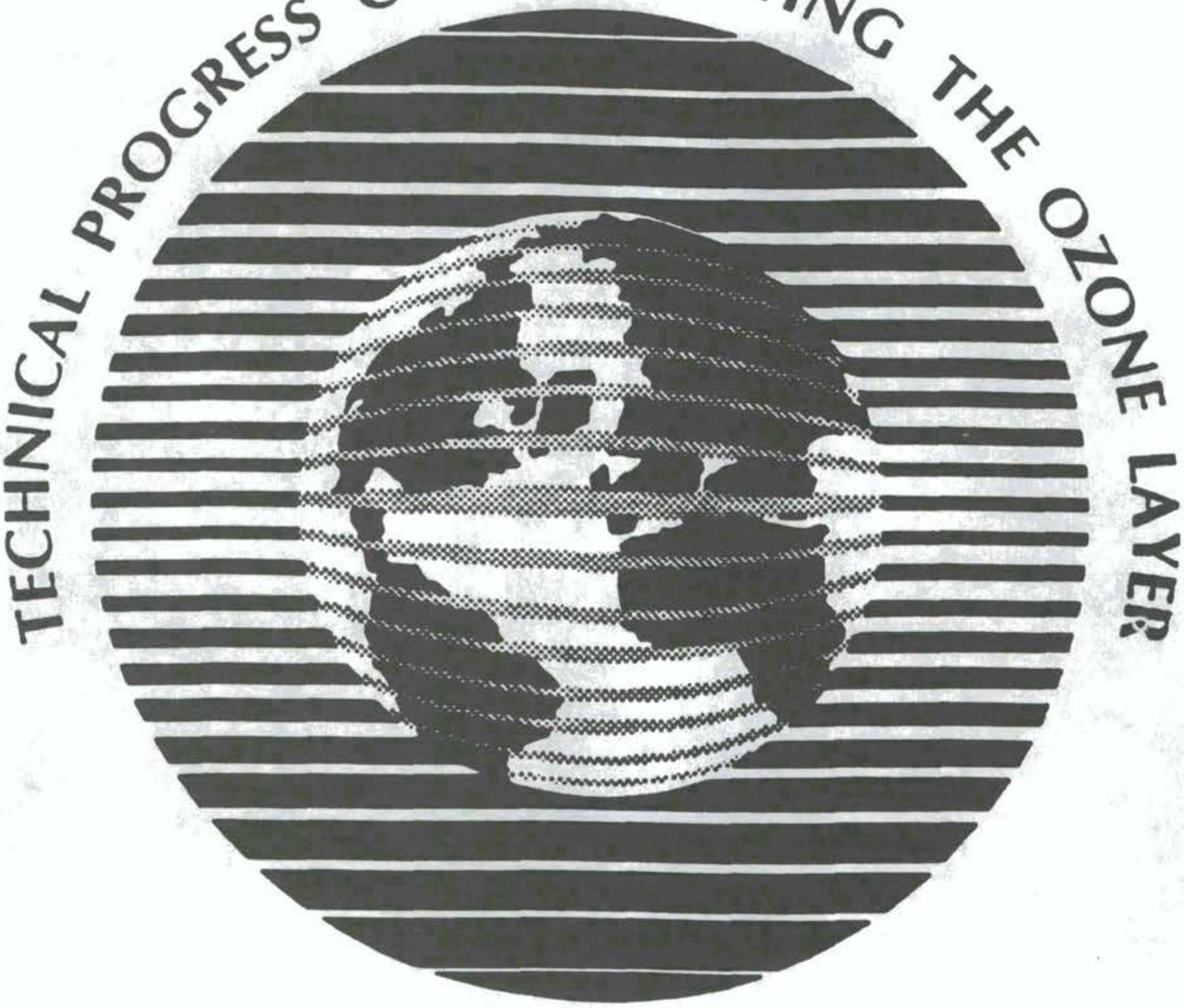


REFRIGERATION, AIR CONDITIONING AND HEAT PUMPS TECHNICAL OPTIONS REPORT

PURSUANT TO ARTICLE (6) OF THE MONTREAL PROTOCOL
ON SUBSTANCES THAT DEPLETE THE OZONE LAYER
UNDER THE AUSPICES OF THE
UNITED NATIONS ENVIRONMENT PROGRAMME

JUNE 30, 1989



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PREFACE

This report is one of a series of six reports prepared to assess the efficacy of controls under the Montreal Protocol and to identify options for achieving compliance. The series consists of a Technology Review Panel Report which provides the overview and integrated statement of findings and five sector-specific Technical Options Reports as follows:

- Refrigeration, Air Conditioning and Heat Pumps (Dr. Lambert Kuijpers, Netherlands, Phone 31 40 742030)

- Flexible stet and Rigid Foams, (Ms. Jean Lupinacci, USA/EPA Phone (202) 475-8468)

- Electronics, Degreasing and Dry Cleaning Solvents (Dr. Stephen Andersen, USA/EPA Phone (202) 475-9403)

- Aerosols, Sterilants and Miscellaneous Uses (Mrs. Ingrid Kökeritz, Sweden, Phone 46 8 799 1000)

- Halon Fire Extinguishing Agents (Mr. Gary Taylor, Canada, Phone (416) 250-0967)

For further information, contact the Panel Chairman (Mr. Vic Buxton, Environment Canada, Phone (819) 997-1640), the Co-Chairman (Dr. Stephen Anderson, USA/EPA at (202) 475-9403), the respective sector report Chairpersons, or the UNEP Secretariat (Phone +254-2-520711)

This report has been prepared for the reassessment of the Montreal Protocol in March 1990. A half-year was available to identify the scope of the paper, designate first, and contributing authors, arrange peer reviews, and complete the final paper. An attempt was made to include authors from a large number of countries, and review from as broad a number of organizations as possible.

This report will require regular updates in order to keep abreast with this rapidly changing technology. The Montreal Protocol requires a regular reassessment every four years. This report will need to be updated at least that often in order to remain current.

This report is submitted on behalf
of the Technology Review Panel,
Dr. Lambert Kuijpers
Chairman Refrigeration, AC, Heat Pump Chapter

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EXECUTIVE SUMMARY

Refrigerant Data

The properties of refrigerants for use in the vapour compression cycle have been considered. The vast majority of present equipment utilizes the vapour compression cycle because of its simplicity and good efficiency. The dominance of this cycle is not likely to change simply due to the need to replace CFCs.

A refrigerant must satisfy a set of criteria, including nonflammability and low toxicity, the need for favourable thermophysical properties, and other, more practical, considerations. Although many fluids and fluid types have been used as refrigerants in the past, halocarbons dominate today because their unique combination of properties best satisfy these sometimes conflicting requirements.

Because of the success of CFC refrigerants, most of the efforts to develop replacement refrigerants have focused on a set of hydrogen-containing, but otherwise similar, compounds. This choice is confirmed by theoretical studies which indicate that simple molecules of relatively low molecular weight and with normal boiling points similar to present working fluids are the ideal refrigerants. These fluids include HFCs-134a, -152a, -125 and -23 and HCFCs-123, -22, -141b, -142b and -124. Mixtures of these fluids are also good candidates. These fluids are the most likely choices for the near- to mid-term replacement of CFCs. Although receiving little attention, HFCs-134, -32 and -143a also deserve consideration; and, for applications where highly flammable fluids can be used, propane, iso-butane, butane and dimethylether. Additional classes of fluids, such as the fluorinated derivatives of dimethylether, show some promise as refrigerants; such fluids, however, present many difficulties and would not be available for many years, if ever.

The thermophysical (i.e., thermodynamic and transport) properties of a fluid determine its energy efficiency and capacity in refrigeration machinery and thus thermophysical property data is required to select the best refrigerant for a particular application. The required thermodynamic properties vary according to the level of development of a fluid. Only simple parameters such as normal boiling point and molecular structure are needed to conduct a coarse screening among many candidates. The minimum data to estimate cycle efficiency are: the critical point parameters and vapour pressure; saturated liquid density; and, ideal gas heat capacity over the temperature range of interest. Single-phase, pressure-volume-temperature, measurements and calorimetric information are needed (in addition to the above) to develop an accurate formulation of the properties; this is the minimum desired level for equipment design purposes. Much more extensive data is needed to define a reference fluid which would be the basis for fluid property models. Transport property information is somewhat lower in priority than the thermodynamic data. Isolated measurements of thermal conductivity and viscosity can be used to screen among fluids, but as a minimum, measurements along the saturation line over a range of temperatures are required for equipment design. Similar data are required for mixtures.

The available property data for the candidate replacement refrigerants are summarized. Priorities identified in this area are the completion of work underway to measure the thermodynamic properties of the leading "new" refrigerants (HFC-134a and HCFC-123); the measurement of transport properties for HFC-134a, HCFC-123 and HCFC-141b; development of HFC-134a to the level of a reference fluid; and measurement of at least skeleton data for the remaining candidate pure fluids and mixtures.

Domestic Refrigeration

For small domestic equipment, good manufacturing processes, exploiting the potential of recycling, and refining current products and processes are important aspects. Reductions in CFC emissions, taking into account the bank of installed equipment, will very much depend on the percentage of recycling.

Domestic refrigerators and freezers use roughly 1.0% of all controlled CFCs in the refrigerant loop (roughly another 4.0% is used in the insulation which is not considered further here). An increase or decrease in the efficiency of any CFC-12 substitute of even 5% would result in a difference in electricity demand growth of 200 MW/year. Therefore, efficiency is an important consideration in finding CFC substitutes for refrigerator and freezer use.

Different options exist for the replacement of CFC-12 in domestic equipment:

> application of CFC-500 would lead to a 40% ODP reduction, but the high CFC-12 content of this mixture makes this an unattractive substitute;
>
> use of NARMs, preferably non-flammable, could result in extremely low ODP values (between 0 and 0.5). Reliable functioning of many products has to be investigated, however, as would energy improvement potential exploited by sophisticated design refinements. The NARMS could lead to short to mid-term CFC savings;
>
> choosing HFC-134a would result in an ODP of zero but result in energy consumption increases estimated to be 8-12% initially and 5-10% after optimization of designs (this makes HFC-134a a less suitable candidate);
>
> applications of flammable refrigerants (such as HFC 152a and DME) offer prospects for reducing energy consumption if their "acceptability" problem can be overcome, and accompanying problems in design and manufacturing solved; but this must be considered a mid- to long-term option;

the recently introduced ternary mixture may offer "drop-in" advantages and better efficiency possibilities if system tests prove satisfactory and toxicity testing has an acceptable outcome. It must be considered a mid- to long-term option;

HFC-134 may prove to be an acceptable long-term option but no testing has been performed so far.

In conclusion, small refrigeration equipment is characterized by the highest requirement for reliability and energy efficiency. Testing of new substances will take time. A considerable time period is needed to make the "best" long-term choice for this type of equipment.

Retail Refrigeration

Retail systems are assembled on site. Unit capacities range from lower than 1 kW to several hundred kW. Refrigerants used are CFC-12, HCFC-22, and CFC-502. Other refrigerants are used only in small amounts and in special applications.

CFC-12 is used for medium temperature systems only. HCFC-22 is used for

evaporation temperatures down to -35 °C and CFC-502 is used for temperatures down to -45 °C. CFC-502 is also used in medium temperature systems, if the same refrigerant for low and medium temperature cooling is to be used. Small amounts of CFC-13, CFC-503, CFC-14, and Halon-1301 (R13B1) are used for low temperature systems in two or more stage cascade systems.

It is estimated that about 5 to 6% of the total CFC consumption is used in retail refrigeration.

There are numerous system designs in the field of retail refrigeration depending on their use.

Leakages are the most important source of CFC emissions in retail refrigeration.

As long as HCFC-22 is accepted as a possible alternative, nearly all the CFC-12, CFC-502, CFC-13 and Halon-1301 consumption in retail refrigeration could be displaced as far as initial charges for new systems are concerned. Costs will be about US$15 million worldwide (US$8 million for the US alone) for savings of about 3% of the total use of CFC-12 and CFC-502 combined.

The change-over from CFCs in existing systems will only be possible for a few of the CFC 502-systems (HCFC-22) and for virtually all the few CFC-13 systems (HFC-23) with costs of about the same magnitude as required for a new charge.

It may be possible to reduce CFC consumption in retail refrigeration to about 20% in the near future. These savings would be from the change-over to HCFC-22, HFC-23, and mixtures in new systems, personnel education for good practice in service, leak testing and disposal in already existing systems, improved leakage control.

Transport Refrigeration

Currently there are about 1300 refrigerated cargo and container ships, representing 10,500,000 cu.m. of refrigerated space. Most of these use HCFC-22, representing a pool of about 2,600 tonnes of HCFC-22. Maintenance and repairs are set to a high standard, requiring the use of about 50 tonnes per year. The continuing availability of HCFC-22 is important, as conversion costs to an alternative (if available) would be very high.

In addition to cargo refrigeration, there could be as many as 35,000 ships with "domestic" refrigeration systems, representing a pool of a further 3,500 tonnes of refrigerant.

Refrigerated containers use CFC-12, and there is no suitable alternative in this very demanding application. The estimated fleet of 300,000 units in late 1990 holds a pool of 1,650 tonnes of refrigerant. Ongoing maintenance and manufacturing require 245 tonnes of refrigerant per year, which is 0.06% of 1986 world production. Should CFC-12 be unavailable beginning 1996, it would involve scrapping US$2,000 million worth of equipment, and would pose formidable problems for manufacturing capacity. Equipment purchased today has an expected economic lifetime of 15-20 years.

Road vehicles currently use CFC-12, but in the short term some change-over to CFC-500 or CFC-502 are in hand. Once proven alternatives are available, further changes will be possible as vehicles have a relatively short life of 7-12 years. There is a world fleet of about 800,000 refrigerated vehicles (220,000 in the EC) with a pool of 3,500 tonnes of refrigerant and a maintenance requirement of 800 tonnes per year. Although the industry is making every effort, reduced CFC use through improved maintenance and handling procedures is difficult to achieve with large numbers of small, mobile units.

On a world scale, transport refrigeration is a small but important user of CFC and HCFC refrigerants which may merit special attention.

Cold Storage/Food Processing

Cold storage covers storage of food products both above freezing 0C to +10C and below freezing (-18C to -28C), both for in-processing storage and for storage and distribution of finished products. Food processing covers chilling from -3C to +10C and freezing to -18C to -28C.

Most large scale industrial chilling, freezing, and cold storage plants utilize ammonia. There are, however, certain areas and countries that use CFC-12, HCFC-22, and CFC-502. Most small scale chilled and cold storage operations use CFC's and HCFC's rather than ammonia. The principal exception is in Eastern Europe, where ammonia is the primary refrigerant.

There is a significant portion of very large site-built plants containing several tonnes of CFC-12 or HCFC-22. These plants have been greatly improved in recent years regarding the need for recharge. Where these plants 5 or 10 years ago had an average loss of 10% of the charge per year, many today report yearly losses down to 1 or 2%. As these plants represent a very high investment and are expensive and difficult to rebuild, additional methods for reducing their charge should be encouraged.

The existing alternatives are:

Ammonia

HCFC-22 and other CFC's where required for operation, safety or climatic reasons.

Greater use of indirect refrigeration for all refrigerants.

Ammonia is quickly biodegradable and is not harmful to the environment. It is toxic to humans in concentrations above 100 ppm after eight hours of exposure. Ammonia is flammable in concentrations of 16 to 25% by volume in air. Codes, regulations, and laws have been developed to deal with the toxic and flammable characteristics of ammonia, which if followed, provide a high degree of safety.

Ammonia is recommended for freezing operations; close-coupled, confined compressor-evaporator systems; and frozen goods storages where the systems are well-managed and not far-flung geographically. Unitized designs can reduce ammonia charge and risk in many applications.

HCFCs and CFCs should still be used where dense populations, public buildings, severe earthquake zones, and special climatic situations prevail. Wherever possible, HCFC-22 should be utilized as it has the least effect on the ozone layer.

A greater use should be made of indirect systems. These systems can use either ammonia or HCFC/CFC refrigerants in a close-coupled arrangement to cool/chill water or a brine solution (glycols, calcium chloride, alcohols, etc.) in a heat exchanger. Indirect systems will provide for a reduced refrigerant charge in most applications. Indirect systems are theoretically less efficient than direct systems due to the extra heat transfer step to cool the water or brine solution. Practical experience, however, shows that because of simultaneity many indirect systems have better performance characteristics than direct systems.

New refrigerants are being developed to provide comparable economic benefits to ammonia and HCFCs and CFCs without the toxic qualities of ammonia and the environmental disadvantages of the HCFCs and CFCs. They can be phased in as appropriate when and if they become available, and the machinery and accessories are adapted to their characteristics.

Refrigeration for food processing, chilling, freezing, storage, and distribution represents a large portion of installed refrigeration tonnage, and it will increase faster than population growth for both chilled and frozen products. The existing plants using CFC-12, HCFC-22, and CFC-502 should be allowed to remain but with targets for lower recharge levels. New installations and major retrofits or modernization should consider the use of ammonia where acceptable on a safety basis followed by HCFC-22 for medium temperature applications and CFC-502 for freezing applications (maybe HFC-32 in the long-term). Use of indirect refrigerations and unitized, factory-built equipment should be encouraged for all refrigerants to reduce refrigerant charges and to minimize potential for leaks.

Industrial Refrigeration

Industrial refrigeration systems include applications within: the chemical, pharmaceutical, and petrochemical industries; the oil and gas industry; the metallurgical industry; civil engineering; sports and leisure facilities; industrial ice making; and, other miscellaneous uses.

All types of refrigerant are used: CFCs; HCFCs; ammonia; and, hydrocarbons. The controlled refrigerants account for approximately 25% of the total refrigerant consumption. The global consumption of CFCs is estimated to be 3500 tonnes per year, of which more than 80% is believed to be CFC-12. The increase in CFC consumption since 1986 has been negligible. The usage of HCFC-22 is approximately twice that of CFCs.

First charge of new plants is believed to account for 30% of the annual consumption. Most of the rest of refrigerant consumption is used for replenishment after leakages and release during service. A small amount is also used for leak testing, etc.

Options for reduction of CFC usage in existing plants are refrigerant conservation, and, to a lesser extent, change-over to alternative refrigerants. In new plants, alternative refrigerants will replace the CFCs gradually. Complete phase-out of regulated refrigerants in new plants is expected to be possible by 1998. Small quantities of CFCs must be available until approximately 2015 for service purposes.

Estimates concerning possible consumption reductions, according to a realistic scenario, appear in Table A. The figures given are relative to CFC consumption in 1986 (3500 tonnes).

The impact on the local environment is considered negligible. The global impact includes a calculated 20% reduction in ozone depleting potential (ODP) of emitted refrigerants (CFCs and HCFC-22) by 1994, increasing to approximately 50% before 1998. About one third of the reduction is due to refrigerant reclamation.

The economic impact is estimated to be a 13-14% investment increase in 1994, which amounts to nearly US$35 million. The corresponding figures for 1998 are 22% and US$55 million respectively. Maintenance costs for the stock is supposed to increase by 12.5% (1998), i.e. by US$13 million per year. This expense will, to some extent, be compensated for by reduced leakage and less refrigerant released during service, which is estimated to represent a value of approximately US$4 million a year at the current price level.

Calculations indicate that the energy consumption will remain fairly constant, provided that no significant efficiency improvements in compressor or plant performances are developed during the period (0% in 1994, +2% from 1998 on). Accordingly, the impacts on energy costs are not important.

Unrestricted availability of HCFC-22 is an absolute prerequisite for the results and conclusions presented here. These scenarios imply a 15-20% increase in the usage of this refrigerant by 1998. Regulations on the use of HCFC-22 will delay the possible phase-out of CFCs considerably, and lead to adverse cost and energy effects.

Comfort Air Conditioning

The portion of comfort air conditioning equipment which is affected by the ban on fully halogenated refrigerants is the very large chilled water systems, which are predominately centrifugal compressor driven. The problems posed and the remedies being considered can be categorized as either existing equipment or new designs. The former of these poses the more difficult challenge, particularly in finding a "drop-in" alternative refrigerant which will require only a reasonable amount of hardware alterations. In fact, it is likely that some cost in performance (i.e. capacity and/or efficiency decrease) will occur even after expensive alterations are carried out. New designs are, of course, possible for new systems. Those presently being

Table A. Possible reduction in CFC consumption industrial refrigeration. (Ref. Table 8.2).

	Estimated reductions, %	
Measure	1994	1998
Retrofitting existing plants to use alternative refrigerants	2	5
Alternative refrig. in new plants	26	38
Refrigerant conservation	15	32
Total	43	75
Refrigerant reclamation	7	17
Total, incl. reclamation	50	92

studied are systems that will employ HCFC-123 and HFC-134a. Also HCFC-22 systems are being studied for possible expansion into a higher capacity range than currently used.

CFCs and refrigerants, in general, can be conserved by improving the equipment handling process throughout. Normal system leakage, servicing, manufacturing, shipping, and installation procedures can be "tightened up" and recovery and recycling procedures can also be implemented. It is estimated that the current CFC usage would be cut in half if such procedural changes were implemented. New designs for both new and existing systems would reduce CFC usage another 23%. The remainder would be phased out gradually by the year 2025 by replacement with non CFC chillers.

Mobile Air Conditioning

Mobile air conditioning currently utilizes CFC-12 exclusively as the refrigerant in a vapour-compression refrigeration cycle. The compressor is engine-driven via a drive belt and associated electromagnetic clutch. The compressor is mounted on the engine while the remaining system components are attached to the vehicle chassis, thereby requiring the use of flexible refrigerant lines to dampen relative engine/chassis movements. In addition to reliably providing for passenger comfort and driving safety over a wide range of ambient conditions, the system must not put the occupants of the vehicle or the public at risk due to exposure to toxic or flammable materials.

Current annual MAC usage of CFC-12 is estimated to be 120,000 metric tons or 28% of global CFC-12 production. Original manufacture uses approximately 29,900 metric tons while 89,700 metric tons are used for servicing existing vehicles.

Current CFC-12 emissions to the atmosphere result from using CFC-12 as a leak detection gas, losses during system charging, system leaks, recharging leaky systems without having to fix the leak, service venting prior to repairs, vehicle scrapping, and poor handling practices in general. Emissions from these sources can be minimized or eliminated. Alternate leak detection gases are available, e.g., HCFC-22. Service venting can be significantly reduced by implementing CFC-12 recycling during service and vehicle scrappage. Resulting annual savings would be on the order of 28,000 metric tons. Elimination of over-the-counter small service cans of CFC-12 would minimize the ability of the general public to recharge leaky systems without repairing them and result in an annual estimated savings of 12,000 metric tons. The practice of MAC system flushing with CFC-11 after component failure can be eliminated by the use of as add-on filter which would contribute to overall CFC savings.

Because there exists no direct "drop-in" replacement for CFC-12 in MAC systems, conversion to another refrigerant is a very major undertaking. Presently, the most viable candidate to replace CFC-12 is HFC-134a, a non-ozone depleting chemical. MAC system changes required for HFC-134a use are relatively modest since HFC-134a thermodynamic properties are similar to those of CFC-12. Given successful lubricant development, favorable final toxicity test results and adequate global supply, HFC-134a could be introduced in new vehicles in 1993. Full implementation (a 3-5 year task) will result in a CFC-12 savings of some 29,900 metric tons annually.

Novel mixtures of refrigerants have been offered as potential replacements for CFC-12 in original equipment and all have been found to be unacceptable, generally due to incompatibility with existing and/or available system materials. Candidates proposed to date for retrofitting existing systems all require significant system changes and, in many cases, flushing with CFC-11 to remove the existing lubricant.

The technology of reducing leakage, recycling CFC-12 and full conversion to HFC-134a in new vehicle manufacture, properly applied, will effect an annual reduction in CFC-12 usage of approximately 70,000 metric tons during the course of the next 7-9 years (Table II). The conversion of new MAC systems to HFC-134a by the mid-late 1990's will leave only the existing CFC-12 fleet in need of CFC-12. This need will diminish with time and can be minimized by timely leak repair, preventative maintenance and CFC-12 recycling. With conversion to HFC-134a and aging of the existing CFC-12 fleet, mobile air conditioning could be entirely converted to an environmentally acceptable refrigerant by the year 2010.

Heat Pumps for Heating Only

Heat pumps for heating only, cover heat demands from a few kW up to several MW, both in the residential and commercial sectors, and in the industrial sector.

CFC-12 and HCFC-22 are the most commonly used refrigerants. CFC-114 is used in industrial applications where high temperatures are required. Roughly it can be stated that HCFC-22 is used for heat delivery temperatures up to 60 C, CFC-12 for temperatures up to 85 C, and CFC-114 up to 130 C.

The annual consumption of CFCs is estimated to be 800 tonnes, evenly divided between first charge in new plants and for recharging of the existing stock.

Conservation is the most promising option to reduce the CFC-consumption in existing plants. Change-over to alternative, non-regulated refrigerants, is not believed to occur to a great extent.

Today, no alternatives exist for the CFC-refrigerants in new plants with standard components, when the heat delivery temperatures exceed the maximum obtainable, using HCFC-22 or ammonia. Therefore, only a gradual change-over to non-CFCs in 15% of the new plants is expected to be possible before 1994. In 1998 it is considered to be possible to use alternative refrigerants in all new plants.

The reduction relative to the expected consumption without any remedial actions to reduce consumption, is expected to be about 25% in 1994 and 80% in 1998.

The heat pump market is anticipated to increase by 10% annually. This implies a 45% increase in CFC consumption by 1994, compared to 1986. In 1998 a CFC consumption reduction of about 45% is expected, with reference to the same year.

The net additional cost for the reduction scenario described is roughly estimated to be US$42 million in 1994, and US$76 million in 1998.

The energy effect of introducing equipment which does not use CFCs is considered to be small. In the long-term, more efficient equipment and system designs will probably be introduced, due to further research and development. This might also refer to absorption heat pumps.

Heat pumps reduce both energy consumption and emission of greenhouse gases and other polluting gases from combustion of fossil fuels. Even if they produce a limited emission of CFCs to the atmosphere, they are assumed to have a net positive effect on the global and the local environment.

Refrigerant Recycling

Refrigerant recycling means a process whereby contaminated used refrigerant is recovered, recycled, and, possibly, reclaimed, so that the refrigerant can be reused in air conditioning and refrigeration equipment. Recycling can be done on-site with portable recycling equipment, while reclaiming is usually done off-site. Off-site refrigerant recycling is performed by CFC manufacturers, independent reclaimers, and individual service companies.

The air conditioning and refrigeration industries are exploring reusing CFC refrigerants by issuing standards for acceptable levels of containments in reclaimed refrigerants. Using the recycled refrigerants which meet these specifications will not void manufacturer warranties, an important step in the widespread use of recycling.

Current servicing practices result in unnecessary emissions of CFCs. Refrigerant is released when manufacturing, repairing, and testing equipment. These releases of CFCs can be reduced with recycling equipment and improved practices.

Recharging of leaky systems without proper repair must be eliminated. This will result in the refrigerant escaping to the atmosphere in a short period of time. Elimination of small cans of refrigerant will reduce the ability of the non-professionals to recharge leaky systems.

Roughly 92 to 99 percent of used refrigerants can be recycled, under proper recycling practices, and may cost about the same as new refrigerant.

However, there are very few facilities and portable recycling equipment available today for recycling refrigerants.

1. INTRODUCTION MONTREAL PROTOCOL REASSESSMENT

1.1. General introduction

CFCs are a family of chemical compounds derived from simple hydrocarbons (methane, ethane, etc.) by substitution of halogen atoms for hydrogen. They have been known and characterized since the 1890s, when a practical method for synthesizing them was discovered by chemists under the guidance of Dr. F. Swarts, a Belgian researcher at the University of Ghent. In the period thereafter there was little more than academic interest though, until 1928 when Thomas Midgley singled them out as working fluids in refrigeration equipment. It was not until the 1950s that their use as aerosol propellants, refrigerants, blowing agents for foams and as solvents led to a rapid increase in their production /Atw88/.

In 1974 the famous ozone depletion theory was published by Rowland and Molina in which they claimed that CFCs would diffuse into the stratosphere where they would be broken down by photolysis to release chlorine atoms which would catalytically destroy ozone. Although the understanding of the science is still imperfect, there is little doubt that CFCs play an important role in the Antarctic ozone hole phenomenon and the decline in ozone observed for the rest of the world.

The other issue which has become increasingly important is the potential of the CFCs to change the Earth's temperature and to modify the climate. Increases in concentration would inevitably lead to a global warming, the so-called "greenhouse-effect". The main concern is about increases in carbon dioxide, but other trace gases including CFCs, could add significantly to this global warming effect.

For governments, a difficult question has been how to respond to this global environmental threat, the first one recognized as such. In 1981 the United Nations Environmental Programme (UNEP) Governing Council passed a resolution requiring the Executive Director to establish a working group to draft a "Convention for the Protection of the Ozone Layer". This "Vienna Convention" was finalized and adopted by a Diplomatic Conference in Vienna in March 1986. After ratification by 20 signatories it entered into force in September 1988.

Attempts to develop a CFC Protocol to the Vienna Convention started in 1984, at the initiative of the Swedish Government. Scientific reviews and economic workshops took place during 1986 and 1987 in order to resolve differences in the approach to the CFC problem between the EC and the Toronto Group (USA/Canada/Nordic countries). An extra round of negotiations was organized in Brussels in June 1987 to prepare a detailed agreement beforehand on possible control measures.

1.2 Montreal Protocol

This work culminated in September 1987 in the adoption of a CFC protocol to the "Vienna Convention" during a Diplomatic Conference in Montreal.

This "Montreal Protocol on Substances which Deplete the Ozone Layer" was ratified by such a sufficient number of countries during the course of 1988 that it could go into force 1 January 1989. In the Montreal Protocol the following reduction steps are described.

A freeze in consumption on 1986 level will start on 1 July 1989 relative to 1986 levels. A 20% cut in consumption will become effective from 1 July 1993. A 50% cut, compared to the 1986 consumption level, will become effective on 1 July 1998. The Montreal Protocol deals essentially with all fully halogenated CFCs and halons.

Each regulated substance has been assigned an "Ozone Depletion Potential" (ODP). The ODPs for each substance are (in brackets):

Group 1 : CFCs 11 (1.0), 12 (1.0), 113 (0.8), 114 (1.0), 115 (0.6)
Group 2 : Halons - 1211 (3.0), 1301 (10.0), 2402 (6.0)

1.3 Reassessment of the Protocol

In accordance with Article 6 of the Montreal Protocol the Parties to the Protocol shall assess the control measures provided for in the Protocol. The first assessment is to be made in 1990, on the basis of available scientific, environmental, technical and economic information. Article 6 provides for the Parties to convene appropriate panels of experts qualified in the aforementioned fields at least one year before each assessment.

An UNEP Scientific Experts Meeting in October 1988 in The Hague, Netherlands, reached agreement on the schedules and processes for undertaking reviews of the current knowledge of scientific, environmental, technical and economic matters relative to the implementation of the Protocol. The above meeting decided that four reports be prepared by four panels.

These reports will be reviewed by an Intergovernmental Multi-Disciplinary Panel of Legal and Technical Experts, composed of legal and economic experts, natural and physical scientists, and technology experts. This Panel, with the assistance of the four panel chairmen, will integrate all the reports into a single report on the current state of knowledge on scientific, environmental, technical and economic matters. The Panel will consider the consolidated report with regard to the likely implications for control measures provided for in the Protocol, and if considered necessary, will recommend to the Parties specific amendments to the Protocol. At the Second Meeting of the Contracting Parties (June 1990), the Parties will review the assessment, consider the proposed amendments and introduce them into the Protocol in accordance with the provisions of paragraphs 9 and 10 of Article 2 of the Protocol /UNE88/.

1.4 Technical Options Reports

The basis for the single Reassessment Report is formed by the four separate reports prepared by the four panels (i.e., Science, Environment, Technical, and Economics). One of these panels is the Technology Review Panel, consisting of a general chairman and five technology chairmen for each of the technology areas (e.g., Refrigeration, Air Conditioning, and Heat Pumps). The Report of the Technology Review Panel, in turn, is developed by the Review Panel Chairmen. This Report, has to summarize options for consumption reductions of CFCs and to make recommendations for a certain strategy. Each of the technology fields, however, is so complex that each of the chairmen has formed an expert panel which describes all options for savings in the Technical Options Report.

The Technical Options Report therefore is the real basis for all recommendations made by the Review Panel and, subsequently, by the Intergovernmental Panel for the Parties.

In the preparation of Technical Options Report for Refrigeration, Air Conditioning and Heat Pumps numerous experts have been involved. First authors of the separate papers were supported by a large number of reviewing authors from all over the world; this without any financial support from UNEP or individual governments. An attempt has been made to include participants from as wide a range of countries as possible. Reviewing authors originate, for example, from Austria, Brazil, China (PRC), The Federal Republic of Germany, India, Italy, Japan, New Zealand, Norway, Sweden, Switzerland, United Kingdom, USA and the USSR.

The work done by the first authors -- for domestic refrigeration (F. Hallett, L. Kuijpers), retail/commercial refrigeration (U. Hesse, H. Kruse), transport refrigeration (R. Heap), cold storage (A. Lindborg), comfort air conditioning (D. Didion, F. Hayes), mobile air conditioning (J. Baker), industrial refrigeration (H. Haukas), heat pumps (P. Frivik), refrigerant handling (S. Taylor, T. Statt), and for refrigerant data (M. McLinden), and the work done by the editor and US coordinator (S. McDonald) -- is greatly appreciated by the Technology Review Panel.

2. REFRIGERANTS FOR REFRIGERATION

The economic impact of refrigeration technology throughout the world is very impressive, and much more significant than generally believed. While the yearly investment in refrigeration machinery and equipment may approach US$100 billion, the value of products treated by refrigeration is perhaps ten times this amount. The total volume of cold stores in the world comes to about 300 Mm^3. This amount of space is sufficient to hold 5% of the yearly total production of foodstuffs. The total amount of the annual food production which is treated by refrigeration is very difficult to estimate. Taking into account all retail shops, refrigerated transport means, domestic appliances etc. it can be stated that between 10 and 25% of the global annual food production is somewhere in the refrigeration "cold-chain".

The use of low temperatures constitutes a major means of conservation of perishable foods during storage and distribution and is widely applied in the developed countries /Lor87/. In the third world, however, at present the use of low temperatures is still mainly limited to food for export.

Refrigerated or frozen foods are generally priced high, too high for the poor in the world at present. There is a pressing need for simple and inexpensive cooling methods to enable low cost mass production of food, (e.g. as realized by the vapour compression cycle using the conventional CFC refrigerants). The future of man, and his food supply in particular, depends on the availability of sufficient energy and on the availability of efficient refrigeration methods. However, this must be balanced by a concern for conservation of the biosphere and the possible occurrence of the greenhouse-effect. Efficiency, therefore, is one of the most important aspects. Refrigeration technology will play an important role in these developments.

Refrigeration technology in the cold-chain implies technology for cold storage and food processing, for retail and commercial equipment, for refrigerated transport and for domestic refrigerators and freezers. These different refrigeration applications are considered separately in this Options Report in order to make estimates about their part in the consumption of CFCs. Next industrial processes and heat pumps are considered. Comfort and automotive air conditioning are characterized by entirely different boundary conditions but are also described in this Technical Options Report. This report, therefore, covers the use of CFCs in 8 subsectors, and contains information on refrigerant handling and the availability and necessity of refrigerant data.

2.1 History of CFCs for Refrigeration

Vapour compression refrigeration, the application of the reverse Rankine cycle, dates back to the 1830s when Perkins applied for a patent for such a machine specifying ether as the refrigerant. Tellier in France designed systems which used dimethylether in 1867. Thus the ethers were the first refrigerants used in vapour compression refrigeration systems.

Vapour compression systems became ubiquitous prior to the availability of CFCs. The reason for this is simple. Compression systems were originally driven by steam engines which made coupling to a compressor quite logical. So by the 1890s, the vapour compression cycle had already largely supplanted air cycle and/or absorption cycle technology.

CFCs, the chemical compounds derived from simple hydrocarbons by substitution with halogen atoms, have been known since the 1890s /Atw88/. A practical method for synthesizing them was discovered by chemists under the guidance of Dr. F. Swarts, a Belgian research scientist at the University of Ghent. However, these substances gained little more than academic interest in the 30 years thereafter.

Vapour compression systems, however, had a continuous growth in all of the sectors where refrigeration systems were used. From the original steam engine drive, development resulted in smaller sized compressors, driven by separate, mostly electric motors. By 1920-30 vapour compression systems were used in all important areas such as commercial systems, comfort air conditioning and household refrigeration.

By 1930, seven refrigerants were mostly used: ammonia; carbon dioxide; methyl-, ethyl-, and methylene-chloride; isobutane; and, sulphur dioxide /Nag88/. Ammonia was the predominant refrigerant in the industrial and large power commercial systems; although its thermodynamic and transport properties were excellent it was not used in the small power applications, such as household refrigerators. Here mainly sulphur dioxide and isobutane were used. The use of isobutane in domestic refrigerators can even be established up to the 1950s, in spite of its flammability aspect. In the comfort air conditioning sector most of the above-mentioned refrigerants were used.

All of these refrigerants had some disadvantages. Some were toxic, others were flammable and others required heavy constructions due to the high pressure levels at which they had to be operated. Nevertheless, ammonia and sulphur dioxide proved to be the best refrigerants.

The need for a new refrigerant became apparent in the small household sector. Not so much the flammability of isobutane, but more the toxicity of sulphur dioxide, was seen as a major disadvantage in small systems. The largest company involved in the household sector, Frigidaire Co, had used sulphur dioxide in their products but a competitive struggle with icebox manufacturing companies on toxicity led the Frigidaire Co to conclude that "... the refrigeration industry needs a new refrigerant if they ever expect to get anywhere" /Mid37/. A research team, headed by Thomas Midgley, explored the field of fluorinated refrigerants, developed a first family (HCFC-21) and eventually settled on dichlorodifluoromethane (CFC-12) as the substance which best meets the criteria for the perfect refrigerant.

Commercial production started in 1931. Soon thereafter processes to manufacture ethane derived CFCs (113, 114 and 115) were developed. This was the breakthrough which made the vapour compression cycle the generally accepted best process in refrigeration. CFCs are vital to the modern practice of refrigeration. However, systems using ammonia or hydrocarbons have enjoyed, and still enjoy acceptance in certain applications long after CFC based systems became viable alternatives. However, limited, or even no future availability of CFCs, is of major concern to refrigeration engineers, since the majority of equipment uses CFCs.

The CFC fluids developed in the 1930s have benefited the refrigeration industry in several less obvious but equally significant ways /Atw88/. By providing a series of fluids covering a range of pressures, the industry gained new flexibility in adapting hardware and systems to specific applications. In addition to their non-toxicity, the inertness of CFCs allowed freedom in the choice of system materials and thereby fostered design flexibility. Moreover, the appropriate CFC based refrigeration systems were reliable and are energy efficient.

The search for more environmentally acceptable refrigerants than CFCs will have to deal with all the criteria, design rules, materials and efficiencies originally developed for CFCs. It will depend upon the specific application area whether either strict saving procedures or fast replacements will yield the environmentally best result in terms of material usage, reliability and, last but not least, energy efficiency.

2.2 Usage Patterns of CFCs

CFCs were developed in the 1930s as refrigerants but it was not until the 1950s that their use in various applications areas led to a rapid increase intheir production. In particular, the use of CFCs as aerosol propellants sharply increased in the 1960s and so, by 1974, the global production (CMA reporting countries /CMA88/) of CFCs-11 and -12 was approaching 800,000 metric tonnes per annum. The latter figure does not include the use of CFCs as a solvent. Fig. 2.1 shows 1986 global consumption of CFCs-11, 12, 113, 114, and 115 by use including refrigeration. Fig. 2.2 shows global consumption by region of these same CFCs.

In Fig. 2.3, the consumption by application, of CFCs-11 and -12 is given as a function of time. It can be observed that in the early 1970s, the main application areas were refrigerants and aerosol propellants. In 1974, 20% of CFCs-11 and -12 was used for refrigeration purposes, 65% was used as an aerosol propellant. Only 15% of these CFCs was applied in other application areas in that specific year.

With the publication of CFC-ozone depletion hypothesis in 1974, many countries implemented measures to reduce the use of these compounds as aerosol propellants. The period of 1974 to 1982 was characterized by a decrease in the of CFCs use as aerosol propellants, in the same period the usage for soft foams and, especially, in rigid foams was increasing. In 1982 the consumption of CFCs-11 and -12 for refrigeration had increased from roughly 155,000 to 180,000 metric tonnes, compared to 1974. Due to an overall decrease in global consumption, the percentage of CFCs-11 and -12 used for refrigeration amounted to 30% by 1982 (see Table 2-1).

The use of CFCs for soft and rigid foams expanded in the 1980s. This usage sharply increased from 29% in 1982 to 36% in 1987. The part of CFCs used in refrigeration, taking into account the CMA reported global value /CMA88/, still amounted to 30% in 1987. This analysis does not take into consideration the use of CFCs for cleaning purposes, and also halons.

Table 2.1 Quantities of CFC-11/12 produced in the period 1983-1987 /CMA88/ on an annual basis

Year	CFC-11	CFC-12
1983	291,731	355,331
1984	312,355	382,107
1985	326,814	376,339
1986	350,148	398,363
1987	382,050	424,726
	Estimate	
1988	415,000	450,000

For refrigeration (closed cell foam)

Year	CFC-11	CFC-12
1983	25,734 (97,985)	175,723 (26,188)
1984	23,915 (110,638)	187,524 (30,669)
1985	26,905 (117,343)	185,023 (33,234)
1986	25,886 (129,618)	198,257 (38,076)
1987	27,644 (160,085)	219,063 (59,900)
Estimate 1988	29,500	240,000

Steep increases can be observed in CFC consumption in 1986-87. Whether this pattern can be extrapolated is uncertain. Nevertheless, it puts pressure on consumption restrictions in 1989. According to the Montreal Protocol, 1989 consumption cannot exceed that realized in 1986.

In this Technical Options Report most of the consumption figures are related to 1987 - and sometimes 1986 - consumption. It is impossible to relate future saving figures to the increase of CFC consumption in the period 1986-89. Saving percentages are therefore only considered in a relative sense, i.e. compared to an arbitrary consumption level.

In Figure 2.4 the global consumption figures in 1987 for the different refrigeration application areas are given. These application areas are separately dealt with in the following sections. The largest consumption can be found in the automotive air conditioning area, followed by refrigera-

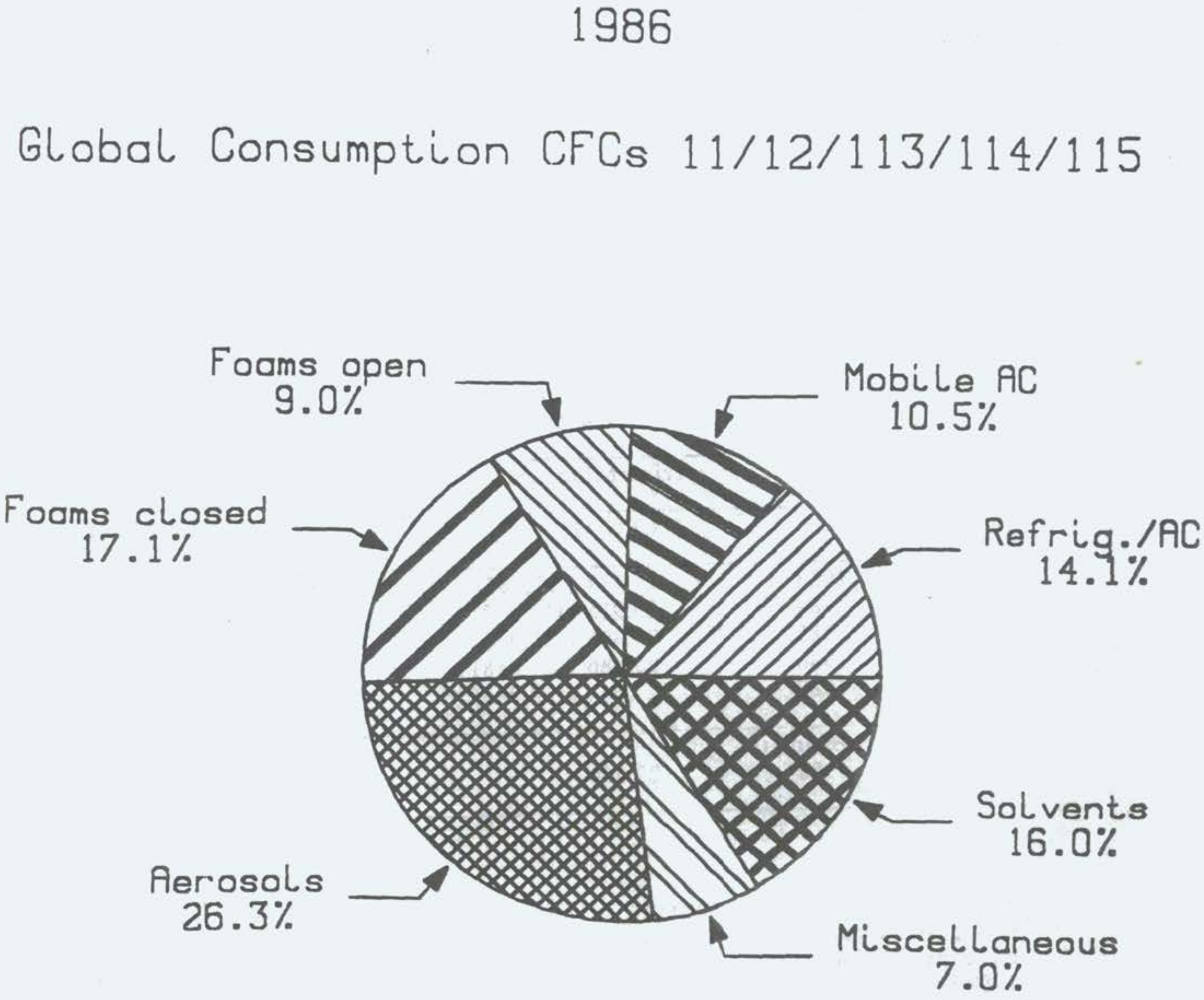


Fig. 2.1 Distribution over End-Users of the Global Consumption for the year 1986 of CFCs-11/12/113/114/115 (UNEP reported value 1,140,000 tonnes) - reference /CMA88/ and best estimates.

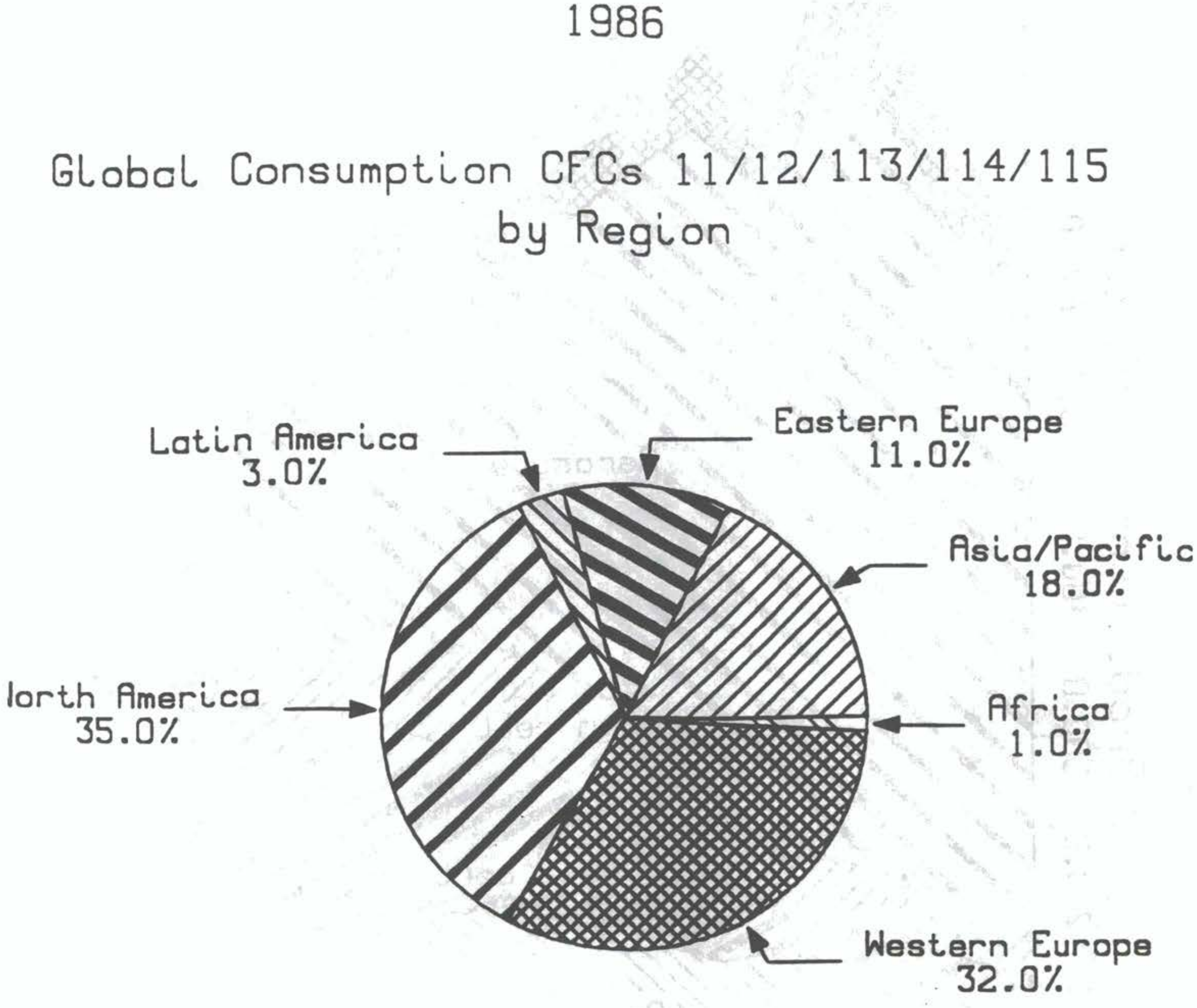


Fig. 2.2 Distribution over Regions of the Global Consumption for the year 1986 of CFCs-11/12/113/114/115 (UNEP data).

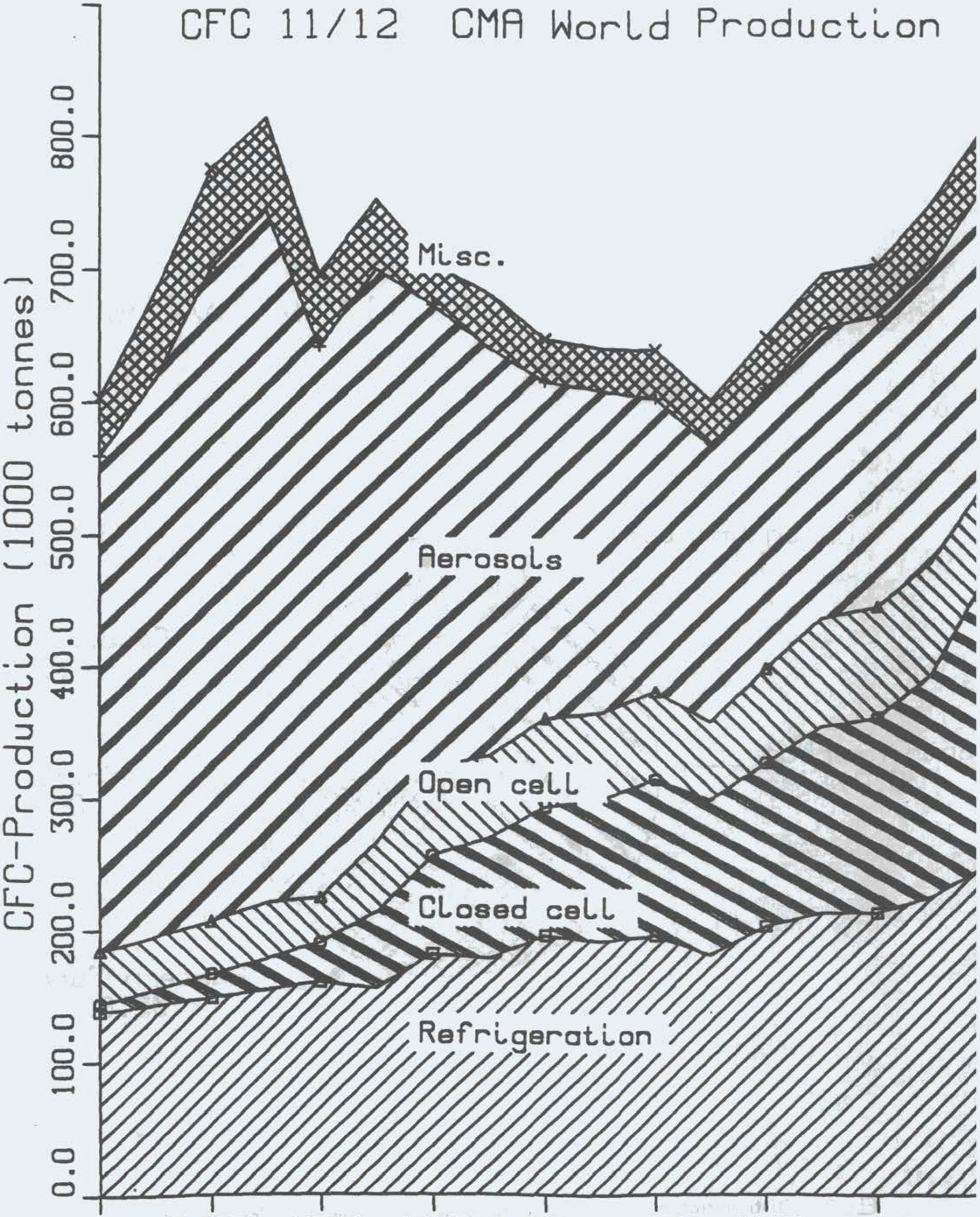


Fig. 2.3 Global CFC-11 and CFC-12 Production During 1971-1987 (tonnes) /CMA88/.

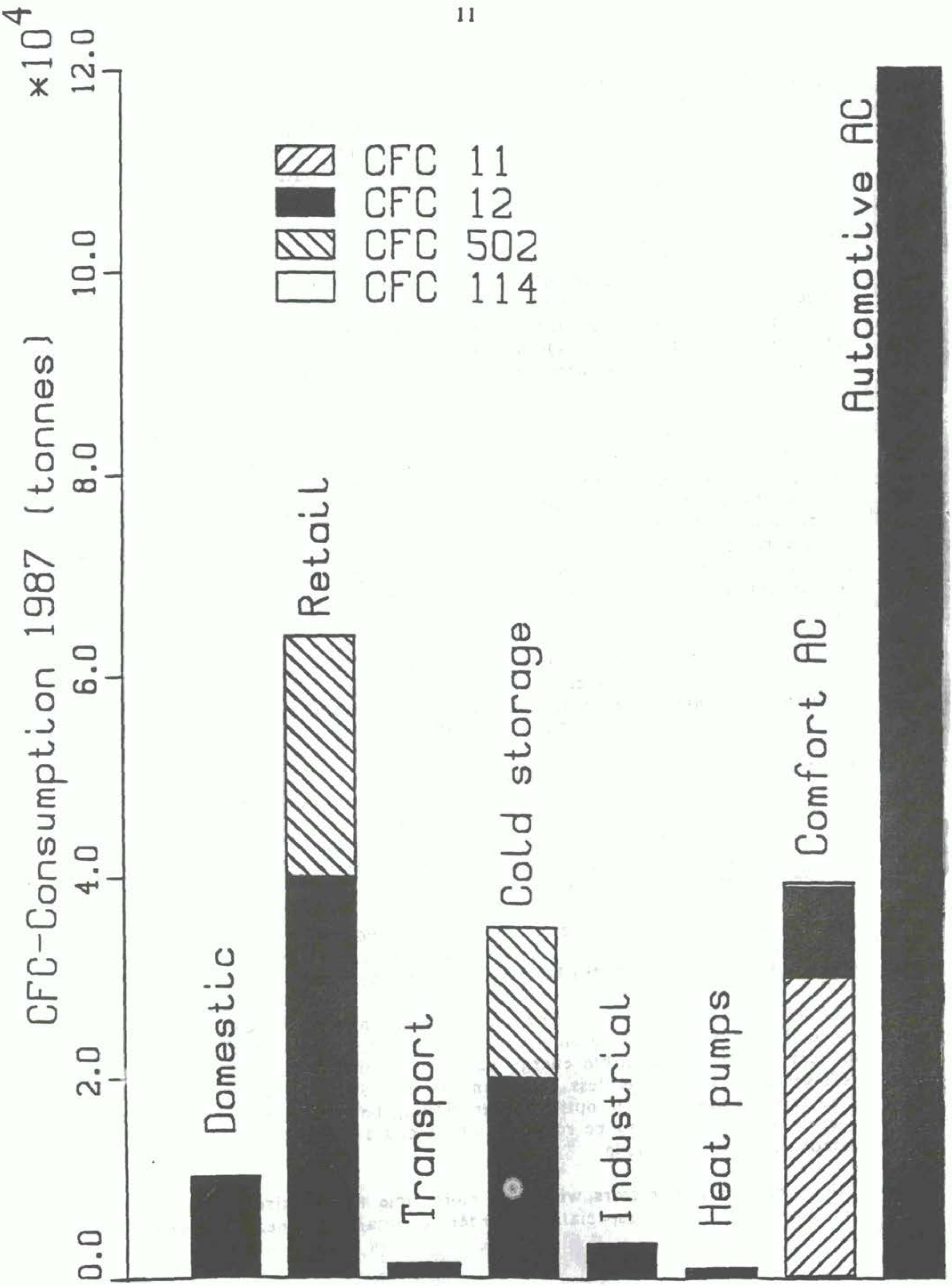


Fig. 2.4 **Global Consumption of CFCs in the Different Refrigeration/AC/-Heat Pump Sectors in 1987 (tonnes).**

tion cold-chain application areas (retail and commercial refrigeration, cold storage and food processing). The automotive air conditioning application area accounts for roughly 50% of the total CFC-11 and -12 use in the refrigeration, air conditioning and heat pump field. Any measure taken in this area will substantially influence the usage pattern of CFCs for refrigeration in total.

2.3 Refrigerant Substitutes

How to reduce the dependence of refrigeration on the environmentally unacceptable CFCs has already been the subject of a number of thorough investigations. Two such studies were performed by the International Institute of Refrigeration (IIR) /Kui88/ and the International Energy Agency /Ber88/; both studies were based upon a questionnaire approach.

Systems using ammonia or hydrocarbons still have large applications in certain areas. The IIR study found that use of these substances should be considered whenever possible; also a finding of the IEA. The next candidate which should be considered for application is HCFC-22. Since this substance is already applied in a large number of refrigeration/air conditioning installations, a switch-over or retrofit needs serious attention. Moreover, because a lot of experience has been gained with this refrigerant, and its thermodynamic properties are well-known, this refrigerant has to be considered as the only short-term pure-fluid substitute refrigerant.

For refrigeration, the application of HCFC-22, with its low ozone depletion potential of 0.05, is therefore considered not to be part of the CFC problem, but part of the solution. This position was put forward at the UNEP meeting at The Hague, October 1988.

On the other hand, statements were also made that in the long-term, HFC refrigerants (e.g. maybe HFC-125 or HFC-32) could take over the role of HCFC-22. However, there is uncertainty in their application until toxicity and/or flammability, can be investigated. This option can therefore only be considered for the long-term and cannot contribute to solutions to seriously reduce CFC emissions in the next decade.

Other, non-azeotropic mixtures are being studied for energy-efficient applications in refrigeration. Should this application be realized in the short-to mid-term, it will still be mixtures which contain HCFC-22.

HFC-134a is widely considered as a replacement for CFC-12. This especially holds for the automotive air conditioning area with its large use of refrigerants. A possible energy penalty, which is important for certain refrigeration sectors, is less important here. Should the installation be regularly serviced, and if optimum functioning be guaranteed, a decrease in energy consumption may be realized, which could offset the thermodynamic disadvantage of HFC-134a.

Other refrigeration sectors will need more time to optimize the equipment for new refrigerants, especially in order to obtain an energy consumption advantage. This involves a possible use of refrigerants other than HFC-134a, under development now, which has a lower efficiency compared to CFC-12. However, this can only be considered a mid- to long-term option since experimental data are still scarce.

It is often emphasized that, in order to balance a possible efficiency drawback of HFC-134a, improved performance can be achieved by better design methods which, up to now, have not been cost-effective. However, in the near future, all possible methods will be required and applied to produce energy-efficient refrigeration equipment. This holds for all components; not only hermetic compressors and evaporators, but also other components such as polyurethane insulation in domestic equipment. Unless absolutely necessary, a baseline efficiency drawback due to the use of HFC-134a should be avoided. However, it is clearly recognized that, so far, no substitutes are known which have gained so much attention concerning application (i.e. experimental tests, data availability, etc.).

It can be assumed that an average increase of 7-8% in energy consumption will occur, when CFC-12 is replaced by HFC-134a in the refrigeration cycle. Suppose that a recently announced mixture /Dup89/ could be applied with a 3% lower energy consumption compared to CFC-12, the difference in efficiency between the two options amounts to roughly 10%. This 10% difference in energy efficiency would have a strong impact on emissions of greenhouse gases as can be illustrated for domestic refrigeration as follows.

Assuming an average lifetime of 15 years for a domestic appliance, an average lifetime power consumption can be determined. Furthermore assuming that CFC-12 refrigerant charge is 120g, the power consumption is roughly 90 MWh/kg. In power plants the averaged emission of CO_2 amounts to 1 tonne per MWh of electricity generated; there is also a 0.004 tonne nitrogen oxide emission. The ratios can then be calculated as 90,000 tonnes of CO_2 and 360 tonnes of NO_x per tonne of CFC-12.

Taking the 10% difference between the application of HFC-134a (with a 0.0 ODP value and the refrigerant mix (with an ODP value of 0.03), it can be calculated that 1 tonne of refrigerant mix will save 9,000 tonnes of CO_2. The question can then be raised whether one tonne of ODP emission is more or less environmentally damaging than 0.3 million tonnes of CO_2 and 1,200 tonnes of NO_x emission. This tradeoff assumes the release of the refrigerant mix into the atmosphere at disposal. However, this eventuality is not necessarily a given.

Although this mixture may be proposed as an alternate for the mid-term, only an optimum design of the refrigeration equipment can yield the energy consumption advantage announced. For the design of the installation, refrigerant data should be available. A summary on data availability and proposals for future refrigerant studies deserve serious consideration in this Technical Options Report and are dealt with in Chapter 3.

3. REFRIGERANT DATA

In this chapter, the requirements for fluids which will serve as replacements for the fully-halogenated CFC refrigerants in the vapour compression cycle are considered and a list of candidates is presented. The focus of this chapter is on thermophysical properties. Included are a discussion of the properties required to evaluate a candidate refrigerant and a summary of the available data.

3.1. Overview

3.1.1 Present Refrigeration Equipment

Refrigerants are the working fluids in refrigeration, air conditioning and heat pumping equipment. The great majority of such equipment operates on the vapour compression cycle. In the basic vapour compression cycle, heat is removed from a low temperature source (such as a refrigerated space) by the evaporation of refrigerant at low pressure within a heat exchanger; the low pressure vapour is compressed to a higher pressure by the input of mechanical work, raising the saturation temperature so that heat can be rejected to a high temperature sink (e.g. ambient air in the case of most refrigeration applications) by the condensation of refrigerant. The condensate is passed through an expansion device to reduce its pressure to that of the evaporator, completing the cycle. Modifications to the basic vapour compression cycle include additional heat exchangers to increase efficiency and the cascading of two cycles to obtain refrigeration at lower temperatures.

Other cycles can produce refrigeration or heat pumping. Air cycles such as the reverse Brayton cycle utilize air as both the working fluid and the cooling medium. Such cycles are often used in aircraft because of weight and space limitations. Reverse Stirling cycles employing a gaseous working fluid find use in low power applications at cryogenic temperatures. Absorption cycles replace the compressor of the vapour compression cycle with a heat-driven absorption/desorption process to generate the required pressure difference between the condenser and evaporator.

Despite the existence of these other refrigeration cycles and their use in specialized niches, vapour compression equipment dominates in most refrigeration and heat pumping applications. This is due to the simplicity of the basic vapour compression cycle, both conceptually and in terms of the required hardware, the ability to realize close to the theoretical cycle in practical equipment and good efficiency, stemming, in part, from the utilization of phase-change heat transfer processes. The remainder of this section will be limited to refrigerants for use in the vapour compression cycle.

3.1.2 Present Refrigerants

The predominant refrigerants in use today are members of the halocarbon family of chemical compounds. To understand this dominance, it is necessary to examine the requirements of a refrigerant. These are summarized in Table 3.1. The most essential requirement is chemical stability--all the other properties would be meaningless if the fluid decomposed or reacted in use to form something else. The next most important characteristics relate to health and safety. Numerous safety codes (e.g. /ASH78/,/BSI80/) require the use of a nonflammable refrigerant with a very low order of toxicity in residential and most commercial applications. It is in these categories that the halocarbons excel over all other fluids for use in the vapour compression cycle. Indeed, it was the conviction that the success of the domestic refrigerator demanded a fluid safer than the ammonia and sulfur dioxide then in use that led to the development of CFC's in the late 1920's /Mid37/. This means that alternative refrigerants must be very carefully investigated with respect to their toxicity, including not only acute health risks but also carcinogenic, mutagenic and teratogenic risks. However, safety risks of the refrigerant cannot be separated from the overall safety of the equipment. Some risks (e.g. flammability) may be countered by appropriate equipment design or may be tolerable in some (e.g. industrial) applications.

To these traditional health and safety criteria, a new environmental criterion must be added. A refrigerant, upon release to the atmosphere, should not contribute to stratospheric ozone depletion, low level smog formation or greenhouse warming. The great stability of some of the halocarbons, long considered an asset, is now seen to be a liability in this regard.

The vapour compression cycle takes advantage of a change in physical state of a working fluid brought about by the application of heat and mechanical work. The salient properties characterizing the physical state of a substance are its thermophysical (i.e. thermodynamic and transport) properties. Thus, to be useful as a refrigerant, the thermophysical properties of a substance must satisfy certain requirements. These properties determine not only whether a fluid is suitable for use at all as a refrigerant, but also the efficiency and economy of the cycle.

The thermodynamic requirements of a refrigerant in the vapour compression cycle have been considered by a number of authors, including Alefeld /Ale87/, Angelino and Invernizzi /Ang88/, Bertinat /Ber86/, McLinden /McL88/, and Narodoslawsky and Moser /Nar88/. While these various reports focus on different aspects and different applications, all are in essential agreement. They reveal that different aspects of the vapour compression cycle lead to different, and often contradictory, thermodynamic requirements. The most important conflict exists between the efficiency of a cycle and its capacity. The efficiency generally increases as the critical temperature of the refrigerant increases while the capacity decreases with increasing critical temperature. This represents an economic tradeoff. The efficiency determines the operating cost while the capacity influences the capital cost of the equipment, particularly the compressor.

The analysis of McLinden /McL88/ used the principle of corresponding states and sheds some light on the type of molecule best suited for use as a refrigerant. This approach utilized the fact that the properties of a range of fluids are similar when scaled according to the critical point parameters. Simulations of cycle performance for a "characteristic" refrigerant over a wide range of conditions revealed that the optimum refrigerant should operate at 0.6 to 0.9 of its critical temperature. Operation as far as possible below the critical point (i.e. using a refrigerant with a high critical temperature) yielded the best efficiency. However taking into account practical considerations such as the desirability of avoiding sub-atmospheric pressures in the cycle and difficulties in designing a cycle for use with very low density vapour, a practical lower limit is operation at approximately 0.6 of the critical temperature. Operation closer to the critical point (i.e. using a refrigerant with a relatively low critical temperature) can increase the capacity by an order of magnitude or more with relatively modest decreases in efficiency. Only for condenser temperatures greater than about 0.9 of the critical temperature do the efficiency penalties become severe. A low to moderate value for the vapour heat capacity was identified as optimum. High values of vapour heat capacity result in excessive losses in the throttling process and also result in condensation in the compression process (a "wet" compression).

By relating the critical temperature and vapour heat capacity to molecular structure, this analysis revealed simple compounds of relatively low molecular weight to be the best refrigerants. This conclusion is entirely consistent with present refrigerants, including the one and two-carbon halocarbons such as CFC-12, HCFC-22 and CFC-114 as well as simple inorganic compounds such as ammonia. More complex molecules, such as the propane-based HCFC's suffer a thermodynamic penalty in the throttling process because of an unfavourably low heat of vapourization to heat capacity ratio; they can also undergo a "wet" compression. While modifications to the cycle could offset these difficulties, it is doubtful that the extra costs associated with the use of complex molecules as refrigerants would be acceptable in most applications. This analysis implies that replacement refrigerants must also be simple compounds with critical points and boiling points similar to existing fluids. However, there will not be a single alternative refrigerant suitable for all uses. The search for alternative refrigerants is one for a variety of substances, each of them satisfying the requirements and best balancing the tradeoffs for a particular application.

The transport properties of viscosity and thermal conductivity have a large impact on the design and required size of system components, particularly the heat exchangers. The desired properties of low viscosity and high thermal conductivity are also associated with simple, low molecular weight compounds. While the halocarbons have transport properties that make them good refrigerants, other compounds, notably ammonia and simple hydrocarbons such as propane, have superior characteristics /McL88/. These other fluids are flammable, toxic, or both and thus see use generally only in large commercial or industrial systems where their superior thermal characteristics outweigh their safety drawbacks.

A number of other, more practical, criteria are also necessary or, at least, desirable. Solubility in lubricating oils, and high vapour dielectric strength are important for hermetic compressors. A freezing point below the lowest expected system temperature is necessary and a means of easily detecting leaks is desirable. Compatibility with common materials, including lubricating oils, seals and motor insulations as well as the metals used to fabricate heat exchangers and compressors is obviously required. While the cost of the fluid must not be exorbitant, the cost of present refrigerants is a tiny fraction of the total system cost and moderate cost increases for the alternative refrigerants can be tolerated. However the use of a particular fluid must not inflict extraordinary costs for the equipment, either due to corrosion problems, high pressures or exceptional safety precautions. Again, the halocarbon refrigerants offer very favourable properties for this final set of criteria.

In summary, there are very good reasons for the present use of halocarbon refrigerants in the vapour compression cycle. While the future use of different cycles or different types of refrigerants cannot be completely ruled out, one must be aware that in the past many systems have been considered and rejected.

3.1.3 Refrigerant Nomenclature

Refrigerants are most commonly referred to by a numbering system originally developed by DuPont and later expanded and formalized into a standard by ASHRAE /ASH78/. This system has been accepted by the International Organization for Standardization /ISO74/ and as a national standard by several countries. In this system, a two to four digit number is used to designate the chemical formula. The right-most digit is the number of fluorine atoms in the molecule. The second digit from the right is the number of hydrogen atoms plus one. The third digit from the right is the number of carbon atoms minus one; this digit is omitted if zero (i.e. single carbon). The presence of bromine is indicated by appending B with the number of bromine atoms. Except for these indicated numbers of fluorine, hydrogen and bromine the carbon atoms are assumed to be fully substituted with chlorine. The fourth digit from the right is one if a carbon-carbon double bond is present; it is omitted for saturated compounds. Different isomeric forms of the same chemical formula are indicated by a lower case letter appended to the number. The most symmetrical isomer does not have an appended letter; the increasingly non-symmetrical isomers are designated with a, b, etc.

In the ASHRAE and ISO standards, the number is preceded by the letter R or the word Refrigerant. The increasingly common, but nonstandard, practice is to replace R by CFC, HCFC or HFC to indicate what atoms the molecule consists of. CFC indicates a molecule composed of chlorine, fluorine and carbon. In present usage, the term CFC means a fully halogenated compound. In the past, however, the term CFC sometimes was used to refer to the entire family of halocarbon compounds, including those that contained hydrogen. HCFC indicates hydrogen, chorine, fluorine and carbon. HFC indicates hydrogen, fluorine and carbon.

The ASHRAE standard also assigns arbitrary numbers to azeotropes (500 series), mixtures (400 series), miscellaneous organic compounds (600 series) and inorganic compound (700 series).

3.2 Possibilities

A number of research centers have undertaken screenings of many possible candidates based on limited property data or methods such as that outlined in section 3.1.2. While these efforts and the development of more reliable screening techniques should be ongoing, a number of fluids have already passed and constitute the most likely alternative refrigerants, at least for the near-to mid-term. These alternative fluids are listed in the right half of Table 3.2 in order of their normal boiling point. For comparison, the fully halogenated compounds are also given (left half of table). Most of the development efforts have been directed towards a limited number of one- and two-carbon halocarbons. HCFC-22 is, of course, a common refrigerant in many applications. HFC-23 is a specialty refrigerant used in certain low temperature applications. HFC-134a, HCFC-123 and HCFC-141b are the focus of intense development efforts by both the chemical industry and refrigeration equipment manufacturers. The interest of the chemical industry in at least four additional compounds, HFC's 125 and 152a and HCFC's 124 and 142b, can be inferred by their inclusion in the presently ongoing Alterative Fluorocarbon Environmental Acceptability Study (AFEAS) funded by a consortium of 14 fluorocarbon producers worldwide. Although not widely used as refrigerants, HFC-152a and HCFC-142b are currently produced as specialty chemicals.

There are several additional halocarbons that warrant consideration, both in terms of their properties and prospects for eventual commercial availability. HCFC-123a, an isomer of HCFC-123, will likely be a minor constituent in commercial grade HCFC-123. Although the thermodynamic properties of HCFC-123 and HCFC-123a are likely to be very similar, there is some indication that HCFC-123a is more stable and possibly less toxic (this is based upon assumptions for the structure and not on testing results) than HCFC-123. Another candidate, HFC-143a, is a byproduct of the process to produce HCFC-142b. HFC-32 has excellent heat transfer properties /McL88/; although presently available only on a custom synthesis basis, it was produced many years ago and a quite straightforward synthesis route is known. Finally, at least one study /Hod88/ reports that, based on estimated properties, HFC-134 has a higher cycle efficiency than its isomer HFC-134a.

Apart from the above halocarbons, possible replacements can be identified in at least two additional fluid categories. The simple hydrocarbons have good thermodynamic and transport properties and are currently used in certain large industrial refrigeration systems. They are commercially available but are, of course, highly flammable. Propane, butane and isobutane are the most suitable for refrigeration use. Dimethylether and its fluorinated derivatives show some promise as refrigerants. Perhaps the most promising member of this group is bis(difluoromethyl)ether, CF_2H-O-CF_2H. A patent /Sim79/ for its use in aerosol applications indicates that this ether is stable, nonflammable and of low toxicity. Its boiling point suggests its use as a possible replacement for CFC-114.

The fluids listed in Table 3.2 are also categorized according to their likely availability. Those fluids categorized as "near-term" are currently available in commercial quantities either as refrigerants (e.g. HCFC-22) or for other uses (e.g. propane). The designation of a fluid as "near-term" relates solely to the availability of the material; there may be significant other impediments to the use of a nontraditional fluid. The "mid-term" fluids are currently available only in limited or test quantities, but process development is underway and commercial quantities should be available by the early to mid 1990's. This category includes the "new" refrigerants under active development such as HFC-134a. The "long-term" fluids are available only in very small (<1 kg) quantities, if at all, and are not being actively pursued by the chemical manufacturers.

The fluids included in the near- and mid-term categories represent the best possibilities for meeting the targets of the Montreal Protocol. The development of the fluids in the long-term group is many years behind the others. The fluids in this group should be explored, but with the realization that research on such fluids is risky. Other crucial goals must not rely on any new "miracle" refrigerant.

Refrigerant mixtures represent an additional possibility for replacement working fluids. Mixtures can expand the set of acceptable pure components. The most obvious example is the combination of flammable and nonflammable pure components to yield a nonflammable mixture. Mixtures can be categorized into three types. Azeotropic mixtures behave essentially like pure fluids; several are in commercial production. With non-azeotropic mixtures, the compositions of coexisting liquid and vapour differ and condensation and evaporation processes occur over a range of temperature in contrast to the isothermal phase change seen with pure components or azeotropes. These effects can be exploited to enhance performance, but require equipment modifications. The final class of mixtures, dubbed "near-azeotropes," exhibit such small deviations from azeotropic behavior to be usable in traditional refrigeration equipment without modification. They offer the potential to tailor the properties of the working fluid to a particular application. The availability of mixtures is dependent both on the availability of the constituent components and also the development of methods to handle mixtures in the charging and servicing of systems. At least some mixtures would be classified as "mid-term."

3.3 Thermophysical properties in the vapour compression cycle

3.3.1 Thermodynamic Properties

Thermodynamic properties determine the efficiency and capacity of the vapour compression cycle and thus are the key data needed in designing refrigeration equipment and in comparing one refrigerant with another. Of prime importance is the energy involved in the various processes, thus the need for accurate enthalpy values. The ideal compression process is at constant entropy; real compressors are often referenced to the isentropic process. Also important are the operating pressures of the condenser and evaporator; these are largely a function of the vapour pressure. For positive displacement (e.g. piston) compressors, the density of the vapour largely determines the mass flow rate through the compressor and thus the refrigeration capacity. For centrifugal-type compressors, the maximum speed of the impeller is limited, in conventional subsonic design, by the vapour sonic velocity; the pressure rise developed by the compressor is a function of the impeller speed and the refrigerant molecular weight.

Thermodynamic properties are invariably formulated in terms of an equation of state. An equation of state not only correlates directly-measured quantities in a thermodynamically consistent way, but also allows the evaluation of derived quantities. For example, enthalpy and entropy are obtained by calculations involving up to second-order derivatives of a pressure-volume-temperature (p-V-T) equation of state. Pressures and densities in themselves need be known to an accuracy of only a few percent. Their importance to the derived quantities, however, places much more stringent requirements on the required accuracy of the p-V-T data.

3.3.2 Transport Properties

While the thermodynamic properties of a fluid determine its performance in the vapour compression cycle, the transport properties have a major impact on the design of the equipment. Thus the transport properties have a major influence on whether it is economically feasible to build a machine which can actually obtain the theoretical efficiency of the thermodynamic cycle.

Transport properties are particularly important in the design of the heat exchangers (condenser and evaporator). The effectiveness of heat transfer with the refrigerant is expressed in terms of a heat transfer coefficient. For the final optimization of heat exchanger design these heat transfer coefficients are often experimentally determined for the exact combination of refrigerant and surface used. In the screening and preliminary design stages, heat transfer coefficients are estimated via correlations involving thermal conductivity, viscosity, surface tension, density and heat capacity.

3.4 Data Status and Needs

The thermophysical property data required for a fluid increase as it progresses from a possible candidate to full commercial production and use. A few basic parameters (such as normal boiling point) can be used to screen among many possible candidates to select a more limited set on which to focus development efforts. At the other extreme, extensive property information is required in order to design efficient equipment using a new refrigerant. The data available for the various candidate refrigerants identified above will be assessed in terms of several such categories.

3.4.1 Pure Fluids

For the thermodynamic properties, the level of data can be classified into the following categories:

1) screening parameters, e.g. normal boiling point temperature, critical point parameters, molecular structure

2) skeleton data, e.g. saturated liquid density, vapour pressure and ideal gas heat capacity over a range of temperature and (if not included in category (1)) the critical temperature, pressure and density

3) traditional p-V-T data, including, for example, pressure-volume-temperature data in the vapour (need is particularly nonexistent) and region, more extensive saturation properties and calorimetric information

4) data of reference fluid quality--an extensive collection of high quality data covering wide ranges of temperature and pressure

The screening parameters (category 1) are needed to sort among the hundreds of fluids which might be considered for use. Almost by definition, this data must be available to even consider a fluid. Fortunately, information such as the normal boiling point is available for a huge number of fluids, including all of the fluids identified above. The next level of data represents the minimum information required to generate reliable estimates of the thermophysical properties (using, for example, the method of Ely /Ely84/). With such information, the performance of a fluid in the vapour compression cycle can be estimated.

The thermodynamic properties of most of CFC refrigerants in use today have been determined to the level of category (3). This is the minimum data set to allow a traditional formulation of the properties using an equation of state. The final category, that of a reference fluid, is reached only for a few fluids; among the common refrigerants, only the data for R22 and R12 approach this level.

The status of the various candidate fluids is given in Table 3.3 according to the above classification scheme. One can infer from this table the areas where more information is needed. As a minimum, category (2) data should be gathered for all of the fluids identified. Category (3) data is the desired level for all fluids being actively developed or seriously evaluated in machinery. The data necessary to develop a material to reference fluid quality restricts this category to a very limited number of fluids. Such a fluid should be well chosen. A fluid in very widespread use would deserve such status. A fluid might also be chosen for more theoretical reasons to serve as a reference fluid for the development of equations of state or other property models which could then be used to extend the more limited information available for other fluids. One or two of the new refrigerants should be developed to this level.

The transport properties can also be categorized in a similar way:

1) screening data, e.g. measurements of thermal conductivity and/or viscosity at some reference condition

2) skeleton data, e.g. measurements over a range of temperatures along the saturation line and of vapour at 1 atmospheric pressure

3) more extensive data including compressed liquid and superheated vapour states

4) reference fluid quality data

The transport properties are somewhat lower in priority than the thermodynamic properties and initial screening studies of many fluids often do not consider the transport properties, implicitly assuming that fluids with similar thermodynamic properties will have comparable transport properties. (An exception would be in the selection of blowing agents for insulating foams where the thermal conductivity of the vapour which is trapped in the foam is important for the insulating value of the final product. In this application, a thermal conductivity value for the vapour at one atmosphere pressure and room temperature is often used as a screening parameter.)

The transport data in categories (2) and (3) are needed for the design of heat exchangers and other components in refrigeration equipment. As with the thermodynamic properties, collecting the data necessary to define a reference fluid (category 4) is practical only for a very limited number of fluids. Since the heat exchanger cost in current systems is from 50 to 70% of the total system cost, transport property data are still of considerable importance.

3.4.2 Mixtures

Mixture data is needed to allow an assessment of near-azeotropic mixtures as CFC replacements and to aid in the identification of possible azeotropic mixtures. A wide variety of measurements on refrigerant mixtures have been reported in the literature. Unfortunately, most of the mixtures studied contain at least one component which is fully halogenated /Mor88/. Virtually no data exist for mixtures of the polar, hydrogen-containing compounds.

Because of this lack of data, virtually any information for mixtures of the polar halocarbons would be of great use in extending mixture models. The most basic and useful data would be bubble point pressures. Even a single such measurement would allow the estimation of the "mixing parameter" required in many mixture models. Bubble point pressures over a range of temperature and composition, as well as liquid density and coexisting liquid and vapour compositions would also be desirable. The transport properties for refrigerant mixtures are especially important since there is some evidence that there may be substantial degradation of desirable properties due to non-ideal mixture effects, leading to heat transfer penalties. As with the pure fluids, establishing an extensive data set for one or more reference mixtures would be highly useful in developing and verifying mixture models, but otherwise, exhaustive measurements such as pressure-volume-temperature data for the single-phase region would be justified only for a mixture that has a high probability of being commercialized.

3.4.3 Priorities for the thermophysical properties

The most urgent priority for thermophysical property data -- a formulation of the thermodynamic properties of HFC-134a and HCFC-123 -- is currently being addressed and preliminary formulations are now available. Remaining as high priority items are the following:

measurement of the transport properties of the leading candidates, in particular, HFC-134a, HCFC-123 and HCFC-141b

development of at least one fluid to the level of a standard reference refrigerant for use in model development and testing; HFC-134a is probably the best choice, both because of its likely commercialization and because it is a prime example of a polar hydrogen-containing ethane-based halocarbon

collection of at least skeleton data for the remaining candidate fluids

collection of data for mixtures of the polar, hydrogen-containing fluids

Completion of the above would enable the evaluation of a wide variety of candidate fluids and thus allow the best choice of working fluid for the various applications. Based on these results, priorities could then be established for further work to better characterize the refrigerants and/or refrigerant mixtures to be used in new equipment.

3.4.4 Other Properties

While the thermophysical properties of a fluid are of major importance for a refrigerant, the original development of CFC's for largely safety-related reasons clearly demonstrates that they are not the only consideration. Toxicity data is available for all of the refrigerants listed as "near-term" in Table 3.2. Long-term toxicity studies are currently underway for at least three of the leading new refrigerants (HFC-134a, HCFC's 123 and 141b). Data for the other fluids is generally very limited, although inclusion of a fluid in Table 3.2 implies at least some indication that it is likely to be of low toxicity. Likewise, only fluids likely to have short atmospheric lifetimes are listed as "environmentally-acceptable" in Table 3.2.

The question of whether flammable refrigerants would be acceptable has received considerable attention recently (e.g. /Kui89/). Table 3.2 does include fluids that can be classified as moderately flammable (refrigerants 141b, 142b, 152a, 143a and 32) or highly flammable (butane, iso-butane, dimethylether, and propane). The use of a flammable refrigerant in a particular application must be addressed on an individual basis.

The identification of a suitable lubricating oil may require lengthy, trial-and-error experimentation. Included in this process would be tests of the chemical stability of oil/refrigerant mixtures in contact with common materials of construction and possible contaminants such as water. Similar tests would be required to ascertain the suitability of desiccants, insulations and seal materials.

3.4.5 Time frame to obtain crucial data

Screening of possible alternatives. The basic data such as boiling point and critical parameters are available or can be reasonably estimated for a few thousand compounds. These parameters have yet to be established for most of the "long-shot" compounds whose molecular structure identifies them as possibly useful. The screening process is already in an advanced stage and should be concluded for the most important applications within one year.

Thermodynamic and transport properties. The measurement of thermophysical properties for a hitherto unknown substance in the quantity and quality necessary to permit the design of refrigeration equipment is a tedious task. The necessary equipment and expertise do, however, exist in a number of research centers and work is already underway. It is also possible, in the interim, to apply estimation methods in order to extend limited information. In view of the urgency of the need, the highest priority measurements should be completed in about two years assuming sufficient funding. The measurement of crucial transport properties may take slightly longer since for many experimental techniques, the thermodynamic properties are required in order to analyze the transport property measurements. Needs in this area will continue for many years, especially if mixtures find widespread use or if additional fluids continue to be developed.

The measurement of thermophysical properties requires only small quantities of fluid sample (on the order of a few hundred grams) so that this should not be a major impediment. Indeed, the determination of these properties may be the most effective use of a material that is in short supply since knowledge of the thermophysical properties may reduce the need for extensive equipment tests requiring many kilograms or even tonnes of refrigerant.

Materials compatibility tests. It is risky to estimate the time necessary to identify and confirm the suitability of lubricating oils, seals, materials of construction, etc. The tests are not only inherently time consuming and expensive, but there is also no guarantee of success. It may take many trials to find a suitable material. This could be a real show-stopper for an otherwise promising refrigerant. As much as five years could be required for this development and testing process.

Toxicity. This is perhaps the most expensive and time consuming step in the qualification of a new refrigerant. Although a preliminary indication of toxicity can be obtained in a few months, the rate-determining step is the long-term testing necessary to reveal any chronic toxicological effects. These tests cannot be speeded up. Positive intermediate results would, however, allow a go-ahead for process development, equipment design, etc., although such development would not be without considerable financial risk. Long-term testing will be initiated in 1989 for HFC-134a, HCFC-123 and HCFC-141b but will not be complete until 1992 or 1993. This testing must be complete before any new refrigerant can be applied on a large scale in any domestic application.

Environmental acceptability data. These data include the impact of a substance on ozone depletion, greenhouse warming, low-level smog formation and possible effects on ground water (this later factor is primarily a concern for the higher-boiling substances). Although these data are of utmost importance, few generally agreed upon predictive methods exist. One concise measure is the atmospheric lifetime. A final verdict on the environmental impact may require many decades.

3.5 Concluding Remarks

There are numerous criteria that a fluid must satisfy in order to be acceptable as a refrigerant. Despite problems with the fully-halogenated CFCs, the hydrogen-containing HFCs and HCFCs remain as the most promising candidates for replacement working fluids; although other fluid types such as the simple hydrocarbons and fluorinated ethers should also receive some consideration. There also seems to be no reason to abandon the vapour compression cycle because of environmental problems with one type of working fluid.

Among the criteria required of a refrigerant, thermophysical properties are of major importance. Thermophysical property data have recently become available to evaluate the leading new refrigerants (HFC-134a and HCFC-123) and to permit at least preliminary equipment design. Significant needs remain for better characterizing these and other candidate fluids and also refrigerant mixtures. Such data are vital in order not to lose the opportunity to select the best working fluid(s) for the next generation of refrigeration equipment.

Table 3.1: Refrigerant Criteria

Chemical:

Stable and inert

Health, Safety and Environmental:

Nontoxic
Nonflammable
Does not degrade the environment

Thermophysical Properties:

Critical point and boiling point temperature appropriate for the application
Low molar vapour heat capacity
Low viscosity
High thermal conductivity

Miscellaneous:

Soluble in lubricating oil
High vapour dielectric strength
Low freezing point
Compatible with common materials
Easy leak detection
Low cost

Table 3.2: Fully Halogenated CFC Refrigerants and Environmentally-Acceptable Alternatives

Fully-Halogenated CFC's			Alternative Refrigerants			
Number	Formula	NBP(C)	Name/Number	Formula	NBP(C)	Avail*
			propylchloride	C_3H_7Cl	47	M-L
11	CCl_3F	24	141b	CCl_2FCH_3	32	M
			123/123a	$C_2HCl_2F_3$	27	M
			ethylchloride	C_2H_5Cl	12	M
			bis(difluoromethyl)ether	CHF_2OCHF_2	5	L
114	$CClF_2CClF_2$	4	butane	C_4H_{10}	-1	N
			142b	$CClF_2CH_3$	-9	N
			iso-butane	C_4H_{10}	-12	N
12	CCl_2F_2	-30	124	$CHClFCF_3$	-12	M - L
			134	CHF_2CHF_2	-20	L
			dimethlyether	CH_3OCH_3	-25	N
115	$CClF_2CF_3$	-39	152a	$CHF2CH_3$	-25	N
			134a	CF_3CH_2F	-27	M
			ammonia	NH_3	-33	N
			22	$CHClF_2$	-41	N
502	22/115	-45	propane	$C3H_8$	-42	N
			143a	CF_3CH_3	-48	M - L
			125	CF_3CHF_2	-48	M - L
13	$CClF_3$	-81	32	CH_2F_2	-52	L
			23	CHF_3	-82	N

*Availability: N = near-term M = mid-term; L = long-term (see text)

Table 3.3: Availability of Property Data for the Environmentally-Acceptable Refrigerants

Fluid	Thermodynamic Properties				Transport Properties				Oil	
	Grp1	Grp2	Grp3	Grp4	Grp1	Grp2	Grp3	Grp4	comp.	Toxic.
141b	+	-	o	o	+	o	o	o	o	o
123	+	+	+	o	+	o	o	o	o	o
bis(difluoromethyl)ether	-	o	o	o	o	o	o	o	o	o
butane	+	+	+	o	+	+	+	o	+	+
142b	+	+	-	o	+	+	o	o	o	o
iso-butane	+	+	+	+	+	+	+	o	+	+
124	+	+	+	o	o	o	o	o	o	o
134	+	o	o	o	o	o	o	o	o	o
dimethylether	+	+	o	o	+	o	o	o	o	+
152a	+	+	+	o	+	+	+	o	o	+
134a	+	+	+	o	+	+	o	o	+	o
22	+	+	+	+	+	+	+	+	+	+
propane	+	+	+	+	+	+	+	+	+	+
143a	+	+	-	o	o	o	o	o	o	o
125	+	+	o	o	o	o	o	o	o	o
32	+	+	+	o	+	+	o	o	o	o
23	+	+	+	o	+	+	o	o	o	o
ethylchloride	+	+	o	o	+	o	o	o	+	+
propylchloride	+	+	o	o	+	o	o	o	+	+
ammonia	+	+	+	+	+	+	+	+	+	+

Legend:
- limited data or of uncertain accuracy
+ reliable data available
o no data available

4. DOMESTIC REFRIGERATION

4.1 Introduction

At the present time, by far the largest number of domestic refrigerators and freezers use the vapour-compression cycle with CFC-12 as the working fluid. The unique properties of CFC-12, particularly its very low toxicity, non-flammability, and superior heat transport characteristics, have contributed to both its worldwide acceptance as the domestic refrigerant of choice and to the high efficiency of refrigerators now in production.

The chemical stability of CFC-12, its compatibility with conventional lubricants, desiccants, and materials, have allowed development of highly refined compressors, heat exchangers, and piping systems over a period of almost fifty years. These components are contained in a large variety of home refrigerators, designed for specific markets and mass produced with extremely low defect rates and long lifetimes (15-20 years).

4.2 Current Use and Global Data

It is difficult to derive very precise global figures for CFC-12 consumption in the manufacturing of domestic appliances. According to the CECED (the European Community Association of Appliance Manufacturers) 14,200,000 units were made in Western Europe in 1987, using roughly 2000 metric tonnes of CFC 12. (13,138,000 CECED plus 10% non-CECED countries) The AHAM (the Association of Home Appliance Manufacturers in the U.S.) gives as data for North America that 1400 metric tonnes were used in the production of domestic applicances.

Table 4.1 presents data from CECED, AHAM, and CMA for the representative global production, using the European average of 140 grams of CFC-12 per unit and an average of 170 g. for the North American units.

Table 4.1 Estimated 1987 world production of domestic refrigerators and freezers and corresponding CFC-12 consumption (metric tonnes)

Area	Number of units	CFC 12 (metric tonnes)
Western Europe	14,200,000	1990
Eastern Europe	11,251,000	1570
USA	8,198,000	1400
Canada	887,000	150
South America	2,937,000	500
Asia	13,644,000	1910
China (PRC)	3,980,000	600
Africa	1,355,000	210
Oceania	550,000	80
World	58,076,000 units	8410 metric tonnes

As a realistic global value for 1987, it can be assumed that 10,000 metric tonnes of CFC-12 are used per year in the production of domestic appliances; when leakage in production and servicing/repair needs are added to the above amount.

The Chemical Manufacturers Association (CMA) data for the total amount of CFC-12 used in 1987 (excluding East European states) is 424,726 tonnes, of which roughly 8,000 tonnes (total minus Eastern Europe) or 1.8% was used in making refrigerators and freezers. Of CFC-12 used for all refrigeration purposes (219,000 tonnes) only 3.7% is used in making refrigerators and freezers.

From Table 2.1 values from CMA can be taken and compared to the amounts of CFC-12 involved in the production of domestic equipment (assumed at a level of 7,500 metric tonnes, when excluding China and the E. European states). It yields a figure of 1.8% of the total amount of CFC-12 produced that is used in domestic refrigeration (i.e., 3.7% of the CFC-12 used for refrigeration.)

When taking into account the total use of all controlled substances under the Montreal Protocol, CFC-12 use by domestic appliances amounts to only 1.0%. However, refrigerators and freezers also use CFC-11 in the polyurethane insulation - about four times as much as CFC-12. So, taken together, these appliances use almost 5.0% of total CFCs consumed globally.

Although foam insulation is dealt with elsewhere in this work, it is important to note, in passing, the added complexity of CFC-11 problem both in:

a. Finding foam blowing agent substitutes and new foam formulations with good structural and thermal insulation properties, and

b. in manufacturing process changes.

There is a growing demand for refrigerators and freezers in the world. The production levels in Western Europe have grown at an average rate of 5% in the last five years. Forecasts for the U.S. concerning housing starts and new household formation will increase by 5% in the next few years.

In the developing countries, these growth rates may easily reach 10%. For example, in China, the production of refrigerators and freezers was raised from 4 to 6 million pieces from 1987 to 1988. A further 30% increase in production levels is predicted for the next 5 years.

The growth in this area will probably be matched by other uses so that the proportion of CFC-12 attributable to refrigerators and freezers (3.7% of refrigeration for CFC consumption) can be considered to be a realistic predictor for some time.

The average refrigerator produced in the U.S. in 1987 had a volume of about 560 litres with an energy consumption under 1000 kWh/year. Freezers averaged 400 litres and consumed about 700 kWh/Year. While new refrigerators and freezers add a substantial new load to U.S. power requirements each year, the units being retired (15-20 years old) are so low in efficiency that total load in this sector is actually declining. It is important to note that the remarkable gains in efficiency are largely due to large increases in use of CFCs, particularly CFC 11 foam insulation which replaced glass wool used for this purpose.

Comparable European figures show much smaller volumes - 200 litres for refrigerators and freezers taken together, with power consumption of 500 kWh/year per unit. For the EC, it equals a power level of about 750 MW put on the market per year. Estimates for other parts of the world are somewhat more difficult to put together, but it is likely that the global picture would show steady increases in worldwide demand for electric power based on increased use of domestic refrigerators and freezers.

Values for the total global power level involved in the operation of these appliances may be derived by assuming a stock of existing refrigerators eight times 1987 production. This would amount to a load of about 30,000 MW. A CFC-12 substitute which was 5% less efficient, then, would add a load of 1500 MW as the new machines replaced the old. This emphasizes the importance of finding efficient CFC-12 substitutes for use in refrigerators and freezers.

4.3 Existing Equipment: Reduction of Emissions

4.3.1 During the Lifetime of the Domestic Appliance

As stated above, there is a large stock of existing refrigerators and freezers. These appliances are hermetically sealed and use the charge of CFC-12 in an efficient way. Less than 10% ever need servicing of any sort, and only a tiny amount of CFC-12 (e.g. 20 tonnes/year for all of the Federal Republic of Germany) is needed for servicing. However, public pressure for environmentally-benign handling has already resulted in demands for use of reclaiming equipment in servicing appliances in parts of Western Europe (in the FRG, use of such equipment is estimated to save 10 tonnes/year).

In the last ten years, large reductions in CFC-12 use in the manufacturing process have been made. Many manufacturers have eliminated use of CFC-12 for leak testing and have planned or installed reclamation facilities for reducing emissions when a leak is found. Other measures include:

a. In the supply and storage of CFCs; use of return lines, welded pipelines and valves, anti-vibration mounting and routine leakage tests.

b. In the processing of CFC refrigerants; inert gas fillings and drying measures using nitrogen, CFC-free leak testing using He, HCFC 22/N2, or pressurized inert gas tests in a water bath, use of halogen leak detection on refrigerant circuits, safe joints soldered or welded by skilled personnel, and loss-free permanently controlled charging procedures.

c. In insulation foaming operations; diffusion tight covering of refoaming or repair points, incineration of scrap foam components, recondensation of CFC 11 from plant exhaust air (although this is only economical if process losses are large.)

These and similar measures might reduce emission of CFCs from refrigerator and freezer manufacturing by as much as 10%.

4.3.2 After Disposal of Domestic Appliances /Bü88/

Considering the large world stock of refrigerators and freezers, the potential for emissions of both CFC-12 and CFC-11 upon disposal is very substantial, and measures to recover or destroy CFCs at the end of appliance life are important. This includes not only CFC-12 and compressor oil, but must include CFC-11 trapped in the foam insulation (with four times as much ODP).

So far, appliances have been treated as ordinary bulky refuse. They are transported without special care, which may rupture tubing and release CFC 12, or they may be crushed or compacted by a trash vehicle which releases CFC 12 and may break insulation and free CFC 11 as well.

Measures must be devised -- and in certain countries they have already been studied -- to transport scrapped appliances to disposal stations without CFC release. Once at the station, refrigerant can be sucked out of the system along with lubricant, some of which may require heating. The compressor case can then be drilled and remaining lubricant drained for disposal. CFC-11 foam presents a tougher problem. Almost all of the original CFC-11 will still be present if the cabinet is intact. (Even exposed foam has a CFC-11 half-life of 100 years). The following measures may be employed:

a. recycling by mechanically grinding with thermal desorption and recondensation of escaping CFC 11.

b. disposal by qualified incineration, i.e., thermal destruction above 590C with subsequent flue gas scrubbing (polyurethane foam will burn readily).

Of these two choices, incineration seems most likely to prove practical. The final choice may depend on the method chosen for other foam applications since refrigerator and freezer insulation comprises only about 10% of the total polyurethane foam market.

Based on experience in the FRG, disposal of CFC-12 as described above will add about US$15 to the cost of disposal of each appliance, and disposal of CFC-11 from the foam will add another US$15.

However, similar calculations in Japan have arrived at an estimated cost of US$94 including transportation, a figure that clearly brings into question the realism of this sort of disposal.

The small amount of CFC-12 refrigerant used in each appliance is a key fact when considering the feasibility of widespread recapture and recycling. The energy cost (and the resulting "greenhouse" impact) of moving appliances to a disposal center, or taking recovery apparatus to the field, might well exceed the benefits of CFC recovery.

However, where the recapture or destruction of CFCs by moving appliances to disposal centers fits in national plans under development for handling other forms of trash and garbage, it may become feasible. Large volume items such as appliances may need special treatment anyway, and CFC considerations can be factored into disposal planning.

4.4 New Installations

A number of options exist for reducing consumption of CFCs in new equipment:

1. minimization of volume of the refrigeration circuit and further adaptations of designs.
2. application of substitutes/mixtures which are currently available in commercial quantity and have lower ODP than CFC-11/12.

The use of non-ozone depleting substances despite degradation of performance
or manufacturing efficiency is not trivial.

4.4.1 Redesigning New Appliances

In most refrigeration circuits, savings can be achieved by reducing the volume of the system - for example, by shortening tubing runs or by reconfiguring condensers to maintain heat transfer surfaces while minimizing non-functional areas, or even by finding better heat transfer techniques which allow reduction in size of heat exchangers. Reductions of 5% of the initial charge are often possible without noticeable effect on energy efficiency.

(Foams blown with CFC-11 diluted with water or with leaner mixtures of CFC-11 can reduce CFC use in foam insulation without major losses in efficiency. A 30% CFC reductions have been reported without measurable increases in energy consumption, although this has not been the case in Japanese experiments. Many European manufacturers have been able to reach 50% with efficiency losses of 5%. However, increases in the aged conductivity value of the foam are expected with this technique, leading to an increased energy consumption.

There is a possibility of using evacuated powder panels in refrigerators. These panels are installed in the walls and foamed in place to provide rigidity. Some preliminary field tests have been performed in the past; mostly aging problems have occurred. Before they can be widely accepted as alternatives to CFC-blown foam, these vacuum technologies must still prove that they can meet performance, durability and fabrication criteria. However, their use should be carefully studied since they may offer the appealing advantage of significantly increased energy efficiency while at the same time having no ozone depletion potential).

The best CFC substitutes for domestic refrigeration have yet to be developed, that is, those which would maintain current levels of energy efficiency. Hasty action due to public pressure on refrigeration appliance manufacturers to reduce CFC use could compel a choice of alternatives which reduce efficiency.

4.4.2 Properties of a Substitute Refrigerant for New Appliances

Summing up, future potential for CFC-12 reduction in refrigerator and freezer design and production is limited, and total demand for CFC-12 in this area is likely to grow as the number of units manufactured overwhelms lower CFC-12 consumption per unit.

The more nearly a refrigerant substitute resembles CFC-12 in all important respects, the quicker and less costly will be the changeover to ozone-safe substances. Because of the hugh investment in design of these highly engineered systems and in the production facilities and procedures used to make them, a high priority must be assigned to development of a "drop-in" low ODP CFC-12 substitute, i.e. a substitute with properties as nearly identical to CFC-12 as possible, permitting its use without extensive redesign and re-tooling. Use of such a substitute can drastically reduce the time it will take to cut back on CFC-12 use.

Conversely, the switch over to any substitute which differs substantially from CFC-12 will be delayed because of design development, material compatibility testing, component life testing, production tooling lead times, and changes in manufacturing procedures required for use of the substitute. However, if the energy efficiency of refrigerators has significantly changed in a positive way by redesigning them, this could overwhelm retooling costs more quickly. One of the materials to be used and tested for new refrigerants in appliances is the desiccant material.

4.4.3 Desiccant for New Refrigerants and Mixtures

Small domestic refrigeration systems are normally equipped with a capillary tube where the expansion process takes place. Even very small amounts of water in a system can cause freeze-blocking of the capillary tube. When a domestic appliance is put into operation about 0.5g of water will diffuse out of the components. In the case of new refrigerants such as HFC-134a, different types of oils such as polyethylene glycols are needed which contain much more water (about 15g per liter) than the conventional mineral oil.

Together with the new refrigerant a dryer has to be used which should contain desiccant material which absorbs the water fast and efficiently. Otherwise proper functioning of the appliance - especially during first use-is impossible and problems will occur in quality testing during the manufacturing process.

However, the question of compatibility of new substitute refrigerants with desiccants (molecular sieve or other) must not only be addressed for new products using new types of refrigerants, but also for the servicing of the existing products with any "drop-in" replacement refrigerant or refrigerant mix. The following information on molecular sieve desiccants should be given.

Molecular sieve desiccants function by having pores that are intermediate in size between water and the refrigerant used. The water enters these pores and is trapped while the refrigerant cannot enter. If pore size is not correct, the refrigerant as well as water molecules are trapped, the water capacity of the desiccant is decreased and refrigerant breakdown will be promoted.

With some of the alternative refrigerants, it has been shown that desiccant pore size relative to the molecular size of the refrigerant is not sufficient information for determining chemical compatibility. Similarly, the name or designation for the desiccant is not sufficient for compatibility information. Therefore, any desiccant product must be tested by an appropriate compatibility method (such as the ANSI/ASHRAE Standard 97-1983: "Sealed Glass Tube Method to Test the Chemical Stability of Material for Use Within Refrigerant Systems," or similar method) to determine whether or not it is acceptable for use with a given refrigerant.

In addition to chemical compatibility, there are other typical requirements for a suitable desiccant material. These include:

- High water capacity at a) low water concentrations in the refrigerant and b) high operating or ambient temperatures.
- Good physical strength properties, for example a) high attrition resistance and b) high crush strength. This resistance to mechanical vibration is very important for mobile equipment.
- Low dusting characteristics.
- Stability in the system.

4.5 Alternative Refrigerants

4.5.1 Commercially Available Single Component Refrigerant

For low temperature CFC-12 refrigeration equipment, a switch to HCFC-22 would be possible /Fan88/, however, only if loss of efficiency (5-8%) and equipment redesign are acceptable. In some systems increasing condenser capacity may allow recapturing efficiency losses. For a number of cases the compressor temperature may become too high, leading to temperature (coking) problems on the discharge valve; therefore a switch to the azeotropic mixture CFC-502 is normally recommended (which still has a certain ODP). Moreover, both options imply higher compressor noise levels.

4.5.2 Commercially Available Azeotropes

CFC-502 has only one-third the ODP of CFC-12, due to a large percentage of CFC-115 in this mixture (50%, ODP 0.6). Since use of either HCFC-22 or CFC-502 would require equipment redesign, a second redesign in the near future to accommodate new substitutes currently under development is not likely. They are not attractive substitutes for short-term or interim use.

It should be emphasized that the redesign of the hermetic compressors poses major problems by itself. Moreover, many redesign problems can be expected in the European-style foamed-in evaporators (roll-bond material) as well.

"Drop-in" mixtures with medium-ODP as substitutes for CFC-12 are known. In small equipment, reductions can be made by using azeotropic mixtures CFC-500 (73% CFC-12, 27% HFC-152a) or CFC-12/DME (87% CFC-12, 13% DME). A CFC-12 reduction of at least 40% has been measured with the mixture CFC-500, a 30% reduction appears feasible with CFC-12/DME mixture /Wit89/. Despite the low weight percentage of DME, the large savings potential of the latter mixture is due to the low density of the dimethylether component. It should be noted that a still high percentage of the controlled CFC-12 has to be applied and that neither of these mixtures can be a final solution. In a drop-in situation, CFC-500 tends to raise discharge and condenser temperatures, adversely affecting reliability in some situations, and also causing higher energy consumption. There are some indications that low level toxicity is produced in the use of CFC-12/DME mixture (see also Chapter 10, Mobile Air Conditioning). On the other hand, due to over 30 year experience in the use of CFC-500 mixture, its application would seem the better short-term choice.

There is, however, another problem involved with going to these mixtures. If recycling for used refrigerants (e.g. CFC-12) is required, recycling of these mixtures would pose additional difficulties. A separate recycling procedure for these mixtures would be necessary if they are not to be allowed to escape to the atmosphere (vented during maintenance or disposal).

Some manufacturers are, indeed, actively pursuing tests on the application of CFC-500 /Gre88/. However, most manufacturers consider the experimental testing programme, still to be done, as a too large and the ODP reduction as a too small to be worthwhile. CFC-500 is not expected to solve the problem therefore.

4.5.3 Commercially Available Non-azeotropes

Combinations of commercially available and acceptable fluids in NARMs (non-azeotropic refrigerant mixtures), may also be used as CFC substitutes. For their application, different development programmes have been set up.

Some NARMs have ODP values below 0.05 and have properties very similar to CFC-12, so that they could be phased in quickly /Kru88/.

For a part of the appliance sector (i.e. two temperature appliances), the application of NARMs could lead to a decrease in energy consumption in the order of 10-15% and new mixtures may be forthcoming to offer even better performance. Different investigators have so far been evaluating the HCFC-22/142b mixture and found small advantages compared to the application of CFC-12 without redesign of the system /Rok88/. It must be understood that these comments apply to two compartment refrigerator-/freezer combinations, where both compartments use separate evaporators /Kru89/.

Also, on single evaporator appliances, some tests have been performed without any circuit redesign. Compared to the application of CFC-12, the results using HCFC-22/142b are generally slightly worse, so a modest efficiency increase might be expected even on single evaporator cabins with judicious circuit rerouting /Rok89/.

4.5.4 New Single Component Refrigerants

HFC-134a has been widely hailed as the most likely substitute for CFC-12 /McL87/. Selection of this chemical has been based mainly on demands from the automotive air conditioner sector for a substitute with pressure levels comparable to CFC-12.

However, as larger quantities of HFC-134a have become available for testing, problems have emerged. A large number of researchers have reported lower volumetric capacities and lower thermodynamic efficiencies /e.g. Mat88/, incompatibility with lubricants /Spa88/, desiccant problems and "copper-plating". The thermal conductivity of HFC-134a vs. CFC-12 is higher, leading to improved heat transfer.

Several companies have tested systems using HFC-134a and found losses in efficiency substantially exceeding estimates based on laboratory data. Preliminary measurements have shown increased energy consumption values in the order of 8 to 15%, depending on the evaporation temperature. Although small refinements in the design of the system may improve performance with HFC-134a, a remaining lower efficiency between 5 and 10% seems likely (and conforms to thermodynamic data published so far).

Recently a comparison was presented of the performance of CFC-12 and HFC-134a on a chest freezer /Han89/; results from the HFC-134a application were even slightly better. It was stated that, given adequate optimization of all components, the energy penalty in the use of HFC-134a would be negligible /Han89/. However, the selection of components needs further investigation because it may have influenced the outcome for this application. Nevertheless, it indicates potential opportunities given the expressed conditions.

Domestic equipment has to meet increasing efficiency standards in the near future. Therefore, next to a possible application of HFC-134a, other candidate refrigerants should be screened which may be more desirable substitutes.

There is another aspect of refrigerants which certainly has to be mentioned here, i.e. flammability. A re-evaluation of all aspects involved with the conventional CFC-properties, i.e. a re-evaluation of conventional thinking about non-toxicity and non-flammability is needed. There are indications that, in the case of application of flammable refrigerants, e.g. HFC-152a or DME, an increase in efficiency (i.e. a lowering of the consumption) is possible without redesigning the equipment /Kui88, Qua88/. This also applies to mixtures of these refrigerants with HCFC-22 /Kui88/. The use of flammable refrigerants requires a critical consideration of existing standards and also of logistics, manufacturing, and consumer safety concerns, and additional capital investments required. Nevertheless, potential energy savings, such as the 3-7% reported with HFC-152a /Wit 89/, make it necessary to consider the trade-offs involved.

Also for an application in a pure form, new refrigerants (such as HFC-134 or HFC-143a) may be evaluated in the near future for normal or low temperature refrigeration. Their efficiencies are probably better than that of HFC-134a, /Kui89/. As mentioned above, however, nothing is known about a number of other properties including toxicity. This makes them possible long-term replacement candidates, and, therefore, they are not considered here.

4.5.5 New Azeotropes

Theoretical investigations on possible azeotropes will undoubtedly be performed in the near future. Especially when more refrigerants will become available for testing, experimental work should confirm the first results. There are indications that azeotropes exist of HFC-152a and HFC-134 or HFC-134a /Did88/. However, whether these azeotropes will require lubrication studies, or copper plating investigations, cannot be stated at this moment. Taking into account efficiency values given by Hodgett in Purdue, 1988, /Kui89/ for both HFC-152a and HFC-134, a possible azeotrope might be highly efficient from a thermodynamic point of view. Also these can only be long-term replacement candidates which are not considered here.

4.5.6 Near Azeotropic Mixes

The world is moving away from the "single option" HFC-134a path. Recently a "technological breakthrough" was announced in the form of a ternary (three-part) mixture of HCFC-22, HFC-152a and HCFC-124 /Dup89/. The mixture has thermodynamic properties which match CFC-12 more closely than HFC-134a, and has an ODP of 0.03. The mixture, in spite of its flammable component, is not flammable although testing of worst case spillage scenarios would be necessary to confirm this. The mixture is stated to be 3% better in energy consumption compared to CFC-12, although system testing has not yet confirmed this claim.

Furthermore some current oils are compatible and desiccants are not expected to pose problems /Dup89/. The mixture might be considered to be the current "front-runner", if only manufacturer preliminary data is used. However, transport properties have not been determined and, moreover, HCFC-124 has not yet emerged from toxicity testing.

An "interim" version of the above-mentioned mixture is now available for testing and "interim" use. Here CFC-114 is used instead of HCFC-124; the resulting ODP value is on the order of 0.35. This makes the mixture even a better "interim" candidate than, for example, the azeotropes CFC-500 or CFC-12/DME, mentioned above. First testing on an upright freezer shows roughly equal consumption values compared to the application of CFC-12 /Wit89/.

Some investigations have been done (NIST/USA, 1988) on ternary mixtures of HFC-134a, HFC-152a and HFC-134 /Did88/, but apparently with no published conclusions. In any case, the amount of HFC-134 available is almost nil and toxicity testing has not even begun. Therefore, this mixture is, at best, a long-term alternative (after 1995).

4.6. Environmental impacts

4.6.1 Efficiency

Household refrigerators and freezers are so pervasive and the electrical load they impose is so constant that even small losses in efficiency can result in need for increased power generation. Since much central station power is generated by combustion of fossil fuels, increased power generation aggravates the greenhouse effect by increasing emissions of carbon dioxide.

The substitutes mentioned for the replacement of CFC-11 in the polyurethane foam of domestic refrigerating equipment, HCFC-123 and HCFC-141b, are characterized by higher heat conductivity values resulting in loss of efficiency (roughly 10%) in appliances insulated with them (they are also aggressive solvents of the plastic liners used in many current designs). Since no better substitutes are available in the short/mid term, using these substitutes will put upward pressure on the energy consumption of appliances unless thicker walls are used (they can very slightly compensate for this loss in insulating quality. One could, e.g., consider the use of a 3-4 cm. thicker back-wall in an appliance, especially the free-standing ones).

If CFC-12 is replaced by HFC-134a in the refrigerant loop, there will be an additional increase of 8% in energy consumption, if realized. This alone could add 3,000 MW extra loads in case this substitute would be used in all existing appliances on the market. Extrapolating to the future, with a growing number of appliances all over the world, this figure would become even larger.

If the recently announced ternary mixture could be applied (3% improvement over CFC-12) to all future production, a different story emerges. The efficiency difference between the two options amounts to 11%, a very significant difference, which equals 4,500 MW difference in installed power required over a period of 10 years (lifetime of appliances).

There are some indications that flammable refrigerants or mixtures could yield an even larger reduction in consumption (5-10%) than the recently announced ternary mixture. This would imply even larger total energy savings than for the ternary blend. However, it assumes that the flammability issue could be dealt with.

4.6.2 Flammability

In years past (1940-1950), substances like propane/butane mixtures and isobutane HC-600a were used in domestic refrigerating equipment. In many larger installations hydrocarbons are still used and the use of flammable ammonia is ubiquitous. Precautions needed for such installations are far beyond those used in manufacturing domestic appliances today. However, as CFC-12 restrictions become tighter, those precautions might not be prohibitive (the aerosol industry has successfully made the transition from nonflammable to flammable gases with virtually no accidents).

Use of flammable refrigerants would, however, introduce a new risk into the household sector. When leakage occurs, it is often in the evaporator, and refrigerant might accumulate inside the cabinet. Under certain circumstances, lights or defrost heaters could serve as an ignition source with possible dangerous consequences. Typical "foamed-in" roll bond evaporators actually have 50% of their surface exposed and are subject to puncture. But many uncertainties are still associated with the flammable refrigerant option. Underwriters Laboratories in the U.S. is studying the problems associated with this option. Since the newest ternary mixture (see above) contains a flammable component, progress in this area is important.

4.7 Concluding Remarks

Good manufacturing practices, exploiting the potential of recycling, and refining current products and processes are important aspects of the small domestic equipment market. The reduction of emissions, taking into account the bank of installed equipment, will very much depend on the percentage of recycling.

Domestic refrigerators and freezers use roughly 1.0% of all controlled CFCs in the refrigerant loop (roughly another 4.0% is used in the insulation which is not further considered here). An increase or decrease in the efficiency of any CFC-12 substitute of even 5% would result in a difference in electricity growth of 200 MW/year. Therefore, efficiency is an important consideration in finding CFC substitutes for refrigerator and freezer use.

Different options exist for the replacement of CFC-12 in domestic equipment:

- application of CFC-500 could lead to a 40% ODP reduction, but the high CFC-12 content makes this only an interim substitute;

- use of NARMs, preferably non-flammable, could result in extremely low ODP values (between 0 and 0.05). Reliable functioning of many products has to be investigated, however, and any energy improvement potential must be exploited by sophisticated design refinements. The application could lead to short- to mid-term CFC savings;

- two evaporator static/forced convection refrigerators (under investigation) which use NARMs, offer a possibility of an increase of 10-20% in energy efficiency. If the NARM heat exchange problem can be overcome, it could be an attractive option.
- choosing HFC-134a would result in an ODP of zero but incur energy consumption increases estimated to be 8-12% initially and 5-10% after optimization of designs (this makes HFC-134a a less suitable candidate);
- HCFC-22, with its low ODP (0.05) must be considered a viable long-term option if efficiency losses can be overcome by component and system redesign;
- applications of flammable refrigerants (such as HFC-152a and DME) offer prospects for reducing energy consumption if the "acceptance" problem can be overcome and accompanying problems in design and manufacturing solved, but this must be considered a mid- to long-term option;
- the recently introduced ternary mixture may offer "drop-in" advantages and better efficiency possibilities if system tests prove satisfactory and toxicity testing has an acceptable outcome. It must be considered a mid- to long-term option;
- HFC-134 may prove to be an acceptable long-term option but no testing has been performed so far.

In conclusion, small refrigeration equipment is characterized by the highest requirement for reliability and energy efficiency. Testing of new substances will take time. A considerable time period will still be needed to make the long-term "best choice" for this type of equipment.

5. RETAIL REFRIGERATION

5.1 Scope

The unit capacities broadly covered under the designation of Retail Refrigeration, range in operating capacity from less than 1 kW up to some hundred kW. Most of this equipment is factory assembled as modules, to be later field installed by interconnecting piping and wiring at the job site. Not covered are the domestic refrigerator and freezer sector; also not covered here are the very large industrial systems, mentioned in a separate chapter.

Refrigerants used in retail refrigeration are CFC-12, HCFC-22 and CFC-502. NH_3 and other refrigerants are used only in small amounts and in special applications.

5.2 Current use: History and Global Data

5.2.1 Applications

Retail systems are used, for example, in shops and supermarkets, local food transportation systems, and in various other commercial and industrial cooling equipment. Most larger systems are field-assembled and charged with refrigerant.

In the past retail refrigeration was mainly used for storing frozen food, meat, dairy products, and for ice making. Today there is a wide field of application. Perishable food merchandising via the display and preservation of cooled and frozen food has become the most commonly recognized use (e.g. supermarkets, restaurants, plant canteens, cafeterias, air-line meal catering, etc.). Refrigeration is also critical for hospital morgues, plasma freezers, whole blood and organ transplant parts storage; even florists. Also, industrial application of retail refrigeration covers a number of important uses such as metal shrinkage, ground freezing for construction site stability, chemical processing, ice making and atomic power plant safety systems as well as the future of high temperature super conductivity.

5.2.2 Refrigerants

The design of retail refrigeration systems and the type of refrigerants used depend on the desired operating temperatures. CFC-12 is currently used both for medium- and high-temperature refrigeration (-15°C to 15°C). HCFC-22 is used for evaporation temperatures down to -35°C, and CFC-502 is used for temperatures down to -45°C. CFC-502 is also used in medium temperature systems. This is because the same refrigerant, is sometimes for low- and medium-temperature cooling.

In industrial applications of retail refrigeration, HCFC-22 is most important. In some industries, NH_3 is also used as a refrigerant; mainly in the brewery industry and warehouse refrigeration (about 80% of the studied cases

/DKV87/). The use of CFC refrigerants in industrial retail refrigeration in this area amounts to 15% of all total refrigerant use.

In commercial applications of retail refrigeration, CFC refrigerants are much more important, since the systems are smaller than in industrial applications. An estimation of the percentage distribution between CFC-12, HCFC-22, and CFC-502 in commercial applications gives the following data:

CFC-12	50%	
CFC-502	40%	
HCFC-22	10%	/DKV87, Rad86/

CFC-12 is preferred because of its advantages (it is inexpensive and it shows nearly no problems in the presence of lubrication oils). The use of CFC-12 also means less stress on the compressor, with its low vapour pressure, and low discharge temperatures.

Small amounts of CFC-13, CFC-503, FC14 and (R13B1) Halon-1301 are used for low temperature systems in two or more stage cascade systems.

5.2.3 Global Data

In the US, retail consumption of CFC-12 is about 4% of total CFC-12 use and therefore twice the amount of domestic CFC-12 consumption /Ran86/. Considering CFC-502, CFC-13 and other CFCs used in retail refrigeration, which are used as refrigerants only, and taking into account that a portion of the unallocated CFC use (20 - 30% of the total) is also used in retail refrigeration, it can be estimated that about 5 to 6% of the total CFC consumption is used in retail refrigeration.

5.3 Existing Equipment

5.3.1 Kind of Equipment

There are numerous system designs in the field of retail refrigeration depending on their use. Small systems are equipped with hermetic compressors. There is a trend to apply them to higher capacities, where semi-hermetic compressors have been used so far. Compressors with shaft seals and open type electric motors are also used. In many cases the condensing units are factory assembled and the evaporator systems are assembled on site.

There are large split systems with extensive piping and several evaporators in the field of retail; mainly in commercial food refrigeration. There is a trend towards larger systems, based on a trend away from small stores towards larger supermarkets. There is a tendency towards systems with larger amounts of refrigerant (450 kg (1,000 lbs) is not unusual).

5.3.2 Reduction of Emissions

Potential measures to reduce the emission of ozone depleting refrigerants in the retail refrigeration field consist of efforts to save these substances during installation and maintenance of equipment and to introduce recycling processes. Because of nonuniform system designs and widespread applications these efforts are not as easily handled as in small size domestic and large size industrial equipment. In small size equipment, because of the high number of similar systems, standardized efforts and industrial recycling processes can be efficient measures. In large size equipment, skilled people working with the equipment continuously are able to work on efficient emission control. The retail refrigeration equipment is often not hermetically sealed and has no standby skilled supervision personnel. A lot of changes have to be made from the design point of view to reduce refrigerant migration into the atmosphere during running and servicing of this equipment. Estimates of the usage of CFCs for retail refrigeration are as follows:

leak testing	2%	
initial charge	50%	
recharge for leakage and service	48%	/Rad86/

Another more detailed estimate of refrigerant emissions from retail refrigeration is:

manufacture leak testing	2%	
installation	3%	
leakage	45%	
service	10%	
disposal	40%	/Rad86/

The emissions from leak testing, installation, service and disposal can be reduced mainly by the introduction of recycling methods and by better education of service personnel (see point 4.3). Nevertheless, systems with small charges, like indirect systems, would also give lower amounts of emissions from leak testing, installation, service and disposal.

Leakages are the most important source of CFC emissions in retail refrigeration. Those CFC emissions can be reduced by:

- use of other refrigerants; change-over to HCFC-22
- use of indirect systems (more operating costs)
- use of smaller refrigerant charges and component design
- use of hermetic compressors with CFCs (no leakage from shaft seals)
- use of brazed connections instead of flanges and screw joints
- use of hermetic and factory preassembled equipment.

By switching to indirect systems, the quantity of refrigerant needed can be substantially reduced (however, with an efficiency penalty due to the fact an extra temperature step is introduced). Moreover, the use of refrigerants can be concentrated in areas where leaks can be kept under control. Indirect systems can also be factory-made, facilitating better control of designs, at least in the long-term. At the same time, it will be more feasible to use more expensive refrigerants with less impact on the environment as they become available.

5.4 Alternatives and Substitutes: New Installations

5.4.1 Recycling

The recycling systems already in place at chemical manufacturers provide a knowledge base for reducing emissions by venting, at leak testing, installation, service, and disposal. Since there are recycling systems available, people servicing the plants have to be educated for improved handling methods and good practices.

5.4.2 Improved Handling Methods and Practices

Raising the standard of education and training in retail refrigeration will be a bigger problem than in other fields of refrigeration since it involves, for a large part, a number of small companies. On the other hand, education may be more important than in other fields, because systems in retail refrigeration are extremely different. An immediate benefit of education will be to reduce emissions from vented refrigerants at service and disposal.

As a first step in leak testing, nitrogen or other dry gas such as CO_2 should be used for bubble tests. HCFC-22 can be used, to detect small leaks and for system testing. The HCFC-22 used for leakage test should be recaptured and recycled as well. The minimum requirement would be to dilute the HCFC with nitrogen. Helium can be used to replace CFCs for leak testing as well, but costs seem too high even for large companies.

Emissions during installation are not only emissions from leak testing but also from triple evacuation to remove moisture. HCFC-22 should be used instead of CFC-12 to absorb moisture. Another practice is "deep evacuation" to purge the system of moisture but it is more time consuming and requires more training (education).

5.4.3 Alternative Substances and Compounds

HCFC-22

HCFC-22 has a low ozone depletion potential of 0.05 compared to CFC-12. It can be used in both medium and low temperature systems instead of CFC-12 and CFC-502.

HCFC-22 is presently being used in about 10 percent of the medium temperature systems. When using HCFC-22, the compressor discharge temperatures are higher making the refrigerant more susceptible to chemical breakdown. In addition, HCFC-22 is not as soluble in compressor oil as CFC-12. However, the use of HCFC-22 is technically feasible. Oils in which HCFC-22 is soluble are available and not much more expensive. To avoid high discharge temperatures (if CFC-502 is replaced by HCFC-22 in low temperature systems), the use of two-stage intercooled compressors, two stage systems, or oil cooled screw compressors is possible; but more complicated and more expensive.

In the medium temperature range, the same compressor can be used for both HCFC-22 and CFC-502. However, discharge pressures for HCFC-22 are significantly higher than for CFC-12, so substitution in existing CFC-12 systems is not practical without also changing the compressor. Using HCFC-22 in a compressor designed for CFC-12 may cause the compressor motor to burn out. Also, the expansion valves would have to be changed.

As HCFC-22 should be considered as a "part of the solution" of CFC problem, most of the new systems in retail refrigeration can be changed to HCFC-22. This change-over is already progressing.

HFC-23

HFC-23 is the only refrigerant with an ODP of zero, which is not flammable, and which is already on the market. The normal boiling point of HFC-23 is -82 C, so it is only a good replacement for CFC-13. HFC-23 is not an alternative for CFC-12 or CFC-502.

As a component in a non-azeotropic refrigerant mixture, or together with a sorption fluid in a compressor driven system with reduced solution circuit pressure levels, HFC-23 can be a part of a substitute for CFC-12 and CFC-502. Since there is research work necessary to investigate these new system designs and to demonstrate the applicability a period of three to five years would be necessary which makes this option a mid- to long-term solution. However, since these new systems may also yield energy saving, more research and demonstration work has to be done.

HFC-134a

HFC-134a will be a substitute for CFC-12 in retail refrigeration as well as in other fields of refrigeration if:

- HFC-134a becomes available,
- a not too expensive lubricant can be found
- large enough quantities are available to satisfy the requests from the domestic and automotive sectors (so that lack of supply does not result in exceedingly high prices)

At least for the near future, HFC-134a does not seem to be the "one and only" solution for retail refrigeration. Also, there is the problem of decreased energy efficiency with HFC-134a (see also Chapter 4).

HFC-32, HFC-125, HFC-134a

The three refrigerants HFC-32, HFC-125 and HFC-143a are chlorine free and so have an ODP of zero. They could become possible substitutes for CFC-502 and HCFC-22 if the use of HCFC-22 is restricted, since the normal boiling points are similar to those of CFC-502 and HCFC-22 as shown in the following table.

Table 5.1 Properties of Some Substitute Refrigerants for HCFC-22 /MLi88/

	CFC-502	HCFC-22	HFC-32	HFC-125	HFC-143a
normal boiling point (°C)	-45	-41	-52	-48	-48
flammable	no	no	yes	no	yes
COP (-15/+30C)	4.37		4.57	4.03	

Of these alternatives, only HFC-125 is not flammable. On the other hand, the energy efficiency of HFC-32 is better than the efficiency of CFC-502 and of HFC-125. This aspect has to be taken into account when considering energy consumption and the greenhouse effect.

However, these products can only be mid- to long-term alternatives, since their toxicity, produceability, and properties have to be further investigated. Also, oil behaviour will be a problem as it is for the other HFCs like HFC-23, HFC-152a and mainly HFC-134a. In any case, the oil behaviour of HFCs is a general field for further investigations.

Flammables, non-CFCs

There are non-CFCs which because of their thermodynamic properties could be suitable substitutes, but are either toxic, or flammable, or both. This does not necessarily exclude them for use as refrigerants, however. Large refrigeration plants are equipped with security devices, are supervised by skilled personnel and are located in special rooms, so that the use of toxic refrigerants like ammonia can be realized. On the other hand small units like domestic refrigerators and freezers are hermetically sealed and the refrigerant charge is very small. Therefore the application of flammable refrigerants like butane, propane or HFC-152a has been under discussion. The use of flammable or toxic fluids in retail equipment is impracticle for nearly all applications. This is because these systems are usually not installed in special rooms and are accessible by unskilled personnel. Flammable or toxic fluids would be dangerous in the event leakages occur. Therefore, for retail equipment non-CFC alternatives are less acceptable.

Mixtures

Mixtures of currently marketed fluids can be possible short-term alternatives. Azeotropic mixtures have the advantage that they show a pure fluid behaviour. Normally they are formed both from fully and partially halogenated refrigerants. Therefore, they will still have some ozone depletion potential. But they can serve as an immediate alternative working fluid with a lower ozone depletion potential than the fully halogenated fluids. So, the azeotrope CFC-500 is an alternative for CFC-12 with a 25% lower ozone depletion potential, as is CFC-12/DME.

Non-azeotropic mixtures can reduce the ozone depletion potential much more. They have thermophysical properties between those of their pure components depending of the composition. For instance, the flammability of one refrigerant can be suppressed by mixing it with a nonflammable refrigerant. For example, the mixture of HCFC-22 and HCFC-142b is nonflammable at a concentration which has a vapour pressure level similar to CFC-12. Non- azeotropic refrigerant mixtures offer further advantages especially regarding energy savings (as well as pressure and capacity adaption or capacity control) and allow simpler system configurations in certain application areas, like lower temperature applications. This is the main reason for their use in the majority of the natural gas liquifaction plants built in the last 20 years where the mixture technique has beendemonstrated successfully. Refrigerant mixtures have entered smaller systems like those for low temperature material testing chambers or capacity controlled heat pumps.

The main disadvantage of mixtures is fractional evaporation and condensation behaviour leading to certain separation effects, which need to be taken into account in equipment design and servicing. But the possibility of handling mixtures in real plants have been demonstrated in the aforementioned applications and elsewhere /Bla88, Kru88/.

On the other hand the fractional evaporation and condensation offer important advantages in special system design for counter flow heat. In most cooling applications of this kind substantial energy saving effects are reported /Did88, Kru89/.

Those blends are called near-azeotropic mixtures which show a near pure fluid behaviour according to a favourable composition of components. For instance, by adding only a small amount of HCFC-22 to HFC-152a to achieve the pressure level of CFC-12, a near pure fluid behaviour can be achieved. In this case no separation problems occur; but this mixture is still flammable. Other convenient combinations for near-azeotropic mixtures are possible.

A disadvantage of the application of mixtures is that there is no recycling system developed so far.

5.5 Environmental Impact

5.5.1 Efficiency

Change-overs in retail from CFC-12 to HCFC-22 do not substantially effect the energy efficiency, since both refrigerants give approximately the same COP. So, there would be no increase in CO_2 emissions from higher energy consumption.

The replacement of CFC-502 in low temperature systems by two-stage HCFC-22 systems can increase the COP reducing energy consumption and

The replacement of CFC-502 in low temperature systems by two-stage HCFC-22 systems can increase the COP reducing energy consumption and CO_2 emissions. This energy saving could reach 30 to 50% depending on temperatures and the type of two-stage cycle. So, the higher complexity of these two-stage systems can be compensated by lower energy use.

As mentioned previously, mixtures also offer the possibility of energy savings, but it is necessary to design systems to adapt them to mixtures.

5.5.2 Flammability and Reliability

As mentioned before, in most cases flammable alternatives will not be acceptable in retail refrigeration. Only by changing to indirect systems located at separate places will the use of flammables - also NH_3 - become more acceptable, but not an important part of the solution.

Reliability will increase with the use of more hermetic and more indirect systems, especially if a greater number of premanufactured units are used. Two-stage systems will decrease reliability. This has to be compensated by greater care and better service.

5.6 Economic Aspects and Impacts

5.6.1 Costs

Changes from CFC-12 to HCFC-22 will increase systems costs by no more than about 10% in newly installed systems. This will be about US$15 million in total for retail refrigeration in all CMA reporting countries (and about US$8 million for the U.S.) if all CFC used in retail were replaced by HCFC-22. By changing from CFC-502 to HCFC-22 the cost will increase by not more than 20% if a two-stage system has to be used. This additional cost can be partially offset by lower energy consumption.

Middle temperature applications of CFC-502 will cause no additional costs when changing to HCFC-22. There might even be a cost decrease since HCFC-22 is cheaper than CFC-502.

5.6.2 Timing

The change-over to HCFC-22 in new systems is already in progress since there is no severe technical problem and costs are not much higher than for CFCs. In cases where condensing temperatures are too high to use HCFC-22, mixtures of HCFC-22 with other refrigerants like HCFC-142b can be a short-term available replacement for CFC-12.

For very low temperature applications, HFC-23 is an available replacement for CFC-13 and Halon-1301 (R13B1).

The mixture of HCFC-22 and HFC-23 can also be a short-term available alternative for CFC-502 and Halon-1301. As long as HCFC-22 is available and accepted as "part of the solution", there is a good chance for a phase-out of CFCs within a reasonably short period in retail refrigeration as far as new systems are concerned.

If HCFC-22 is not available as alternative the change-over to other substitutes like flammables will need more time than in other areas of application. The only alternatives would then be HFC-134a, HFC-23, and their mixtures.

5.7 Concluding Remarks

As long as HCFC-22 is accepted as a possible alternative, nearly all CFC-12, CFC-502, CFC-13 and Halon-1301 consumption in retail refrigeration could be eliminated as far as initial charges for new systems are concerned. Costs will be about US$15 million worldwide and US$8 million for the U.S., for savings of about 3% of the total use of CFC-12 and CFC-502 combined.

The change-over from CFCs in existing systems will only be possible for a few of CFC 502-systems (HCFC-22) and for virtually all CFC-13 system (HFC-23) implying costs of the same magnitude as required for a new change.

The change-over in other existing CFC systems will be nearly as expensive as installing new equipment. But emissions of CFCs from these systems can be reduced as far as leakage testing, service, and disposal is concerned by evacuation and recycling. Better education is the basis for increased recycling and reduced emissions. These changes will reduce emissions by about 50% of total CFC emissions from retail refrigeration. Most of the remaining 50% of CFC emissions are from leakages. Since large changes to reduce emissions in already existing systems are too expensive, leakage control has to be improved. For instance periodical leakage control should replace leakage control by failure.

It can only be estimated that the savings from

- change-over to HCFC-22, HFC-23 and mixtures in new systems,
- personnel education for good practice in service, leak testing and disposal in already existing systems,
- improved leakage control

can reduce global CFC consumption in retail refrigeration to about 20% of the 1986 consumption in the near future (up to 1995).

6. TRANSPORT REFRIGERATION

6.1 Introduction

This report covers cargo refrigeration systems in ships, containers, and lorries (trucks). No information has been collated on refrigerated railcars, which are believed to be a small proportion of the total.

There are also four closely related areas which are not covered in detail, but are mentioned briefly here to ensure they are considered in other application areas. These are:

1. Vehicle and marine air conditioning. Vehicle or mobile air conditioning is a separate specialised topic (see chapter 10). Marine air conditioning is neither cargo refrigeration nor building air conditioning and is difficult to classify. It is estimated that 3500 tonnes of refrigerants CFC-12 and HCFC-22, mostly the latter, are currently in use in marine air conditioning systems. Only HCFC-22 is used in new installations.
2. Marine domestic refrigeration for storage of foodstuffs. There could be around 35,000 such installations, carrying a total of at least 1000 tonnes of refrigerant, at least 75% of which is HCFC-22. The remaining 200 tonnes or so is CFC-12, but the exact quantity is uncertain.
3. Fixed refrigeration installations at ports.
4. Rigid foams. The use of CFCs as blowing agents in thermal insulation materials is an essential part of the overall design of much refrigerated transport equipment, as there are no alternatives offering comparable thermal performance within the same volumes. Any increase in volume results in a loss of cargo space and, as space is the commodity being sold in transport applications, this is a serious commercial consideration.

Transport refrigeration is seen by many transport operators as a priority application area for CFC-12, at least in the short- to medium-term. This is because both the economics and the technology of transport refrigeration differ from those of other refrigeration applications in a number of important ways, as follows:

1. Transport refrigeration is used for the short-term maintenance of quality of foodstuffs, and to a lesser extent medical and chemical supplies. The value of the cargo, both in financial terms and in relation to human needs, is often vastly greater than the value of the refrigeration system, which means that reliability of operation and adequacy of temperature control (often in very narrow limits) are of paramount importance. Equipment to meet this objective is generally more expensive and less thermodynamically efficient than in applications such as general air conditioning.

2. Transport refrigeration operates in a very wide range of ambient conditions, also for a wide range of cargo temperatures. This wide range of conditions, combined with the need for close temperature control, means that current systems are close to the technological limits for existing refrigerants, and consequently alternative systems could not be developed quickly or easily.

3. Much transport refrigeration is only used for a small proportion of the year, due to seasonal and operational restraints. This, combined with the high cost of equipment referred to above, means there is a need for a long economic life for such systems, frequently 15 to 20 years. Container refrigeration equipment on order now is presently anticipated to be in use up to the year 2011.

4. Ships, containers, and some lorries travel around many countries, and have to be suitable for repair and maintenance at any point in their travels.

The refrigerated transport industries are aware of the environmental considerations raised in the Montreal Protocol and are willing to play a part in reducing and eliminating environmental hazards. Because of the factors listed above, there is difficulty in anticipating rapid reductions in CFC use within the relatively small usage sector represented here. There is also concern that too-rapid changes in availability of refrigerant fluids might prevent continued and uninterrupted refrigeration transport service.

6.2 The Current Situation

6.2.1 Ships

The total number of refrigerated cargo ships and container ships (over 100 tonnes gross) is estimated at 1200 to 1300, with total refrigerated cargo space of maybe 10,500,000 cubic metres. This includes slots for insulated porthole containers, but not integral refrigerated containers. About 84% of these ships are refrigerated with HCFC-22, representing a pool of around 2600 tonnes of HCFC-22. Some older ships use CFC-12, but these represent less than 20 tonnes in total and many are likely to be scrapped before 1998. Other ships exist using CFC-502 or ammonia as refrigerants. The use of CFC- 12 in ships' cargo refrigeration systems is therefore, in terms of total world usage, negligible.

It must be noted that most cargo installations are virtually totally dependent on HCFC-22. Unavailability of this refrigerant would result in change-overs that were both slow to implement and expensive to achieve.

Refrigeration systems vary in size from a few tens of kilowatts input power up to multiple compressor systems of a few Megawatts.

The refrigeration equipment used may be either of the direct expansion type or may use recirculated brine as a secondary refrigerant.

Cargo safety, personnel safety, and economics all favour a responsible attitude to refrigerant leakage, which is effectively kept to a minimum. An overall refrigerant replacement rate, covering both unavoidable leakage and repairs, is estimated at 2% per year. This is about 50 tonnes of HCFC-22 per year for all the world's refrigerated cargo ships.

6.2.2 Containers

By the end of 1990, it is estimated that there will be a world stock of 300,000 refrigerated containers, each with its own integral refrigeration machinery. Manufacturing and growth rates suggest an eventual maximum world demand of about 450,000 such containers, each having an economic life of 15 to 20 years. The refrigeration machinery is rated generally at 5 to 8 h.p.

Virtually all these containers use CFC-12 refrigerant. At the present time, neither machinery manufacturers nor refrigerant manufacturers are able to offer any alternative which meets the service requirements. The total amount of CFC-12 'banked' in these 300,000 container units is about 1650 tonnes.

As an example to show the severity of the requirements, a single container refrigeration system may have to be able to do any of the following at different times:

> cool down a cargo from 40C in a 40C ambient temperature,
>
> maintain a cargo at -20C in 50C ambient temperature,
>
> maintain cargo temperature control within 0.25C at -1.5C in ambient temperature varying between 40C and -20C.

This is achieved presently using single stage refrigeration machinery operating to the limits of practical applicability of CFC-12. The equipment is of necessity very reliable, suitable for the marine environment, and as compact as possible.

Refrigerant leakage is minimised in order to increase reliability. There have been various design improvements over recent years such that modern units are estimated to require only 3% of the charge replaced annually (on average), compared with up to 10% on older units. Taking an overall average of 5% for 1990, the total CFC-12 required for repairs is thus about 80 tonnes per year. The current manufacturing rate of around 30,000 units per year requires 165 tonnes of CFC-12, making an overall total requirement of 245 tonnes of CFC-12 per year, continuing for the foreseeable future. This is 0.06% of the 1986 world production of CFC-12, and is used to carry an estimated 130 million tonnes of refrigerated cargo each year.

6.2.3 Lorries

In the United Kingdom, there are about 9000 refrigerated semi-trailers and perhaps 20,000 to 30,000 smaller refrigerated rigid bodied vehicles. These mostly use diesel engine driven refrigeration plant with CFC-12 refrigerant, though a small number use either CFC-500 or CFC-502. The total amount of CFC-12 is estimated at 100 to 150 tonnes for UK registered vehicles. Some of the total number of refrigerated vehicles in the EEC is estimated at 220,000; in Japan, there are 83,000.

Many vehicles are designed to carry frozen produce, and have less precise temperature control than that available in container refrigeration units. Because of the shocks and vibration of road transport, the life of equipment is relatively short. One US survey has suggested that less than 10% of refrigerated vehicles are over six years old, and a similar proportion holds for Japanese vehicles.

In the United States, equipment manufacturers have reacted positively to the environmental problem, and are offering new equipment using CFC-500 or CFC-502 azeotropic mixtures with lower ozone depletion potentials than CFC-12, but still containing a proportion of controlled substances.

Estimates of the world fleet size for refrigerated truck and trailers put the total fleet at nearly 800,000 vehicles. These vehicles contain around 3500 tonnes of refrigerant, with an annual maintenance requirement around 800 tonnes. New production may account for about 400 tonnes per year.

6.2.4 Overall Situation

The overall situation as determined above is summarised in Table 6.1.

6.3 Short/Mid-Term Improvements

There are three areas for consideration in minimising emissions from current units. These are: improved maintenance procedures to minimise leaks; recovery or recycling of used refrigerant; and, gradual design improvements to reduce leakage.

In ships, cargo care and safety requirements are such as to encourage good housekeeping. The only area likely to prove beneficial in reducing emission further is encouragement of refrigerant recovery when equipment is scrapped, and this depends on availability of facilities in the country in which equipment is dismantled.

In container and lorry units, as these represent large numbers of small units dispersed over large areas, both maintenance and refrigerant recovery are more difficult to control. For routine container repairs, refrigerant is pumped into the circuit accumulator, so losses should be minimal. This is also true for most lorry units, but there could be exceptions.

For more major repairs, improved flushing procedures are being encouraged, but the recovery and recycling of refrigerant is difficult. Recovery

Table 6.1 Refrigerant Use In Transport (tonnes)

Application Area	Refrigerant Pool	Annual Use	
		M	NP
Marine Air Conditioning	3500 mostly HCFC-22	?	?
Marine Domestic Refrigeration	800 HCFC-22 200 CFC-12	?	?
Ships Cargo Refrigeration	2600 HCFC-22	50	200
Integral Refrigerated Containers	1650 CFC-12	80	165
Trucks & Trailers	3500 CFC-12	800	400
Total Pool	6900 HCFC-22 5350 CFC-12	?	?

M: - Maintenance NP: New Plant

equipment is little advertised and expensive, and minimum quantities quoted by CFC producers represent perhaps a whole year's use of refrigerant for a single dealer. There is a need for collection and storage of small quantities of used refrigerant by either government or specialised companies, and at present there is no economic incentive or legislative requirement to encourage the development of a suitable service.

Design improvements to reduce leakage are ongoing, and refrigeration machinery manufacturers and purchasers are responding positively to the environmental needs.

The changing of a refrigerant in existing systems to a currently available alternative with a lower ozone depletion potential is not clearly feasible, and would be unwise prior to the setting up of suitable refrigerant recovery networks for dealing with the existing refrigerant charge. In the USA, new truck and trailer units are moving rapidly to CFC-502, which has only 30% of the ODP of CFC-12.

6.4 Longer-Term Alternatives

For ships, cargo refrigeration is substantially limited to HCFC-22, and as long as this continues to be available and unlimited by the Montreal Protocol, there is no need for change. Should HCFC-22 become a controlled substance, the amount used in cargo refrigeration as a proportion of total use is so small that early restrictions on this particular application need not be necessary. However, should HCFC-22 become unavailable at some future date, all new ships would have to have alternative systems, possibly using ammonia, which would require a complete re-design of not only the refrigeration components but also the overall refrigeration layout relative to cargo and crew spaces. Such a design change would take a long time to implement throughout shipping fleets, as refrigerated ships have a lifetime of 20 to 30 years.

For containers, dependence on CFC-12 is total until such time as permanent alternatives are available. Alternatives considered include the following:

> HFC-134a currently under major investigation, but not as yet approved for toxicity, not compatible with normal compressor lubricants, and possibly not compatible with present motor winding insulation. Requires more power for less capacity compared to CFC-12. Could be the basis for new equipment from about 1995, not suitable for direct "drop-in" use in existing units.
>
> HCFC-22 not a practical alternative for the range of operating conditions necessary, using existing types of system. Two stage HCFC-22 systems could be developed, but this would only be considered if the availability of HCFC-22 were guaranteed for the next 25 to 30 years.
>
> CFC-502 as this contains 51.2% CFC-115, it is not a suitable alternative.
>
> Tenary mixtures the tenary mixture of HCFC-22/152a/124, as recently proposed by a manufacturer may be an option, but testing is needed.
>
> Other mixtures non-azeotropic mixtures are being considered by some CFC suppliers, but the problem of preferential leakage and the consequent need for re-charging rather than topping up any leaks is problematic.
>
> Ammonia this is a conceivable alternative, but is unlikely to be favoured for multiple small units on safety grounds. No detailed studies have been reported and considerable development would be necessary.

At the present time there is no suitably qualified alternative refrigerant to CFC-12 for this application, and any future alternatives are unlikely to be compatible with existing equipment. This view is shared by operators, equipment manufacturers, and CFC suppliers.

Once a suitable new refrigerant is developed, new equipment will use this, and the question of the economic life of then-existing CFC-12 units will need further consideration.

For lorries, most equipment has a lifetime of 7 to 12 years, so there is scope for replacement with systems using interim refrigerants such as CFC-500 and CFC-502 whilst improved refrigerants (e.g. HFC-134a) are developed and tested. Mixtures such as blends of CFC-12 with dimethylether (DME) or of HCFC-22 with HCFC-142b have been suggested.

6.5 Economic Considerations

The cost of refrigerant is a minor part of total costs of transport refrigeration, and although projected costs of future alternative refrigerants are about five times the cost of existing refrigerants, this is not likely to be a serious economic restriction.

No direct data on energy use has been included in this study. Energy use is a secondary factor to cargo care in transport, and saving energy by design improvement is a slow but continuing process. There is no scope for alternative "drop-in" refrigerants of known properties, so there is little point in evaluating likely increases in energy use as a result of changing refrigerants in existing systems.

The short- to medium-term provision of refrigerant recovery equipment and services is potentially a substantial added cost for repairers, with no direct benefits. This is an area to which government or international financial support could well be directed.

For containers, the cost of a new 5-7 kW refrigeration system is US$10-12,000, the expected lifetime is at least 15 years, and by the end of 1990 it is estimated that 67% of units will be less than 7 years old. At the present time, there is a two-year backorder for refrigeration containers world-wide.

If it were to be decided in 1990 that CFC-12 would be phased out over the following ten years, and new units were to come available in 1996, this could involve the scrapping of equipment valued at around US$2,000 million in order to save the use of 245 tonnes of CFC-12 per year. This would depend on availability of CFCs from recycling and aftermarket drop-ins (e.g., the tenary mixture). It could also involve the setting up of appreciable additional manufacturing capacity for a limited changeover period.

For ships, should it be necessary and possible to change to a new HCFC refrigerant, the conversion cost for a single large ship could be around US$1.8 million, perhaps US$700 million in total for the world fleet.

For lorries, the expected lifetime of refrigeration units is shorter than for ships or containers, and consequently the costs of a phased changeover over a number of years would be considerably less.

For both lorries and containers, any changes in refrigeration systems are likely to be accompanied by changes in the insulated structure, which is at present largely dependent on CFC blown rigid foams. The compounding of these two changes would place severe strains on development and manufacturing capabilities worldwide.

6.6 Concluding Remarks

Currently there are about 1,300 refrigerated cargo and container ships, representing 10,500,000 cubic metres of refrigerated space. These mostly use HCFC-22, representing a pool of 2,600 tonnes. Maintenance and repairs are to a high standard, using about 50 tonnes per year. The continuing availability of HCFC-22 is important, conversion costs to an alternative (if available) would be very high.

In addition to cargo refrigeration, there could be 35,000 ships with "domestic" refrigeration systems, representing a pool of at least a further 1,000 tonnes of refrigerant.

Refrigerated containers use CFC-12, and there is no suitable alternative in this very demanding application. The estimated fleet of 300,000 units in late 1990 holds a pool of 1,650 tonnes of refrigerant. Ongoing maintenance and manufacturing require 245 tonnes per year, which is 0.06% of 1986 world production. Should no CFCs from recycling be available and no drop-ins be found, US$2,000 million worth of equipment would be scrapped and this would pose formidable problems of manufacturing capacity. Equipment purchased today has a currently expected economic life of 15-20 years.

Road vehicles currently use CFC-12. In the short-term, some changes to CFC-500 or CFC-502 are in hand. Once proven alternatives are available, further changes will be possible as vehicles have a relatively short life of 7-12 years. There is a world fleet of about 800,000 refrigerated vehicles (220,000 in the EEC) with a pool of 3,500 tonnes of refrigerant and a maintenance and manufacturing requirement of 1,200 tonnes per year. Although the industry is making every effort, reduced CFC use through improved maintenance and handling procedures is difficult to achieve with large numbers of small, mobile units.

On a world scale, transport refrigeration is a small but important user of CFC and HCFC refrigerants.

7. COLD STORAGE/FOOD PROCESSING

Cold storage covers storage of food products both above freezing 0C to +10C and below freezing (-18C to -28C), both for in-processing storage and for storage and distribution of finished products.

Food processing covers chilling from -3C to +10C and freezing to -18C to -28C. Chilling occurs both in-process prior to preservation and containerization in its final form and in preparation of chilled products for direct distribution (meats, fish, poultry, fruits, vegetables and baked goods, as well as value-added finished products). Freezing occurs both to prepare products for further processing (as in ingredients for prepared foods and concentrates) and to freeze finished products for distribution and sale.

7.1 History and Global Data

7.1.1 History

Long ago the ancestors used chilling and freezing for food preservation. Two examples are the use of water-ice taken from frozen lakes for chilling fish and meat, and the evaporation of water from the outside of clay bottles to keep the food inside cool. Hunters in low temperature regions used, and still use, freezing for preservation of their game. This is achieved by hanging the game outdoors.

Through mixing water-ice and salt, temperatures close to -20C could be achieved. This freezing system was used over decades for production of ice-cream which was a delicacy at many exclusive dinners long before mechanical refrigeration was developed. Society has become substantially dependent upon chilling and freezing for the food supply to all the densely populated areas.

Other methods to preserve food are drying, canning, aseptic, fermentation, salting (sugar) and irradiation. Whatever method being used, chilling and freezing are regarded as the most important methods to reduce losses in an ever-demanding world.

7.1.2 Global Data of Food

The world frozen food supply in 1987 was:

USA	11,800,000 tonnes
Western Europe	6,000,000 tonnes
Other developing countries	2,000,000 tonnes
Rest of the world	500,000 tonnes
Approx.	20,300,000 tonnes

The 1987 frozen food consumption in kg per capita (including poultry) for some countries was:

USA	48.2
Japan	9.0
Sweden	25.5
UK	34.2
Denmark	32.4
Netherlands	16.2
Switzerland	20.1
France	17.9
West Germany	20.5
Italy	5.7
Norway	18.7
Belgium	13.0
Finland	11.7

Chilling is a much larger component of food consumption than frozen and is at least 200,000,000 tonnes of food world-wide. In Sweden, for example, the chilled consumption is some six times the frozen consumption. When milk products are included, chilled consumption is ten times frozen. It is estimated that chilled consumption in the USA is at least five times frozen and more than ten times frozen for the balance of the world.

It is expected that world-wide tonnage of both chilled and frozen foods will increase in the years ahead.

7.1.3 Refrigerants

Most large scale industrial chilling, freezing, and cold storage plants utilize ammonia. There are, however, certain areas and countries that use CFC-12, HCFC-22, and CFC-502. These include France and French speaking countries; in Japan, where there are dense populations and earthquake risks; and in the Middle East, where CFC-12 is popular due to lack of water and high ambient temperatures.

Most small scale chilled and cold storage operations use CFC's and HCFC's rather than ammonia. The principal exception is in Eastern Europe, where ammonia is the primary refrigerant.

7.2 Existing Equipment

Almost all refrigeration plants for freezing and frozen storage of products are designed for evaporation temperatures from -25C down to - 40C. At-25C many of the plants use single stage compression, whereas at -40C almost all of the plants use two stage compression. The installations are mostly site-built, but there is a large trend to unitized equipment packages to reduce field labour and improve quality.

Chilling plants along with cool storage (above freezing temperature) are done with evaporation temperatures from +10C to - 15C with single stage compression. The installations are largely site-built, but again with a major trend to unitized equipment packages both for CFC/HCFCs and ammonia.

There is a significant portion of very large site built plants containing several tonnes of CFC-12 or HCFC-22. These plants have been greatly improved in recent years regarding the need for recharge. Where these plants 5 or 10 years ago had an average loss of 10% of the charge per year, many today report yearly losses down to 1 or 2%. As these plants represent a very high investment and are expensive and difficult to rebuild, additional methods for reducing their charge should be encouraged.

In many cases, it is the qualified maintenance of equipment and its good design which will justify further use and operation for several years. High recharge rates eventually make these plants uneconomical to operate, as the costs for CFCs/HCFCs increase due to lack of availability.

7.3 Alternatives - New Installations

The existing alternatives are as follows:

Ammonia

HCFC-22 and other CFC's where required for operation, safety or climatic reasons.

Greater use of indirect refrigeration for all refrigerants.

7.3.1 Ammonia

Ammonia is quickly biodegradable and is not harmful to the environment. It is toxic to humans in concentrations above 100 ppm after eight hours of exposure. It also has a pungent well-known odor at very low concentrations (under 2 ppm), which provides excellent opportunities for timely repairs of leaks and reaction time for personnel evacuation. Ammonia is flammable in concentrations of 16 to 25% by volume in air. This condition is almost never reached in a well-designed plant that is in code compliance.

Codes, regulations, and laws have been developed to deal with the toxic and flammable characteristics of ammonia, which if followed, provide a high degree of safety. The key is compliance for those involved - the designer, installer and user. Ammonia safety is vigorously supported and promoted by such organizations as ASHRAE, IIAR, IIR, RETA, and MCA. This effort has improved compliance, safety and performance in a large proportion of the over 50,000 large ammonia systems world-wide. This effort has concentrated on code compliance, design, operator training, periodic inspections, and preventive maintenance.

The major risk with ammonia is large spills and/or explosions. These incidents are very infrequent, but when they do occur, are often severe to personnel, product, and property. It is possible, however, to keep such risks near zero with code compliance, operator expertise, scheduled inspections, and proper maintenance. These same factors also provide the most economical operation, thereby altering an apparent cost into a savings.

Ammonia is an excellent refrigerant for large industrial freezing and cold storage operations, and can stand a lot of abuse and neglect (which are often the root causes of major spills).

Ammonia is recommended for freezing operations; close-coupled, confined compressor-evaporator systems; and frozen goods storages where the systems are well-managed and not far-flung geographically. Unitized designs can reduce ammonia charge and risk in many applications. It should not be used in areas of dense population or in severe earthquake zones without proper seismic piping design.

7.3.2 HCFCs and CFCs

HCFCs and CFCs should still be used where dense populations, public buildings, severe earthquake zones, and special climatic situations prevail. Wherever possible, HCFC-22 should be utilized as it has the least effect on the ozone layer. CFC-502, however, is superior to HCFC-22 for freezing applications; in the long-term HFC-32 may be a replacement for CFC-502 (see also Section 8.4.2.1). New installations should be designed for minimum refrigerant charges and low recharge rates.

7.3.3 Indirect systems

A greater use should be made of indirect systems. These systems can use either ammonia or HCFC/CFC refrigerants in a close-coupled arrangement to cool/chill water or a brine solution (glycols, calcium chloride, alcohols, etc.) in a heat exchanger. The water or brine solution is piped and circulated to the area requiring refrigeration.

Indirect systems will provide for a reduced refrigerant charge in most applications as well as a close-coupled refrigerant circuit that can be a reduced risk for refrigerant losses. These systems also lend themselves well to factory packaging which further improves quality and reduces capital costs.

Indirect systems, for example, could provide an alternative to long refrigerant lines and large charges with attendant risks in large food processing/freezing plants that contain process refrigeration, freezing apparatus and cold storage facilities.

Indirect systems are theoretically less efficient than direct systems due to the extra heat transfer step to cool the water or brine solution. Practical experience, however, shows that because of simultaneity many indirect systems have better performance characteristics than direct systems. This has been proven in retail refrigeration/supermarkets and large chill depots for fruits and vegetables. These types of systems should be investigated further regarding economics and safety advantages.

7.3.4 New Refrigerants

New refrigerants are being developed to provide comparable economic benefits to ammonia and HCFCs and CFCs without the toxic qualities of ammonia and the environmental disadvantages of the HCFCs and CFCs.

They can be phased in as appropriate when and if they become available, and the machinery and accessories are adapted to their characteristics.

7.4 Environmental Impacts

Ammonia is not an environmental threat, but there is a fear of ammonia from the general public and government officials. This will limit its use to large food processing and cold storage plants that are located away from residential and commercial areas and areas of dense populations. Ammonia suffers from the NIMBY (not in my backyard) syndrome. Better code compliance, education, inspections, and maintenance will improve safety performance in existing plants. New installations and modernization can be even safer with more use of unitized equipment and indirect refrigeration. There is a limit, however, to the inroads that ammonia can make without legislation to mandate it.

Thus, there will continue to be a need for HCFCs and CFCs for the sensitive locations. Insofar as possible, existing plants should be required to operate with low, acceptable recharge levels. New plants and retrofits should make maximum use of HCFC-22, indirect refrigeration, factory-built unitized equipment, and low charge levels of refrigerant. These steps will minimize potential release of the HCFCs and CFCs to the environment.

7.5 Economic Impacts

The use of ammonia, HCFCs, and CFCs as suggested will have acceptable investment and operating costs. Investment costs will be higher by an estimated 10 to 20% in most cases, and operating costs may be higher depending on load simultaneity with indirect refrigeration. Most users will probably not accept these solutions voluntarily. Hence, there will need to be changes in codes, regulations and laws to force compliance with respect to charge levels, indirect refrigeration, and factory-built unitized equipment.

7.6 Freezing Methods

Large scale food freezing is generally accomplished with ammonia using low temperature air (-30C or lower) in various freezer configurations or by contact freezing between plates or belts. There is some freezing done with HCFCs and CFCs, but it is less trouble-free due to oil and moisture problems - hence, leaks and relatively high recharge levels.

Another method of freezing includes liquid nitrogen and liquid carbon dioxide freezers, wherein the freezant is used on a once-through basis. This is a high cost method for large scale production and it is principally used for smaller production rates of high cost products or for short runs for research or test markets.

A special liquid freezer was developed in the early 1970's wherein liquid CFC-12 at atmospheric pressure was used in immersion or spray to freeze the product. CFC-12 that was evaporated was largely recovered by an ammonia evaporator coil which condensed CFC-12 for reuse. These freezers are no longer manufactured, and those in use can be replaced with ammonia low temperature freezers or LN_2 or LCO_2 freezers to provide comparable quality and often less operating cost.

Finally, there are freeze-dry systems for various products such as coffee. They operate with either ammonia, HCFCs, or CFCs. Those with HCFCs or CFCs can be converted to ammonia and provide lower operating costs, particularly where recharge rates are high.

7.7 Concluding Remarks

Refrigeration for food processing, chilling, freezing, storage, and distribution represents a large portion of installed refrigeration tonnage, and it will increase faster than population growth for both chilled and frozen products.

The existing plants using CFC-12, HCFC-22, and CFC-502 should be allowed to remain but with targets for lower recharge levels. Legislation or codes should be proposed to limit recharge to a specified percentage of the total charge per annum.

New installations and major retrofits or modernization should consider the use of ammonia where acceptable on a safety basis followed by HCFC-22 for medium temperature applications and CFC-502 for freezing applications (maybe HFC-32 in the long-term). CFC-12 use should be limited to areas of high ambient temperatures that have a shortage of water. HCFC/CFC installations should be required to have low recharge rates.

Use of indirect refrigeration and unitized, factory-built equipment should be encouraged for all refrigerants to reduce refrigerant charges and to minimize potential for leaks.

Changes in codes, regulations, and laws may be required in some cases to force users into higher capital cost solutions and to provide improved ongoing operation and maintenance to achieve objectives.

8. INDUSTRIAL REFRIGERATION

8.1 Introduction

The area of application covered by this chapter includes the chemical, pharmaceutical and petrochemical industries, the oil and gas industry, the metallurgical industry, civil engineering, sports and leisure facilities, industrial ice making, and other miscellaneous uses.

Food processing and cold storage, beverage industry etc., which are normally considered a part of the industrial refrigeration sector, are not included here, as these areas of application are presented in separate chapters in this report.

8.2 Overview

8.2.1 General

As industrial refrigeration systems cover a broad range of uses, it is difficult to generalize. One thing in common for many plants, however, is that the process is linked to continuous industrial production. This makes special demands on system reliability and energy efficiency.

On the other hand, a broad spectrum of designs is found; and plant capacity, refrigerant charge, and temperature level may vary over a wide range.

The technical lifetime of industrial systems is normally 25-30 years. However, it is believed that the economic lifetime for plants with CFC refrigerants will be significantly shorter in the current situation, perhaps 15-20 years due to leakage caused by equipment age.

8.2.2 System Design and Refrigerant Charge

Refrigeration systems for the industrial sector are often "tailor-made" for specific purposes. A large number of such systems utilize direct refrigeration systems (no intermediate circuit between the refrigerant and the material or space to be cooled). Direct systems have usually a large refrigerant charge, from 1-2 liters per kW refrigerating effect and up to more than 30 l/kW. Thus, the refrigerant price is a significant cost factor.

Advantages of direct systems are lower energy consumption, and favourable first cost compared to indirect systems. Indirect systems have, in general, a lower refrigerant charge (0.2-0.8 l/kW). The energy consumption is typically 10-15% higher than for direct systems. The difference in initial investments is estimated to average 20%, average, in favour of direct systems.

8.2.3 Capacity and Temperature Range

The lower capacity limit per plant in the category considered, runs from 200 kW refrigerating effect, to the largest systems which may produce several MW (megawatts) of refrigeration. Temperatures usually vary between +10C and -80C.

8.2.4 Types of Equipment Used

Industrial systems use all types of compressors: reciprocating compressors, rotary, screw compressors and turbocompressors.

The first three types of compressors are positive displacement and are therefore, not much affected by the refrigerant properties. They cover in particular the low and medium capacity range. Screw compressors up to 8 MW refrigerating effect at 0C are available, however.

Turbocompressors are used in the medium- and upper-capacity range. Choice of refrigerant plays an important role, as heavy gases (e.g., CFCs/HCFCs) are compressed more easily than light gases (e.g., ammonia). CFC compressor is, therefore, simpler and less expensive. Most of the turbocompressor units in the industrial sector use CFC-12.

8.2.5 Types of Refrigerants Used and Choice of Refrigerant

All types of CFC/HCFC refrigerants are used for industrial refrigeration purposes, as well as ammonia and hydrocarbons. The latter refrigerant group is used mainly in the oil and gas industry and in the petrochemical industry. CFCs/HCFCs are chosen for practical and economic reasons. They are nontoxic and nonflammable and are particularly suitable for turbocompressors. Safe and easy handling of the refrigerant itself is perhaps the foremost advantage of CFC/HCFC refrigerants.

HCFC-22 is not currently included in the Montreal Protocol, and may replace some of the regulated chemicals. Disadvantages compared to CFCs are high system pressure (particularly compared to CFC-11) and high discharge temperature. In low temperature systems, a more complex 2-stage system may have to be used, which, on the other hand, improves the energy efficiency.

Ammonia has traditionally had a substantial market share within industrial refrigeration, particularly in the food industry, ice making, skating rinks, and so on. A trend towards more extensive use of CFCs/HCFCs during recent years is apparent, however, in these areas of application. Ammonia would be the logical refrigerant choice from an efficiency point of view. Both the refrigerating effect per unit power required, and the efficiency of the heat exchangers are favourable compared to CFCs. Another advantage is the refrigerant price, which is approximately 1/10 the price of CFCs (on volume basis). For these reasons, the initial cost of industrial systems with ammonia are generally 5-10% less expensive than similar CFC/HCFC systems.

Ammonia is toxic and flammable. Its characteristic penetrating smell gives a very early warning effect, but may represent a substantial hazard where panic among untrained personnel may occur. The use of ammonia for refrigeration purposes is, therefore, subject to regulations by the authorities. The safety codes exclude ammonia from most commercial and residential refrigeration purposes, and also affects its application within industrial refrigeration.

The safety codes differ in strictness from country to country. This fact, among others, has lead to a somewhat different development in the usage of ammonia in industrial refrigeration. While it possesses a substantial market share in Europe, the American and, in particular, the Japanese industry rely on CFC/HCFC refrigerants to a much larger extent.

8.2.6 Current CFC Consumption in the Industrial Sector.
Basis for a CFC Reduction Scenario.

The US consumption of CFC-12 within industrial process refrigeration was approximately 700 tonnes in 1985 /Rad87/. With regard to ozone depleting potential (ODP), this figure is supposed to equal 75% of that of the industrial sector as a whole, which then amounts to a little more than 900 tonnes per year for the United States.

CFC consumption in the considered areas of application, is estimated to be approximately 1000 tonnes per year (equivalent to CFC-12 in ODP) in the European Community (1986). This figure is based on total use of CFC refrigerants in the EC countries, combined with detailed statistics from the Federal Republic of Germany /Jen89/.

The consumption of CFC refrigerants in Japan was equal to 90% of that of the EC countries in 1986 /Jen89, JAR89/. Supposing a similar ratio for the industrial sector, a Japanese consumption of 900 tonnes/year results.

It is anticipated that these three large consumers account for 80% of total world consumption of CFCs for industrial use, which then adds up to approximately 3500 tonnes per year. (Equivalent to CFC-12 in ODP). This is on the order of 1.5% compared to the refrigeration, air conditioning and heat pump sector as a whole. The major part, probably more than 80%, is believed to be CFC-12.

The demand for industrial refrigeration plants in the United States is reported to be practically constant /Rad87/. The situation is supposed to be similar for most of the world. Thus, 3500 tonnes may apply for 1986 (basis for calculation of CFC reductions), and for 1989 as well.

The annual consumption of the non-regulated refrigerants amounts to 7000 tonnes of HCFC-22, roughly estimated, and somewhat less for ammonia. Hydrocarbons account for a minor part of the total, probably a few hundred tonnes.

Only a portion of the consumed CFCs, ranging from 20% to 60%, is used for charging new plants /Rad87, Jen89/; 30% may serve as a global average figure. The major part is used for servicing the existing stock, which in volume is believed to be 20 times the number of new plants installed annually.

Recharging is necessary because of accidental loss (breakdowns etc.) and leakage, and for refrigerant deliberately released to the atmosphere in connection with repair work. It is anticipated that 1/3 of the amount for recharging is used in connection with repair work. A quantity equivalent to 2/3 of the amount for the initial charge is thought to be released from scrapped plants annually.

According to the assumptions above, the current situation for industrial refrigeration can be summed up as shown in Table 8.1:

Table 8.1 CFC consumption and emission scheme. Industrial refrigeration (1986 and 1989)

	Tonnes
Annual CFC consumption, total	3500
, first charge	1050
, replenishment	2450
CFC charge in stock	21000
Annual CFC emission, total	3150
, leakages	1650
, repair work	800
, scrapped plants	700

The market for industrial refrigeration systems is not expected to grow significantly in the coming years.

8.3 CFC Consumption Reduction in Existing Equipment

8.3.1 Refrigerant Change-over

Blends are the only "drop-in" refrigerants available to-day, and will probably remain so also in the future. Most blends are non-azeotropic. One exception is CFC-12/dimethylether (DME) (87/13% by weight), which is introduced as an intermediate "drop-in" refrigerant for CFC-12. Change-over to any one-component refrigerant in existing systems necessitates system modification in most cases.

8.3.1.1 CFC-12/DME-blend

CFC-12/DME-blend has 30% less ozone depleting potential than pure CFC-12 per unit volume. Industry is in general reluctant to utilize this mixture

/Hau89/. The risks involved by introducing a new chemical, together with a rather marginal saving over a limited time period, are apparently the main reasons. This option is not considered to contribute significantly to CFC consumption reduction in the industrial sector.

8.3.1.2 Non-azeotropic Mixtures

It is assumed that the comments given for CFC-12/DME-blend, also hold for non-azeotropic mixtures, at least in the short-term.

8.3.1.3 Alternative Existing Refrigerants

Possible alternative refrigerants are CFC-500, CFC-502, HCFC-22, ammonia and hydrocarbons. None of these alternatives can be used in low pressure systems designed for CFC-11, but may replace CFC-12.

CFC-500 is an azeotrope containing CFC-12 and HFC-152a (74% CFC-12 by weight). CFC-502 is also an azeotropic mixture, composed of HCFC-22 (49%) and CFC-115 (51%) (ODP of 0.3). CFC-502, in particular, may be regarded as part of the short-term solution. In the long-term, however, both chemicals become part of the problem. For this reason, and the fact that considerable system modification may be necessary, other options are preferred for existing systems.

Retrofitting a plant designed for CFC-12, CFC-500 or CFC-502 to use HCFC-22 or hydrocarbons is considered to be technically possible for the major part of the stock. It is expected to be economically feasible (10-20% extra cost), however, only in connection with scheduled reconstruction of the plant or larger overhauls, and even then only as an exception. A general redesign of plants is, therefore, not believed likely /Hau89/.

Retrofitting to use ammonia is much more difficult, and will certainly not be implemented to any significant extent. Change-over to alternative "old" refrigerants in existing plants is, on the whole, expected to be carried out for only a minor part of the stock, perhaps 1% per year, in the short- and mid-term (5-10 years). Shortage of CFC supply, or substantial price increases may change this picture. The additional cost for this option is expected to amount to 20% of the investment of a new plant.

8.3.1.4 New Refrigerants

The substitute refrigerants HFC-134a (for CFC-12) and HCFC-123 (for CFC-11) are not considered as "drop-in" refrigerants. Compatibility problems have been reported, and a suitable lubricant for HFC-134a has not yet been found. A significant change-over to any of these substitutes is, therefore, not likely to occur in the next few years. In the long-term (10 years), a certain change-over is expected, however. It is supposed here, that 2% of the existing plants will have been retrofitted to use any of these substitutes by 1994, increasing to 8% at the end of 1998. The cost is assumed to be similar to that for change-over to existing refrigerants.

8.3.2 Refrigerant Conservation

The large portion of CFC used for service purposes (70% anticipated), indicates that measures for short-term reductions must first of all be directed towards the existing plants.

The refrigerant conservation option includes measures with two distinct aims:

1. To recover refrigerant at service, when plants are retrofitted to use other refrigerants, and at plant disposal (reducing "deliberate" refrigerant release)

2. To reduce leakage from the plants and avoid breakdowns causing loss of refrigerant

Industrial refrigeration plants are relatively few in number, each containing a considerable amount of refrigerant. This makes the conditions for refrigerant recovery favourable.

It is technically possible to reduce the release of refrigerant during repair work and after plant condemnation. Whether refrigerant recovery will be economically feasible or not, is more difficult to judge. This very much depends on the refrigerant price and availability. Regulations in some countries concerning the handling of CFC waste may reduce the (short-term) effect of this option.

Recovery of 30% of the refrigerant released during repair work is assumed to be a realistic goal for 1994, with an increase to 60% in 1998. It is assumed that the recovered refrigerant can be returned to the plant when the work is completed. Recovery at disposal and in connection with retrofit, also depends on the possibilities of handling the waste (cleaning or destruction). This may lead to a somewhat delayed market penetration compared to recovery at service. A goal similar to that for recovery at service has nevertheless been set here.

Equipment for refrigerant recovery is available on the market. Refrigerant is being reclaimed on a commercial basis by at least one American company /Ome88/. It is, therefore, assumed that the cost for refrigerant recovery (equipment and labour) will be of a similar order of magnitude as the value of the refrigerant reclaimed. Accordingly, any extra cost for this option is not included.

Improved preventative maintenance, including better leak-testing procedures (and equipment), is one way to reduce refrigerant release through breakdowns and leakages. Better training of the personnel operating the plant is another important measure. The possible gain in CFC conservation by such measures is not easily judged. It is believed, however, that a 25% reduction is attainable within 1994, increasing to 50% by 1998.

The extra cost in connection with a higher maintenance level may be in the order of 10-20% compared to current maintenance cost.

8.4 CFC Consumption Reduction in New Equipment

8.4.1 General

There are several ways to reduce the dependence of CFCs in new systems; use of alternative refrigerants, reduction of refrigerant charge, improved manufacturing and service routines (including refrigerant recovery) and so forth. Alternative refrigerants will take over from CFCs gradually. It is believed that a complete phase out of regulated refrigerants in new equipment will be possible before 1998.

8.4.2 Alternative Refrigerants

8.4.2.1 CFC-500 and CFC-502

CFC-500 and CFC-502 can easily replace CFC-12 in new equipment for most applications in the industrial sector. Some companies look upon this option as a realistic short-term solution, in particular CFC-502. Others state that they would prefer not to change to these fluids, as they represent interim solutions /Hau89/.

It is believed that CFC-502 will gain a small part (5%) of CFC-portion of the industrial market before 1994. After this date, the use of CFC-502 is expected to decline, and soon to terminate.

The option is not expected to imply a significant increase in initial costs. The energy consumption is expected to rise by approximately 10%, however.

8.4.2.2 HCFC-22

From a technical point of view, HCFC-22 may replace CFC-12 (and also CFC-500/502) in new plants today, for most of the industrial refrigeration sector. The main exception is plants operating with high condensing temperatures (heat recovery), where HCFC-22 will cause too high a pressure. For low temperature purposes, 2-stage compression may have to be used.

The major part of the industry considers a change-over to HCFC-22 as the most important short- and mid-term solution /Hau89/. This measure has already been implemented by several companies, while others are about to start. Thus, a considerable increase in the usage of HCFC-22 is expected. A 40% gain of CFC market is foreseen in the short-term (1994), and with a further increase up to 50% in 1998. It is, therefore, of ultimate importance to the industry that HCFC-22 remains available in the foreseeable future.

In some cases, 2-stage plants will have to be used, where the corresponding CFC plants are using one stage. A one-stage plant with HCFC-22 is, on the other hand, often less expensive than a similar plant with CFC-12, while the two-stage plant saves energy.

The cost effect of implementing HCFC-22 is estimated to vary between -5% and +25%, on average +10%. Estimated energy effect is a 0-15% decrease, where the latter figure is applicable for a two-stage system compared to a one-stage system. On average, a couple of per cent lower energy consumption can be expected.

8.4.2.3 Ammonia

Technically, ammonia can cover most applications in the industrial sector, with the equipment available today. In practice, the growth of ammonia usage is limited by safety regulations and, at least in the short-term, by lack of experience with this refrigerant by many companies.

Apart from being the most efficient refrigerant, ammonia has no ozone depleting effect at all. For these reasons, together with uncertainties connected with the future of HCFC-22, the companies familiar with ammonia refrigeration, foresee a substantial growth in their use of this chemical /Hau89/. The ammonia plant will sometimes be more complex than the corresponding CFC plant (2-stage compression, indirect systems etc.), which implies penalties in the initial costs.

It is believed that within 5 years, ammonia may take over 30% of the market share today held by CFCs in this sector. The market share of ammonia is expected to remain constant in the following years. The cost effect is estimated to vary between -10% (simple one-stage system) to +20% (two-stage or indirect system). On average, +15% is estimated.

The estimated energy effect ranges from -15% to +10% (2-stage system/indirect one stage system). On average, -5% may apply.

8.4.2.4 Hydrocarbons

The use of hydrocarbons (and possibly flammable halocarbons) is believed to be growing within industries where handling of flammables is part of the normal activities (e.g. the oil and gas, and petrochemical industries). The gain in market share for hydrocarbons, at the expense of CFCs, is supposed to be 3% in 1994 and 10% in 1998.The investment for a hydrocarbon plant is estimated to be 10-30% higher than for a CFC plant. As to energy efficiency, the two types of systems are considered comparable.

8.4.2.5 Non-azeotropic Mixtures

Most of the industry does not show particular interest in azeotropic mixtures for industrial refrigeration /Hau89/. Questions are raised about their energy efficiency, and lack of experience with such fluids is a substantial draw-back. A certain increase in initial costs is also expected. Non-azeotropic mixtures are, therefore, not considered to play any significant role. If HCFC-22 should become regulated, the situation may change.

8.4.2.6 HFC-134a and HCFC-123

Market penetration of new refrigerants is expected to take 5-10 years /Rad87, Hau89/. HFC-134a and HCFC-123 will, accordingly, not gain a particularly large market share in the short-term, but may gain some significance towards the end of the century.

The usage of CFC-11 in industrial plants is rather modest, and will most probably be replaced by HCFC-123. This requires that some technical problems are solved and that extensive field testing of the new fluid is undertaken.

HFC-134a may take over from CFC-12 in turbocompressors, and for high temperature applications. The unsolved questions in connection with this refrigerant create some uncertainties, which need clarification. The predicted energy penalty, and a substantially higher price are also noticeable draw-backs, in particular for industrial systems. HCFC-22, and to a lesser extent ammonia and hydrocarbons, are, therefore, believed to be preferred where applicable.

The new refrigerants are expected to hold a 5% share of the "CFC market" in 1994, increasing to 20% by 1998.

The estimated cost effect is a 10-20% increase, while an energy penalty of 5-15% is expected. Average figures may be 15% and 10% respectively.

8.4.3 Measures Taken So Far

The industry has already implemented measures to reduce the consumption of the controlled substances. A change-over to chemicals with less ODP in new plants, in particular HCFC-22, whenever possible is reported. Several companies also report a substantial growth in their use of ammonia /Hau89/. New designs with less refrigerant charge have appeared, and training courses for personnel have been held.

8.5 Future Consumption of CFC Refrigerants

8.5.1 Development According to the Scenario

A development according to the scenario described in Sections 8.3 and 8.4, affects CFC consumption as demonstrated in Table 8.2. The table contains calculated reduction due to different measures, in per cent of total CFC usage in 1986 (3,500 tonnes).

The analysis indicates that a more than 40% reduction in CFC consumption by 1994 should be attainable. If the goals concerning refrigerant reclamation are reached, a 50% reduction is within reach. Towards the end of the century, the consumption can be reduced to one fourth compared to the situation today. If the calculated effect of refrigerant recovery is added, a net CFC supply of less than 10% of the amount currently used will be necessary.

The development concerning CFCs in stock and CFC emission from the plants, will be somewhat delayed compared to the consumption. Table 8.3 shows the calculated results. Again the reduction is relative to the figures for 1986. (See Table 8.1 for reference data).

8.5.2 Future Dependence on CFC Refrigerants

The economic lifetime of refrigeration plants with CFCs will be affected by the current situation, as stated before. 15-20 years is assumed to apply in the coming period of time. Accordingly, existing plants will need CFCs for service purposes well beyond the turn of the century. To service new plants plants, which still may be built for 5-10 years, small quantities of CFC must be available until approximately 2015.

8.5.3 Future Dependence on HCFC-22

Extended use of HCFC-22 is the cornerstone of the presented scenario. Unrestricted availability of this refrigerant is, therefore, an absolute prerequisite to the results and conclusions. If HCFC-22 should become strictly regulated, the phase-out of CFCs will have to be considerably postponed, if serious adverse effects on the economy shall be avoided.

8.6 Local and Global Environmental Impacts

8.6.1 Local Impacts

The measures described may cause negative effects on the local environment through:

- increased usage of ammonia (toxic, flammable) and hydrocarbons (flammable)
- increased usage of HCFC-22 (service personnel often feel HCFC-22 to be less pleasant than CFC-12 when they are exposed to high concentrations)

It should also be mentioned that the toxicity testing of HFC-134a and HCFC-123 has not yet been completed.

Refrigerant recovery during service will have a positive effect, as service personnel will be exposed to lower concentrations. Experience shows that ammonia and hydrocarbons are safe refrigerants when handled in a proper way. Taking into consideration the industrial environment in which they are located, increased usage of these chemicals is not considered to represent significant additional risks to people or property.

As a whole, the impacts on the local environment are considered negligible.

8.6.2 Global Impacts

A development as indicated in the scenario will result in a reduction of CFC released to the atmosphere of at least 15% in 1994, and approximately 35% in 1998. These figures may be increased to 23% and 53% in 1994 and 1998 respectively, if refrigerant recovery is implemented according to the scenario.

Table 8.2 Calculated reduction in CFC consumption
Basis: 3500 tonnes (1986)

	Calculated reduction in CFC consumption, %	
Measure	1994	1998
Retrofitting existing plants to use alternative refrigerants	2	5
Alternative refrig. in new plants	26	38
Refrigerant conservation	15	32
Total	43	75
Refrigerant reclamation	7	17
Total, incl. refrig. reclamation	50	92

Table 8.3 Calculated reduction of CFC charge
in stock and CFC emission.

	Calc. reduction %	
	1994	1998
CFC charge in stock	7	29
CFC emission, without/with recovery	15/23	34/53

When the increased use of HCFC-22 is taken into account (Ozone Depleting Potential ODP=0.05), the total ODP of released refrigerants (CFCs and HCFC) will be reduced by up to 20% in 1994 and 48% in 1998.

The estimated energy effects are not of particular importance. (0% in 1994, +2% in 1998).

8.7 Economic Aspects and Impacts

The total value of CFC plants installed annually in this sector is estimated to be roughly US$250 million. The economic impacts of a development as described, are estimated to be a 13-14% increase in investment costs in 1994, which amounts to US$35 million. The 1998 figures are 22%, i.e. approximately US$55 million. The estimated costs for retrofitting existing plants to use non-regulated refrigerants are included in these figures, with US$12 million and US$25 million for 1994 and 1998 respectively.

Improved maintenance, including recovery at service, is believed to be fully implemented by 1998. This is supposed to add 12.5% to the current maintenance cost level. The value of the total stock of CFC plants, is estimated to be on the order of US$3500 million in 1998. If current maintenance costs are set equal to 3% of this figure, the additional costs amount to approximately US$13 million a year. According to the scenario, close to 1000 tonnes CFC will be saved each year, representing a value of perhaps US$4 million. (This figure may be substantially higher in case of CFC shortage at that time). Net costs then amount to US$9 million per year.

The energy costs are not considered to change significantly. (See paragraph 8.6.2).

8.8 Concluding Remarks

The industrial sector represents a very small part of the entire field of refrigeration, and the consumption of regulated chemicals is estimated to be only 1-2 per cent of the total. On the other hand, it is one of the sectors where a substantial reduction in the dependence of CFC refrigerants can most easily be achieved.

The results and conclusions are based on the assumption that HCFC-22 will not be regulated by a future revision of the Montreal Protocol. If the opposite should be the case, the phase-out of CFCs will have to be considerably postponed, and adverse cost and energy effects will result.
Calculations based on a realistic scenario indicate that the consumption of CFCs within the industrial sector can be reduced by more than 40% in the short-term (1994) and by 75% in the mid-term (1998). If refrigerant recovery is implemented, these figures may increase. Total reduction figures of 50% (1994) and more than 90% (1998) are indicated as possible, if the goals in the scenario are reached.

The corresponding figures for refrigerant release to the atmosphere is an estimated reduction of 15% (23%) in 1994 and 34% (53%) in 1998. The figures in parenthesis applies when refrigerant recovery according to the scenario is assumed.

The estimated increase in consumption of HCFC-22 is in the order of 10% by 1994 and 17.5% by 1998, in relation to the consumption today.

To sum up, with reference to change in ODP resulting from the discussed scenarios, the following can be stated:

the HCFC-22 volume used today as 7000 tonnes per year will increase by 17.5% by 1998, or an increase in ODP (HCFC=0.05) from 350 to 410

CFC volume used today as 3500 tonnes per year will decrease by 92% in 1998, or a decrease in ODP from 3500 to 280

The combined reduction in ODP is from 3850 today to 690 in 1998, equivalent to more than 80% reduction.

A similar analysis of the emission data, show that the ODP in CFC and HCFC emitted from industrial refrigeration plants will decrease by nearly 50% from 1989 to 1998.

9. COMFORT AIR CONDITIONING

9.1 Introduction

There are two basic types of vapour compression systems used in commercial buildings for comfort air conditioning, unitary air conditioners and water chillers. Unitary air conditioners cool and dehumidify by having the air pass directly over a coil containing refrigerant which is evaporating. Water chillers cool water (or a water/glycol mixture) which is then pumped through a heat exchanger in an air handler for cooling and dehumidifying air.

Unitary air conditioners range in capacity from a few tons to over 352 kW (100 tons). All use positive displacement compressors. The refrigerant used is essentially all HCFC-22, although a few older systems use CFC-12 or CFC-500. Thus, there is little potential for ozone depletion reduction in unitary air conditioners.

Water chillers are of two types: positive displacement compressor and centrifugal compressor systems. Positive displacement compressor chillers use reciprocating, scroll, or screw compressors and have capacities ranging from about 35 kW (10 tons) to over 3500 kW (1000 tons). They are almost exclusively HCFC-22 systems, although a few use CFC-12. Centrifugal compressor chillers range from about 350 kW (100 tons) to over 28000 kW (8000 tons). They primarily use CFC-11 and CFC-12, although some use of CFC-114, CFC-500, and HCFC-22.

Since centrifugal water chillers are by far the largest users of CFC's in comfort air conditioning, they are the principal focus of ozone depletion reduction in the Comfort Air Conditioning sector.

CFC-11 is used in water-cooled centrifugal water chillers from approximately 350 kW (100 tons) to 5600 kW (1600 tons) capacity. Some systems use multiple-stage compressors with direct-drive hermetic motors. Some have open drives of various types. High speed, single stage designs are used up to 3300 kW (950 tons). These compressors are gear driven and may have either hermetic or open motor drives. CFC-11 has the highest cycle efficiency of the commonly used refrigerants. Its low density results in designs having relatively large impellers and interconnecting piping. Maximum working pressure is low enough to exempt systems from having to meet ASME pressure vessel code requirements, which implies lower costs. Pressure differences for leakage of refrigerant from the high side (condenser side) of the system are low. The evaporator side operates below atmospheric pressure, resulting in the potential for air leakage into the system. Purge systems are provided to remove air and other non-condensibles, but the purged gas also includes some refrigerant.

CFC-12 is used in water-cooled centrifugal water chillers from approximately 350 kW (100 tons) to 4200 kW (1200 tons). It also is used in air-cooled centrifugal water chillers. The moderate density and pressure differential of CFC-12 causes the compressors in these systems to operate at higher rotational speeds, have either single or multiple stages, and in most cases are gear driven by hermetic motors. Open drives are used also. CFC-12 systems operate at higher pressure than CFC-11 systems and thus must meet ASME pressure-vessel code requirements. The potential exists for refrigerant leakage from both the low-side and the high-side of the system because pressures are above atmospheric throughout the system.

CFC-500 (3/4 CFC12 and 1/4 HFC152a) is sometimes used in centrifugal water chillers designed for CFC-12 in order to broaden the capacity range. Systems using these refrigerants operate above atmospheric pressure throughout and so offer a potential for CFC leakage as well.

CFC-114 is used in centrifugal chillers for applications on naval vessels including submersibles. Naval chillers are built in the range from 440 kW (125 tons) to 1400 kW (400 tons). Operation with the evaporator above atmospheric pressure is desirable to prevent inward leakage of moisture-laden air, which can lead to corrosion problems. CFC-114 is a stable compound and can be handled without difficulty by air purification systems on submersibles.

HCFC-22 is generally used in the largest centrifugal water chillers, usually 7000 kW (2000 tons) capacity and above. Compressor rotational speeds are higher, and system pressures are considerably above atmospheric resulting in large pressure differences and potential leakage.

Because centrifugal water chillers are designed for specific refrigerants, direct refrigerant substitutions can only be made in cases where the properties of the substitute refrigerant are nearly the same as those of the refrigerant being replaced (in order to maintain the same capacity and level of performance as obtained with the original refrigerant). There is no possibility for substituting HCFC-22 into CFC-11, CFC-114 or CFC-12 chillers, for example. Furthermore, any of the proposed new alternative refrigerants (e.g. HCFC-123 and HFC-134a) are not likely to prove to be "drop-in" replacements in the existing machines without significant hardware changes and some loss in thermodynamic performance.

9.2 Existing Equipment

Significant commercial use of centrifugal water chillers began in the mid 1930's and ARI /Den89/ estimates that there were approximately 74,000 in service in the United States in 1986. The estimated distribution of refrigerant type and average charge among these units are shown in Table 9.1.

No data are available for world wide use of refrigerants in centrifugal water chillers. Chiller industry estimates are that the United States has at least two-thirds of the total world wide installations. On this basis, the total world wide centrifugal chiller installations in 1986 was about 110,000.

For equipment in the field, the primary CFC emissions from centrifugal chillers are due to normal leakage, servicing, and disposal. Mooz /Moo82/ provided estimates for U.S. emissions due to these sources in 1980. Using average values from the Mooz report and extrapolating to 1986 world wide emissions for existing centrifugal chillers yields the results shown in Table 9.2. The last column of Table 9.2 shows estimates of emission levels which might be achieved within five years with the following control measures.

Table 9.1. U.S. Centrifugal Chillers in Service

Refrig. Type	Approx No. of Units	Percent of Total Units	Average Charge Kg	(lbs)	Refrig. in Service millions Kg	(lbs)
CFC-11	59,200	80	500	(1100)	29.6	(65.1)
CFC-12	7,400	10	727	(1600)	5.4	(11.8)
CFC-114	1,000	1	364	(800)	0.4	(0.9)
HCFC-22	2,960	4	1818	(4000)	5.4	(11.8)
CFC-500	3,700	5	1182	(2600)	4.4	(9.6)
	74,260				45.2	99.2

Table 9.2. Estimated World Wide Emissions from Existing Centrifugal Chillers, tonnes (10^6 lbs)

Source	Est. 1986 Emissions		With Control Measures	
Leakage	3,000	(6.6)	1,800	(4.0)
Servicing	4,400	(9.6)	0,900	(2.0)
Disposal	0,500	(1.1)	0,050	(0.1)
Total	7,900	(17.3)	2,750	(6.1)

9.2.1 Leakage

Leakage which results from the aging or failure of seals, pressure relief valves, and fittings can be reduced by improved leak detection methods andmaintenance procedures. Also, the purge units for CFC-11 chillers can be made more efficient. Control measures for reducing these emissions could include installation of leak detection and warning systems, improved purge systems, and improved pressure relief devices. Implementing these measures will require design, educational and cultural changes throughout the industry.

9.2.2 Servicing

Emissions during servicing can occur in several ways including failure to remove charge from systems before servicing, failure to save refrigerant for reuse, and use of refrigerant to flush open systems or systems with hermetic motor burns. Servicing offers the greatest potential CFC emission reduction from chillers. To significantly reduce servicing emissions a two-fold solution is required: first, to develop and implement the technology for in-service recovery and recycling of CFC's, and second, to assure that work practices take advantage of such technology. Much of the service work is done by independent local contractors. In order to assure that they make the investment in equipment, training, and on-the-job time necessary to minimize emissions, some form of regulation may be necessary.

9.2.3 Disposal

Refrigerant can also be recovered and recycled upon equipment disposal. Again, the two-fold solution discussed under "Servicing" is required.

9.2.4 Substituting

Further reduction of CFC emissions from existing centrifugal chillers by substituting environmentally acceptable alternatives for CFC's in the field is a possibility, but there are many problems associated with this and the costs would be very high. Following are some of the problems:

9.2.4.1 HCFC-123 for CFC 11

HCFC-123 is a more aggressive solvent than CFC-11. Elastomers and seals may have to be replaced with materials which are more compatible with HCFC-123. Materials used in motors of hermetic chillers may not be compatible with HCFC-123, putting motor reliability at risk or requiring motor replacement. In some models where high voltage motors are used, the low corona voltage limit of HCFC-123 makes it totally incompatible. System capacity will be reduced with HCFC-123, possibly as much as 10%. This may necessitate changeout of the compressor to a higher-capacity model or purchase of additional chillers in some installations. Cycle efficiency will be reduced at least 1 or 2% and this may be compounded by heat transfer surfaces not working as well in HCFC-123 as in CFC-11, further reducing cycle efficiency. The higher toxicity of HCFC-123, combined with more restrictive safety codes, also may create problems in retrofit (substitution) situations.

9.2.4.2 HCFC-123/CFC-11 Azeotrope for CFC-11

HCFC-123 and CFC-11 are reported to form an azeotrope which contains 78% HCFC-123 and 22% CFC-11. This azeotrope is said to have a boiling point close to that of pure CFC-11, making it more attractive than pure HCFC-123, especially for substitution in existing systems. The nature of the azeotrope appears to be such that HCFC-123 may be added to CFC-11 chillers as needed to replace CFC-11 removed by servicing or through leaks. However, no thermodynamic data exists on HCFC-123/CFC-11 mixtures so that performance calculations cannot be made at this time. Furthermore, this approach would not significantly alleviate the material compatibility problems associated with HCFC-123.

9.2.4.3 HFC-134a for CFC-12

HFC-134a requires about 15% higher tip speeds than CFC-12, thus requiring impeller replacement and/or gear box replacement. CFC-12 desiccants are not compatible with HFC-134a. CFC-12 oils are not miscible with HFC-134a. HFC-134a oils (polyglycols) are not compatible with CFC-12, thus requiring a thorough flushing of the system before replacement. HFC-134a cycle efficiency is slightly lower than CFC-12, and existing heat transfer surfaces will not work as well in HCFC-134a if the small nucleate cavities retain residual oils. Some desiccants (e.g. activated alumina) commonly used in CFC-12 systems are not compatible with HFC-134a.

9.2.4.4 HFC-152a/HCFC-124/HCFC-22 Mixture for CFC-12

One refrigerant manufacturer has recently proposed this ternary non--azeotropic mixture as a substitute for CFC-12. At this time little information is available concerning its potential for replacement of CFC-12 in centrifugal chillers. It is soluble with the conventional refrigeration oils. However, any non-azeotropic mixture during evaporation and condensation is likely to have poor heat transfer performance (> 10% decrease) in the flooded evaporation and shell side condensation normally used in centrifugal chillers. Thus, there is likely to be a significant performance penalty when substituted in existing chillers. Servicing such a system brings on new difficulties because any vapour losses will change the composition and thus the performance. The industry has yet to develop measuring and charging equipment and procedures that can mitigate this problem.

9.2.4.5 HCFC-124 for CFC-114

HCFC-124 has been suggested as an alternative to CFC-114 in centrifugal chillers, such as those used in naval applications. The thermal properties of HCFC-124 are not well-documented, so accurate analysis is not possible at this time. However, HCFC-124 requires operation at higher pressure levels, higher RPM, and with smaller compressor components than CFC-114. HCFC-124 is not suitable for use in existing CFC-114 systems but is a candidate for use in new system designs.

9.3 New Equipment

Total U.S. centrifugal chiller production has fluctuated around 3500 units per year since 1965 /Rad87/. According to knowledgeable persons in the industry, the world-wide production is not significantly larger than this, probably around 4000 units per year.

CFC emissions during the manufacture and shipping/installation of centrifugal chillers was also estimated by /Moo82/ for U.S. production. Extrapolating these estimates to world-wide production yields the results shown in Table 9.3.

9.3.1 Manufacture

Emissions during the manufacture of new chillers come from two sources, leak testing and unit "run-in". CFC-12/air mixtures are normally used for leak testing, regardless of the type of refrigerant which will ultimately be used in the unit. Most manufacturers already employ reclaim systems for recovering this refrigerant. However, the ozone depletion potential of these emissions could be significantly reduced by switching to HCFC-22 as the test gas. The HCFC-22 must be mixed with another gas such as nitrogen for leak detection because HCFC-22/air mixtures are flammable at high pressure. The second source of manufacturing emissions, "run-in" testing, is not conducted on all units. In this case the specific refrigerant is used and recovered/recycled after the test. It should be noted that manufacturing improvements also can reduce leakage emissions in the field. Tighter leak rate specifications, for example, could reduce field emissions.

Table 9.3. Estimated CFC Emissions from Manufacturing and Shipping/ Installation of Centrifugal Chillers, 10^6 Kgs (10^6 lbs)

	1986		With Control Measure	
Manufacture	900	(0.2)	5	(0.01)
Shipping/Installation	300	(0.06)	20	(0.05)
Total	1,200	(0.26)	25	(0.06)

9.3.2 Shipping/Installation

Emissions from new units also occur during shipping and installation. Most units are shipped with a small holding charge of nitrogen and are charged with refrigerant at the job site. Occasionally there may be damage during shipping which is not detected until there is excess leakage during the charging process. Of course, those units which are shipped charged with refrigerant would lose the charge if damage occurred during shipping. In general, shipping/installation emissions are quite small and offer little potential for reduction.

The charge required for new units is not an emission, but is a part of the annual CFC market. Based on an industry survey, ARI /Den89/ estimates the average charge in a centrifugal chiller to be 600 kg (1340 pounds). For the world-wide production of centrifugal chillers, this results in approximately 2.5 million kg (5.4 million pounds) per year for charging new chillers.

There is potential for reducing the average charge per chiller with new heat exchanger designs, and some manufacturers have already made design changes to reduce refrigerant charge. However, in view of the current uncertainty in CFC availability, manufacturers are unlikely to invest in additional development programs to reduce refrigerant charge in present designs.

9.3.3 Summary

With restrictions on CFCs, the principal choices open to centrifugal chiller manufacturers are to redesign CFC-11 and CFC-12 chillers to operate with HCFC-123 and HFC-134a and to develop new chillers which can operate with HCFC-22 at lower loads. In the case of redesigning CFC-11 chillers to use HCFC-123, this will likely involve the use of different materials for elastomers, seals and hermetic motor insulation, and may involve resizing of heat exchangers and the possible need for new heat transfer surfaces. In the case of redesigning CFC-12 chillers to use HFC-134a, design modifications will likely include changing gear boxes, increasing impeller diameters, use of a new oil, resizing of heat exchangers, and possibly the need for new heat transfer surfaces. Extending HCFC-22 to lower loads will require the development of new designs for all major system components.

In the event that serious problems should arise which rule out all of these choices, the most probable outcome will be an extension in the range of positive displacement compressor chillers (with HCFC-22) to higher loads. This, however, may result in energy efficiency penalties estimated to be 6 to 7%.

9.4 Environmental Impact

Table 9.4 shows a summary of eight potential control measures for reducing the centrifugal chiller market requirements for CFC's. Several of these control measures, while having a direct favourable impact on the greenhouse effect and ozone depletion, can have an indirect negative environmental impact because they would increase energy use. For example, field retrofit with HCFC-123 and HCFC-134a (Control Measure 4) could lower chiller efficiency as much as 5%. Extrapolating from estimates of U.S. centrifugal chiller energy usage given by Fischer /Fis88/· this could result in a world-wide energy use penalty of approximately 8.8 x10^9 kWh (0.03 quads). Because most of our energy comes from fossil fuels, the increased CO_2 generated will have a negative impact on the greenhouse effect. Also, replacement of CFCs-11 and -12 in the field with HCFC-123 and HFC-134a, respectively, is likely to have a negative impact on reliability of most chiller designs even though the retrofit includes some component material changes to provide compatibility with the new refrigerants.

Conversion of new centrifugal chillers to HCFC-123 and HFC-134a (Control Measure 7) is likely to have a smaller impact on energy efficiency (2.5% assumed). In this case, extrapolating the Fischer U.S. figures yields a world wide energy use penalty of 4.4 x 10^9 kWh (0.015 quads). The impact on reliability will be smaller but still significant. The high reliability which is present today is due in part to the 50 years experience with CFCs. Making a change in the system design as fundamental as the working fluid will almost assuredly result in a less reliable system until new experience is gained.

Control Measure 8 of Table 9.4 refers to expanding the range of positive displacement compressor chillers upward and extending the range of HCFC-22 centrifugal compressor chillers downward to cover the range of CFC-11, CFC-12, CFC-500 and CFC-114 centrifugal chillers. This would be an alternative to implementation of HCFC-123 and HFC-134a centrifugal chillers. While HCFC-22 chillers are competitive in their current ranges, extending HCFC-22 positive displacement chillers upward to cover the range currently served by centrifugal chillers would result in a 6 to 7% energy penalty. Also, positive displacement compressors generally require more frequent and more substantial periodic overhauls than centrifugal compressors.

9.5 Economic Aspects

In order for control measures 1, 2, and 3 of Table 9.4 to be effective, one of two things must happen: (1) they must be mandated or (2) the price of refrigerant must rise high enough that recovery and recycling of refrigerants is economically feasible. Current U.S. regulatory policy is directed towards the second alternative. At the present time there is at least one company in the business of recovering and recycling refrigerants. For recovery and recycling to be practical on a broad scale, the price of refrigerant must increase significantly.

Control Measure 4, the field retrofit of CFC centrifugal chillers with HCFC-123 and HCFC-134a, will be very expensive to the consumer. In some cases the retrofit expense might approach the cost of a new system. Contributors to the high retrofit cost could include the following:

Possible replacement of elastomers and seals in CFC-11 systems.

Replacement of the oil in CFC-12 systems, with thorough flushing to remove CFC-12 which is not compatible with the new oil for HFC-134a.

Replacement of the impeller and/or gear box in CFC-12 systems.

Possible replacement of the motor in hermetic CFC-11 systems.

Possible replacement of heat exchanger tubes to achieve reasonable efficiencies.

Possible purchase of additional chiller capacity to offset capacity reduction.

Replacement of the compressor in CFC-11 system with a larger capacity compressor to maintain the same cooling capability.

CFC reduction of 7,900 tonnes/year (17.3 million lbs/yr.) can be reached only after a number of years have passed. This time is required to produce enough refrigerant, obtain conversion hardware and financing, and apply competent service people to complete the process.

Table 9.4. Environmental Impact

Control Measure	Probable CFC Market Reduction tonnes year (10^6 lbs/yr)	Penalty (quads/year) 10^{12} kWh	Reliability Impact
1. Leakage Reduction	1,200 (2.6)	None	+
2. Improved Servicing	3,500 (7.6)	None	+
3. Recovery at disposal	500 (1.0)	None	None
4. Field Retrofit with HCFC-123 and HCF-134a	7,900* (17.3)	0.009 (0.03)	--
5. Substitute HCFC-22/N_2 for CFC-12 in leak testing	100 (0.2)	None	None
6. Shipping/Inst. Use Reduction	5 (0.01)	None	+
7. Conversion to HCFC-123 & HFC-134a	2,500 (5.4)	0.004 (0.015)	-
8. Expand range of 22 systems	2,500** (5.4)	0.0012 (0.04)	-

\+ Control measure increases reliability.
\- Control measure decreases reliability.
* Not additive with 1, 2, 3, and 6.
** Not additive with 7.

Control Measure 7 is the conversion of CFC chiller designs to HCFC-123 and/or HFC-134a. One manufacturer has estimated that this would require approximately a 50 man-year effort and $2 million capital cost expenditure over a 3 year period. Similar efforts and capital expenditures might be expected by the other chiller manufacturers. Chiller manufacturers are cautious to move ahead with these redesigns because of uncertainties surrounding the long-term safety and availability of HCFC-123 and HFC-134a.

Control Measure 8, the conversion to HCFC-22 positive displacement and centrifugal compressor chillers in CFC centrifugal tonnage range, is an alternative to Control Measure 7. Conversion to HCFC-22 will be more expensive, at least tripling the costs shown for Control Measure 7; it could be higher for some manufacturers. It is estimated that 6 years or more would be required to replace the full range of products with HCFC-22 offerings.

9.6 Concluding remarks

The most logical scenario for reducing CFC usage to support the centrifugal chiller market involves two strategies:

A. For existing equipment in the field it is necessary to implement control measures to reduce leakage, improve servicing and encourage recovery for recycling or safe disposal. In order for these measures to happen there will either have to be a mandate which requires them, or the price of the refrigerant will have to rise sufficiently to make the procedures cost effective.

B. For new chiller equipment, it will be necessary to implement new design procedures for the conversion of CFC chiller designs to HCFC-123 and/or HFC-134a and the extrapolation of HCFC-22 positive displacement and centrifugal compressor machines to CFC centrifugal compressor machines to CFC centrifugal capacity range.

Strategy A would yield approximately a 50% reduction in world-wide CFC usage in support of the centrifugal chiller market, and Strategy B would yield an additional 23%. The remainder would be phased out gradually as currently installed CFC chillers are replaced. ARI /Den89/ estimates the phase out would be essentially complete by 2025.

10. MOBILE AIR CONDITIONING

10.1 Introduction and Current Global Usage

Air conditioning was introduced in automobiles as a means of comfort control as early as 1953. Air conditioning also contributes to safety by increasing driver alertness and providing fog-free windows. In the 1987 world market of some 45.7 million new cars, trucks and buses, approximately 21.9 million (48%) were equipped with air conditioning /MWM88/GMC89/. CFC-12 usage for these new vehicles is approximately 29,900 metric tonnes annually. The amount of CFC-12 currently required for servicing air conditioned vehicles is estimated to be three times that required for new vehicles, or some 89,700 metric tonnes. Thus, the global annual usage of CFC-12 for mobile air conditioning is on the order of 120,000 metric tonnes (Table I). Based upon the latest Chemical Manufacturers Association data /CMA88/ for 1987 CFC-12 production (424,726 metric tonnes), mobile air conditioning currently accounts for approximately 28% of the global usage of CFC-12.

10.2 Technology Status

10.2.1 General Description

Mobile air conditioning (MAC) has evolved into a relatively small, high capacity system to satisfy the unique air conditioning needs of motor vehicles. Present systems utilize a vapour-compression refrigeration cycle with CFC-12 as the refrigerant. Current automobile systems use approximately 1.2 kg of CFC-12 while light-duty trucks use about 1.5 kg. CFC-12 is used exclusively because of its thermodynamic properties and because it is stable, non-toxic, non-flammable, and non-corrosive. With mineral oil as the system lubricant, the CFC-12/mineral oil combination forms a compatible, cooling agent/lubrication system for the typical vehicle MAC system. Most present day MAC systems are installed at time of vehicle production and are designed specifically for each particular vehicle line.

The typical MAC system consists of a compressor, a condenser, an expansion device, an evaporator, a refrigerant (CFC-12), a mineral oil lubricant and assorted interconnecting hoses. The compressor is belt-driven from the engine through an electromagnetically-actuated compressor clutch pulley. It compresses low pressure refrigerant vapour from the evaporator to a high pressure, high temperature vapour. Circulating with the refrigerant is the system oil to provide proper compressor lubrication. The compressor is mounted on the engine while the remaining system components are attached to the vehicle chassis.

The output from the compressor is fed into the condenser which is typically located on the chassis behind the front grille. The condenser function is to cool the high temperature, high pressure vapour refrigerant and cause it to condense and form a high pressure liquid. The high pressure liquid refrigerant is metered by the expansion device or orifice tube and enters the evaporator in a low pressure vapour-liquid state. As the air within the passenger compartment is passed over the evaporator, heat from the air passes through the evaporator core into the low pressure refrigerant causing it to vapourize, thereby cooling the air and increasing passenger comfort. As a secondary benefit, as the cooling of the air takes place, moisture in the air condenses on the outside surface of the evaporator core and is drained off as water. The humidity within the passenger compartment is therefore also reduced as part of the cooling process. From the evaporator the resulting low pressure vapour is returned to the compressor where the cycle is repeated.

10.3 Specific Requirements

Because of the necessity of using an air-cooled condenser within the engine compartment at ambient air temperatures up to 50 C, condensing temperatures can approach 100 C. Since the condensing temperature must be less than the refrigerant's critical temperature, and to avoid both extreme condensing pressures and low-side vacuum operation, CFC-12 has proved to be the optimum refrigerant for MAC use.

The horsepower demand and drive efficiency require that the compressor be driven by the engine. This necessitates the use of belt-driven, open-type compressors with shaft seals. Because system components are located on both the engine and the chassis, flexible, and therefore permeable, refrigerant lines must be used to allow for relative motion and to dampen noise and vibration.

10.4 Reasons for CFC-12 Emissions

Under current practices, CFC-12 can be emitted to the atmosphere in many ways. During MAC component fabrication, leak detection is often accomplished using CFC-12 as the leak detection gas with subsequent escape of said gas to the atmosphere. Charging stands used in production and service release a certain amount of CFC-12 as hoses are disconnected from the newly charged vehicle. If a vehicle system leaks, refrigerant will be released until the leak is found and fixed or the system is completely discharged. In service, a system may be first charged with CFC-12 to aid in detecting system leaks and then vented to the atmosphere to repair the leak. In addition, the refrigerant is vented to the atmosphere during system repair or when other non-MAC repairs require removal of MAC components. MAC system venting has become commonplace because it was perceived to be a safe practice. CFC-12 is also released as a result of normal system component aging, in vehicular accidents, and during scrappage of the vehicle. Consumers also release CFC-12 through improper use of purchased service cans for recharging a low performing MAC system rather than taking the vehicle in for repair. As a result of the awareness brought on by the worldwide concern for the protection of the Earth's stratospheric ozone, all of these practices are currently under review.

10.5 Existing Equipment - CFC Reductions

10.5.1 Conservation - CFC-12 Recovery and Reuse

Conservation implies the judicious use of CFC-12. This can be facilitated by instituting better handling practices in both the original manufacture and service arenas. Current charging systems should be reviewed to reduce hose lengths and to provide shut-off connectors designed to minimize refrigerant release when disconnected. The ability to recharge leaking systems without necessarily having to repair the leak can be discouraged by the elimination of the small service cans (14 ounce can, 400 gram can, etc.) that are currently sold over-the-counter to the general public. It is estimated that this market accounts for 20,000 metric tonnes of CFC-12 annually. The requirement for CFC-12 for recharging repaired MAC systems by trained technicians can be met with the currently available "30 pound refrigerant cylinder". The resultant annual savings could be on the order of 12,000 metric tonnes.

Refrigerant recovery and reuse during original equipment manufacturing, servicing, repair, and when the vehicle is scrapped have been shown to be technically feasible in a recent United States Environmental Protection Agency /EPA89/ coordinated ad hoc mobile air conditioning industry study. Equipment performance specifications, recycling procedures and equipment availability must be addressed and resolved to achieve the benefits recycling appears to offer. The ability to recycle, coupled with an educational effort to emphasize the importance of minimizing the release of CFC-12, appears to hold great promise for short-term emission reductions. The U.S. EPA believes that up to 18,700 metric tonnes of CFC-12 are potentially available to be recovered and reused annually through recycling in the United States. Given the anticipated effectiveness of the recycling process, the availability of sufficient recycling equipment (an estimated 3-year task) and incentives for its use (legislation/CFC-12 price), a realistic estimate of CFC-12 annual savings would be 14 thousand metric tonnes in the United States. On the assumption that the U.S. has one-half of the world's air conditioned vehicles, the potential global savings would be on the order of 28 thousand metric tonnes. Based on a average reclaimer/recycler cost of US$3000 and an estimated 300,000 MAC service outlets worldwide, the investment in widespread recycling would approach US$900 million /KWM89/.

10.5.2 System Flushing and Leak Testing

CFC's are also used for flushing MAC systems following component failure (e.g., CFC-11) and for the leak testing of original equipment components during manufacture (CFC-12). Flushing can largely be eliminated via the use of currently available add-on service filters to trap debris generated during the failure while leak testing usage can be replaced by either helium leak detection methods or the substitution of HFCF-22 for CFC-12 as the test gas. While CFC savings estimates are not available for these usages, the elimination of MAC system flushing with CFC-11 could result in an estimated savings of 500 metric tonnes.

10.6 Drop-in Replacement Refrigerants

Presently, there is no known refrigerant that is a direct, "drop- in" substitute for CFC-12. As a result, the use of any substitute requires significant system modifications for new MAC systems and therefore cannot be used in servicing the existing CFC-12 fleet. As a result, conservation and recycling appear to be the best candidates for short-term impact on CFC-12 reductions.

The concept of retrofitting existing vehicles to accept a less environmentally harmful refrigerant is theoretically attractive. To date, however, no pure refrigerant, azeotrope or blend exists that can be used to replace CFC-12 in existing systems without major system changes. Such azeotropes and blends are treated in greater detail later in this treatise. A switch to such refrigerants would require a different desiccant which would, in turn, require changing the accumulator or receiver. In addition, the existing hoses would very likely have to be replaced by hoses of lower refrigerant permeability. Should a different lubricant be required, the system would have to be flushed prior to conversion. Current flushing procedures use CFC-11, a controlled substance, which is exhausted to the atmosphere during the process. In the worst case, e.g., a complete retrofit with HFC-134a, the cost to remove and replace the entire system would approach US$1000-1500 per vehicle. Thus, the concept of retrofitting existing vehicles is not considered to be a desirable solution.

10.6.1 Refrigerant Containment Enhancements

The possibility of using an hermetic A/C system in mobile air conditioning has been thoroughly investigated and has been found to require electrical power far in excess of that available with current electrical systems. The costs would be very high, the required development time is estimated to be in excess of ten years, and it does not, in itself, eliminate the need for CFC-12.

Enhancing system leak integrity has been suggested as a short-term means of conserving CFC-12. Such enhancements include hoses of reduced permeability, improved compressor shaft seals, and minimized system charge levels. Hoses covering a range of permeabilities are currently used in MAC systems and the possibility exists to convert the hoses on many new vehicles to those of lower permeability. Since hoses of lower refrigerant permeability tend to be more rigid, the effects of an increase in noise and vibration transmission would require study. The added cost is estimated to be US$5 per new vehicle. This would reduce emissions from hoses in new vehicles sold before HFC-134a replaces CFC-12. On the subject of improved shaft seals, the currently-used face seals and lip seals provide comparable refrigerant containment and represent state-of-the-art technology. Reducing system charge to a lower level essentially creates a critically-charged system which is known to exhibit transient performance problems and increase the risk of compressor damage due to poorer oil return. Such reduced charge would also have a tendency to bring the customer in for service more often, resulting in CFC-12 losses during recharging. Each of these enhancements is an ongoing engineering issue that each system manufacturer is continually attempting to address within the framework of system durability and customer satisfaction.

10.6.2 Future Service Needs for CFC-12

To use an alternate refrigerant that is as safe for humans as CFC-12 and, at the same time, does not harm the environment will require the redesign and revalidation of the vehicle air conditioning system. As redesigned systems using such a refrigerant supplant CFC-12 based systems, the need for CFC-12 in new vehicles will be eliminated. However, even after the total new vehicle fleet is converted to the alternative refrigerant, a need will still exist for a period of time for CFC-12 refrigerant in order to repair and recharge existing in-service CFC-12 systems. Data published in MVMA Motor Vehicle Facts & Figures '88 /MVM88/ gives the median lifetime of a car to be 10.9 years and that of light trucks to be 14.9 years. The same reference gives maximum usable life for both cars and light trucks to be in excess of 20 years. Thus, the need to service the existing CFC-12 fleet will disappear with time.

10.7 New Equipment - Alternate Refrigerants

10.7.1 General

Because there exists no direct drop-in replacement for CFC-12, conversion from CFC-12 to another refrigerant is a major undertaking. This effort involves developing and commercializing a new refrigerant/lubricant system. Since MAC is a system that is integrally designed into each vehicle line, the design, validation and implementation of a modified MAC system for new vehicles will require substantial resources to meet the current timetable envisioned by the Montreal Protocol.

There are few chemical substitutes for the CFC-12 refrigerant in a MAC system that have the necessary combination of being thermodynamically suitable, stable, non-toxic, non-corrosive, non-flammable and non-ozone depleting. In addition, they should not contribute significantly to the "Greenhouse Effect".

10.7.2 HFC-134a

Presently, the most viable candidate to replace CFC-12 is HFC-134a because it does not contain chlorine and, therefore, would not contribute to ozone depletion. The system changes required for the use of HFC-134a are relatively modest; the pressure/temperature characteristics of HFC-134a are similar to those of CFC-12 although enhanced condensing will be required to restore CFC-12 performance and durability levels. In addition to enhanced condensing, two problem areas remain in applying HFC-134a to MAC systems. First, a suitable lubricant that is compatible with HFC-134a has not yet been fully developed, but the prospects appear favourable. Second, the toxicity of HFC-134a has not been fully evaluated but looks promising. Both of these items are aggressively being investigated by the MAC industry and its suppliers. Given successful lubricant development, favourable final toxicity results (expected in late 1992 /PAF89/) and adequate global supply, HFC-134a could be introduced in new vehicles as early as 1993. Complete MAC industry conversion to HFC-134a is estimated to require 3-5 years due to anticipated component changes, critical supply pipelines, service training needs, equipment supply bottlenecks, etc. Full implementation will result in an annual CFC-12 savings of 29,900 metric tonnes. Based on preserving current performance and durability levels, conversion costs are estimated to be US$30 -100 per vehicle with an anticipated investment of approximately US$1,000 million.

10.7.3 HCFC-22

HCFC-22 is not presently on the controlled CFC list but, because it contains chlorine, it could become controlled at a later date. HCFC-22 is not easily contained by the currently available elastomers used for seals and flexible hoses required in MAC installations. Lubricants are also not readily available for use with HCFC-22 in a mobile air conditioning system. Finally, the thermodynamic characteristics of HCFC-22 are sufficiently different from those of CFC-12 that a complete redesign of every component of the MAC system would be required with long lead times and a major reinvestment to accomplish the conversion. HCFC-22 is not presently viewed as a viable substitute for automobile air conditioning and would likely only be considered, along with refrigerant blends, if HFC-134a were found to be unacceptable for use.

10.8 Refrigerant Blends

Blends such as HCFC-142b/22, CFC-12/DME and CFC-500 have been proposed as interim substitutes until an environmentally acceptable refrigerant with little or no ozone depletion potential (ODP) can be implemented. HCFC-142b/22 has similar problems in application to those of HCFC-22, particularly in containment. When used in a MAC system, the HCFC-22 in this blend selectively escapes the system through hoses and seals, eventually creating a flammable system mixture. The CFC-12/DME blend is also not a MAC "drop-in" substitute for CFC-12. Flammability concerns indicate a mixture containing 10-12% dimethylether (DME) would have to be considered to provide an adequate safety margin. The present MAC system desiccant strongly adsorbs the dimethylether thereby preventing the desiccant from further removing moisture from the system. A new desiccant compatible with DME would be required. Copper plating tendencies need to be evaluated relative to compressor wear. DME material compatibility needs to be evaluated to determine its impact on the various systems that presently exist in the field and on new system materials. Permeation rates of DME through system hoses are expected to be higher than CFC-12 thereby changing the mixture composition with time. Decomposition of the two materials under operating conditions is of concern since they may react with one another to form extremely potent carcinogens (chlorinated methylethers) creating health and handling concerns.

CFC-500, a blend of CFC-12 and HFC-152a, has been determined to aggressively attack currently known desiccants. Although CFC- 500 reduces the amount of CFC-12 in a system, it does not eliminate CFC-12 from future release to the atmosphere. As a result, further review of this mixture as a replacement refrigerant has been deferred.

Du Pont recently announced two ternary refrigerant blends for consideration as interim refrigerants pending the development of HFC-134a. The first is a blend of HCFC-22, HFC-152a and CFC-114 (available now) with a reported ODP of 0.38 and the second is a blend of HCFC-22, HFC-152a and HCFC-124 with a reported ODP of 0.02. Both have been touted as possible direct replacements for CFC-12 in refrigeration and air conditioning systems. An initial evaluation of these blends has revealed that they cannot be considered "drop-in" replacements for CFC-12 in existing MAC systems because the majority of current MAC hoses are not capable of containing the HCFC-22 in the blends and the existing system desiccant will be chemically attacked and completely destroyed by the HFC-152a present. Also, the blends require the use of an alkylbenzene lubricant, necessitating both extensive compressor development testing and flushing out the existing lubricant with CFC-11, a controlled chemical. In addition, CFC-114 is a controlled substance under the current Montreal Protocol and HCFC-124 is currently under suspicion by the U.S. EPA of being carcinogenic. Toxicity testing of HCFC-124 is scheduled to follow that of HFC-134a /PAF89/. Given the above, neither of these blends qualify at this time for use in new or existing MAC systems.

While mixtures may appear attractive for short-term reductions in CFC-12 consumption, each mixture demands significant time and resources to evaluate, particularly in the areas of compressor durability, desiccants, lubricants, hose and o-ring materials that not only exist for new cars but the entire in-use fleet. One question is whether to extensively examine refrigerant blends or to apply resources to the development of systems capable of utilizing HFC-134a which would remove mobile air conditioning systems from the ozone layer depletion problem completely.

10.8.1 Alternate Refrigeration Cycles

Use of alternate cycles has also been proposed as a means of eliminating CFC-12 usage. There currently are no alternative cycles that can match the performance, power, efficiency, packaging, and the cost of the current vapour-compression cycle system. Alternative cycle systems for mobile air conditioning are, at best, a very long-term solution. They cannot be expected to be part of the solution for meeting the Montreal Protocol.

10.9 Summary

Mobile air conditioning currently utilizes CFC-12 exclusively as the refrigerant in a vapour-compression refrigeration cycle. The compressor is engine-driven via a drive belt and associated electromagnetic clutch. The compressor is mounted on the engine while the remaining system components are attached to the vehicle chassis, thereby requiring the use of flexible refrigerant lines to dampen relative engine/chassis movements. In addition to reliably providing for passenger comfort and driving safety over a wide range of ambient conditions, the system must not put the occupants of the vehicle or the public at risk due to exposure to toxic or flammable materials.

Current annual MAC usage of CFC-12 is estimated to be 120,000 metric tonnes or 28% of global CFC-12 production. Original manufacture uses approximately 29,900 metric tonnes while 89,700 metric tonnes are used for servicing existing vehicles.

Current CFC-12 emissions to the atmosphere result from using CFC-12 as a leak detection gas, losses during system charging, system leaks, recharging leaky systems without having to fix the leak, service venting prior to repairs, vehicle scrapping, and poor handling practices in general. Emissions from these sources can be minimized or eliminated. Alternate leak detection gases are available, e.g., HCFC-22. Service venting can be significantly reduced by implementing CFC-12 recycling during service and vehicle scrappage. Resulting annual savings would be on the order of 28,000 metric tonnes. Elimination of over-the-counter small service cans of CFC-12 would minimize the ability of the general public to recharge leaky systems without repairing them and result in an annual estimated savings of 12,000 metric tonnes. The practice of MAC system flushing with CFC-11 after component failure can be eliminated by the use of as add-on filter which would contribute to overall CFC savings.

Because there exists no direct "drop-in" replacement for CFC-12 in MAC systems, conversion to another refrigerant is a very major undertaking. Presently, the most viable candidate to replace CFC-12 is HFC-134a, a non-ozone depleting chemical. MAC system changes required for HFC-134a use are relatively modest since HFC-134a thermodynamic properties are similar to those of CFC-12. Given successful lubricant development, favourable final toxicity test results and adequate global supply, HFC-134a could be introduced in new vehicles in 1993. Full implementation (a 3-5 year task) will result in a CFC-12 savings of some 29,900 metric tonnes annually.

Novel mixtures of refrigerants have been offered as potential replacements for CFC-12 in original equipment and all have been found to be unacceptable, generally due to incompatibility with existing and/or available system materials. Candidates proposed to date for retrofitting existing systems all require significant system changes and, in many cases, flushing with CFC-11 to remove the existing lubricant.

10.10 Conclusions

The technology of reducing leakage, recycling CFC-12 and full conversion to HFC-134a in new vehicle manufacture, properly applied, will effect an annual reduction in CFC-12 usage of approximately 70,000 metric tonnes during the course of the next 7-9 years (Table II). The conversion of new MAC systems to HFC-134a by the mid-late 1990's will leave only the existing CFC-12 fleet in need of CFC-12. This need will diminish with time and can be minimized by timely leak repair, preventative maintenance and CFC-12 recycling. With conversion to HFC-134a and aging of the existing

CFC-12 fleet, mobile air conditioning could be entirely converted to an environmentally acceptable refrigerant by the year 2010.

Table 10.1. Estimated Global CFC-12 Usage for Mobile Air Conditioning

New Vehicles	30,000 metric tonnes
Service	90,000 metric tonnes

Table 10.2. Options to Reduce Mobile Air Conditioning CFC-12 Usage

	Estimated Reductions		Earliest Date of
Option	New Vehicles	Service	Introduction
Recovery and Reuse of CFC-12		28,000 mt	1990
Elimination Recharge of Leaking Systems (Eliminate Small Service Cans)		12,000 mt	1990
Conversion to HFC-134a	30,000 mt		1993

Total Estimated Reduction in CFC-12 Usage 70,000 metric tonnes

Table 10.3. 1987 Free World Car & Light Truck Air Conditioning Demand
(million of units)

	CARS			TRUCKS			TOTAL VEHICLES		
WORLD AREA	VEHICLES	A/C	%A/C	VEHICLES	A/C	%A/C	VEHICLES	A/C	%A/C
NORTH AMERICA:									
U.S.A.	10.5	7.9	76	5.0	2.5	50	15.5	10.4	67
CANADA	1.1	0.7	60	0.4	0.2	40	1.5	0.9	60
OVERSEAS:									
EUROPE	12.4	1.2	10	1.5	0.1	8	13.9	1.3	9
LATIN AMERICA	1.1	0.7	60*	0.4	0.2	50*	1.5	0.9	60*
MID EAST	0.3	0.2	60*	0.3	0.2	50*	0.6	0.4	67*
AFRICA	0.3	0.2	60*	0.2	0.1	50*	0.5	0.3	60*
JAPAN	4.1	3.6	88	1.5	0.7	50	5.6	4.3	78
ASIA-PACIFIC (LESS JAPAN)	0.3	0.2	67	2.1	1.1	50	2.4	1.3	54
TOTALS	30.1	14.7	48.8%	11.4	5.1	44.7%	41.5	19.8	47.7%

* ESTIMATED DATA SOURCES:

1. WARDS AUTOMOTIVE YEARBOOK - 1988
2. JAPAN A/C, HEATING & REFRIGERATION NEWS - 11/25/88
3. PRS CONSULTING GROUP REPORT - JULY 1988
4. AUTOMOTIVE NEWS 1988 YEARBOOK

11. HEAT PUMPS FOR HEATING ONLY

11.1 Scope

CFCs are used in closed-cycle, vapour compression, heat-only heat pumps. Only this kind of heat pump is considered here. A heat pump might also be of a dual mode type (heating and cooling), which is outside the scope of this chapter.

11.2 Heat Pumps Systems. An overview

11.2.1 General

A heat pump, in principal, is identical to a refrigeration plant. It differs in that it utilizes the hot side to provide heating (e.g. for residential and commercial use or in industry). In this way, low grade energy in the surroundings environment (air, water, soil, waste heat, etc.) is converted to a temperature level high enough to be utilized, with a minor input of high grade energy (e.g., electricity).

Unlike producing cold, heat can be generated in different ways; for example, direct use of electricity for resistance heating, combustion of oil, or gas in a furnace. Heat pumps have low operating costs, but fairly high investment costs. With today's low oil and gas prices, other heating technologies give heat pumps serious competition.

In countries where electricity is generated from hydropower, a heat pump reduces the need for primary energy by approximately 1/3 when generating low temperature heat for the residential and commercial sector. Compared with using an oil furnace, CO_2 emissions are reduced to perhaps 1/10. Even in these countries, however, heat pumps have problems being economically feasible.

In countries having fossil fuel or nuclear generated electricity, the average efficiency of heat pumps must be increased, to give a sufficient reduction of primary energy use and emissions before heat pumps will be commonly used.

The fact that the world faces an urgent need to reduce CO2-emissions to the atmosphere, and must utilize high grade energy more efficiently, will undoubtedly give heat pumps an important role in building an energy system for a sustainable world in the future /Gol88/.

Present world-wide installed heat capacity of heating-only heat pumps is approximately 7500 MW. If the potential for residential and commercial use is identified as all heat needed at a temperature level below 100C, it yields a capacity at least 100 times higher than present installed capacity. In addition, an enormous additional potential exists in the present industrial sector.

Heat pumps may be naturally divided into those serving residential and commercial demand, and those in industrial applications. The capacities installed in the two sectors are approximately 6000 MW and 1500 MW respectively /Cal87, Iea87, Brg88, Que89/.

A broad spectrum of designs, plant capacity, refrigerant charge and temperature level may be found within the two groups.

11.2.2 Boundary Conditions

Residential and Commercial Application

The heating capacities of heat pumps serving residential and commercial applications may vary from 1 kW for small room units or water-heaters, to 50-500 kW for those serving office buildings or public baths, to several megawatts (MW) for large heat pumps serving district heating networks.

Most heat is delivered at temperatures between 40C - 90C, using water or air as a heat sink. The most common heat sources are air, sea water, soil, sewage and waste water; giving heat source temperatures between -10C and +10C. When air is used as a heat source, temperatures as low as -15C may be reached before the heat pump is shut down.

The annual number of equivalent operating hours for heat pump systems, refers to the number of hours the system would have to operate in full capacity to satisfy the yearly heat demand. This number is a crucial parameter for the payback time for such equipment. For heat pumps serving space heating this number will vary between 1000 - 3000 hours depending on climate and, thus, the duration of the heating season. For separate hot water production, this period may be somewhat longer, maybe 5000 hours, since this need is fairly constant.

A heat pump system might be of a bivalent type using, for example, an oil furnace to cover peak load as a back-up system. Using equipment with lower investment costs for a given capacity to cover the highest loads, (required for short periods of the year), is normally most economically feasible.

Greatly varying working conditions are characteristic for residential and commercial heat pump systems. The required heat output varies seasonally, daily, etc., and the temperature of the heat source may change significantly.
The seasonal performance factor, i.e. the heat delivered, divided by input of primary energy through the season, is typically between 2 - 4 for heat pump systems serving residential and commercial needs. The magnitude depends mainly on the average temperature lift for the heat pump and the size of the equipment.

Industrial Applications

In contrast to residential and commercial application, industrial heat pumps generally have a very large number of equivalent operating hours, as high as 8000 hours. This is a more favourable economic situation for heat pumps in industrial plants. Stable heat output and working conditions (e.g. temperature lift), are also common.

Heat pumps are used in industrial processes to move and upgrade heat from parts of the process where there is surplus heat to an area with heat demand.

The capacity of industrial heat pumps is typically greater than for residential and commercial application, ranging from about 100 kW to several megawatts. Common seasonal performance factors may vary from 3 to perhaps 20 (when the temperature lift is small), and the heat delivery temperatures are between 25C and 120C.

11.2.3 System Design and Types of Equipment

Heat pumps use many types of compressors. Generally, reciprocating and, to some extent, scroll and rotary-vane compressors are used for low-range capacities, screw and possibly scroll compressors for the mid-range, and turbo compressors for the high capacity range.

All the compressor types can be of the open or (semi)hermetic type, but hermetic type compressors are used mainly for the low- and low-to-mid-range capacities. The open type compressors are susceptible to leakages at the shaft seal, which is between the motor and the compressor.

Most heat pumps use an indirect system in the evaporator and condenser. In other words, an intermediate heat transfer fluid is used between the heat pump and the heat source/sink. A direct system, where the refrigerant evaporates or condenses directly by heat exchange in the source/sink, is more seldom used. Such a design usually requires larger refrigerant charges.

11.2.4 Refrigerant Charges and Refrigerants Used

The relative refrigerant charge in existing heat pumps is usually between 0.5 and 1.5 kg/kW, depending on evaporator design, and on factors previously mentioned. The small hermetic units, often found in the lower range and in new designs, need charges as low as 0.1-0.2 kg/kW in small water/water heat pumps. 1 kg/kW is a good average estimate for existing equipment in this sector.

CFC/HCFC refrigerants are used in most heat pump systems. Ammonia and hydrocarbons are sometimes used within the industrial sector. CFCs/HCFCs are not especially favourable thermodynamically. However, since they are non-toxic and non-flammable they become practical and economical to use. They also have special advantages in turbo compressors since they are heavy gases, which are more easily handled in existing equipment constructions.
The most commonly used refrigerants are listed in Table 11.1.

HCFC-22 is the only refrigerant in Table 11.1 not controlled by the Montreal Protocol. It has the advantage of managing a given capacity with a relatively small swept volume in the compressor. HCFC-22 is used in the upper temperature range of the 25 bar pressure range. High discharge temperatures with HCFC-22 give somewhat troublesome conditions, which may lead, for example, to a shorter lifetime for the compressor. Proper systems design (e.g. compression in two stages, often overcomes these problems, but results in higher investment costs.

Table 11.1. Most Commonly Used Refrigerants in Heat Pumps

Refrigerant	Tmax (25 bar) °C	Regulated by Montreal Protocol	Ozone depletion factor (ODP)
HCFC-22	60	No	0.05
CFC-502	55	Yes*	0.33
CFC-500	70	Yes*	0.74
CFC-12	80	Yes	1.0
CFC-114	130	Yes	1.0
CFC-11	160	Yes	1.0

* The azeotropes CFC-502 (48.8% HCFC-22/ 51.2% CFC-115) and CFC-500 (73.6% CFC-12/ 26.4% HFC-152a) are regulated due to their content of substances regulated by the Protocol.

HCFC-22 is commonly used in the lower temperature range. It is the most widely used refrigerant in small unitary equipment. It is also used at higher temperatures than those given in Table 11.1, for larger plants designed for higher pressures (for example, 30 or 40 bar).

CFC-502 and CFC-500 may be used in approximately the same range as HCFC-22 and CFC-12 respectively. Serving the same duty, CFC-502 gives lower discharge temperatures than HCFC-22, and is used whenever this might be preferable (e.g., heat pumps using air as a heat source).

CFC-12 has relatively good thermodynamic properties and is the most widely used refrigerant in heat pump systems, taking the total charge into account. CFC-12 is a common choice in residential and commercial heat pump applications due to the fact that old heating systems (etc.) often demand a higher temperature requirement which excludes HCFC-22. In industry, CFC-12 is used mainly for heat sink temperatures between 50C and 70C.

CFC-114 is used as working fluid in high temperature heat pumps (70-110C) in industry, due to its relatively high critical temperature.

CFC-11 requires a very large swept volume. This makes it suitable for use in turbo compressors from the upper-middle-range to the high-range capacities. A high normal boiling point gives a vacuum pressure in the evaporator at normal evaporating temperatures for residential and commercial application. It is therefore used only to a minor extent in this sector. In the industrial sector, is it used as a working fluid in high temperature heat pumps.

11.2.5 Current CFC Consumption in the Heat Pump Sector
Basis for a CFC Reduction Scenario

The global consumption of CFCs within the heat pump sector is estimated to be on the order of 800 tonnes per year. This is less than 0.1% of the total consumption of CFCS in the world. The major part, probably more than 90%, is believed to be CFC-12. Consumption figures for non-regulated refrigerants are roughly estimated to be 600 tonnes, consisting mostly of HCFC-22.

On average, the world heat pump market, in terms of installed heating capacity, is expected to grow at a rate of 10% per year. Since the heat pump market is relatively new, only a small number of existing plants are expected to be scrapped in the period considered.

CFC consumption includes the initial charging of new plants and servicing of existing equipment. On average, initial charging accounts for 50% of the consumption (i.e., 400 tonnes).

Recharging is necessary because of accidental losses (breakdowns etc.), leakages, and refrigerant deliberately released to the atmosphere during repair work. Of the total charge in the stock, 10% per year is assumed to be leaking out. A third of the amount for recharging is expected to be released in connection with repair work.

Table 11.2. CFC Consumption in Heat Pumps (tonnes)

	1986	1989
First Charge	400	400
Recharge	240	400
Annual CFC Consumption Total	640	800

The total installed capacity in 1986 is estimated to be at 2400 MW, and a constant growth of 400 MW per year is anticipated. Table 11.2 shows the current CFC consumption relative to the reference year, 1986. The figures are based on the assumptions mentioned above.

11.3 CFC Consumption Reduction in Existing Equipment

11.3.1 Refrigerant Change-Over

"Drop-in" refrigerants are able to replace CFCs without requiring any major redesign of the system. Mixtures of different refrigerants are the only available "drop-in" refrigerants today. However, these mixtures seem to have other draw-backs, so no universal "drop-in" refrigerant appears to be available at this time.

11.3.1.1 Non-Azeotropic Mixtures

Non-azeotropic mixtures are characterized by evaporation and condensation over a certain temperature range, corresponding to a difference in concentration of the different components in the mixture. The difference in concentration may cause problems in cases where leakage occurs. The relative fraction of the different substances in the system will change and thereby alter the thermodynamic properties of the mixture. A recharging problem will also follow, due to the unknown concentration of the different substances left in the system.

Small hermetic heat pump units are subject to a very small leakage rate throughout their lifetime. This may justify non-azeotropic mixtures in such equipment, but a change-over in existing units of this kind is rarely economically rational. The need for replacement refrigerants is limited for small units since HCFC-22 is the most commonly used refrigerant.

The use of non-azeotropic mixtures in middle range capacity plants will not significantly reduce CFC consumption reduction due to the leakage problem.

Non-azeotropic mixtures might be considered in large plants, where equipment for measuring the content of the different substances in the mixture can be afforded. However, this is not the case for plants having evaporators designed for pool boiling. Non-azeotropic mixtures will have serious adverse effects on the effectiveness of such equipment.

Non-azeotropic mixtures in large plants are not considered a short-term solution, due to the need for more research.

11.3.1.2 Azeotropic and Near-Azeotropic Mixtures

An azeotropic mixture behaves like a one-component refrigerant. Such blends will not give leakage problems as those described above. A near-azeotrope behaves almost like an azeotrope.

CFC-500 and CFC-502 are well known azeotropic mixtures available on the market today. They may serve as a short-term solution, due to their somewhat lower ozone depletion potential than CFC-12, see Table 11.1. The fact that considerable system modification may be needed, and that the actual reduction potential is limited, does not make this a cost-effective solution.

An azeotropic mixture of CFC-12 and dimethylether (DME) has been introduced as an intermediate drop-in refrigerant for CFC-12. The blend has 30% less ozone depletion potential than CFC-12. However, industry seems reluctant to use this mixture. The risks involved by introducing a new chemical, and the rather marginal ODP saving it would give, are apparently the main reasons. This mix will also not be used because of the growing data linking its breakdown products to known carcinogens.

The azeotropic and near-azeotropic mixtures available and proposed so far, are not considered to contribute significantly to CFC consumption reduction. The likelihood of new and better proposals is very strong but does not provide a currently available short-term solution. HCFC-124 one component of the proposed mixture, must undergo a two-year toxicity test as in the case of HFC-134a and HCFC-123.

11.3.1.3 Alternative Existing One-Component Refrigerants

Possible alternative refrigerants are HCFC-22, HFC-152a, HCFC-142b, hydrocarbons and ammonia. None of these alternatives can be used in systems designed for CFC-11 or CFC-114, but they may replace CFC-12, CFC-500 and CFC-502 to a small extent.

It is considered to be technically feasible for a minor part of the mid-size heat pumps designed for CFC-12, CFC-500 and CFC-502, to retrofit the design for use of HCFC-22, however, only in connection with scheduled reconstruction or larger overhauls. This applies to heat pumps serving residential and commercial use, provided that the temperature requirements are not too high or may be easily reduced.

The same kind of retrofitting for use of inflammables like HFC-152a, HCFC-142b and hydrocarbons may be possible for a minor part of industrial plants and, perhaps for some large plants serving district heating systems, but this option is assumed to be too expensive to be realistic. This option is not feasible for smaller, unattended installations due to safety considerations.

Retrofitting to use ammonia is much more difficult and will certainly not be realized to a significant extent due to safety considerations.

11.3.1.4 New Refrigerants

It was hoped that the substitute refrigerants HFC-134a and HCFC-123 would replace CFC-12 and CFC-11 as drop-in refrigerants. This is not possible in the case of HFC-134a, since compatibility problems and difficulties in finding a suitable lubricant have been reported. HFC-134a yields 10-15% higher energy consumption in existing equipment than CFC-12. In heat pumps, where the energy saving aspect is crucial, this is not a desirable option. Any significant change-over to this refrigerant is not likely to occur if the shortage of CFC supply does not demand such an option. HFC-134a and HCFC-123 are years from introduction on the commercial market, and this makes predicting the viability difficult.

11.3.1.5 Expected Change-Over

With reference to the current installed capacity, a gradual refrigerant change-over is expected in 5% of the stock by 1994 and 10% by 1998. The additional cost for such an option is assumed to be equal to 15% of the initial investment of the plants.

11.3.2 Refrigerant Conservation

Fifty percent of CFC used in heat pumps is attributed to recharging. Short-term CFC consumption reductions must first of all come from reduced emissions from existing plants, since only a minor part will come from refrigerant change-over. The aims for refrigerant conservation may be naturally divided into two groups:

1. To recover refrigerant when servicing or scrapping an existing system.
2. To reduce leakages and refrigerant emissions due to breakdowns of the plant.

The amount which is economically feasible to recover is difficult to judge, considering the variety of different-sized heat pumps. The gain is also very dependent on regulations and possibilities of handling CFC waste in each country. However, it is assumed that 20% of the emissions from servicing may be recovered after an implementation period of 5 years, i.e., 1994, and 40% by 1998.

Costs connected with refrigerant recovery in large plants are assumed to be of a similar magnitude to the value of the refrigerant reclaimed. For small plants a cost of US$30/kg is assumed /Cow88/.

Maintenance routines vary widely, mostly depending on the size of the heat pumps, but generally improved training of the personnel operating/servicing the heat pumps, combined with improved maintenance routines, such as better leak testing routines, will reduce unintended refrigerant release.

The reduction potential is difficult to judge for this option too, but an average 30% reduction of such emissions by 1994, increasing to 50% by 1998, seems realistic.

11.3.3 Measures Taken So Far

Change-over to refrigerants having less ozone depletion potential, has already been carried out in some heat pumps, and is under consideration for others. Routines for recovery and better maintenance routines have been introduced in some countries.

11.4 CFC Consumption Reduction in New Equipment

11.4.1 General

The fact that CFCs will probably disappear from the market has led to the choice of other non-restricted refrigerants where possible. In addition, there is a trend towards reduced refrigerant charges, improved manufacturing and service routines, etc.

In the following subchapters, the expected potential for different alternative refrigerants are presented. Attention must be drawn to the fact that this picture may change considerably due to new results from research and development, market development and restrictions imposed by society etc. At the end of each subchapter, the assumed cost and energy effects, related to current technology, have been indicated.

11.4.2 Alternative Refrigerants

11.4.2.1 HCFC-22

There may be three main problems with HCFC-22 in the heat pump area:

1. High discharge temperatures if the pressure ratio is high.
2. Large throttling losses for a one-stage process if the condensation temperatures are high.
3. High condenser pressures (condensation at 62C and 85C gives 25 bar and 40 bar, respectively)

There are two main ways to overcome these problems. One is to lower the required discharge temperature from the heat pump. This is assumed to be possible in many new installations in the residential and commercial sector if the entire heating system is planned for such a constraint without high extra costs.

Another possibility is to use a two-stage system with a compressor and the condenser designed for higher pressures. This is probably only cost effective for systems in the mid- and large-capacity range, using reciprocating and turbo compressors respectively.

The cost effect of implementing HCFC-22 is estimated to vary between +0% and +30%, and the energy effect -5% to +5%. HCFC-22 is supposed to be a substitute, to a certain extent, in areas now covered by CFC-12 and CFC-500.

11.4.2.2 Ammonia (NH_3 or R-717)

Ammonia is an excellent refrigerant choice from an efficiency point of view, and has no ozone depleting effect. Both thermodynamic and transport properties are favourable compared with other refrigerants and offers great potential in designing more efficient systems. The need of reduced tube dimensions, heat exchanger areas and the possibility of designing more compact and efficient compressors, give a potential to design cheaper heat pumps /Lor88/.

Ammonia is, however, toxic and flammable. Its characteristic penetrating smell, which gives a very early warning effect of leakages, contributes to keeping the plants leakage free on one hand, but it may also represent a substantial hazard where panic may occur. This requires development of a sufficiently self-contained unit which eliminates the toxic and flammable hazard. Even if this is possible, ammonia has serious problems in certain countries due to the strictness of existing safety codes.

Ammonia may efficiently serve all temperature requirements up to 120C from a theoretical point of view. A 25 bar design pressure is used in most equipment available today. This limits the obtainable condensation temperature to 58C, at the present time. Design pressures of 40 bar and 95 bar will raise obtainable condensation temperatures to 78C and 122C, respectively.

Some special designs are required to reduce discharge temperatures if the pressure ratio is high, for example, multistage compression. Development of cost effective turbo compressors for ammonia will be necessary, if the highest capacity range is to be reached. The mid- and lower high-range capacities are covered by standard piston and screw compressors.

The cost effect of implementing ammonia is estimated to vary between -5% and +40%, the energy effect -5% to -20%. In the short term, ammonia may replace CFC-12 and CFC-500 to some extent in industry, and perhaps to a small extent in the commercial sector as well. In the long term, it may replace CFC-114 in some applications in industry.

11.4.2.3 Non-Azeotropic Mixtures

Mixtures give the possibility of making refrigerants with desirable properties like low relative energy consumption and swept volume. In addition, qualities such as non-flammability and low toxicity are possible to control by a proper choice of components and relative mix. Mixtures also offer the potential for reduced losses in connection with heat transfer, if the gliding temperatures at evaporation and condensation correspond to the temperature glide in the heat source/sink.

Non-azeotropic mixtures might replace restricted refrigerants in all types of equipment, but due to problems, explained in section 11.3.1.1, it is not likely. However, they may serve as replacements in small hermetic units and large capacity plants for reasons explained previously. The cost effect of implementing non-azeotropic mixtures is estimated to vary between +5% and +20%, the energy effect between -5% and +5%.

11.4.2.4 Hydrocarbons and Flammable Halocarbons

Hydrocarbons and flammable halocarbons (for example, HFC-152a and HCFC-142b) are considered possible replacements in small units containing small amounts of refrigerant without any hazard problems due to explosion etc. Test units, containing less than 1.5 kg HFC-152a, are installed in the residential sector in Sweden.

In larger plants these refrigerants may be preferred to ammonia due to lower pressures and discharge temperatures even though they are explosive in much lower concentrations. However, they have the disadvantage of being heavier than air and are less easy to detect. The cost effect of using these substitutes is estimated to vary between +15% and +60%, the energy effect between 0% and +5%.

11.4.2.5 HFC-134a

HFC-134a may serve as a substitute for CFC-12, CFC-500 and CFC-502. Higher relative energy consumption using HFC-134a compared to CFC-12, especially at higher temperatures, has been reported. With a proper design this might be improved, with somewhat higher system costs. The cost effect of implementing HFC-134a is estimated to vary between +0% and +15%, the energy effect between +0% and +15%.

11.4.2.6 Expected Change to Non-CFCs in New Equipment

It is hard to predict to what extent the different options will appear in the future. However, a gradual change to non-CFCs in 15% of the new plants in 1994, and 100% in 1998 is anticipated. The average extra cost to install CFC-free equipment is estimated to be +15%

11.5 Future Consumption of CFC Refrigerants

11.5.1 Development According to the Scenario

Assuming developments described in sections 11.3 and 11.4, CFC consumption in the heat pump sector will be as shown in Table 11.3. The figures are compared to the estimated consumption in 1986, and to the estimated consumption if no remedial action is taken to reduce CFC consumption.

Table 11.3. Estimated CFC Consumption in Heat Pumps in 1994 and 1998 (tonnes)

	Consumption in tonnes	Relative to consumption in 1986	Relative to what consumption would have been in reported years without remedial action to reduce CFCs
1994			
total	930	+46%	-24%
new equipment	490		
recharging	440		
1998			
total	359	-44%	-80%
new equipment	0		
recharging	359		

A reduction in CFC consumption relative to the consumption in the reference year 1986, is not estimated to occur before 1997. This is due to an assumed growth in the market, and the fact that some research and development is needed before new plants, not containing CFC, can become an alternative to any great extent. The consumption reduction in 1998 is expected to be 44%, relative to 1986. However, relative to what consumption would have been in 1998 without any remedial actions to reduce consumption, the reduction in 1998 is expected to be 80%.

11.5.2 Future Dependence on CFC Refrigerants

CFC refrigerants are the only possible refrigerants in many existing heat pumps, or at least the only economical ones. The average lifetime of a heat pump is about 15-20 years. In existing plants, CFC refrigerants will be needed at least until year 2010 if this equipment is not taken out of service. New plants still containing CFCs will probably be installed up to 1998. This means that small quantities of CFCs will be needed until approximately the year 2020.

11.5.3 Future Dependence on HCFC-22

HCFC-22 is a part of the solution in this area. With reference to heating capacity, approximately 40% of the existing stock is assumed to contain HCFC-22. This is expected to rise to approximately 70% by 1998.

11.6 Local and Global Environmental Impact

11.6.1 Local Impact

The impact on the local environment is considered to be negligible. The use of flammable and/or toxic refrigerants to a larger extent, demands that they are handled in a proper way, thus avoiding any increased impact on the local environment.

Service personnel report greater discomfort when exposed to high concentrations of HCFC-22, than CFC-12. The fact that recovery during service will increase will reduce the concentrations to which personnel are exposed.

The toxicity tests of HFC-134a and HCFC-123 have not yet been completed. However, it is assumed that they will not become marketable, if proper handling is not possible.

Heat pumps often replace equipment burning fossil fuels and are expected to have a positive effect on the local environment.

11.6.2 Global Impact

The reduction in consumption and emissions of CFCs from heat pumps is not anticipated to occur as quickly as in many other CFC consuming areas. However, heat pumps cause a very small part of the global emissions of CFCs. Most heat pumps installed reduce both energy consumption and emissions of polluting gases from the combustion of fossil fuels. Even if they give a limited emission of CFCs to the atmosphere, they are assumed to have a net positive effect on the global environment.

The energy effect of introducing equipment not using CFCs is considered to be small. In the long term, more efficient equipment and system designs will probably be introduced due to research and development.

11.7 Economic Aspects and Impacts

Some financial figures related to the scenario, are given in Table 11.4. These figures are only rough estimates of the economic impact of the scenario. A change-over to non-regulated refrigerants will most certainly involve additional costs, at least in the time period considered. How large these additional costs the market is prepared to accept, and still find economically feasible, is hard to tell. This depends on a number of uncertain factors (e.g., oil price and regulations). However, an additional cost of 15% for heat pumps using non-regulated refrigerants is believed to be acceptable with a growth in the market due to the scenario.

The average energy costs are not considered to change significantly. In the long term, they might be reduced due to the introduction of more efficient systems.

11.8 Concluding Remarks

The sector, heat pumps for heating only, is on a global scale, a very small part of the entire field of refrigeration (with reference to capacity). CFC consumption in this sector is estimated to be only 0.3% of the total consumption in this field.

In the short-term, no obvious substitutes for the regulated CFC refrigerants are available. Conservation gives the most promising possibility for this time frame, but such measures may go slower than in other sectors. The installed capacity is divided into many, often small, units. This makes it more difficult and more expensive to introduce proper routines than in sectors where the capacity is divided between a few large plants, which are maintained much more continuously.

In the long-term perspective (1998), the possibility of developing cost effective systems using non-regulated CFCs, looks promising. The cost factor is very important in this sector. Serious problems for the heat pump market will arise if overly strict regulations are imposed on the use of CFCs before cost effective alternatives are available. This would create an unfortunate situation, not only for people involved in this trade, but mostly because of the positive effects heat pumps give in reducing the energy consumption and the emissions from the combustion of fossil fuels. Although not dealt with in this chapter, absorption heat pump development must be mentioned as a possible long-term option.

Calculations based on the scenario described in this report indicate a consumption reduction, in short-term perspective (1994), of 25%, relative to what consumption would have been without remedial actions. In the end of the mid-term period (1998), an 80% reduction should be possible. Even with large reductions, small quantities of CFCs must be available for recharging, until approximately the year 2020. HCFC-22 is assumed to continue as "part of the solution." If this refrigerant should be regulated by a future revision of the Montreal Protocol, then the situation described herein would change considerably.

Table 11.4. Economic Aspects of the Scenario on Heat Pumps (US$ millions)

	1994	1998
Total value of installations, heat pumps only	2600	3800
Total value of plants installed annually	260	400
Additional costs for units using non-regulated refr.	26	51.6
Additional costs to retrofit existing units	1.6	3.2
Additional maintenance costs	15.5	22.6
Additional costs due to the scenario	43.1	77.4
Value of refrigerant saved due to conservation	- 0.7	- 1.4
Net additional costs	42.4	76.0

The figures in Table 11.4 are based on following assumptions:

- Average value of a CFC heat pump US$400/kW
- An average 15% additional cost for equipment using non-regulated refrigerants
- Cost to retrofit existing CFC plants, 10% of the plant value
- Current maintenance-cost, 3% of the plant value per year
- 20% extra maintenance-cost for maintenance due to the scenario
- Value of CFC-refrigerant, US$4.5/kg

12. REFRIGERANT RECYCLING

12.1 Introduction

For stationary systems, recycling a refrigerant becomes practicable when the total refrigerant charge exceeds 50 kg. In some cases, mandatory recycling may be required by law. The recycling is done either on-site using portable equipment or off-site at a central refrigerant recovery plant. On-site recovery and recycling of refrigerant is, by far, the more popular method. While recycling refrigerant from mobile air conditioners is not practiced widely today, at least one nation (U.S.) is planning to implement mandatory recycling requirements /EPA88/. Reclaim, recovery, and recycling are defined as /ASH89/:

> Recovery -- means to move refrigerant in any condition from a system and store it in an external container without necessarily testing or processing it in any way.
>
> Recycling -- means to clean up refrigerant for reuse by oil separation and single or multiple passes through moisture absorption devices, such as replaceable core filter-drivers. This term usually implies procedures implemented at the field job site or at a local service shop.
>
> Reclaim -- means to reprocess refrigerant to new conditions, by means which may include distillation. May require chemical analysis of the contaminated refrigerant to determine that appropriate process specifications are met. This term usually implies the use of processes or procedures available only at a reprocessing or manufacturing facility.

The purpose of recycling refrigerant is to remove moisture and other contaminants that lead to equipment failures. The contaminants include dirt, metallic particles, non-condensible gases, and products from motor burnout /ASH86/. Non-condensible gases can result from incomplete evacuation of the refrigeration system, and are produced either from components releasing gases (either absorbed on system parts or by decomposition), low-side leaks, or chemical reactions /ASH86/. Additional contaminants in hermetic refrigeration systems would be products from decomposing organic materials like oil, insulation, motor varnish, gaskets, and adhesives which produce sludge, wax, and tars.

During a motor burnout in hermetic refrigeration systems, the resulting high temperatures and arc discharges destroy the motor insulation, producing carbonaceous sludge, acids, and water. Some deterioration of the refrigerant and lubricating oil may also occur. If the contaminants from a motor burnout are not carefully removed, there will be a strong likelihood of repeated failures of new motors and compressors. The majority of centrifugal chillers are open refrigeration systems and, thus, are not subject to motor burnouts and decomposing organic contaminants.

Current recycling practices are discussed in section 12.2. Section 12.3 describes the status of recycling technologies. On-site and off-site recycling equipment are discussed in sections 12.4 and 12.5, respectively. Issues concerning recycling refrigerant are described in Section 12.6. Conclusions are presented in Section 12.7.

12.2 Recycling Practices

Currently, refrigerants are accidentally released, or allowed to escape, during installation, testing, servicing, or replacement of equipment. However, it is possible to recover and recycle or reclaim used refrigerant. Having done so, the used refrigerant is again available to serve existing equipment. It is likely that as restrictions imposed by the Protocol take hold, and existing sources of new CFCs dwindle, recycling will become both more attractive and necessary.

There is a benefit to refrigerant recovery beyond the prevention of release of refrigerant to the atmosphere. As mentioned previously, recycled or reclaimed refrigerant can be an important source of restricted chlorofluorocarbons (CFCs). These CFCs can be used to extend the useful life of equipment for which no ready alternatives are available. This in turn will reduce the economic impact of reduced CFC supplies by avoiding early retirement of equipment.

At present, recycling of CFCs is limited. This recycling is conducted by manufacturers of CFCs, independent reclaimers, and individual service companies /Mue89/. Chemical manufacturers recycle CFCs, as other chemicals, in order to reduce waste, including hazardous waste. In addition to recycling their own CFCs, some manufacturers provide this service to their large-volume customers, which tend to be in the chemical solvent industry.

Independent reclaimers receive and reprocess used refrigerants from large installations. Typically, old refrigerant is removed and replaced with new or previously recycled refrigerant. A credit may be given for the used refrigerant which is taken to a central facility where it is cleaned and stored for future use.

A type of recycling is performed by the service industry. It has become standard practice at some large installations to undertake measures to reduce or eliminate loss of CFCs during servicing. By recovering, reclaiming or recycling when necessary, and reusing CFCs in the system, the need for new additional CFCs for recharging is reduced.

There is a growing market for recycling equipment. Although not an established practice at present, recycling and careful refrigerant handling will become standard operating procedure in the near future. The most immediate application will probably be mobile air conditioning (MAC). Servicing centrifugal chillers will also become more common.

Refrigerants captured from an existing piece of equipment are often contaminated with foreign substances. Standards for recycled refrigerants are being established. These standards will dictate the maximum level of contaminants which will be allowed. Recently, car manufacturers in the

United States have agreed on a standard of purity for recycled CFC-12. Thus, service people can reuse old refrigerant without invalidating the warranty for automobile air conditioners.

It is possible to use recycled refrigerants in applications other than the original use. For instance, CFCs can be reformed to fluoromonomers, which in turn are precursors to products such as Teflon. Recycled CFCs could also be reused as blowing agents to produce rigid plastic foams. Finally, it may also be possible to polymerize certain CFCs into plastics which would prevent release into the atmosphere.

12.3 Technology Status

At present, there are three general categories of CFC recycling equipment: plant-based distillation units; vapour-phase solvent recovery units; and portable recycling units. Vapour-phase solvent recovery units apply to CFCs which are used as solvents in the manufacture of electrical components. Since solvent uses of CFCs are the subject of another Technical Option Report, this method is not described further here. The remaining two technologies are described in more detail below.

Plant-based distillation units are in use both at chemical plants which manufacture CFCs and at facilities operated by independent CFC reclaimers. These units are used to purify refrigerants to acceptable standards. Typically, these units facilities are designed for large-scale reclamation of CFCs.

Portable recycling units are designed for small-scale operations. Typical applications are for equipment which is being serviced and which requires the temporary recovery and storage of the CFC charge. Cleaning and purification of refrigerant is also performed during this operation.

In order for used refrigerants to be acceptable for reuse in equipment, standards must be developed which specify limits to contaminants. The Air Conditioning and Refrigeration Institute (ARI) has such a standard (Standard 700) for non-automotive applications. Basically, this standard specifies that levels of contaminants in recycled refrigerants cannot exceed those of a newly produced refrigerant. This is a very high standard since new refrigerants are extremely pure. It has not yet been fully determined how excessive the level of contaminants can become before operation of a particular unit degrades or is damaged. Until such information is known, standards less stringent than Standard 700 are unlikely.

The dominant method of purification, whether manufacturing new CFCs or reclaiming used refrigerants, is distillation. This is because CFCs are highly volatile, which makes this method of purification particularly suitable. The recovered CFC-contaminant mixture is first processed to remove dirt and particulate matter. Next, the mixture is passed into a distillation column. Components of the mixture are separated by boiling-off and vaporizing the CFCs which have a lower boiling point than the contaminants. The contaminants, which mainly consist of lubricating oils and water, are drained-off at the bottom of the column /Mue89/.

12.4 On-Site Recycling

On-site recycling refers to the recovery and recycling of CFCs from equipment in the field or at the service shop. Typical uses of on-site recycling equipment would be for mobile (e.g. automobile) air conditioners and residential HVAC equipment. On-site recycling holds great potential for recovery of CFCs and prevention of emissions.

For instance, recycling of CFC-12 in the automotive industry would produce savings of 28,000 metric tonnes annually. The elimination of small service cans would result in another 12,000 metric tonnes annually with savings of $50,000,000 at service shops (see Table 12.1). With major suppliers now producing recycling equipment worldwide, a great reduction in the service emissions of CFCs should be realizable. For recycling the refrigerant in automotive air conditioners, the amount of refrigerant recovered in a storage tank using hoses with automatic valves has been reported to range from 92 to 99 percent of the total amount charged in to the vehicle. This means the total loss for the entire servicing procedure including connections, evacuation, recharging, recovering the residual charge from the manifold, and recovering the vehicle charge falls in the 1 to 8 percent range /MAN89/.

Table 12.1 Potential Savings of CFC-12
1985 CFC-12 Emissions from Automobile Air Conditioners
(Thousands of metric tonnes)

Emission Source	Quantity Emitted
Fill waste	1.0*
Leakage	15.8
Service Venting	10.4*
Refill Waste	5.9*
Accident	2.8
Disposal	1.4*
TOTAL	37.3
* POTENTIAL REDUCTIONS THROUGH RECYCLING (assuming 100% of used refrigerant is recycled. In practice, around 70-80% of used refrigerant is actually recycled)	18.7
PERCENT REDUCTION THROUGH RECYCLING	50.1%

In general, three functions are provided by portable recycling equipment: removal and temporary storage of the refrigerant, mechanical filtering to remove particulates, and simple purification through evaporation /Mue89/. Removal of the CFC is typically accomplished by drawing vapour or a vapour/liquid mixture from the A/C compressor service valves. Evaporation, oil separation, compression, and condensation are typically accomplished on the recovery device as the refrigerant is pumped into the refillable storage tank as a liquid. There may or may not be one or more replaceable core filter/driers in this circuit. The equipment may or may not provide means to recharge the A/C system from the recovery/recycle device /MAN/89/. Most of the contaminants which were removed with the CFC will be left behind in the portable recovery device after evaporation. The contaminants can be drained off and later disposed.

Cost considerations usually mean that the service contractor will limit recycling efforts to oil separation and filtration. Distillation systems are far more efficient and reliable to operate than the average filter system being used today. Distillation systems, i.e., the REJUVENATOR, require filter changes on a less frequent basis thereby making it a more economical system for the end user. This is accomplished using a replaceable core filter with either activated alumina or molecular sieve construction. This type of filter removes acid, moisture, and particulate matter. Analysis of purity is usually limited to a visual inspection, checking a colour indicator for moisture content, and a simple acid test of an oil sample, and a means to detect and purge excess amounts of non-condensibles (air) may be provided. Since lubricating oils are highly miscible with refrigerants such as CFC-12, the oil content of the recycled refrigerant will be higher than with new refrigerant. However, this higher oil content is similar to actual system conditions and does not affect heat transfer at anticipated levels of less than 1% /ASH86/.

Recycling systems include in-line single pass filter(s) and multiple pass recirculating filter types. In the first type, one or more filters are inserted in the recovery device and filtration occurs ahead of the storage tank. This type system often lacks the capability to measure the purity of the recycled refrigerant or the option to continue recycling if measurement capabilities are included.

The recirculating system provides the option of continuing the recycling process until a predetermined purity level is achieved. It also allows for changing the filter core and continuing the recycling process. This system requires a storage container with liquid and vapour ports. One type of recirculating loop would pull liquid out of the storage container, through a flow control device, and into the evaporator inlet of the recovery circuit. The filter drier could be located between the evaporator and compressor or between the condenser and the storage tank. Another type of recirculating loop would pull liquid out of the storage container and a separate liquid pump would circulate the refrigerant to the storage container. Many patents exist concerning recycling methods for refrigerant cleanup /ASH86/.

Some air and other non-condensibles will probably remain in the recovery container after recycling. Measuring vapour temperature and converting this to the saturation pressure of the pure refrigerant could provide a basis for comparison to the measured refrigerant pressure. An excessive saturation pressure will indicate the presence of a large amount of non-condensibles in the refrigerant container. The non-condensible gases could then be purged from the storage container, with some loss of the refrigerant.

The cost of portable reclaiming units can range between $1,000 and $5,000 per unit, depending on capacity and effectiveness in removing impurities. Unit capacities typically range from one to ten pounds per minute, although some recovery rates may range as high as 30 pounds per minute /Par88/. Most refrigerant recovery equipment manufacturers already suppliers of a wide range of other servicing equipment.

12.5 Off-Site Recycling

In some cases, the refrigerant may be so highly contaminated that on-site recycling is not feasible. For these cases, off-site recycling is done where the refrigerant recovered at the job site is transported to an off-site recycling facility. The equipment will be recharged with new or recycled refrigerant from other installations /Man88/. On-site clean-up of compressor burnouts have been accomplished satisfactorily utilizing the REJUVENATOR for many years.

Losses of refrigerant occur during recycling through losses in hoses, from purging, refrigerant remaining in the lubricating oil, and refrigerant that is decomposed, due to high temperatures and pressures. For portable units servicing automotive air conditioners, the recovery rate of CFCs can be from 92 to 99 percent for the entire service procedure. Off-site recycling, while producing a refrigerant of a higher purity with equal or higher yields in the reclamation process, must add the on-site recovery and service losses as refrigerant cannot be reclaimed without first being collected /MAN89/.

Recycling of CFCs is also performed "on-site" at CFC manufacturers. The purpose of this recycling is to minimize waste during production. Excessive waste is undesirable both from the perspective of the loss of raw materials and also the high cost of disposing of the waste. For the most part, this recycling effort is designed for the specific use of the manufacturer, is an integral part of the manufacturing process, and is not designed to filter out contaminants found in used CFCs which have already been put in operation. However, at least two manufacturers (e.g., Dupont and ICI) are considering accepting used CFCs (from all sources) for recycling purposes.

Independent companies also provide off-site reclaiming services. These firms generally accept used CFCs from both firms which service large chillers in commercial buildings and solvent distributors. As previously mentioned, these used CFCs might contain a number of contaminants (e.g. water, oil, other solvents, acids, and non-condensible gases). At present, there is only one major independent firm offering this service in the United States /Mue89/.

Reclamation of used CFCs at central plants can achieve purity rates as high as new CFCs (99.99% contaminant free). Given current price structures, reclaiming of refrigerant is only economic for large quantities of CFCs, such as those found in large chillers undergoing service. Depending on the cost of shipment, the cost of reclaiming used refrigerant may be more expensive than purchase of new CFCs. Recycling is not economically feasible unless the cost of the recycling process is about half the cost of new CFCs. The additional costs of transporting used refrigerant from the equipment being serviced to the off-site recycling site and the cost of disposal of removed contaminants can double this cost making recycled refrigerants as expensive as new refrigerants.

Typical fees for reclaiming of used refrigerant are shown in Table 12.2. Costs will vary slightly depending on the type and proportion of contaminants found in a particular mixture. The fees do not include the cost of disposal of distillation residues. These residues (mostly water and oil) are the contaminants found in used CFCs (and may also be classified as hazardous waste). An additional fee of $1.20/kg of residue may be assessed for this disposal. After all these factors are considered, the cost of recycling used CFCs is about equal to the cost of new refrigerants, at least at this time.

Table 12.2: CFC Recycling Costs

TYPE	COST, $/Kg
CFC-11	1.00-1.60
CFC-12	1.50-1.90
CFC-113	1.70-3.00

Recovery of CFC's at time of disposal particularly for mobile air conditioners, domestic appliances, and small air conditioning units (room coolers) provides for off-site recycling or reclamation. Significant savings in CFC emissions can result from this practice which will be more economical as refrigerant prices rise. At least one appliance recycler in the USA has a contract with a large power company to recover CFC's from units turned in to the power company as part of an incentive program to purchase more energy efficient units /MAN89/.

12.6 Recycling Issues

A number of policy-related issues still need to be resolved with regard to recycling and reuse of used CFCs. For instance, standards must be adopted for the quality of used refrigerants. The Air Conditioning and Refrigeration Institute (ARI) has formed an Ad Hoc Committee to address this problem. Furthermore, members of the Motor Vehicle Manufacturer's Association (MVMA) have agreed that if recycled CFC meet SAE standards, they would be acceptable for use in motor vehicle equipment without warranty invalidation /citation missing/. Without standards for reclaimed refrigerants, manufacturers of HVAC equipment would need to develop separate procedures for CFC handling and equipment warranty when reclaimed CFCs are being used.

Procedures are being developed by ASHRAE for the handling of controlled CFCs in order to prevent release and damage of the environment (ASHRAE Guideline Project Committee GPC 3P "Guideline for Reducing Emissions of fully Halogenated Chloroflourocarbon (CFC) Refrigerants in Refrigeration and Air Conditioning Equipment and Appliances") /ASN89/. The purpose of the ASHRAE guideline is to recommend practices and procedures that will reduce inadvertent release of fully halogenated CFC refrigerants during manufacture, installation, testing, operation, maintenance, and disposal of refrigeration and air conditioning equipment and systems. The guideline covers all refrigeration and air conditioning equipment and systems that use fully halogenated CFCs. Reducing emissions of all halogenated refrigerants may have positive impact with respect to environmental concerns. In addition to environmental benefits, savings from reduced refrigerant losses can be expected by applying the ASHRAE guideline to equipment and systems that use other types of refrigerants.

ASHRAE research project 601RP titled "Chemical Analysis and Recycling of Used Refrigerant from Field Systems" has an objective; 1) to identify and quantify the typical contaminant levels in refrigerants from several representative refrigeration and air conditioning applications, 2) to chemically formulate a refrigerant sample with typical contaminant levels based upon the data obtained, and 3) to make a brief preliminary evaluation of refrigerant recycling. The applications are CFC12 commercial refrigeration, CFC11 systems, CFC502 low temperature frozen food cases, and CFC22 heat pumps. This data and particularly the levels of high boiling residue are expected to support modification of ARI Standard 700 /MAN89/.

Even though the incentive for recycling is expected to increase both restricted supplies and higher prices for the regulated CFCs a number of important policy issues need to be resolved for recycling /Mue89/:

> If used CFCs or contaminants contained in distillation residues are classified as hazardous waste, this will greatly increase the cost transporting and reclaiming used CFCs
>
> Recovery of CFCs from automobile air conditioners will be impeded as long as consumers have ready access to small refrigerant cans. This is because of the increased risk of accidental or intentional venting during owner servicing.
>
> Unless regulations are imposed, recycling may not become widespread until driven by economics some time in the future.
>
> Though it is possible to reclaim refrigerants to high levels of purity, until recycled refrigerants are proven safe to use there may be substantial market resistance from equipment manufacturers and service personnel.

12.7 Summary

Refrigerant recycling means a process whereby contaminated used refrigerant is recovered, recycled, and, possibly, reclaimed, so that the refrigerant can be reused in air conditioning and refrigeration equipment. Recycling can be done on-site with portable recycling equipment, while reclaiming is usually done off-site. Off-site refrigerant recycling is performed by CFC manufacturers, independent reclaimers, and individual service companies.

The air conditioning and refrigeration industries are exploring reusing CFC refrigerants by issuing standards for acceptable levels of containments in reclaimed refrigerants. Using the recycled refrigerants which meet these specifications will not void manufacturer warranties, an important step in the widespread use of recycling.

Roughly 92 to 99 percent of used refrigerants can be recycled, under proper recycling practices, and may cost about the same as new refrigerant. However, there are very few facilities and portable recycling equipment available today for recycling refrigerants.

13. CONCLUDING SCENARIO INVESTIGATIONS

In this report, a number of different application areas of refrigeration have been dealt with concerning the potential for CFC-usage reductions. An integrated analysis and a recommendation for the saving percentage for the area as a whole will be given in this chapter.

Refrigerant data analysis shows that, for a reliable planning of CFC substitutes in the short and mid-term, only HCFC-22 and ammonia can be considered; some areas could use non-azeotropic mixtures. Should toxicity tests of HFC-134a yield favourable results, this substitute can be included in a replacement scenario.

The use of flammable refrigerants (e.g., HFC-152a, propane and isobutane), could be considered in the short-term; at least given current data. However, for most of the application areas, the flammability aspect has not been considered thoroughly and, also due to economic impacts in production, may be hampered when safety standards are taken into account as well. Flammable refrigerants should therefore be considered as a solution for the mid- to long-term, especially if non-flammable refrigerants under study at present do not meet health or efficiency requirements.

Improved education and handling could substantially reduce the need for refrigerants in normal servicing operations. Various application areas mention savings on the order of 25 to 50% as a global average. Improved refrigerant handling, reclamation, and recycling may yield a saving up to 60% (see Chapters 8 to 11). These measures should therefore be considered as the most important ones in the short-term.

Nevertheless, it is difficult to derive possible realistic saving figures from these rough assumptions for the entire refrigeration area in a global sense. Therefore estimations have been made using a computer analysis in which the above assumptions have been used. The assumptions are explicitly given here; these are once more summarized in Table 13.1 below. In Table 13.1, the percentage reduction in leakage refers to the leakage quantity in the first set of rows. Likewise, the percentage of recovery refers to the service quantity. Finally, the percentage of substitutes relates to the initial charge.

The replacement of CFCs by available substitutes in refrigeration and comfort AC installations is assumed to be implemented in a gradual way in the period 1990-1998 around the world. Furthermore, a replacement of CFCs by the substances HFC-134a/HCFC-123 is considered to be possible from 1994 onward. A gradual increase is assumed from 1994 to 1998, when substituting will have a value of 100%. Also, the mobile AC sector will apply HFC-134a from 1994 onwards and reach a 100% value in 1998. It is the only realistic assumption since commercial production of HFC-134a will not start before 1993-1994; the entire demand cannot be covered before 1998.

In all refrigeration areas, realistic growth percentages are assumed as a global average; varying from 2 to 5% in the next decade (1990-1998). A small percentage (1-2%) of the existing large refrigeration installations is assumed to be retrofitted each year for the use of substitutes already available at present (e.g. HCFC-22 and ammonia). In some application areas (e.g. retail refrigeration), the use of non-azeotropic mixtures is assumed to be possible.

Better education and handling procedures will yield a gradually increasing effect in the period 1990-1998; the same holds true for reclaimation. For improvement in education and handling procedures, an overall saving of 50% is assumed for 1998 (for the world as a whole). For reclamation, a value of 60% is generally used. Slight differences can be observed for the automotive AC sector. Improved design, assembly, and maintenance will result in 12% reduced leakage in new equipment by 1994, increasing to 25%

Table 13.1 Values for CFC-emission/supply scenarios

	industrial	transport	heat pumps	domestic	chilling	storage	retail	automotive
Consumption 1987	3,500	1,400	700	10,000	12,500	20,000	56,000	120,000
initial charge	1,050	450	350	8,500	3,300	6,000	22,000	28,000
leakage	1,650	650	175	1,200	5,700	8,000	25,000	52,000
service	800	300	175	300	3,500	6,000	9,000	40,000
lifetime(years)	20	12	17	12	20	15	8	15
retrofitting (%/year)								
1990-1994	1	-	1	-	1	2	-	-
1994-1998	3	-	1	-	1	2	-	-
increase (%/year)	2	5	8	5	2	2	5	5
reduction leakage (%)								
1990	10	10	10	10	10	10	10	10
1994	25	25	25	25	40	25	25	12
1998	50	50	50	50	50	50	50	25
recovery (%)								
1990	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
1994	30	30	20	10	30	30	40	60
1998	60	60	40	20	60	60	60	60
substitutes (%)								
1990	10	10	10	0	10	10	10	0
1994	68	30	30	20	30	68	30	20
1998	100	100	100	100	100	100	100	100

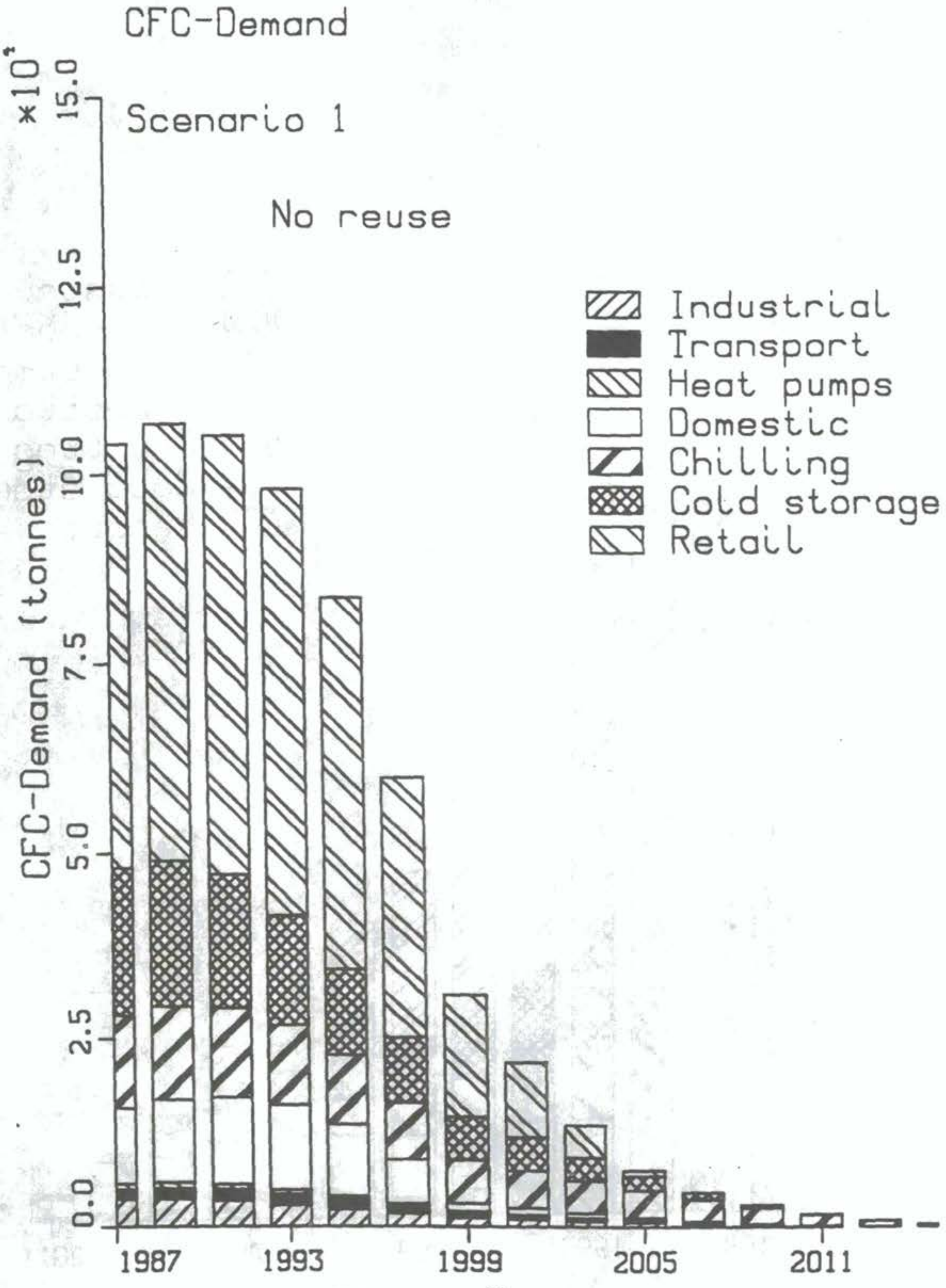


Fig. 13.1 CFC Demand Values for the Period to 2015 for all Refrigeration Sectors, excluding Automotive Air conditioning, assuming No Reuse of Recovered Refrigerant -Scenario 1-

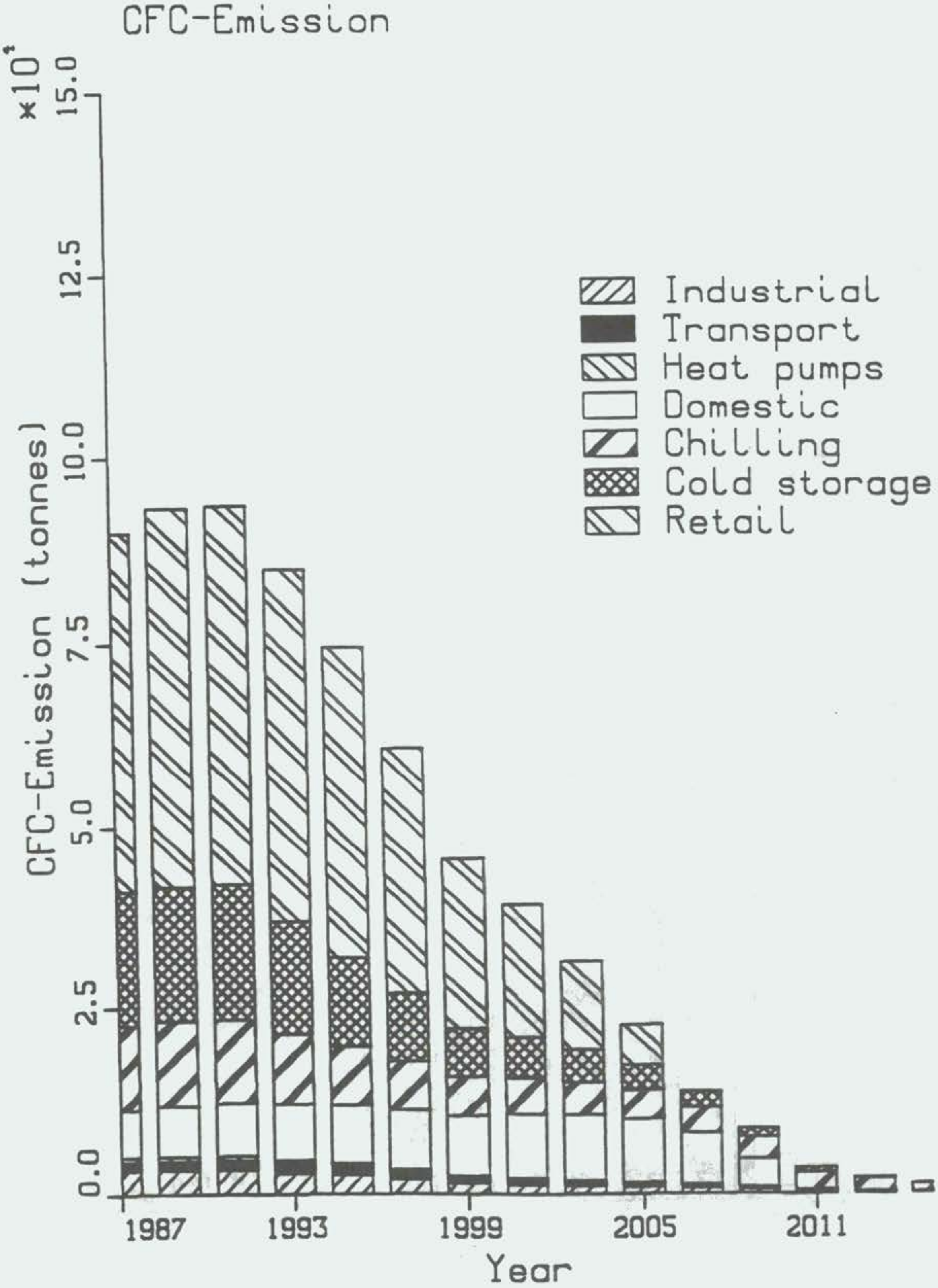


Fig. 13.2 Resulting CFC Emission Values for the Period to 2015 from all Refrigeration Sectors, excluding Automotive Air conditioning, assuming No Reuse of Recovered Refrigerant -Scenario 2-

by 1998. A 60% reclaim/recycling will be realized in 1994 (assuming a gradual increase over the period 1990-1994). All these figures influence the analysis in a substantial way; therefore it must be emphasized that these are first estimates and assumptions. More detailed analysis will not be possible before these effects have at least partially been implemented.

Two scenarios have been investigated.

1. Reclaim procedures are applied in each of the refrigeration, AC, and heat pump sectors. There is no reuse of refrigerant. This scenario gives a lower estimate for possible global saving figures.
2. Reclaim procedures are as in Scenario 1, but recycling and reuse is applied. This scenario represents the upper estimate for the possible global saving figures. In reality, this scenario may turn out to be too optimistic.

13.1 Scenario 1

In this scenario no reuse of the reclaimed refrigerant is assumed. In Figs. 13.1 and 13.2, CFC demand and CFC emissions values are shown for all refrigeration, AC, and heat pump sectors except the automotive AC sector.

CFC demand values are sharply decreasing in the period 1997-2000 here, mainly due to a 100% use of environmentally benign substitutes in the last part of the decade in the refrigeration industry. However, a demand of about 50%-conforming to the Montreal Protocol - remains until the end of the decade. Thereafter, only small amounts (15% of the 1986 value) are necessary for servicing until 2010-2015.

Due to the long lifetime of these installations, CFC emissions cannot be substantially reduced until 2010. Only a extremely high value for reclaim of used refrigerant could lower this value.

In Figs. 13.3 and 13.4, CFC demand and emissions values for the automotive AC sector are given. An important aspect is that the application of HFC-134a will be introduced in 1994 and reach saturation (100% application) in 1998.

In Figs. 13.5 and 13.6, CFC demand and emission values are given for all sectors. Compared to the 1986-87 values, CFC supply can be reduced to 50% in 1998. This value is already based on the assumption that environmentally acceptable substitutes are applied in all sectors, which might be questionable for certain sectors (e.g., perhaps domestic refrigeration). Although environmentally acceptable substitutes are assumed to be used after 1998, the need for servicing existing installations requires that a certain CFC supply has to be guaranteed in the period 2000-2015. The length of this time period will depend upon the lifetime of the installations. Especially large installations with a high economic value and long lifetimes will need small amounts of CFCs for servicing even after 2015 when the recovered material will not be available for reuse.

The automotive AC sector plays a significant role in determining the need for CFCs.

CFC emissions will gradually decrease to zero in the first part of the 21st century, when it is assumed that only environmentally acceptable substitutes are used after 1998.

13.2 Scenario 2

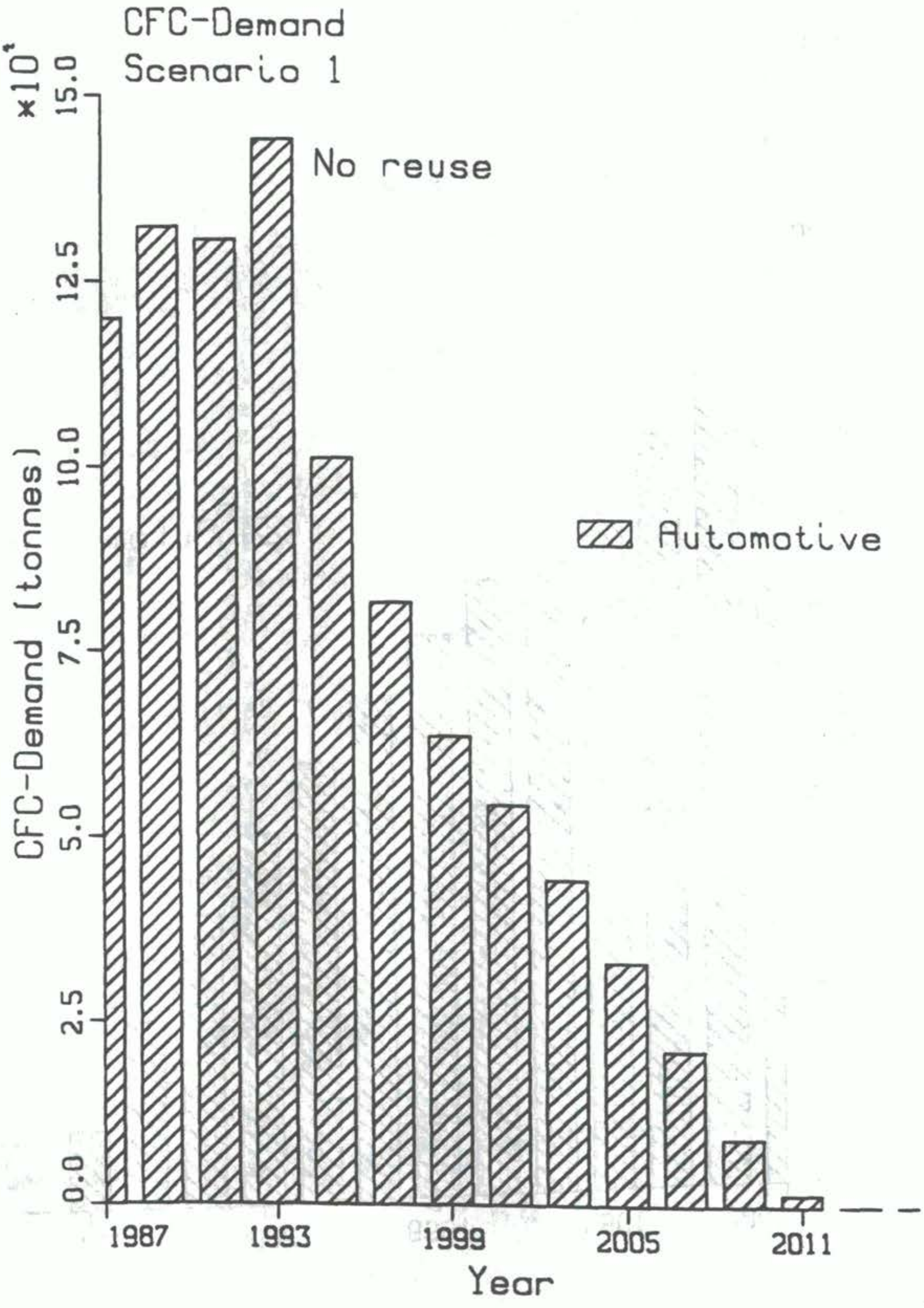
This scenario presents the maximum in savings, using the estimates given in Table 13.1, due to assumed recycling and reuse. In Fig. 13.7, CFC demands for the refrigeration/AC heat pump sectors are given. Fig. 13.8 gives CFC demand for the automotive AC sector. In this scenario reuse of the recovered CFCs is assumed. In cases where some refrigeration sectors have a surplus of refrigerant, it is assumed to be distributed over those sectors which are in need of CFC refrigerants.

In 1998, 20% of the refrigerant contents of domestic appliances is assumed to be recycled. Therefore, the small need for CFCs in servicing can be covered by using the reclaimed refrigerant. This area is assumed to no longer need CFC refrigerants after 1998 (when only acceptable refrigerants are assumed to be applied). This assumption is based on positive results as to material compatibility and lubrication. This result may be somewhat optimistic as far as world-wide usages are concerned.

Large installations (e.g., industrial refrigeration) may need CFCs for a long period for servicing. However, this need might be partially satisfied by recycling. Nevertheless, it should be stressed here that recycling is only possible when there is still new CFC production. A certain minimum production level is therefore necessary for a long period after 1998.

The need for CFCs decreases after the turn of the century. The time when CFCs are no longer required is determined by the assumptions for the percentage of the installations which is retrofitted and scrapped (which procedures yield CFC refrigerant for servicing existing installations, after having been recycled). A 50% reduction compared to the 1986 values does not seem to be possible earlier than 1997. After this year, CFC supply decreases further.

In Fig. 13.9 CFC demand values for all refrigeration sectors are given. Again reuse of the recovered CFCs is assumed; possibly via redistribution over all sectors which are in need of CFC refrigerants. Although there still is an increase in the necessary net supply of CFC refrigerants to 1991, the demand sharply decreases after this time (when automotive CFC recovery and recycling procedures have been started). Due to the large installed potential of automotive AC equipment, the need for servicing existing installations determines a certain net CFC demand up to the year 2005 (small amount compared to the 1986 production value). A 50% reduction seems feasible in 1997. A savings of roughly 85-90% saving compared to 1986, could be assumed in the period 2003-2005. Further reductions cannot be accurately forecasted at this moment.



<u>Fig. 13.3</u> **CFC Demand Values for the Period to 2015 for Automotive Air conditioning only, assuming No Reuse of Recovered Refrigerant -Scenario 1-**

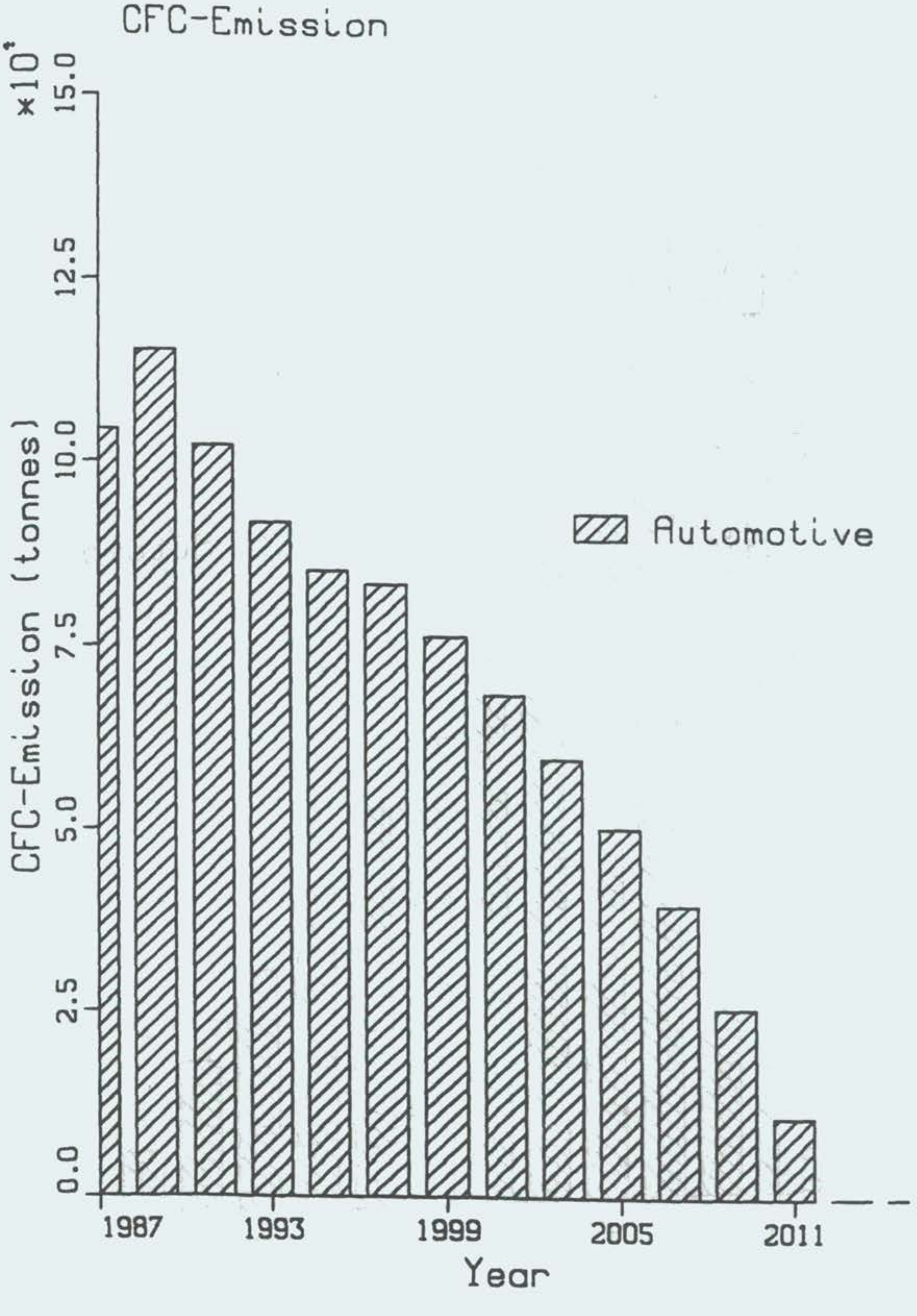


Fig. 13.4 Resulting CFC Emission Values for the Period to 2015 from Automotive Air conditioning only, assuming No Reuse of Recovered Refrigerant -Scenario 1-

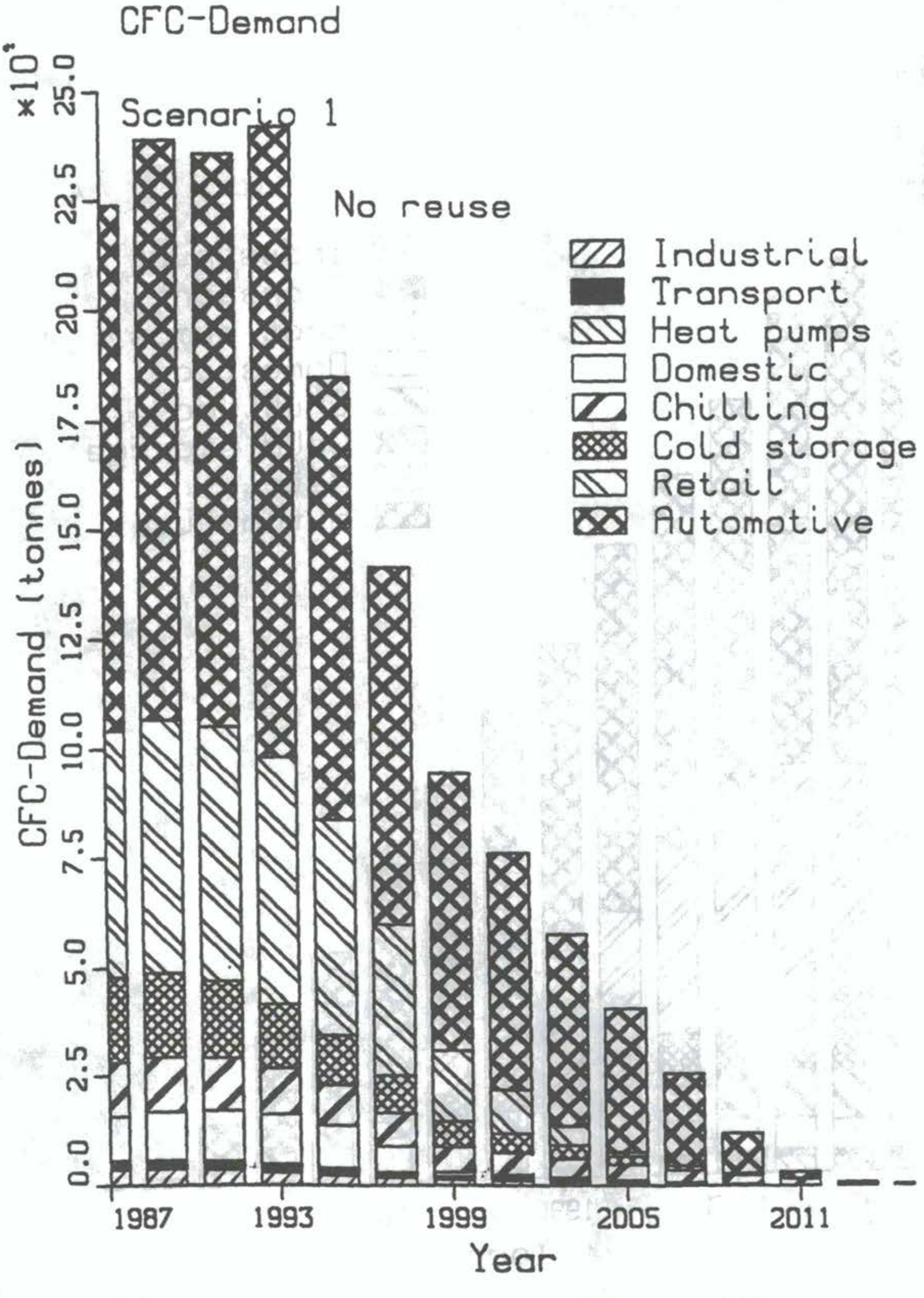


Fig. 13.5 CFC Demand Values for the Period to 2015 for all Refrigeration/AC/HP Sectors (Data from Table 13.1), assuming No Reuse of Recovered Refrigerant -Scenario 1-

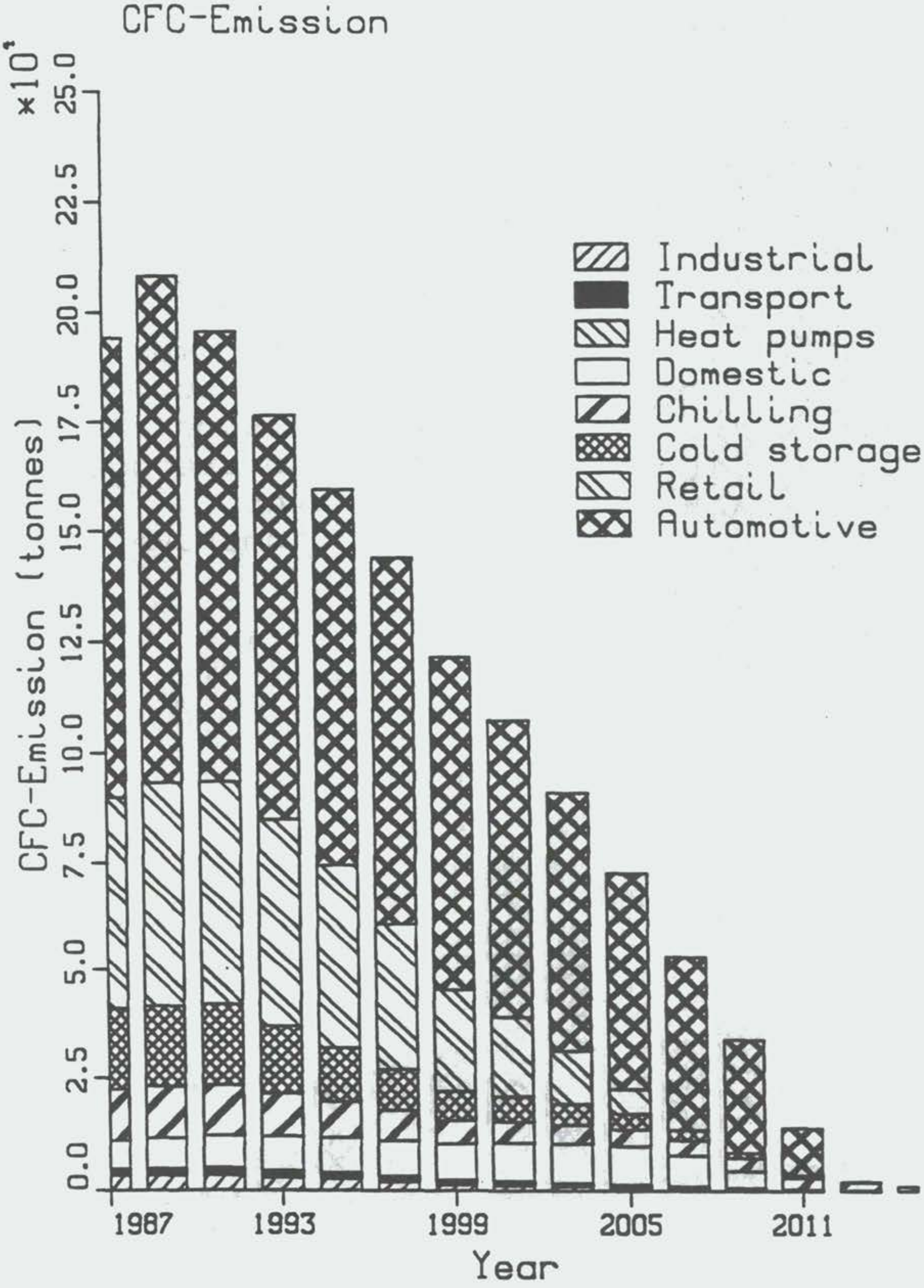


Fig. 13.6 Resulting CFC Emission Values for the Period to 2015 from all Refrigeration/AC/HP Sectors (Data from Table 13.1), assuming No Reuse of Recovered Refrigerant -Scenario 1-

In case of reuse, the emission values are equal to the ones valid for the first scenario, where no reuse is assumed.

13.3 Concluding Remarks

Taking into account:

- that there will be a continuous growth, also in the developed countries, in refrigeration equipment in the 1990s.
- that large installations (industrial and chilling equipment) will need small amounts of CFCs for servicing which, for the larger part, can be obtained as recycled refrigerant (certainly after 2005).
- that the recovery and recycling of 60% of the used refrigerant seems realistic for the end of the century (however, a redistribution from sectors which have a surplus to sectors which are in need of CFCs of servicing might be too optimistic an assumption with regard to worldwide usage);
- that the growing use of a substitute refrigerant is assumed in the automotive AC field from 1994 on;
- that HCFC-22 is available as a substitute and that production is permitted to increase by a factor of two or three for refrigeration (in this way not adding more than about 1% to the "1986 ODP production"), - this assumption is crucial -,

then large saving percentages, on the order of 50%, are realistic before 1998. This assumes the availability of an acceptable substitute from 1994 onwards (i.e., HFC-134a).

The two scenarios presented here give a lower and upper estimate of CFC saving after 1998. Taking into account the inaccuracy of the estimates used, it can nevertheless be stated that the necessary CFC supply in the first decade of the 21st century can be reduced to around 10-15% of the 1986 value. After this time the need for servicing existing equipment will rapidly decrease and consequently the need for CFCs.

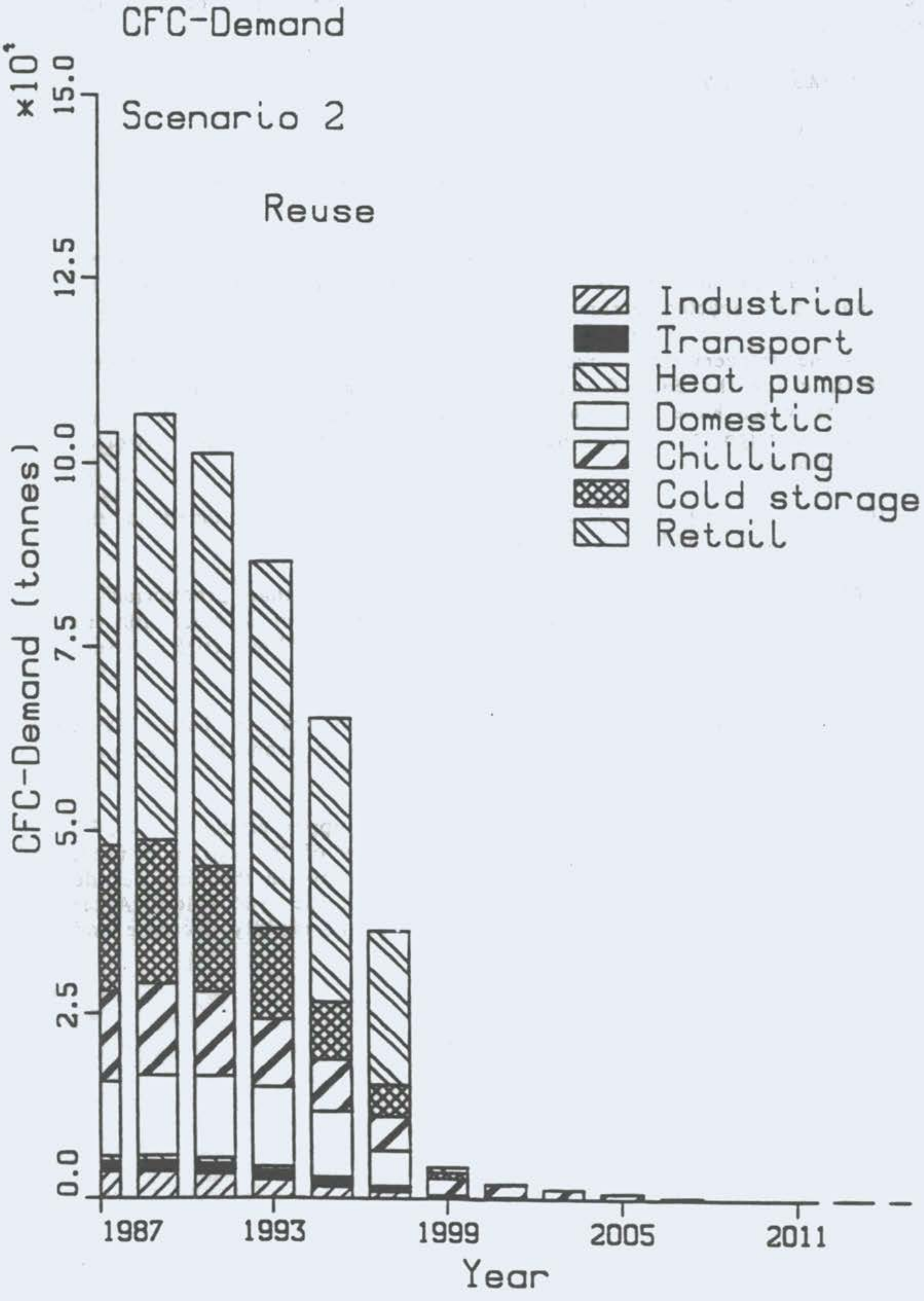


Fig. 13.7 CFC Demand Values for the Period to 2015 for all Refrigeration Sectors, excluding Automotive Air conditioning, assuming Reuse of Recovered Refrigerant -Scenario 2-

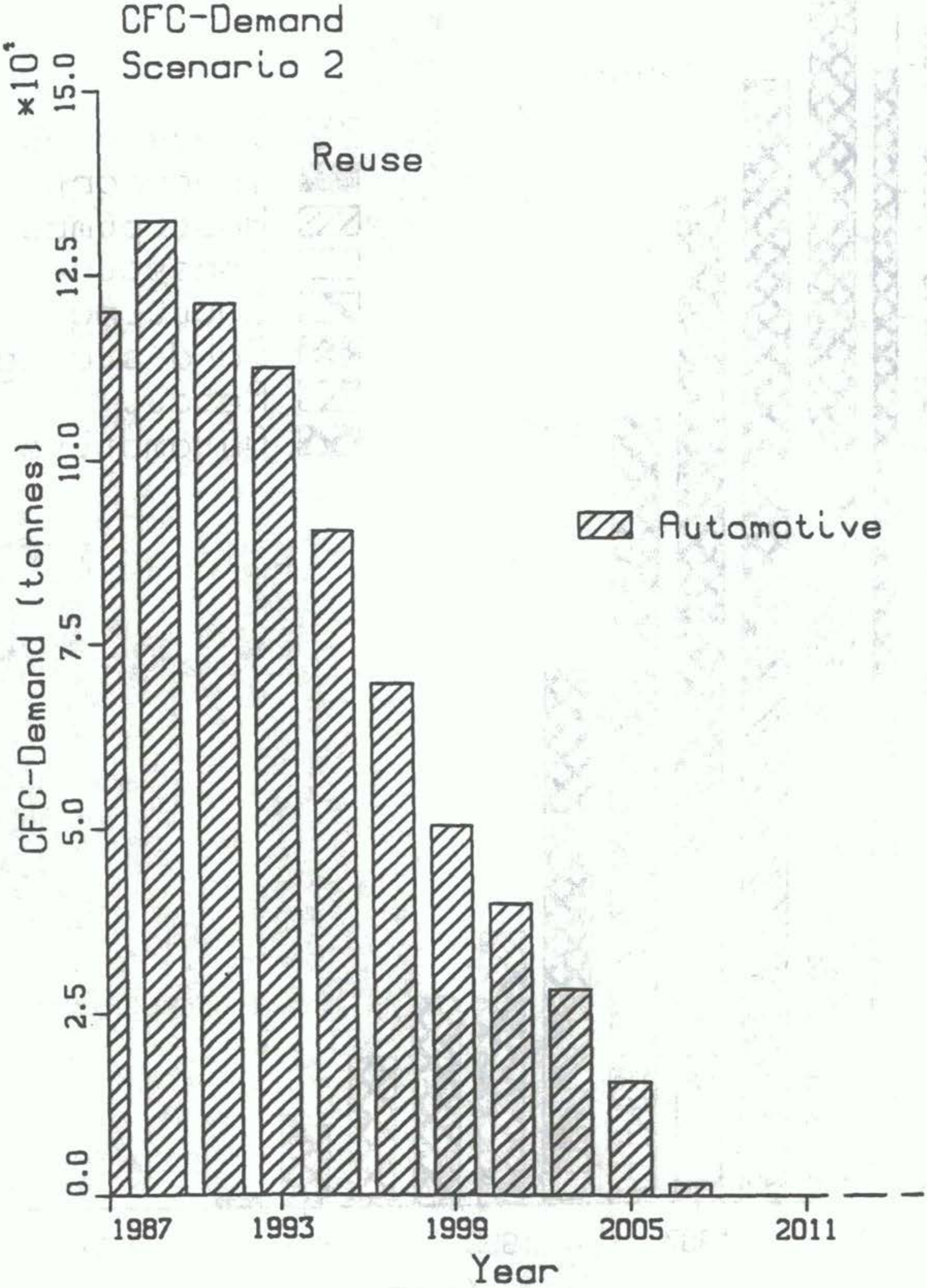


Fig. 13.8 CFC Demand Values for the Period to 2015 for Automotive Air-Conditioning only, assuming Reuse of Recovered Refrigerant -Scenario 2-

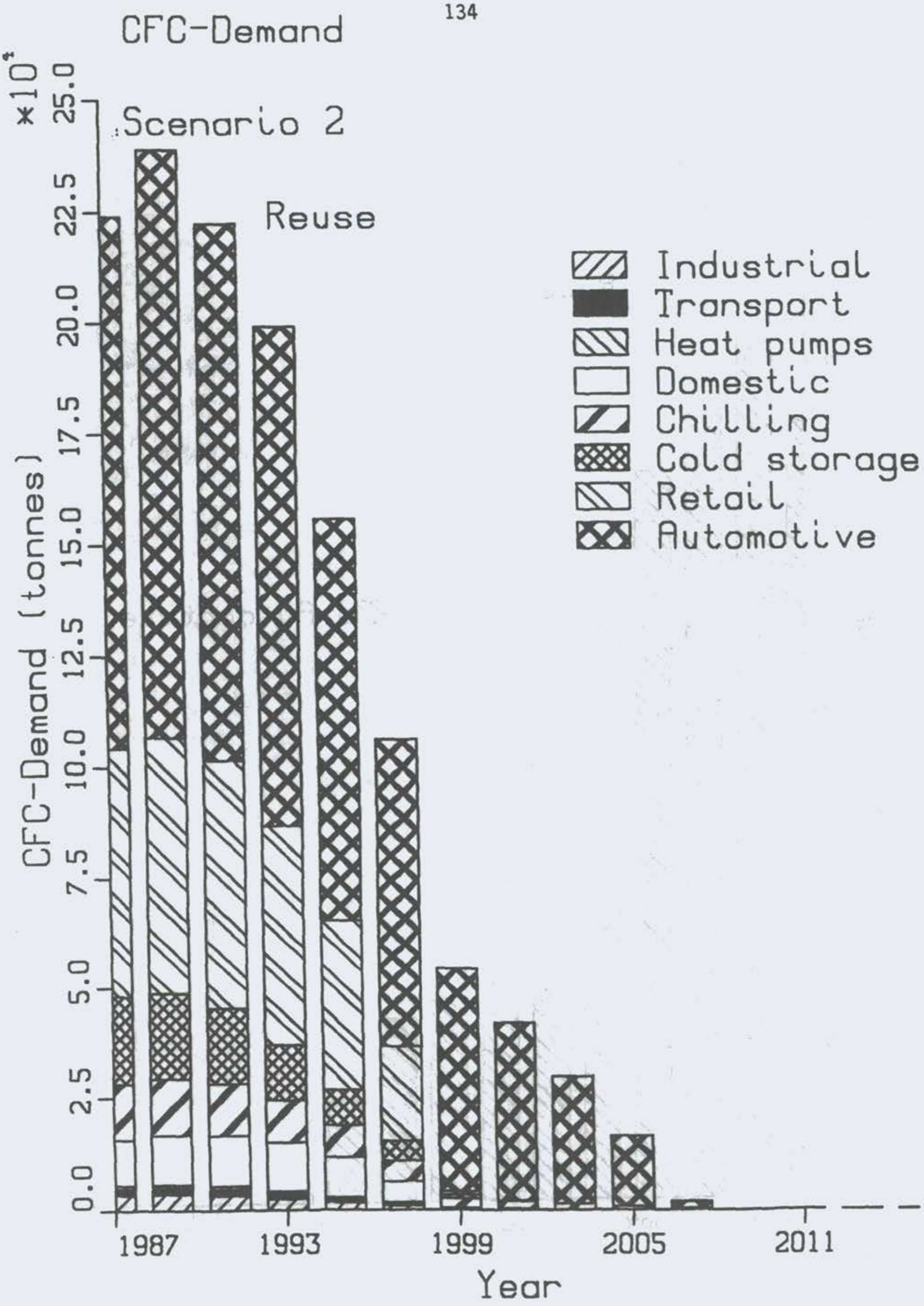


Fig. 13.9 CFC Demand Values for the Period to 2015 for all Refrigeration/AC/HP Sectors (Data from Table 13.1), assuming Reuse of Recovered Refrigerant -Scenario 2-

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15. ACKNOWLEDGEMENTS

Thanks are indebted to a number of authors in preparing papers on the different chapters for this Technical Options Report on Refrigeration, Air Conditioning and Heat Pumps:

Refrigerant Data		
Dr. Mark McLinden	NIST	United States
Domestics		
Fred Hallett	White Cons. Inc.	United States
Dr. Lambert Kuijpers	Philips Research Labs.	Netherlands
Retail		
Dr. Horst Kruse	University Hannover	Fed. Rep. Germany
Dr. Ulrich Hesse	University Hannover	Fed. Rep. Germany
Transport		
Robert Heap	SCRCA	United Kingdom
Cold Storage		
Anders Lindborg	Frigoscandia	Sweden
Industrial		
Dr. Hans Haukas	NTH Refr. Eng.	Norway
Comfort AC		
Floyd Hayes	The Trane Co.	United States
Dr. David Didion	NIST	United States
Mobile AC		
James Baker	Harrison Rad. Div. GM	United States
Heat Pumps		
Dr. Per. Erling Frivik	SINTEF	Norway
Refrigerant Handling		
Shelton Taylor	Refr. Rec. Systems	United States
Terry Statt	DOE	United States

and, of course to a number of co-authors for various chapters:

J. Kenneth Taulbee	White Cons. Inc.	United States
Ernesto Heinzelmann	Embraco Joinville	Brazil
Lindsey Roke	Fisher & Paykel Ind.	New Zealand
Werner Viloehr	Bosch Siemens Hausger.	Fed. Rep. Germany
Tadatoshi Banse	Toshiba Cons. Prod.	Japan
Ren Jinlu	G. Mach. Res. Inst.	China
Ronald Ares	Hussman Co.	United States

Kent Anderson	Consultant	United States
Peter Cooper	Sainburys	United Kingdom
Per Samuelsen	Finsam Ltd.	Norway
A. Stera (Wilson)	Lloyd's Register	United Kingdom
Kazumi Tsakuhara	Mitsubishi Ind.	Japan
Jose Schatten	Schatten BV	Belgium
M. Tirel	Matal, S.A.	France
Akari Aguri	Daikin Ltd.	Japan
Kent Hickman	York Int. Co.	United States
Harry Hale	Carrier Co.	United States
Yu Bingfeng	Xi'an Jiatonneg Univ.	China
Flemming Boldvig	Sabroe Refr. A/S	Denmark
Peter Moser	Sulzer AG	Switzerland
Dr. Thore Berntsson	Chalmers Inst.	Sweden
R. Benstead	Electr. Council RC	United Kingdom
M. Schneeberger	Oberoest. Kraftwerk AG	Austria
Richard Radecki	Harrison Div. GH	United States
Dr. Rolf Wallner	Julius Behr GmbH	Fed. Rep. Germany
S. Sumikawa	Diesel Kiki Co. Ltd.	Japan
Rolf Segerstrom	Electrolux AB	Sweden
Nobuhiko Yokota	Refr. AC Industr. Ass.	Japan
Dr. Nobuo Ishikawa	Tokyo Inst. Technology	Japan
Dr. M. Narodoslawsky	Graz University	Austria
Dr. R. Agarwal	Indian Inst. Technology	India
Dr. S. Bhaduri	IIT Powai	India
Dr. Gianfranco Angelino	Politecnico Milano	Italy
Ayub Hira	E.A. Mueller	United States

Thanks are also given to a large number of peer reviewers within the ASHRAE and IIR institutes, to CMA/CEFIC, and to CECOMAF. The coordination and editing done by Mr. Sean McDonald, Battelle Pacific Northwest Laboratory, Washington, DC has also been greatly appreciated.

This report has been prepared for the reassessment of the Montreal Protocol in June 1990. A half-year period was available for the set-up of the first and reviewing authors organization, the writing and the reviewing of the contributions. In the course of 1989 this report will be distributed as widely as possible via UNEP and via the International Refrigeration Associations.

However, conservation procedures, new refrigerant developments and progress in alternative processes will require regular updates of this report. At least every four years (conform to the procedure for regular reassessment of the Montreal Protocol) this report should be published in an updated version.

Preliminarily it is proposed that the first authors of every subsector fulfil a coordinating position in gathering information from all over the world. It also requires that newest knowledge obtained by refrigeration experts is made available to these authors. UNEP kindly recommends the above-mentioned procedure.

Eindhoven, 30 June 1989
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