4

Refrigeration

Coordinating Lead Authors
Sukumar Devotta (India), Stephan Sicars (Germany)

Lead Authors
Radhey Agarwal (India), Jason Anderson (USA), Donald Bivens (USA), Daniel Colbourne (United Kingdom), Guy Hundy (United Kingdom), Holger König (Germany), Per Lundqvist (Sweden), Edward McInerney (USA), Petter Nekså (Norway)

Contributing Authors
Ayman El-Talouny (Egypt)

Review Editors
Eduardo Calvo (Peru), Ismail Elgizouli (Sudan)

Contents

EXECUTIVE SUMMARY

Domestic refrigeration

Domestic refrigerators and freezers are used throughout the world for food storage in dwelling units and in non-commercial areas such as offices. More than 80,000,000 units are produced annually with internal storage capacities ranging from 20 litre to greater than 850 litre. With an estimated average unit lifespan of 20 years, this means there is an installed inventory of approximately 1500 million units. As a result of the Montreal Protocol, manufacturers initiated transition from CFC refrigerant applications during the early 1990s. This transition has been completed in developed countries and significant progress has been made in developing countries. The typical lifespan for domestic refrigerators means that products manufactured using CFC-12 refrigerant still comprise approximately one-half of units in the installed base. This has significantly slowed down the rate of reduction in the demand for CFC-12 refrigerant in the servicing sector.

Isobutane (HC-600a) and HFC-134a are the dominant alternative refrigerants for replacing CFC-12 in new domestic refrigeration appliances. Each of these has demonstrated mass production capability for safe, efficient, reliable and economic use. Both refrigerants give rise to similar product efficiencies. Independent studies have concluded that application design parameters introduce more efficiency variation than that attributable to the refrigerant choice. Comprehensive refrigerant selection criteria include safety, environmental, functional, cost and performance requirements. The choice of refrigerant can be strongly influenced by local regulatory and litigation environments. Each refrigerator typically contains 50–250 grams of refrigerant contained in a factory-sealed hermetic system. A simplified summary of the relative technical considerations for these two refrigerants is:

- HC-600a uses historically familiar mineral oil lubricants. Manufacturing processes and designs must fully take into account the flammable nature of the refrigerant. For example, the need for proper factory ventilation and appropriate electrical equipment, preventing leaking refrigerant from gaining access to electrical components, using sealed or non-sparking electrical components, and the use of proper brazing techniques or preferably the avoidance of brazing operations on charged systems. Service procedures must similarly include appropriate precautions for working with flammable refrigerants;
- HFC-134a uses moisture-sensitive polyolester oils. Manufacturing processes should ensure that low moisture levels are maintained. Long-term reliability requires a more stringent avoidance of contaminants during production or servicing compared to either CFC-12 or HC-600a practices.

The use of the hydrocarbon blend propane (HC-290)/isobutane (HC-600a) allows CFC-12 volumetric capacity to be matched and avoids the capital expense of retooling compressors. These blends introduce manufacturing complexities and require the use of charging techniques suitable for refrigerant blends which have components with different boiling points. The application of these blends in Europe during the 1990s was an interim step towards the transition to HC-600a using retooled compressors. The same safety considerations apply to hydrocarbon blends as to HC-600a.

Alternative refrigeration technologies such as the Stirling cycle, absorption cycle, thermoelectrics, thermionics and thermoacoustics continue to be pursued for special applications or for situations with primary drivers that differ from conventional domestic refrigerators. These technology options are not expected to significantly alter the position of vapour compression technology as the choice for domestic refrigeration.

Vapour compression technology is mature and readily available worldwide. The availability of capital resources is dictating the timing of conversion to HC-600a and HFC-134a. Current technology designs typically use less than half the electrical energy required by the units they replace. This reliable performance is provided without resorting to higher cost or more complex designs. Continued incremental improvements in unit performance and/or energy efficiency are anticipated. Government regulations and voluntary agreements on energy efficiency and labelling programmes have demonstrated their effectiveness in driving improved efficiency product offerings in several countries.

Good design and the implementation of good manufacturing and service practices will minimize refrigerant emissions; however, special attention must be given to the retirement of the large number of units containing CFC-12. With a typical 20-year lifespan, refrigerator end-of-life retirement and disposal happens to about 5% of the installed base each year. This means approximately 75 million refrigerators containing 100 grams per unit, or 7500 total tonnes of refrigerant are disposed of annually. This refrigerant will be predominantly CFC-12 for at least another 10 years. The small refrigerant charge means that refrigerant recovery is not economically justifiable. Regulatory agencies around the world have therefore provided incentives or non-compliance penalties to promote recovery of this ODS.

In 2002, the total amount of refrigerants banked in domestic refrigeration amounted to 160,000 tonnes, with annual refrigerant emissions of 5.3% of banked system charge. The annualized HFC emissions rate from this sector was 1.0% in 2002. HFC emissions mostly occur during useful life. Production transition to HFCs started during 1995; consequently in 2002 the installed product age was 7 years or less compared to a typical lifespan of 20 years. Further, recovery during service and disposal is required in most early conversion countries.

Commercial refrigeration

Commercial refrigeration makes fresh and frozen food available to customers at the appropriate temperature levels: chilled food in the range of 1°C–14 °C and frozen food in the range of –12°C to –20°C.

On a global basis, commercial refrigeration is the refrigeration subsector with the largest refrigerant emissions calculated as CO_2-equivalents. This amounts to 40% of the total annual refrigerant emissions, see Table 11.5. In 2002 worldwide commercial refrigeration emission rates were reported to be 30% yr^{-1} of the installed commercial refrigeration banked inventory of 605,000 tonnes refrigerant. This means that in an environment with an average energy mix, the refrigerant emissions represent about 60% of the total emissions of GHG resulting from system operation, the rest being indirect emissions caused by power production.

Refrigeration equipment types vary considerably in terms of size and application. Stand-alone equipment consists of systems where the components are integrated, such as beverage vending machines, ice cream freezers and stand-alone display cases. Refrigerant charge sizes are small (0.2–1 kg), and the CFCs CFC-12 and R-502 are being replaced by HFCs HFC-134a, R-404A and R-507A. HCFC-22 is also used, but is subject to phase-out requirements. Refrigerant emissions are low in these mainly hermetic systems and are similar to domestic refrigerator emissions. However, end-of-life recovery is almost non-existent on a global basis and this results in an average annual leakage of 7–12% of the refrigerant charge, dependent on the equipment lifetime. Some stand-alone equipment using hydrocarbons as refrigerants have been developed and are available in European countries, with refrigerant charge sizes in accordance with the limitations imposed by European and national safety standards.

Condensing units are small commercial systems with compressors and condensers located external to the sales area, and the evaporators located in display cases in the sales area, or in a cold room for food storage. These units are installed in shops such as bakeries, butchers and convenience stores as well as in larger food retailer stores. Similar refrigerants are used in these applications as in stand-alone equipment; however, with the larger refrigerant charges in these systems (1–5 kg), hydrocarbon refrigerant applications may be limited by national safety standards. Refrigerant emissions depend on the robustness of the system design, installation, monitoring and refrigerant recovery at end of equipment lifetime.

Full supermarket systems can be categorized by whether refrigerant evaporation occurs in the display cabinets and cold stores, or whether a low-temperature, secondary heat transfer fluid that is cooled centrally, is circulated to the display cabinets and cold stores. The first type is termed a direct system and the second type an indirect system.

Supermarket centralized direct systems consist of a series of compressors and condensers located in a remote machinery room, providing a cooling medium to display cabinets and cold storage rooms in other parts of the building. The size of systems can vary from cooling capacities of 20 kW to more than 1 MW, as used in larger supermarkets. Refrigerant charge sizes can range from 100–2000 kg. The most common form of centralized system is direct expansion. Specific units can be dedicated to low-temperature or medium-temperature evaporators. HCFC-22 continues to be extensively used in these systems, with R-502 for low-temperature applications being replaced by R-404A and R-507A. Due to European regulations on HCFCs that have been in force since January 2001, R-404A and R-507A are the most commonly used refrigerants for large capacity low- and medium-temperature systems in Europe.

The 'distributed' system is a variation of the direct system. In this the compressors are located in sound-proof boxes near the display cases, permitting the shortening of refrigerant circuit length and a corresponding 75% reduction of refrigerant charge. Condensing units can be air-cooled or water-cooled. When compressor systems are installed as small packs with roof-mounted, air-cooled condensers, or as small packs adjacent to the sales area in conjunction with remote air-cooled condensers, they are sometimes referred to as close coupled systems. The refrigerants used are mainly HCFC-22 and the low-temperature refrigerants R-404A and R-507A. Other refrigerants such as R-410A are also being considered. With the close-coupled system design, refrigerant emissions are estimated to be 5–7% of charge on an annual basis. Compared to the centralized systems, the absolute reduction in refrigerant emissions is much greater due to the considerable reduction in refrigerant charge size.

The design of indirect systems for supermarkets permits refrigerant charge size reduction of 75–85%. Fluorocarbon-based refrigerants are generally used in these systems. However, if the centralized refrigeration system can be located in a controlled-access room away from the customer area, indirect systems may also use flammable and/or toxic refrigerants, dependent on system safety measures and national safety regulations. Refrigerant emissions are reduced to about 5% of charge yr^{-1} due to the reductions in the reduced piping lengths and the number of connecting joints.

Systems that use ammonia and hydrocarbons as primary refrigerants in indirect systems operate in several European countries. Published results show that ammonia and hydrocarbon indirect systems have a 10–30% higher initial cost than direct expansion systems and an energy consumption 0–20% higher than that of direct expansion systems, due to the additional system requirements (heat exchanger and circulating pumps with their costs and energy penalties). Development work on indirect systems design is continuing with the goals of reducing the cost and energy penalties in these systems.

Carbon dioxide is being evaluated in direct systems for both low- and medium-temperature applications, and in cascade systems with carbon dioxide at the low-temperature stage and ammonia or R-404A at the medium-temperature stage. Thirty cascade systems have been installed in supermarkets and the initial costs and energy consumption are reported to be similar to R-404A direct expansion systems.

Important considerations in the selection of designs for supermarket refrigeration systems and refrigerants are safety, initial cost, operating cost and climate change impact (refrigerant emissions and carbon dioxide from electricity produced to operate the refrigeration systems). In the 1980s the centralized direct systems had annual refrigerant emissions up to 35% of charge. Recent annualized emission rates of 3–22% (average

18%) were reported for 1700 supermarket systems in several European countries and the USA. The reduced emission rates were due to a combination of factors aimed at improving refrigerant containment, such as system design for tightness, maintenance procedures for early detection and repairs of leakage, personnel training, system leakage record keeping, end-of-life recovery of refrigerant and in some countries, increasing the use of indirect cooling systems.

In 2002, worldwide commercial refrigeration emission rates were reported to be 30% yr^{-1} of the installed commercial refrigeration banked inventory of 605,000 tonnes of refrigerant. The higher worldwide emission rates indicate less attention was paid to refrigerant containment and end-of-life recovery than in the limited survey data reported above.

Traditional supermarket centralized direct systems must be designed for lower refrigerant emissions and higher energy efficiency in order to reduce climate change impact. From an overall perspective, significant research and development is underway on several designs of supermarket refrigeration systems to reduce refrigerant emissions, use lower global-warming refrigerants and reduce energy consumption. Life cycle climate performance calculations indicate that direct systems using alternative refrigerants, distributed systems, indirect systems and cascade systems employing carbon dioxide will have significantly lower CO_2-equivalent emissions than centralized direct systems that have the above-stated, historically-high refrigerant emission rates.

Food processing, cold storage and industrial refrigeration

Food processing and cold storage is one of the important applications of refrigeration for preserving and distributing food whilst keeping food nutrients intact. This application of refrigeration is very significant in terms of size and economic importance in both developed and developing countries. The annual consumption of frozen food worldwide is about 30 Mtonnes yr^{-1}. Over the past decade, consumption has increased by 50% and is still growing. The amount of chilled food is about 10–12 times greater than the supply of frozen products. Frozen food in long-term storage is generally kept at –15°C to –30°C, while –30°C to –35°C is typical for freezing. Chilled products are cooled and stored at temperatures from –1°C–10°C.

The majority of refrigeration systems for food processing and cold storage are based on reciprocating and screw compressors. Ammonia, HCFC-22, R-502 and CFC-12 are the refrigerants historically used, with other refrigerant options being HFCs, CO_2 and hydrocarbons. HFC refrigerants are being used instead of CFC-12, R-502 and HCFC-22 in certain regions. The preferred HFCs for food processing and cold storage applications are HFC-134a and HFC blends with an insignificant temperature glide such as R-404A, R-507A and R-410A. Ammonia/CO_2 cascade systems are being introduced in food processing and cold storage.

Some not-in-kind (non-vapour compression) technologies, such as vapour absorption technology and compression-absorption technology, can be used for food processing and cold storage applications. Vapour absorption technology is well established, whereas compression-absorption technology is still under development.

For this category, limited data are available on TEWI/LCCP. A recent study of system performance and LCCP calculations for a 11 kW refrigeration system operating with R-404A, R-410A and HC-290 showed negligible differences in LCCP, based on the assumptions used in the calculations.

Industrial refrigeration includes a wide range of cooling and freezing applications in the chemical, oil and gas industries as well as in industrial ice-making, air liquefaction and other related industry applications. Most systems are vapour compression cycles, with evaporator temperatures ranging from 15°C down to –70°C. Cryogenic applications operate at even lower temperatures. Capacities of units vary from 25 kW to 30 MW, with systems often being custom made and erected on-site. Refrigerant charge size varies from 20–60,000 kg. The refrigerants used are preferably single component or azeotropes, as many of the systems use flooded evaporators to achieve high efficiency. Some designs use indirect systems (with heat transfer fluids) to reduce refrigerant charge size and to the risk of direct contact with the refrigerant.

These refrigeration systems are normally located in industrial areas with limited public access, and ammonia is the main refrigerant. The second refrigerant in terms of volume use is HCFC-22, although the use of HCFC-22 in new systems is forbidden for all types of refrigerating equipment by European regulations since January 2001. Smaller volume CFC refrigerants CFC-12 and R-502 are being replaced by HFC-134a and R-404A, and R-507A and R-410A. CFC-13 and R-503 are being replaced by HFC-23 and R-508A or R-508B. HCFC-22 is being replaced by R-410A, as the energy efficiency of R-410A is slightly higher than that of HCFC-22. The energy efficiency of R-410A can be similar to that of ammonia for evaporation temperatures down to –40°C, dependent on the compressor efficiency. Hydrocarbon refrigerants have historically been used in large refrigeration plants within the oil and gas industry.

Carbon dioxide is another non-HFC refrigerant which is starting to be used in industrial applications, as the energy efficiency of carbon dioxide systems can be similar to that of HCFC-22, ammonia and R-410A in the evaporator temperature range of –40°C to –50°C for condensing temperatures below the 31°C critical temperature of carbon dioxide. Cascade systems with ammonia in the high stage and carbon dioxide in the low stage show favourable cost and energy efficiency. Carbon dioxide is also being used as a heat-transfer fluid in indirect systems.

Attempts are being made to reduce refrigerant emissions in industrial refrigeration, food processing and cold storage by improving the system design, minimizing charge quantities, ensuring proper installation, improving the training of service personnel with respect to the detection of potential refrigerant leakage, and improving procedures for recovery and re-use of refrigerant. The total amount of refrigerants banked in the combined sectors of industrial refrigeration, food processing and cold storage was 298,000 tonnes in 2002, with ammonia at 35% and HCFC-22 at 43% of the total banked inventory. Annual refrigerant emissions were 17% of banked system charge.

Transport refrigeration

Transport refrigeration consists of refrigeration systems for transporting chilled or frozen goods. Transport takes place by road, rail, air and sea; further, containers as refrigerated systems are used with moving carriers. All transport refrigeration systems must be sturdily built to withstand movements, vibrations and accelerations during transportation, and be able to operate in a wide range of ambient temperatures and weather conditions. Despite these efforts, refrigerant leakage continues to be a common issue. It is imperative that refrigerant and spare system parts are available on-board and along the transport routes. Ensuring safe operation with all working fluids is essential, particularly in the case of ships where there are limited options for evacuation.

Ships with cargo-related, on-board refrigeration systems have either refrigerated storage spaces or provide chilled air supply. There are about 1100 such ships, with HCFC-22 being the main refrigerant. In addition, there are approximately 30,000 merchant ships which have refrigerated systems for crew food supply, again mainly using HCFC-22. Alternative refrigerants being implemented are R-404A/R-507A, R-410A, ammonia and ammonia/CO_2.

Refrigerated containers allow storage during transport on rail, road and seaways. There are more than 500,000 such containers that have individual refrigeration units of about 5 kW cooling capacity. Refrigerants in this sector are transitioning from CFC-12 to HFC-134a and R-404A/R-507A.

Refrigerated railway transport is used in North America, Europe, Asia and Australia. The transport is carried out with either refrigerated railcars, or, alternatively, refrigerated containers (combined sea-land transport; see Section 4.6.2) or swap bodies (combined road-land transport; see Section 4.6.4).

Road transport refrigeration systems (with the exception of containers) are truck-mounted systems. The refrigerants historically used were CFC-12, R-502 and HCFC-22. New systems are using HFC-134a, R-407C, R-404A, R-410A and decreasing amounts of HCFC-22. There are about 1 million vehicles in operation, and annual refrigerant use for service is reported to be 20–25% of the refrigerant charge. These high leakage rates call for additional design changes to reduce leakage, which could possibly follow the lead of newer mobile air-conditioning systems. Another option would be for systems to use refrigerants with a lower global-warming potential (GWP).

The non-HFC refrigerant hydrocarbons, ammonia and carbon dioxide are under evaluation, and in some cases these are being used for transport applications in the various sectors, with due consideration for regulatory, safety and cost issues. Fishing trawlers in the North Pacific Ocean already use ammonia for refrigeration, with a smaller number of trawlers using R-404A or R-507A. Carbon dioxide is a candidate refrigerant for low-temperature refrigeration, but the specific application conditions must be carefully considered. Carbon dioxide systems tend towards increased energy consumption during high-temperature ambient conditions, which may be significant when containers are closely stacked on-board ships, leading to high condensation/gas cooler temperatures because of lack of ventilation. In the case of reefer ships and fishing vessels, a promising alternative technology is equipment with ammonia/carbon dioxide systems. These systems have similar energy efficiency to existing refrigeration systems but higher initial costs.

Low GWP refrigerant options will technically be available for transport refrigeration uses where fluorocarbon refrigerants are presently used. In several cases, these low GWP options may increase the costs of the refrigeration system, which is an important consideration for owners of transport equipment. A technology change from an HFC, such as R-404A, to a low-GWP fluid will usually lead to a reduction of TEWI, if the energy consumption is not substantially higher than in existing systems.

The total amount of refrigerants banked in transport refrigeration was 16,000 tonnes in 2002, with annual refrigerant emissions of 38% of banked system charge consisting of CFCs, HCFCs and HFCs.

4.1 Introduction

The availability and application of refrigeration technology is critical to a society's standard of living. Preservation throughout the food chain and medical applications are examples of key contributors to quality of life. Integrated energy consumption information is not available, but this largest demand sector for refrigerants is estimated to use about 9% of world power generation capacity (Bertoldi, 2003; EC, 2003; ECCJ, 2004; EIA, 2004; ERI, 2003; UN-ESCAP, 2002, Table 1.1.9). This consumption of global power-generation capacity means that the relative energy efficiency of alternatives can have a significant impact on indirect greenhouse-gas (GHG) emissions.

Refrigeration applications vary widely in size and temperature level. Sizes range from domestic refrigerators requiring 60–140 W of electrical power and containing 40–180 g of refrigerant, to industrial and cold storage refrigeration systems with power requirements up to several megawatts and containing thousands of kilograms of refrigerant. Refrigeration temperature levels range from –70°C to 15°C. Nearly all current applications use compression-compression refrigeration technology. The potential market size for this equipment may approach US$ 100,000 million annually. This diversity has resulted in unique optimization efforts over the decades, which has resulted in solutions optimized for different applications. For discussion purposes, the refrigeration sector is divided into the five subsectors:

- Domestic Refrigeration: the refrigerators and freezers used for food storage primarily in dwelling units;
- Commercial Refrigeration: the equipment used by retail outlets for holding and displaying frozen and fresh food for customer purchase;
- Food Processing and Cold Storage: the equipment to preserve, process and store food from its source to the wholesale distribution point;
- Industrial Refrigeration: the large equipment, typically 25 kW to 30 MW, used for chemical processing, cold storage, food processing and district heating and cooling;
- Transport Refrigeration: the equipment to preserve and store goods, primarily foodstuffs, during transport by road, rail, air and sea.

Data in Table 4.1 indicate that the annualized refrigerant emission rate from the refrigeration sector was 23% in 2002. This includes end-of-life losses. There is a wide range of annualized emissions from the five subsectors, from 5% for domestic refrigeration to 30% for commercial refrigeration to 38% for transport refrigeration. For commercial refrigeration, the 30% annual refrigerant emissions represent typically 60% of the total emissions of GHGs resulting from system operation, the rest being indirect emissions from power production. This indicates the importance of reducing refrigerant emissions from this sector, in addition to the importance of the energy efficiency of systems stated above.

4.2 Domestic refrigeration

4.2.1 Background

Domestic refrigerators and freezers are used for food storage in dwelling units and in non-commercial areas such as offices throughout the world. More than 80,000,000 units are produced annually with internal storage capacities ranging from 20 litre to greater than 850 litre. With an estimated typical unit life of 20 years (Weston, 1997), the installed inventory is approximately 1500 million units. Life style and food supply infrastructures strongly influence consumer selection criteria, resulting in widely differing product configurations between different global regions. Products are unitary factory assemblies employing hermetically-sealed, compression refrigeration systems. These typically contain 50–250 g of refrigerant.

4.2.2 Refrigerant options

Conversion of the historic application of CFC-12 refrigerant in these units to ozone-safe alternatives was initiated in response to the Montreal Protocol. Comprehensive refrigerant selection criteria include safety, environmental, functional, performance and cost requirements. A draft refrigerant selection-decision map and a detailed discussion of requirements were included in the 1998 report of the Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee (UNEP, 1998). The integration of these requirements with other potential drivers such as global-warming emissions reduction, capital resource availability and energy conservation results in a comprehensive analysis of refrigerant options for strategic consideration. Two different application areas must be addressed: (1) new equipment manufacture, and (2) service of the installed base. New equipment manufacture can be addressed more effectively, since the ability to redesign avoids constraints and allows optimization.

4.2.2.1 New Equipment Refrigerant options

Most new refrigerators or freezers employ either HC-600a or HFC-134a refrigerant. Each of these refrigerants has demonstrated mass production capability for safe, efficient, reliable and economic use. There are no known systemic problems with properly manufactured refrigerator-freezers applying either of these primary options. The key variables influencing selection between these two refrigerants are refrigerator construction details, energy efficiency, building codes, environmental considerations and the economics of complying with standards. Other selected alternative refrigerants or selected refrigerant blends have had limited regional appeal, driven by either niche application requirements or by availability of suitable compressors or refrigerants. Some brief comments about selected refrigerant use are now given.

Isobutane (HC-600a) refrigerant

HC-600a applications use naphthenic mineral oil, the historic

Table 4.1. Refrigerant bank and direct emissions of CFCs, HCFCs, HFCs and other substances (hydrocarbons, ammonia and carbon dioxide) in 2002, the 2015 business-as-usual scenario and the 2015 mitigation scenario, for the refrigeration sector, the residential and commercial air-conditioning and heating sector ('stationary air conditioning') and the mobile air-conditioning sector.

	Banks (kt)					Emissions (kt yr^{-1})					Emissions ($MtCO_2$-eq yr^{-1}) SAR/TAR[2]	Emissions ($MtCO_2$-eq yr^{-1}) This Report[3]
	CFCs	HCFCs	HFCs	Other	Total	CFCs	HCFCs	HFCs	Other	Total		
2002												
Refrigeration	330	461	180	108	1079	71	132	29	18	250	848	1060
- Domestic refrigeration	*107*	-	*50*	*3*	*160*	*8*	-	*0.5*	*0.04*	*9*	*69*	*91*
- Commercial refrigeration	*187*	*316*	*104*	-	*606*	*55*	*107*	*23*	-	*185*	*669*	*837*
- Industrial refrigeration[1]	*34*	*142*	*16*	*105*	*298*	*7*	*24*	*2*	*18*	*50*	*92*	*110*
- Transport refrigeration	*2*	*4*	*10*	-	*16*	*1*	*1*	*3*	-	*6*	*19*	*22*
Stationary Air Conditioning	84	1028	81	1	1194	13	96	6	0.2	115	222	271
Mobile Air Conditioning	149	20	249	-	418	60	8	66	-	134	583	749
Total 2002	**563**	**1509**	**509**	**109**	**2691**	**144**	**236**	**100**	**18**	**499**	**1653**	**2080**
2015 BAU												
Refrigeration	64	891	720	136	1811	13	321	115	21	471	919	1097
- Domestic refrigeration	*37*	-	*189*	*13*	*239*	*5*	-	*8*	*1*	*13*	*51*	*65*
- Commercial refrigeration	*6*	*762*	*425*	-	*1193*	*5*	*299*	*89*	-	*393*	*758*	*902*
- Industrial refrigeration[1]	*21*	*126*	*85*	*123*	*356*	*4*	*21*	*11*	*21*	*56*	*88*	*104*
- Transport refrigeration	*0.1*	*2.8*	*20.3*	-	*23.2*	*0.1*	*1.3*	*7.4*	-	*9*	*22*	*26*
Stationary Air Conditioning	27	878	951	2	1858	7	124	68	0	199	314	370
Mobile Air Conditioning	13	23	635	4	676	5	11	175	1	191	281	315
Total 2015-BAU	**104**	**1792**	**2306**	**143**	**4345**	**25**	**455**	**359**	**23**	**861**	**1514**	**1782**
2015 Mitigation												
Refrigeration	62	825	568	186	1641	8	202	52	15	278	508	607
- Domestic refrigeration	*35*	-	*105*	*60*	*200*	*3*		*3*	*1*	*6*	*27*	*35*
- Commercial refrigeration	*6*	*703*	*378*	-	*1087*	*3*	*188*	*40*	-	*230*	*414*	*494*
- Industrial refrigeration[1]	*21*	*120*	*65*	*126*	*331*	*3*	*13*	*5*	*14*	*36*	*53*	*63*
- Transport refrigeration	*0.1*	*2.8*	*20.3*	-	*23.2*	*0.0*	*0.9*	*4.3*	-	*5*	*13*	*15*
Stationary Air Conditioning	27	644	1018	2	1691	3	50	38	0	91	145	170
Mobile Air Conditioning	13	23	505	70	611	3	7	65	7	82	119	136
Total 2015 Mitigation	**102**	**1493**	**2090**	**259**	**3943**	**14**	**259**	**155**	**22**	**451**	**772**	**914**

(1) Including food processing/cold storage

(2) Greenhouse gas CO_2-equivalent (GWP-weighted) emissions, using direct GWPs, taken from IPCC (1996 and 2001) (SAR/TAR)

(3) Greenhouse gas CO_2-equivalent (GWP-weighted) emissions, using direct GWPs, taken from Chapter 2 in this report

choice for CFC-12 refrigerant, as the lubricant in the hermetic system. Competent manufacturing processes are required for reliable application but cleanliness control beyond historic CFC-12 practices is not required. HC-600a has a 1.8% lower flammability limit in air, increasing the need for proper factory ventilation and appropriate electrical equipment. This flammable behaviour also introduces incremental product design and servicing considerations. These include preventing leaking refrigerant access to electrical components or using sealed or non-sparking electrical components, using proper brazing methods or preferably avoiding brazing operations on charged systems, and ensuring a more robust protection of refrigerant system components from mechanical damage to help avoid leaks.

HFC-134a refrigerant: HFC-134a applications require synthetic polyolester oil as the lubricant in the hermetic system. This oil is moisture sensitive and requires enhanced manufacturing process control to ensure low system moisture level. HFC-134a is chemically incompatible with some of the electrical insulation grades historically used with CFC-12. Conversion to the electrical insulation materials typically used for HCFC-22 applications may be necessary. HFC-134a is not miscible with silicone oils, phthalate oils, paraffin oils or waxes. Their use should be avoided in fabrication processes for components in contact with the refrigerant. Common items for concern are motor winding lubricants, cutting fluids in machining operations and drawing lubricants. Careful attention to system cleanliness is required to avoid incompatible contaminants. Trace contaminants can promote long-term chemical degradation within the system, which can reduce cooling capacity or cause system breakdown. Necessary process controls are not technically complex but do require competent manufacturing practices and attention to detail (Swatkowski, 1996).

Isobutane (HC-600a)/propane (HC-290) refrigerant blends
The use of these hydrocarbon blends allows matching CFC-12 volumetric capacity and avoids capital expense for retooling compressors. These blends introduce design and manufacturing complexities. For example, they require charging techniques suitable for use with blends having multiple boiling points. The use of HC-600a/HC-290 blends in Europe during the 1990s was an interim step towards a final transition to HC-600a using retooled compressors. Unique application considerations are consistent with those discussed above for HC-600a.

Other refrigerants and refrigerant blends
Example applications of additional refrigerants in new equipment include HC-600a/HFC-152a blends in Russia, HCFC-22/HFC-152a blends in China and HCFC-22 replacing R-502 in Japan. These all are low volume applications supplementing high-volume primary conversions to HC-600a or HFC-134a refrigerant. Demand for <u>all</u> refrigerants other than HC-600a and HFC-134a totals less than 2% of all Original Equipment Manufacturer (OEM) refrigerant demand (UNEP, 2003). These special circumstance applications will not be further discussed in this report.

4.2.2.2 Service of existing equipment
Service options range from *service* with original refrigerant, to *drop-in*, where only the refrigerant is changed, to *retrofit*, which changes the refrigerant and other product components to accommodate the specific refrigerant being used. Several binary and ternary blends of various HFC, HCFC, PFC and hydrocarbon refrigerants have been developed to address continuing service demand for CFC-12. These blends are tailored to have physical and thermodynamic properties compatible with the requirements of the original CFC-12 refrigerant charge. Their application has been successful and is growing. Some of these are near-azeotrope blends; others have disparate boiling points or glide. If refrigerants and lubricants other than original design specification are proposed for use, their compatibility with the specific refrigerator-freezer product configuration and its component materials must be specifically reviewed. An extended discussion of domestic refrigerator service options was included in the 1998 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (UNEP, 2003).

4.2.3 Not-in-kind alternatives

Alternative refrigeration technologies such as the Stirling cycle, absorption cycle, thermoelectrics, thermoacoustics and magnetic continue to be pursued for special applications or situations with primary drivers that differ from conventional domestic refrigeration. Two examples of unique drivers are portability or absence of dependence on electrical energy supply. The 1994 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee concluded that no identified technology for domestic refrigerator-freezers was competitive with conventional compression-compression technology in terms of cost or energy efficiency (UNEP, 1994). The 1998 and 2002 reports of this committee reaffirmed this conclusion (UNEP, 1998; UNEP, 2003). No significant near-term developments are expected to significantly alter this conclusion.

4.2.4 Energy efficiency and energy standards

Relative refrigerator energy efficiency is a critical parameter in the assessment of alternatives. In practice, similar refrigeration system efficiency results from the use of either HFC-134a or HC-600a refrigerant. Independent studies have concluded that the relative energy efficiencies of these two primary alternatives are comparable. Efficiency differences from normal manufacturing variation exceed the differences introduced by the refrigerant choice (Sand *et al*., 1997; Fischer *et al.,* 1994; D&T, 1996; Wenning, 1996). Energy efficiency of a product is strongly influenced by configuration, component hardware selection,"thermal insulation, heat exchange surfaces and control algorithms. Effective options are readily available from multiple commercial sources. The improved energy efficiency of domestic refrigeration products is a national initiative in several countries. Energy labelling and energy standards are both being effectively used to facilitate these initiatives. The

Table 4.2. Global refrigerant demand for domestic refrigeration (tonnes) (UNEP, 2003; Euromonitor, 2001).

Refrigerant	Refrigerant demand (tonnes) 1992	1998	2000
New equipment			
CFC-12	10,130	4460	3330
HFC-134a	-	5520	7150
HC-600a	-	430	1380
Other [(1)]	80	200	230
Sub-total New equipment	**10,210**	**10,610**	**12,090**
Field service			
CFC-12	4458	5002	4484
HFC-134a	-	349	391
HC-600a	-	4	146
Other [(2)]	15	40 [(3)]	- [(3)]
Sub-total Field service	**4473**	**5395**	**5021**
Total Global demand	**14,683**	**16,005**	**17,111**

(1) HCFC-22, HFC-152a and HC-190 refrigerants
(2) Three refrigerants above, plus numerous HFC and/or HCFC and/or HC blends
(3) Reliable demand data not available due to disperse nature of demand

Collaborative Labelling and Appliance Standards Program (CLASP) maintains a website with substantive information including links to various national programmes (URL: http://www.clasponline.org).

Energy standards and tests procedures
Energy test procedures provide the basis for energy regulations and labelling initiatives. These test procedures must be reproducible and repeatable and should ideally provide an indication of energy consumption under consumer use conditions. They should also provide an effective amendment protocol to accommodate evolving product technologies. Test procedures have been developed by several global standards organizations. The tests are different, and the results from one should never be directly compared with the results from another. Each can provide a relative energy consumption value for the test conditions specified. The interested reader is referred to instructive discussions and comparisons of energy test procedures, their limitations and their future needs (Bansal and Kruger, 1995; Meier and Hill, 1997; Meier, 1998).

4.2.5 Consumption and consumption trends

Table 4.2 presents consumption of the three most used domestic refrigerator refrigerants during 1992, 1996 and 2000 (UNEP, 2003). Table 4.3 presents consumption details by global region for the year 2000 (UNEP, 2003). New equipment conversions from CFC-12 to ozone-safe alternatives are occurring in advance of the Montreal Protocol requirements. By the year 2000, 76% of new unit production had been converted: 53% to HFC-134a, 21% to HC-600a and 2% to all other (UNEP, 2003). Subsequent developments have maintained this trend with an apparent increase in the percentage converting to hydrocarbon refrigerants. Two large market examples are the production in India converting to either HFC-134a or an HC-600a/HC-290

Table 4.3. Global refrigerant demand in 2000 for domestic refrigeration by global region, in tonnes (UNEP, 2003; Euromonitor, 2001).

Region	Segment[(1)]	Global refrigerant demand in 2000 (tonnes) CFC-12	HFC-134a	HC-600a	Other [(2)]	Total
Western Europe	OEM		900	770		**1670**
	Service	34	14	12	n.a.	**60**
Eastern Europe	OEM	230	420	40	30	**720**
	Service	180	17	4	n.a.	**201**
North America	OEM		2460			**2460**
	Service	60	60		n.a.	**120**
Central and South America	OEM	200	1200			**1400**
	Service	990	20		n.a.	**1010**
Asia and Oceania	OEM	2030	1900	570	200	**4700**
	Service	2420	230	130	n.a.	**2780**
Africa and Mid-east	OEM	870	270			**1140**
	Service	800	50		n.a.	**850**
World	OEM	3330	7150	1380	230	**12,090**
	Service	4484	391	146	n.a.	**5021**
	Total	**7814**	**7541**	**1526**	**230**	**17,111**

(1) OEM: Original Equipment Manufacturer
(2) n.a.: data not available

blend (UNEP, 2000) and some units converting from HFC-134a to HC-600a in Japan.

Conversion of the service demand has been less successful. Field service procedures typically use the originally specified refrigerants. The long useful product life (up to 30+ years for some units with an average around 20 years), large installed base (approximately 1500 million units) and uncertainties with field conversion to alternative refrigerants have resulted in a strong continuing service demand for CFC-12. The estimated percentage of refrigerators requiring post-warranty service of the hermetically sealed system and replacement of the original refrigerant charge at sometime during their service life is 1% in industrialized countries and 7% in developing countries. In industrialized countries this demand is typically satisfied with reclaimed or stockpiled CFC-12 when not contrary to local regulations. (Note: 'Reclaimed' refrigerant refers to recovered refrigerant that has been purified to original specifications. Unpurified recovered refrigerant should never be used in long-life domestic refrigerators. Probable impurities are likely to catalyze systems degradation and cause premature failures.) CFC-12 is normally the lowest cost refrigerant in developing countries. Regardless of location, use of the CFC-free refrigerant service blends mentioned above only becomes significant when CFC-12 availability becomes limited. Since post-warranty service is typically provided by small, independent businesses, reliable service demand data are not available. Further, the limited capital resources in developing countries promotes the labour-intensive refurbishing of units compared to retirement and replacement with new units. This not only prolongs the phase-out of CFC-12, but also results in increased failure rates from the highly variable quality of workmanship.

4.2.6 Factors affecting emissions

A text-box example included in Chapter 3 of this report (see Table 3.5) tabulates emission factors which must be considered for comprehensive Life Cycle Climate Performance (LCCP) or Total Equivalent Warming Impact (TEWI) of domestic refrigeration design options. There are two general types of emissions: *direct*, which for discussion of the refrigerant choice are limited to the refrigerant itself; and *indirect*, which depends on the refrigerator design and the infrastructures of supporting services in the use environment (Sand *et al*., 1997). The emission of insulating foam blowing-agents is not addressed in this chapter. Insulating foam is addressed in Chapter 7

Direct emissions

Efficient factory operations and effective process and product designs will minimize emissions at the start of the product life cycle. Significant process variables include refrigerant transfer and storage, charge station operations, maintenance protocols and factory process efficiencies. Key refrigerator design variables include hermetic-system internal volume, number of joints, mechanical fatigue and abuse tolerance and, of course, the choice of refrigerant. Domestic refrigerators contain refrigerant in factory-sealed, hermetic systems. Once sealed, refrigerant emission can only occur if there is a product defect or quality issue. Typical examples are brazing defects or containment component fatigue. In all cases, excluding life-ending failures, the defect will require the product hermetic system to be repaired. Variables influencing emissions during service include refrigerant recovery procedure usage and efficiency, charge technique employed, technician training and technician work standards. Refrigerant recovery during service is practiced in many countries. The small refrigerant charge quantity, typically 50–250 g per unit, make this recovery economically unattractive. Regulations and non-compliance penalties are usually required to provide incentives for recovery. Audits and refrigerant charge logs can provide useful metrics for the quality of refrigerant recovery practices.

Clodic and Palandre (2004) have detailed worldwide refrigerant bank and emissions data for domestic refrigerators (see Table 4.1). CFC emissions for domestic refrigeration in 2002 were estimated to be 8000 tonnes. HFC emissions for domestic refrigeration in 2002 were estimated to be 0.3% of the domestic refrigerant bank, or 500 tonnes. Domestic HFC refrigerant emission estimates will have increased in 2015 to 3000–8000 tonnes, dependent on the extent of refrigerant containment and recovery assumed.

With a typical 20-year lifespan, refrigerator end-of-life retirement and disposal happens to about 5% of the installed base every year. In quantified terms this means approximately 75 million refrigerators containing approximately 100 g per unit or 7500 total tonnes of refrigerant are retired and disposed of annually. For the next few years, or possibly even decades, CFC-12-containing product will continue to be a significant fraction of the waste stream. As is the case for service recovery, the small refrigerant charge makes end-of-life recovery uneconomical. Equipment and procedures commonly used for refrigerant recovery during service can be used but recovery is more typically accomplished in central disposal locations. This allows the use of faster, less labour-intensive procedures to moderate recovery costs. Nevertheless, regulations and non-compliance penalties normally provide incentives for this recovery. Regulating agencies in various global regions administer these requirements and are an appropriate source for further information.

Indirect emissions

Product design affects indirect emissions through refrigerator operating efficiency, and ease of refrigerator disassembly and separation for recycling. Higher efficiency units consume less electricity which, in turn, proportionately reduces the emissions derived from electrical power generation and distribution. Parameters influencing energy efficiency are fundamental design considerations such as heat exchangers, control efficacy, refrigerant systems, heat losses, parasitic power demands such as fans and anti-sweat heaters and product safety. The design approaches taken and options selected are directly related to the desired product features, performance and regulatory environment. A comprehensive discussion of detailed design parameters is beyond the scope of this report. Information is commercially available from multiple sources. Example references listing areas of opportunity are the UNEP Refrigerants Technical Options Committee assessment reports (UNEP, 1994, 1998, 2003), the International Energy Agency energy efficiency policy profiles report (IEA, 2003) and the Arthur D. Little global comparative analysis of HFC and alternative technologies (ADL, 2002). Objective discussions of many options are contained in the Technical Support Documents of the US Department of Energy rulemakings for domestic refrigerators and freezers (US DOE, 1995).

4.2.7 Comparison of emissions from alternative technologies

HFC-134a and HC-600a are clearly the significant alternative refrigerants for domestic refrigeration. Consequently, the significant global-warming emissions comparison for this application sector is HFC-134a compared to HC-600a. An accurate comparison of these is very complex. The multiple and widely diverse product configurations available globally are the consequence of consumer needs and choices. Comparative analysis results will be influenced by the example scenario selected and its assumed details. The available degrees of freedom are too high to achieve a comprehensive perspective within a manageable number of scenarios. Any single technical solution will not provide an optimized solution.

Harnisch and Hendriks (2000) and March (March, 1998) estimated the conversion cost from HFC-134a to HC-600a, expressed as unit emissions avoidance cost. Harnisch and Hendriks assumed no product cost or performance impact and a 1 million per manufacturing site conversion cost which yielded an avoidance cost of 3.4 per tonne CO_2-eq. March (1998) assumed higher product and development costs, also with no performance impact, which resulted in an avoidance cost of 400 per tonne of CO_2. These two estimates differ by more than two orders of magnitude in direct emissions abatement costs with assumed equivalent indirect emissions. Table 4.4 summarizes emission abatement opportunities with increased application of HC-600a refrigerant in the three most common domestic refrigerator configurations. Estimates for manufacturing cost premiums, development costs and required implementation investments are also included. Emission abatement opportunities are based on Clodic and Palandre (2004).

The objective is to assess the total emissions from *direct* and *indirect* sources. HC-600a clearly has the advantage of minimizing *direct* GHG emissions. *Indirect* emissions can dominate overall results using some scenarios or assumptions. The energy consumption of basic HFC-134a and HC-600a refrigeration systems is similar. At issue is what product modifications are required or allowed when converting to an alternative refrigerant and what effect these modifications have on product efficiency and performance. This uncertainty is particularly applicable to larger, auto-defrost refrigerators where a trade-off between system efficiency and other product attributes necessary to maintain product safety is not obvious. The consequences of trends in consumer purchase choices and their influence on the rate of emissions reduction are also difficult to predict. LCCP and TEWI are powerful, complementary tools, but results are sensitive to input assumptions. Assumptions should be carefully validated to ensure they are representative of the specific sce-

Table 4.4. Domestic refrigeration, current status and abatement options.

Product Configuration		Cold Wall	Open Evaporator Roll Bond	No-Frost
Cooling capacity	From	60 W	60 W	120 W
	To	140 W	140 W	250 W
Refrigerant charge (HFC)	From	40 g	40 g	120 g
	To	170 g	170 g	180 g
Approximate percentage of sector refrigerant bank (160 kt) in configuration		20 units * 100 g average 18% of 160 kt	15 units * 100 g average 14% of 160 kt	50 units * 150 g average 68% of 160 kt
Approximate percentage of sector refrigerant emissions (8950 tonnes) in subsector		18% of 8950 tonnes	14% of 8950 tonnes	68% of 8950 tonnes
Predominant technology		HC-600a	HFC-134a	HFC-134a
Other commercialized technologies		HFC-134a, CFC-12	HC-600a, CFC-12	HC-600a, CFC-12
Low GWP technologies with fair or better than fair potential for replacement of HCFC/HFC in the markets		R-600a	HC-600a	HC-600a
Status of alternatives		Fully developed and in production	Fully developed and in production	Fully developed and in production
R-600a Mfg. Cost Premium		No Premium	3–5 US$	8–30 US$
Capital Investment		0	45–75 million US$	400–1500 million US$
Emission reduction		1432 tonnes	1253 tonnes	6086 tonnes

narios of interest.

Several investigators have analyzed total emission scenarios comparing HFC-134a and HC-600a for domestic refrigeration:

- An Arthur D. Little, Inc. LCCP study (ADL, 1999) estimated that approximately 14 grams (10% of initial charge) of HFC-134a would be the total net lifetime emissions from a domestic refrigerator in the USA regulatory environment. Using US power generation emission data, this equates to a 0.3% energy consumption increase over a typical 20-year product life;
- Ozone Operations Resource Group of the World Bank Report No. 5: 'The Status of Hydrocarbon and Other Flammable Alternatives Use in Domestic Refrigeration' (World Bank, 1993) cited TEWI assessments presented at the 1993 German National Refrigeration Congress in Nurnberg. Regarding the relative refrigerant selection effects, this TEWI analysis concluded that 'The *direct* contribution of HFC-134a to global warming … should not be given serious consideration within this rough estimate because it does not amount to more than a few percent of the *indirect* contribution caused by the energy consumption of the appliance' (Lotz, 1993).

4.2.8 Emission abatement opportunities

The following emission abatement opportunities are available for domestic refrigerators:

- Conversion to alternatives having reduced GWP: The refrigerant direct emission contribution ranges from less than 2% up to 100% of total emissions. Direct emissions of 100% reflect the condition where the power generation and distribution infrastructure has zero dependence on fossil fuel energy sources. Direct emissions favour HC-600a over HFC-134a. Regional regulatory and product liability considerations can hamper the viability of HC-600a application. Indirect emissions depend upon relative product energy efficiency. Thermodynamic cycle efficiencies of the alternatives are comparable. Product efficiency is dependent upon design attributes required to accommodate the flammability of HC-600a. There is no penalty with the cold-wall evaporator configurations common in Europe. Information concerning configurations commonly used for forced-convection, automatic-defrost products is limited or proprietary;
- Reduction of refrigerant leakage during service life: Annual leakage rates for the factory-sealed, hermetic systems in domestic units are typically less than 1%…This leakage typically drives service demand;
- Recovery of refrigerant during end-of-life disposal or during field repair: Approximately 5% of the installed base are retired each year. The annual service call rate is significantly less than that. Recovery efficiency is a critical variable;
- Reduction of indirect emissions through improved product energy efficiency: The indirect emission contribution for domestic refrigeration ranges from zero to more than 98% of total emissions. Current production refrigerators consume less than half the energy of the typically 20-year-old unit they replace. With a 5% yr^{-1} retirement rate, this translates to a 2.5% yr^{-1} improvement in indirect emissions from the installed base;
- Opportunities for reduced indirect emissions exist via improved product energy efficiency. The IEA energy efficiency policy profiles report (IEA, 2003) estimated the potential improvements to be 16–26%, dependent upon product configuration. Average cost inflation was estimated to be 23 (US$ 31) for manufacturing and 66 (US$ 88) for purchase. The report presents comparative Least Life Cycle Cost analyses for alternatives. Arthur D. Little conducted Life Cycle Climate Performance studies of HFC and other refrigerant alternatives (ADL, 2002). Their report gives heavy domestic refrigeration emphasis on the relative energy efficiency and Total Equivalent Warming Impact assessment of various blowing-agent alternatives.

4.3 Commercial refrigeration

Commercial Refrigeration is the part of the cold chain comprising equipment used by retail outlets for preparing, holding and displaying frozen and fresh food and beverages for customer purchase.

For commercial systems, two levels of temperature (medium temperature for preservation of fresh food and low temperature for frozen products) may imply the use of different refrigerants. Chilled food is maintained in the range 1°C–14°C but the evaporating temperature for the equipment varies between –15 °C and 5 °C dependent upon several factors: the type of product, the type of display case (closed or open) and the type of system (direct or indirect). Frozen products are kept at different temperatures (from –12 °C to –18 °C) depending on the country. Ice cream is kept at –18 to –20 °C. Usual evaporating temperatures are in the range of –30 to –40 °C.

On a global basis, commercial refrigeration is the refrigeration subsector with the largest refrigerant emissions calculated as CO_2 equivalents. These represent 40% of the total annual refrigerant emissions, see Table 11.5. Annual leakage rates higher than 30% of the system refrigerant charge are found when performing a top-down estimate (Clodic and Palandre, 2004; Palandre *et al*., 2004). This means that in an environment with an average energy mix, the refrigerant emissions might represent 60% of the total emissions of GHG resulting from system operation, the rest being indirect emissions caused by power production. This indicates how important emission reductions from this sector are.

There are five main practices in order to reduce direct GHG emissions:

1. A more widespread use of non-HFC refrigerants;
2. Leak-tight systems;
3. Lower refrigerant charge per unit of cooling capacity;
4. Recovery of refrigerant during service and end-of-life;
5. Reduced refrigeration capacity demand.

4.3.1 Sector background

Commercial refrigeration comprises three main types of equipment: stand-alone equipment, condensing units and full supermarket systems.

Stand-alone equipment consists of systems where all the components are integrated: wine coolers, beer coolers, ice cream freezers, beverage vending machines and all kinds of stand-alone display cases. This equipment is installed in small shops, train stations, schools, supermarkets and corporate buildings. Annual growth is significant. All types of stand-alone equipment are used intensively in industrialized countries and are the main form of commercial refrigeration in many developing countries. These systems tend to be less energy efficient per kW cooling power than the full supermarket systems described below. A main drawback to stand-alone units is the heat rejected to ambient air when placed indoors. Therefore, the heat must be removed by the building air conditioning system when there is no heating requirement.

Condensing units are used with small commercial equipment. They comprise one or two compressors, a condenser and a receiver which are normally located external to the sales area. The cooling equipment includes one or more display cases in the sales area and/or a small cold room for food storage. Condensing units are installed in specialized shops such as bakeries, butchers and convenience stores in industrialized countries, whilst in developing countries a typical application is the larger food retailers.

Full supermarket systems can be categorized by whether refrigerant evaporation occurs in the coolers, or whether a low-temperature secondary heat transfer fluid (HTF) that is cooled centrally is circulated in a closed loop to the display cabinets and cold stores. The first type is termed 'direct expansion' or direct system and the second type is termed indirect system. Direct systems have one less thermal resistance and no separate fluid pumping equipment, which gives them an inherent efficiency and cost advantage. The HTF circulated in an indirect system normally gains sensible heat, but may gain latent heat in the case of ice slurry or a volatile fluid like CO_2.

Many different designs of full supermarket systems can be found. *Centralized systems* consist of a central plant in the form of a series of compressors and condenser(s) located in a machinery room or an outside location. This provides refrigerant liquid or an HTF at the correct temperature levels to cabinets and cold stores in other parts of the building. Each rack of multiple compressors is usually associated with a single air-cooled condenser. Specific racks are dedicated to low-temperature or medium-temperature evaporators. The quantity of refrigerant is related to the system design, refrigerating capacity and refrigerant choice varies. The centralized systems can be either direct or indirect systems. Centralized direct systems constitute by far the largest category in use in supermarkets today. The size can vary from refrigerating capacities of about 20 kW to more than 1 MW. The centralized concept is flexible in order to utilize heat recovery when needed (Arias, 2002).

Distributed Systems are characterized by having smaller compressors and condensers close to or within the coolers, so that many sets of compressor/condenser units are distributed around the store. The compressors can be installed within the sales area with remote condensers. When they are installed as small packs with roof-mounted, air-cooled condensers, or as small packs adjacent to the sales area in conjunction with remote air-cooled condensers they are sometimes referred to as C*lose Coupled Systems*. The quantity of such units could range from just a few to upwards of 50 for a large supermarket. They are direct systems, but when installed inside the building that may employ a HTF, usually water, for collecting heat from the different units.

Hybrid systems cover a range of possibilities where there is a combination of types. An example is a variation of the distributed system approach, where low-temperature cabinets and cold stores comprise individual water-cooled condensing units, which are supplied by the medium-temperature HTF. Thus, in the indirect medium temperature section, the refrigerant charge is isolated mainly to the machinery room, whilst an HTF is circulated throughout the sales and storage areas at this temperature level.

In some countries, indirect, close-coupled, distributed and hybrid systems have been employed in increasing number in recent years because they offer the opportunity of a significant reduction in refrigerant charge. Additionally, with indirect systems the refrigerant charge is normally located in a controlled area, enabling the use of low-GWP refrigerants that are flammable and/or have higher toxicity. This approach has been adopted in certain European countries due to regulatory constraints on HCFCs and HFCs (Lundqvist, 2000). A review of possible system solutions is provided by Arias and Lundqvist (1999 and 2001). The close-coupled systems offer the advantages of low charge, multiple compressors and circuits for part load efficiency and redundancy, as well as the efficiency advantage of a direct system (Hundy, 1998).

4.3.2 Population/production

There is a lot of variation in the geographical distribution of commercial refrigeration systems, even in neighbouring countries, due to differing consumption habits, regulation of opening hours, leadership of brand names, state of the economy and governmental regulations.

A number of leading US and European manufacturers are expanding worldwide, especially into Eastern European countries and other countries with fast growing economies, such as: Argentina, Brazil, China, Indonesia, Mexico, Thailand and Tunisia. The growth of all types of commercial refrigerating systems in China is one of the most significant of the past 4 years. For example, the number of small supermarkets (average total sales area of about 380 m^2) has increased by a factor of six in the past 4 years.

Table 4.5 shows the average total sales area of supermarkets, which differs significantly per country. The 'hypermarket' concept of selling food, clothing and all types of household

Table 4.5. Typical sales areas of supermarkets in selected countries (UNEP, 2003).

	Brazil	China	France	Japan	USA
Average surface of supermarkets (m^2)	680	510	1500	1120	4000
Average surface of hypermarkets (m^2)	3500	6800	6000	8250	11,500

Table 4.7. Evaluation of the number of items of commercial equipment (UNEP, 2003).

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

goods, is expanding worldwide.

Table 4.6 shows an estimate of supermarket and hypermarket populations and Table 4.7 an evaluation of the population of smaller commercial units.

It is only possible to evaluate the refrigerant quantities based on the number of supermarkets if additional data are used concerning the total sales area of fresh and frozen food and the type of refrigerating system. Nevertheless in terms of the number of supermarkets, China represents more than 30% of the total global population of supermarkets (UNEP, 2003).

For small commercial supermarkets, China represents about 40% of the total global population, with the exception of vending machines. The growth of vending machines is still very significant, especially in Europe (UNEP, 2003).

4.3.3 HFC and HCFC technologies, current usage and emissions

4.3.3.1 Refrigerant choices

Refrigerant choices for new equipment vary according to national regulations and preferences.

Europe: Following CFC phase out for new equipment and servicing in Europe, commercial refrigeration tended towards the use of HCFC-22 and HCFC-22 blends. However, in the Nordic countries, the period with HCFC-22 was very short, and HFCs such as R-404A became the preferred solution from 1996 onwards. Since 2000, European Regulation 2037/2000 (Official Journal, 2000) has prohibited HCFCs in all type of new refrigerating equipment. HFC-404A and HFC-507A are now the most commonly used refrigerants for larger capacity low- and medium-temperature systems, such as condensing units and all types of centralized systems. For stand-alone systems, HFC-134a is used for medium-temperature applications, while both HFC-134a and HFC-404A are used for low-temperature applications.

Table 4.6. Number of supermarkets and hypermarkets (UNEP, 2003).

	Number of Supermarkets	Number of Hypermarkets
EU	58,134	5410
Other Europe	8954	492
USA	40,203	2470
Other America	75,441	7287
China	101,200	100
Japan	14,663	1603
Other Asia	18,826	620
Africa, Oceania	4538	39
Total	**321,959**	**18,021**

Japan: In Japan where HCFCs are still permitted, a voluntary policy is followed by OEMs and more than one-third of new equipment employs HFCs, with the remainder using HCFC-22. Typically, HFC-407C is used for medium temperature and HFC-404A for low temperature in all categories of commercial systems.

USA and Russia: In the USA, HCFC-22 and HCFC-22 blends are commonly used in existing systems, primarily for medium-temperature applications. HCFC-22 continues to dominate new supermarket systems, but HFC-404A and HFC-507A are becoming more widely used. HFC-404A and HFC-134a are used in new stand-alone equipment. These trends are also seen in Russia, where alternatives include HFC-134a, HCFC-22 and HCFC-22 blends as well as HFC-404A in a broad range of commercial equipment.

Developing countries: Stand-alone equipment is the main form of commercial refrigeration in developing countries, with condensing units being used by larger food retailers. CFCs, HCFCs and HFCs are all being used, with trends towards HFCs HFC-134a and HFC-404A in the future.

In China, HCFC-22 and HFC-134a are the major refrigerants for commercial refrigeration, with R-404A showing rapid growth. Only limited amounts of CFC-12 and R-502 are in use, as most of the systems designed for these refrigerants have converted to HFC-134a and R-404A. HCFC blends have very little application, as Chinese regulatory groups prefer to switch directly to HFCs instead of using any transitional HCFC blends.

4.3.3.2 Emissions

Emission rates derived with a bottom-up approach suggest a global annual emissions rate from the commercial refrigeration sector of 30% of the refrigerant charge (leakage and non-recovery) (Palandre *et al.*, 2004). Expressed in CO_2 equivalents, commercial refrigeration represents 40% of total annual refrigerant emissions, see Table 4.1. The emission levels (including fugitive emissions, ruptures, emissions during servicing and at end-of-life) are generally very high, especially for supermarkets and hypermarkets. The larger the charge, the larger the average emission rate. This is due to the due to the very long pipes, the large numbers of fittings and valves, and the huge emissions when ruptures occur.

In the 1980s, the reported average commercial refrigeration emission rates for developed countries were in the range of 20–35% of refrigerant charge per year (Fischer *et al*., 1991; AEAT, 2003; Pedersen, 2003). The high emission rates were due to design, construction, installation and service practices being followed without an awareness of potential environmental impact. In some countries emissions from these systems have been decreasing due to industry efforts and governmental regulations with respect to refrigerant containment, recovery and usage record keeping, increased personnel training and certification, and improved service procedures, as well as increased attention for many system mechanical details including the reduction or elimination of threaded joints and a reduction in the number of joints in refrigerating systems.

Recent annualized emission rates in the range of 3–22% (average of 18%) were reported for 1700 supermarket systems in several European countries and the USA. The country-specific data and references are listed in Table 4.8. It may be concluded that if the emission estimates of Palandre *et al*. (2003 and 2004) are correct, the above-reported values of 3–22% must represent selected company data within countries that have a strong emphasis on emission reductions.

Emission rates vary considerably between equipment categories. Annual emission rates for the several categories are listed in Table 4.9. Individual system leak rates, however, can range from zero to over 100% yr^{-1}. It should also be noted that end-of-life recovery data are mostly not included, and therefore the annual average leakage rates may be 5–10% higher than the values given in the tables.

Table 4.8. Leakage rates of supermarket refrigeration systems.

Country	Year(s)	Annual Refrig. Loss	References
The Netherlands	1999	3.2	Hoogen *et al*., 2002
Germany	2000–2002	5-10%	Birndt *et al*., 2000; Haaf and Heinbokel, 2002
Denmark	2003	10%	Pedersen, 2003
Norway	2002–2003	14%	Bivens and Gage, 2004
Sweden	1993 1998 2001	14% 12.5% 10.4%	Bivens and Gage, 2004
United Kingdom	1998	14.4%	Radford, 1998
USA	2000–2002	13%, 18%, 19%, 22%	Bivens and Gage, 2004

Table 4.9. Indicative leakage rates from commercial refrigeration equipment categories found in the literature.

Category	Annual Refrigerant Loss	References
Stand-alone hermetic	≤1%	March, 1999; ADL, 2002
Small condensing unit	8–10%	March, 1999; AEAT, 2003
Centralized direct (DX)	3–22%	Several; see main text
Distributed	4%	ADL, 2002
Indirect (secondary loop)	2–4%	ADL, 2002

It is important to note that in certain cases, data collection should be considered in context. Some of the base data used in emission and emission projection studies has been collated from telephone interviews, and other similar techniques, from historical reports. This reliance on anecdotal data may suggest underestimated emissions, since both the end-users and refrigeration contractors have an interest in reporting low values because of exposure of poor practices and the threat of restrictive legislation.

As well as measures designed to decrease emissions, there are also drivers – typically at field level – that inhibit emission reduction and must be addressed at a policy level. These include partial success in finding system leaks, end-users employing contractors on an ‘as-the-need-arises’ basis rather than a preventative basis, additional attendance time for refrigerant recovery and leak testing, and a financial incentive for contractors to sell more refrigerant to the end-user.

There have been important observations on system emission characteristics and how emission reductions have been accomplished. Some are listed below.

In the Netherlands, emissions have been significantly reduced through national mandatory regulations established in 1992 for CFCs, HCFCs and HFCs. These measures have been assisted by an industry supported certification model (STEK, which is the abbreviation for the institution for certification of practices for installation companies in the refrigeration business). Elements of the regulation are detailed by Gerwen and Verwoerd (1998), and include the technical requirements to improve tightness, system commissioning to include pressure and leakage tests, refrigerant record keeping, periodic system-leak tightness inspections, and maintenance and installation work by certified companies and servicing personnel (Gerwen and Verwoerd, 1998). The STEK organization was founded in 1991 to promote competency in the handling of refrigerants and to reduce refrigerant emissions. STEK is responsible for company certification, personnel certification and the setting-up of training courses.

The success of the Dutch regulations and the STEK organization in reducing refrigerant emissions was demonstrated by the results from a detailed study in 1999 of emission data from the refrigeration and air conditioning sectors. For commercial refrigeration, annual refrigerant emissions (emissions during leakage plus disposal) as low as 3.2% of the total bank of refrigerant contained in this sector were reported (Hoogen and Ree, 2002).

In Germany, the report by Birndt *et al*. (2000) found that no leaks were identified in 40.3% of the systems, 14.4% of the leaks contributed to 85% of the refrigerant loss and 83% of the leaks occurred in the assembly joints. The report by Haaf and Heinbokel (2002) was on R-404A systems in medium- and low-temperature supermarket refrigeration. Data was taken on systems installed after 1995 with improved technologies for leak tightness, plus a reduction of refrigerant fill quantities by 15%. Annual leakage rates were determined to be 5% of charge, which represented a 10% reduction on the level reported in previous years.

The data from Sweden showed annual refrigerant losses decreasing from 14% in 1993 to 10.4% in 2002 (Bivens and Gage, 2004), with the lower emissions being attributed, in part, to an increased application of indirect cooling systems with reduced refrigerant charges in supermarkets.

A set of 2000–2001 USA emissions data were available for 223 supermarkets in the California South Coast Air Quality Management District (Los Angeles area). The data were reported in system charge sizes from 23 kg up to 1285 kg. Over the two-year period, 77% of the smaller charge size systems (23−137 kg) required no refrigerant additions, 65% of the medium charge size systems (138−455 kg) required no refrigerant additions and 44% of the larger charge size systems (456−1285 kg) required no refrigerant additions. These are the outcomes expected, based on larger charge size systems having longer piping runs, more assembly joints, more valves and more opportunities for refrigerant leakage. For the 223 supermarkets, total averaged refrigerant emission rates were 13% of charge in 2000, and 19% in 2001 (Bivens and Gage, 2004).

The data from Germany and the USA indicate that, since the average emission rates include systems with no emissions, the leaking systems have higher loss rates than the averages. This amplifies the importance of monitoring refrigerant charge using sight glasses and liquid levels, and of periodic checking with leak detectors. These both represent a significant opportunity for identifying and repairing high leakage rate sources. Procedures for emission reduction have been developed by ANSI/ASHRAE, 2002.

The trend away from the ozone-depleting CFCs and HCFCs, and towards an increased use of HFCs means, that despite lower leakage rates, HFC leakage from refrigeration is set to increase considerably. For example in Europe, a 50% cut in leakage rates due to the initiation of STEK-like programmes in every member state would result in emissions rising from 2.5–4.3 Mtonnes CO_2-eq in 1995 to around 30 Mtonnes CO_2-eq in 2010, instead of 45 Mtonnes CO_2-eq under a business-as-usual scenario (Harnisch and Hendriks, 2000; Enviros, 2003).

The continuing collection of reliable emissions data is an important factor in getting a clear picture of the leakage situation and thereby establishing progress in the reduction of refrigerant emissions. Palandre *et al.* (2003 and 2004) and US EPA (2004) report two global programmes for the collection of such data. Data from the Clodic and Palandre (2004) permits the calculation of the worldwide commercial refrigeration emission rate for the year 2002 and this amounted to 30% of the commercial refrigeration systems inventory. The US EPA model information also permits the calculation of a potential 20−30% reduction business-as-usual HFC emissions from commercial refrigeration in the year 2015, by applying abatement options that require a more aggressive leak detection and repair and the increased use of distributed and indirect systems (Bivens and Gage, 2004).

4.3.4 Non-HFC technologies (vapour compression)

A number of HCs, ammonia and CO_2 systems of different refrigerating capacities have been installed in various European countries during the past 5 years. A few examples of these are now given.

4.3.4.1 Stand-alone equipment and condensing units

Some well-established beverage companies and ice cream manufacturers have recently stated (2000−2001) that by 2004 they will no longer purchase new equipment that uses HFCs in their refrigerant systems, provided that alternative refrigerants or technologies become available at an acceptable cost. HCs, CO_2 and Stirling technology are being evaluated by one of the companies (Coca Cola, 2002). The HFC-free strategy of the companies were confirmed during June 2004 (RefNat, 2004).

4.3.4.1.1 Hydrocarbons

Various companies in several countries have developed vending machines and small commercial equipment using HCs. The equipment uses HC-600a, HC-290 and HC-based blends. Limitations on charge sizes are specified by safety standards (e.g. EN 378, IEC 60335-2-89), where maximum amounts per circuit are 2.5 kg, 1.5 kg and 150 g, dependent on the application. Nevertheless, HC charges tend to be about 50% less than equivalent HFCs and HCFCs due to lower densities which minimize the impact of such limits. Recent developments with charge-reduction techniques (Hoehne and Hrnjak, 2004) suggest that charges for future systems will become even less. Christensen (2004) reports on the experience with stand-alone equipment installed in a restaurant in Denmark. Results from a detailed quantitative risk assessment model that examined the safety of hydrocarbons in commercial refrigeration systems are reported in Colbourne and Suen (2004).

4.3.4.1.2 Carbon dioxide (CO_2)

CO_2 is being evaluated by a European company interested in developing stand-alone equipment with a direct expansion CO_2 system (Christensen, 1999) and is also one of the refrigerants being evaluated by Coca Cola (2002). The company confirmed their HFC-free strategy in June 2004 and announced that CO_2-based refrigeration is their current choice for future equipment (Coca Cola, 2004). R&D activities for CO_2-based solutions have also been announced by another company (McDonalds, 2004).

4.3.4.2 Full supermarket systems

4.3.4.2.1 Direct systems

CO_2 direct systems
CO_2 is non-flammable, non-toxic and has a GWP value of only 1. It is therefore highly suited for use in direct refrigeration systems, as long as acceptable energy efficiency can be achieved at a reasonable cost. There are two basic types of CO_2 direct systems using only CO_2 as a refrigerant and cascade systems.

Direct systems using only CO_2 as a refrigerant have been developed with a transcritical/subcritical cycle, depending on ambient temperature, for both low- and medium-temperature refrigeration are developed. In addition to giving a totally non-HFC solution, reduced pipe diameters due to higher pressures, good heat transfer characteristics of CO_2 and the possibility to obtain energy efficient heat recovery can be mentioned. Five medium-sized supermarkets have been installed with this concept by the beginning of June 2004, in addition to some smaller field test systems (Girotto and Nekså, 2002; Girotto *et al*. 2003; Girotto *et al*. 2004).

Cascade systems are being developed with CO_2 at the low-temperature stage associated with ammonia or other refrigerants (R-404A for example) at the medium-temperature stage. Several of these systems have been installed in the field and are currently being evaluated in different European countries. Haaf and Heinbokel (2003) have described 33 such CO_2 cascade systems from one manufacturer that were in service in 2003. It is emphasized that this technology could receive widespread interest because it has also been developed for the food industry (Rolfsmann, 1999; Christensen, 1999).

In addition to these two options, a third distributed system concept was described by Nekså *et al*. (1998). Self-contained display cabinets, each with CO_2 refrigeration units, are connected to a hydronic heat-recovery circuit that heats service water and buildings. A large temperature glide in the hydronic circuit, typically 50–60 K, and a correspondingly low volume flow rate and small pipe dimensions can be achieved by using the transcritical CO_2 process. Waste heat with a high temperature (70–75°C) is available for tap water and/or space heating. Excess heat is ejected to the ambient air.

The Institute of Refrigeration in London has released a 'Safety Code for Refrigerating Systems Utilizing Carbon Dioxide'. This contains a lot of relevant information despite much of the focus being on larger capacity industrial sized systems.

4.3.4.2.2 Indirect systems

Ammonia and hydrocarbons (HCs)
The quantity of ammonia can be 10% of the usual HFC refrigerant charge, due to indirect system design and the thermodynamic properties such as latent heat vaporization and liquid density (Presotto and Süffert, 2001). For HCs, the refrigerant charge is typically 10% of the direct system HFC reference charge (Baxter, 2003a,b).

In Northern Europe, ammonia or HCs (including HC-1270, HC-290 and HC-290/170 blends) have been used as refrigerants for the same type of indirect systems. For safety purposes, the refrigerant circuits are either separated in a number of independent circuits to limit the charge of each system or a number of independent chiller circuits are used (Powell *et al*., 2000).

Heat transfer fluids (HTF)
The HTFs used in indirect systems require special attention, especially at low temperatures where pumping power may be excessive. The choice of the correct HTF to obtain the desired energy efficiency is critical and a handbook on fluid property data is available from IIR/IIF (Melinder, 1997).

CO_2 as a heat transfer fluid
For indirect systems, CO_2 can be used as either a standard HTF without phase change or as a two-phase HTF that partially evaporates in the display case evaporators and condenses in the primary heat exchanger.

At low temperatures, phase-changing CO_2 HTF shows promising results. Due to the viscosity constraint of other alternatives at low temperatures and the good heat transfer properties of CO_2, the use of CO_2 as a low-temperature HTF has received more consideration than the alternatives. When CO_2 is used with phase change, the diameter of the tubes can be significantly reduced, and the heat transfer in the display case heat-exchanger is far more effective. If the temperature can be maintained below –12°C, traditional technologies in which the tubes and heat exchanger are designed for a maximum operating pressure of 25 bar, are possible. About 50 such systems are in operation in Europe. Expansion vessels, cold finger concepts or simply using the cold stored in the goods, are possible alternatives for keeping the pressures within acceptable limits.

Ice slurry as a heat transfer fluid
An interesting new technology for medium temperature, which offers the possibility of energy storage and high-energy efficiency, is indirect systems that use ice slurry as the HTF. Research has been carried out in some pilot installations. A handbook is currently being developed by the International Institute of Refrigeration and several recent papers on various aspects of the technology are described in Egolf and Kauffeld (2005).

4.3.5 Not in-kind technologies (non-vapour compression)

There are very few examples of the successful implementation of ‘not-in-kind’ technologies in this sector. One possible example is the Stirling cycle. For low capacity, high-temperature lift applications in particular (>60 K), the Stirling cycle may reach competitive COP values. Although Stirling systems have been developed, cost is still an issue (Lundqvist 1993; Kagawa, 2000). This technology is also being evaluated for display cabinets (Coca Cola, 2002). Another interesting recent technology is thermoacoustic refrigeration (Poese, 2004).

Heat-driven cycles have not found their way into commercial refrigeration. The use of heat-driven cycles such as absorption and adsorption in supermarkets have been discussed in literature (Maidment and Tozer, 2002). Some attempts with solar-driven refrigeration for fresh food handling have also been developed and tested (Pridasawas and Lundqvist, 2003). The use of sorption technologies for dehumidification, thus lowering the cooling load on display cabinets, is an interesting option.

4.3.6 Relevant practices to reduce refrigerant emissions

As stated at the beginning of this section, several abatement strategies can be used to reduce refrigerant greenhouse gas emissions. New design ideas have been mentioned throughout the chapter and these may be summarized as a general trend towards lower refrigerant charge, using direct or indirect systems, and the use of non-HFC refrigerants such as ammonia, CO_2 or HCs. These options should be considered on the basis of a balanced evaluation of refrigerant emission reductions, initial investment costs, safety, operating costs and energy consumption.

The European Commission has proposed a new regulation to reduce the emissions of fluorinated greenhouse gases, including HFCs from refrigeration equipment. In addition to a general obligation to avoid leakage, installations with over 3 kg of charge will require at least annual inspections, and a refrigerant detector will be required for systems over 300 kg. Reports will also be required for the import and export of refrigerants, and end-of-life recovery, recycling or destruction of the refrigerant. Additional information on country initiatives for refrigerant conservation is described in the 2002 UNEP TOC report, Sections 4.7 and 10.1 to 10.9 (UNEP, 2003).

Several programmes, for example in the Netherlands and Sweden, have shown good results with respect to leakage mitigation for existing plants. A common denominator has been a combination of regulation, education and accreditation of service personnel (STEK, 2001). In Denmark and Norway a tax on refrigerants in proportion to their GWP value has proven successful in curbing emissions and promoting systems that use non-HFC refrigerants.

A reduction of the refrigeration capacity demand, for example by using better insulation and closed rather than open cabinets, might indirectly reduce refrigerant emissions, but also the power consumption of a supermarket. Design integration with air-conditioning and heating systems are also important measures in this respect.

An interesting development in new design tools for supermarkets, opens up new possibilities for improving the design of systems using an LCC perspective, which favours more energy efficient systems with lower operating costs (Baxter, 2003a,b).

4.3.7 Comparison of HFC and non-HFC technologies

The current rapid developments in the subsector are moving the targets for energy efficiency, charge reduction and cost. This makes a comparison between technologies difficult. Furthermore, the relatively complex links between energy efficiency, emissions and the costs of systems and their maintenance means that it sis difficult to make fair comparisons.

4.3.7.1 Energy consumption of supermarkets

Depending on the size of the supermarket, the refrigeration equipment energy consumption represents between 35–50% of the total energy consumption of the store (Lundqvist, 2000). This ratio depends on a number of factors such as lighting, air conditioning, and so forth. For typical smaller supermarkets of around 2000 m^2, refrigeration represents between 40–50% of the total energy consumption and for even smaller stores it could be up to 65%.

New, high-efficiency commercial supermarkets have been designed in some European countries and the USA by using a number of efficient technologies. These references can be seen as prototypes and one example from UK presents energy consumption figures which are a factor of two lower compared to usual stores (Baxter, 2003a,b). Most examples however show reductions of between 10–20%.

The high annual growth rate of stand-alone equipment, which tends to be less energy efficient per kW cooling power than centralized systems, should be addressed. Integrating heat rejection from the individual cabinets in a water circuit may be one way of obtaining improved energy efficiency. Excessive heat rejection within the store might also lead to an increased demand for air conditioning, further increasing the energy demand.

4.3.7.2 Energy efficiency of direct systems

The energy efficiency of refrigeration systems first of all depends on the temperature levels for which refrigeration is provided and on the global design of the system. Measurements of system efficiency can be found in the literature, for example in UNEP (2003). However, comparisons of different systems are often difficult because the boundary conditions are rarely comparable.

Potential energy-saving measures may be divided into four different groups: advanced system solutions, utilization of natural cold (free cooling), energy-efficient equipment (display cases, efficient illumination, night curtains, etc.) and indoor climate/building-related measures. Energy-efficient illumination has the double effect of reducing loads on display cases as well as direct electric consumption. Heat recovery from condensers is sometimes preferred in cold climates but internal heat generation from plug-in units and illumination is often enough to heat the premises (Lundqvist, 2000).

The refrigeration system efficiency also depends on a number of parameters: pressure losses related to the circuit length, system control and the seasonal variation of the outside temperature. For a number of global companies energy consumption, and with this the energy efficiency of refrigerating systems, has become an important issue, especially in countries where electricity prices are high. One approach to energy savings is to utilize 'floating condensing temperature' in which the condensing temperature follows ambient temperature. The issue of climate change and the desire to reduce GHG emissions has also heightened the interest in increasing the energy efficiency.

4.3.7.3 Energy efficiency and cost of indirect systems

The evaluation of the additional energy consumption related to indirect systems is an ongoing process. Direct field comparisons between direct and indirect systems are difficult (Lundqvist, 2000; Baxter, 2003a). Moreover, the main driver for centralized systems is initial cost. Due to the design of heat exchangers in display cases (especially medium-temperature, open-type) the performances of some indirect systems can be equal or even slightly better than direct systems (Baxter, 2003a). For low temperatures, the energy penalty can be substantial depending on the design.

On the other hand, the relative energy consumption of indirect systems – compared to conventional direct expansion systems – can show an increased energy consumption of up to 15%. Conclusions can only be drawn if reference lines for the energy consumption of centralized systems are plotted in which the origin of energy inefficiencies are apparent. Due to the extra temperature difference required, inherently indirect systems should give higher energy consumptions compared to direct systems. Recent practical experiences and experimental studies (Mao *et al*., 1998; Mao and Hrnjak, 1999; Lindborg, 2000; Baxter, 2003a,b), however, indicate that well-designed indirect systems may have energy efficiencies approaching those of good direct systems. Further research is clearly needed to clarify the reasons for this. More efficient defrost, better part-load characteristics, better expansion device performance and more reliable systems are believed to contribute to indirect system energy efficiency. The costs might be 10–30% higher, but these can potentially be reduced (Yang, 2001; Christensen and Bertilsen, 2003).

4.3.7.4 Energy efficiency and cost of ammonia systems

There are several indirect systems in operation that are successfully using ammonia as the primary refrigerant (Haaf and Heinbokel, 2002). As ammonia is toxic and may create panic due to the strong smell at low concentrations appropriate safety precautions are required. Excellent energy efficiency can be achieved with properly-designed systems. The drawbacks for ammonia systems are limited service competence (Lindborg, 2002) and higher initial costs, typically 20–30%. A life-cycle cost evaluation is therefore required.

4.3.7.5 Energy efficiency and cost of hydrocarbon systems

Full supermarket systems using hydrocarbons in an indirect design have been installed in several European countries. A dedicated ventilation system (if installed in a machine room), gas detectors, gas-tight electric equipment and so forth have been installed for safety reasons. The use of hydrocarbons has increased the R&D effort to significantly minimize refrigerant charge. A small prototype system of approximately 4 kW cooling capacity using 150 g of HC-290 and micro-channel heat exchanger technology has been demonstrated by Fernando *et. al*. (2003). Cost is still an issue, typically up to 30% higher, but further development is expected to reduce costs. HC-290 and HC-1270 are excellent refrigerants from a thermodynamic point of view and equipment design is relatively straightforward. The availability of some standard components is still limited, but to a certain extent the hydrocarbon systems can use the same type of system components as HFC systems. Cascade systems with HC-290 and CO_2 for full supermarket systems were reported to have an energy efficiency equal to conventional direct system design (Baxter, 2003a,b).

For stand-alone equipment and condensing units, several references report a higher efficiency of HC refrigerants systems compared to equivalent systems with HFCs, for example Elefsen *et al*. (2002). Others claim that higher efficiency can be achieved with HFC systems, if the extra costs used for the safety precautions of HC systems are used to improve system efficiency of the HFC system (Hwang *et al*., 2004).

4.3.7.6 Energy efficiency and cost of CO_2 systems

Centralized CO_2 direct systems for both medium and low temperature, operating in either transcritical or subcritical cycle dependent on the ambient temperature, are reported to require about 10% higher energy consumption than a state-of-the-art R-404A direct system (Girotto *et al*., 2003 and 2004). Several measures for improvements have however been identified. The cost is reported to be about 10–20% higher than for direct expansion R-404A systems and this difference is mainly due to components produced in small series.

Haaf and Heinbokel (2003), report energy consumption and investment costs for R-404A/CO_2 cascade systems that are similar to R-404A direct systems. This is due to the fact that components for CO_2 cascade systems are more similar to R-404A components (maximum pressure 40 bar), allowing more standard components to be used. Girotto *et al*. (2004) report higher costs for cascade systems (see also comment about HC-290/CO_2 above).

4.3.7.7 Energy efficiency and cost of HFC systems with reduced emissions

Ongoing R&D efforts to minimize refrigerant charge without compromising energy efficiency are applicable to HFC refrigerants as well. The standard approach to charge minimization is to use no receiver or hermetic compressors and to keep piping as short as possible. Tight systems require brazed joints and these are most reliably made when systems are factory assembled. The potential for charge reduction is illustrated by Fernando *et al*. (2003). They present HC systems using as little as 150 g refrigerant for a 5 kW domestic heat pump. The density of HFC refrigerant is approximately twice that of HC and therefore a comparable system using 300 g of HFC refrigerant is within reach, if further heat exchanger development is undertaken. More complex cycles are another way of improving systems. Beeton and Pham (2003), report a 41% capacity increase and a 20% efficiency increase for low-temperature economizer systems using R-404A and R-410A.

4.3.8 Comparison of LCCP and mitigation costs

The number of publications that give TEWI or LCCP data for commercial refrigeration systems is limited but is growing rapidly. Harnisch *et*. *al*. (2003) calculated the LCCP for several different types of full supermarket refrigeration systems in Germany. They used a straightforward model which took production, emissions and energy usage into account. CO_2 emissions from power production were calculated using an average emission factor of 0.58 kg CO_2 kWh^{-1}. The transparent method to evaluate the various systems allows sensitivity analyses to be performed using other literature references referred to in this report. Table 4.10 presents characteristic figures from Harnisch *et*. *al*. (2003) and compares these to calculated results based on representative data from other literature references.

The data used for the table are selected as follows: The 30% emission is based on Palandre *et al*., 2004 and the 11.5% and 6.5% emission scenarios are based on Harnisch *et al*. (2003), Bivens and Gage (2004) Baxter (2003a) and ADL (2002). The 11.5% and 6.5% emissions represent 10% and 5% emissions yr^{-1}, with a 15% end-of-life recovery loss apportioned over a 10-year lifetime. Energy consumption figures are extracted from Harnisch *et al*. (2003), Haaf and Heinbokel (2002), Girotto *et al*. (2003) and Baxter (2003b). It is clear that several different alternatives result in reductions in CO_2 equivalent emissions of the same order of magnitude. The same applies for an HFC alternative, if the annual emission rate can be as low as 5%. If a 5% leakage is possible, the dominating contribution from most systems is an indirect effect due to power production.

Supermarket system and mitigation cost estimates are scarce. Harnich *et al*. (2003) give data for German supermarkets with costs ranging from 20–280 US$ per tCO_2–eq mitigated. The lowest values are given for a system using direct expansion CO_2 for low temperature and direct expansion with R-404A for high temperature. Mitigation costs are estimated using a 10% leakage rate and a 1.5 % recovery loss, with a 10-year lifetime and a discount rate of 10% to reflect commercial decision-making. An average cost of 100 US$ m^{-2} of supermarket area is used as a baseline for cost estimates. This figure is confirmed by Sherwood (1999) who reports on cost figures for a 3200 m^2 supermarket in the USA.

Using this data with a broader range of leakage rates and estimated costs, significantly reduces the typical mitigation costs per tonne of CO_2 suggested by Harnisch *et al*. (2003) but also expands the total range to values of 10–300 US$ per tonne CO_2-eq mitigated.

Additional mitigation costs for the various systems suggested in the chapter have not been calculated. Cost estimates for various technologies given in the literature suggest a cost increase between 0 and 30% for alterative technologies compared to a baseline, full supermarket, direct system using R-404A as refrigerant. Some detailed figures are already given under each section and a general summary is given for each technology in Table 4.11.

Table 4.10. LCCP values of full supermarket systems.

Configuration	Refrigerant Emissions % charge yr^{-1}	Energy Consumption	LCCP, in tCO_2-eq yr^{-1} Indirect	Direct	Total
Direct Expansion (DX)	30%	baseline	122	183	305
DX (Harnisch *et al*., 2003, data)	11.5%	baseline	122	70	192
DX distributed 75% charge reduction	6.5%	baseline	122	10	132
Sec. Loop R-404A 80% charge reduction	6.5%	baseline + 15%	140	8	148
Sec. Loop propane 80% charge reduction	6.5%	baseline + 10%	134	0	134
Sec. Loop ammonia 80% charge reduction	6.5%	baseline + 15%	140	0	140
DX R-404A and DX CO_2 50% charge reduction	6.5%	baseline	122	20	142
DX CO_2/CO_2	11.5%	baseline + 10%	134	0	134

Table 4.11. Sector summary for commercial refrigeration – current status and abatement options.

Subsector		**Stand-alone Equipment**	**Condensing Units**	**Full supermarket system** **Direct Centralized**	**Indirect Centralized**	**Distributed**	**Hybrids**
Cooling capacity	From	0.2 kW	2 kW	20 kW			
	To	3 kW	30 kW	>1000 kW			
Refrigerant charge	From	0.5 kg	1 kg	100 kg	20	*	*
	To	~2 kg	15 kg	2000 kg	500 kg	*	*
Approximate percentage of sector refrigerant bank in subsector		11% of 606 kt	46% of 606 kt	43% of 606 kt			
Approximate percentage of sector refrigerant emissions in subsector		3% of 185 kt	50% of 185 kt	47% of 185 kt			
2002 Refrigerant bank, percentage by weight		CFCs 33%, HCFCs 53%, HFCs 14%					
Typical annual average charge emission rate		30%					
Subsector		**Stand-alone Equipment**	**Condensing Units**	**Full supermarket system** **Direct Centralized**	**Indirect Centralized**	**Distributed**	**Hybrids**
Technologies with reduced LCCP EmR – Direct Emission Reduction (compared to installed systems)		**Improved HFC** SDNA	**Improved HFC** SDNA	**Improved HFC** EmR 30% ChEU 0% ChCst 0 ±10%	**Ammonia** EmR 100% ChEU 0–20% ChCst 20–30%	**HFC** EmR 75% ChEU 0–10% ChCst 0–10%	**Cascade-HFC/CO_2** EmR 50–90% ChEU 0%
ChEU – Change in Energy Usage (+/-) (compared to state of the art)		**HC** SDNA	**R-410A** SDNA	**CO_2 (all-CO_2)** EmR 100% ChEU 0 ±10% ChCst 0±10%	**HC** EmR 100% ChEU 0–20 % ChCst 20–30%	**Economized-HFC-404A** SDNA	**Cascade-Ammonia/CO_2** SDNA
ChCst – Change in Cost (+/-) (compared to state of the art)		**CO_2** SDNA	**HC** SDNA		**HFC** EmR 50–90% ChEU 0–20% ChCst 10–25%	**Economized-HFC-410A** SDNA	**Cascade-HC/CO_2** SDNA
SDNA – Sufficient data on emission reduction, energy usage and change in cost not available from literature			**CO_2** SDNA			**CO_2** SDNA	
LCCP reduction potential (world avg. emission factor for power production)		SDNA		35–60%			
Abatement cost estimates (10 yr lifetime, 10% interest rate)		SDNA		20-280 US$ per tonne CO_2 mitigated			

* Alternatives in these categories have been commercialized, but since the current number of systems are limited, they are only referenced as options below

In this report energy efficiency has been treated as relative changes in energy usage for several recent types of systems, the main purpose of which is to mitigate emissions, see also Table 4.11. However, the systems investigated are based on current technological standards for components such as heat exchangers, compressors and so forth. No attempts have been made to predict the future energy-saving potential in commercial refrigeration applications if future possible improvements are achieved. Several possibilities for reducing the energy consumption of refrigeration systems exists, but in principle most of these may be applied irrespective of the refrigerant used in the system. These options may also lead to negative mitigation costs, as for instance reported in Godwin (2004) and March (1998).

The authors firmly believe that the ongoing technical development of components and systems together with various energy-saving measures (such as heat recovery, more efficient compressors and display cases, larger heat exchangers, floating condensation, energy efficient buildings and so forth) may lower supermarket energy consumption considerably.

4.4 Food processing and cold storage

4.4.1 *Introduction*

Food processing and cold storage is one of the important applications of refrigeration, and is aimed at preserving and distributing food whilst keeping its nutrients intact. This application of refrigeration is very significant in terms of size and economic importance, and this also applies to developing countries. Food processing includes many subsectors such as dairy products, ice cream, meat processing, poultry processing, fish processing, abattoirs, fruit & vegetable processing, coffee, cocoa, chocolate & sugar confectionery, grain, bread & flour confectionery & biscuits, vegetable, animal oils & fats, miscellaneous foods, breweries and soft drinks (March, 1996).

The annual global consumption of frozen foods is about 30 Mtonnes yr^{-1}. Over the past decade, consumption has increased by 50% and it is still growing. The USA accounts for more than half of the consumption, with more than 63 kg per capita. The average figure for the European Union (EU) is 25 kg and for Japan 16 kg. The amount of chilled food is about 10–12 times greater than the supply of frozen products, giving a total volume of refrigerated food of around 350 Mtonnes yr^{-1} (1995) with an estimated annual growth of 5% (IIR, 1996; UNEP, 2003). Like chilling and freezing, food processing is also of growing importance in developing countries. This is partly due to the treatment of high-value food products for export. Even in 1984, about half of the fish landed in developing countries (more than 15 Mtonnes) was refrigerated at certain stages of processing, storage or transport (UNEP, 1998). The estimated annual growth rate in food processing between 1996 and 2002 was 4% in developed countries and 7% in developing countries (UNEP, 2003).

Frozen food in long term-storage is generally kept at −15°C to −30°C, while −30°C to −35 °C is typical for the freezing process. In so-called 'super-freezers', the product is kept at −50°C. Chilled products are cooled and stored at temperatures from −1°C to 10°C.

The majority of refrigerating systems for food processing and cold storage are based on reciprocating and screw compressors. System size may vary from cold stores of 3 kW cooling demand to large processing plants requiring several MW of cooling. Reciprocating compressors are most frequently used in the lower capacity range, whereas screw compressors are common in larger systems (UNEP, 2003).

4.4.2 *Technical options*

Most of the refrigerating systems used for food processing and cold storage are based on vapour compression systems of the direct type, with the refrigerant distributed to heat exchangers in the space or apparatus to be refrigerated. Such systems are generally custom-made and erected on site. Indirect systems with liquid chiller or ice banks are also commonly used in the food processing industry for fruit and vegetable packing, meat processing and so forth. Ammonia, HCFC-22, R-502 and CFC-12 are the refrigerants historically used. The current technical options are HFCs, and non-fluorocarbons refrigerants such as ammonia, CO_2 and hydrocarbons (UNEP, 2003). Table 4.12 gives the main refrigerant technical options along with percentage annual emissions for food processing, cold storage and industrial refrigeration applications (Clodic and Palandre, 2004).

4.4.3 *HFC technologies*

HFC refrigerants are being replaced by place of CFC-12, R-502 and HCFC-22 in certain regions. The preferred HFCs for food processing and cold storage applications are HFC-134a, HFC blends with insignificant temperature glide such as R-404A, R-410A and azeotropic blends like R-507A. The HFC blend R-407C is also finding application as a replacement for HCFC-22.

HFC-134a has completely replaced CFC-12 in various applications of refrigeration. However, CFC-12 was not widely used in food processing and cold storage because it requires considerably greater compressor swept volume than HCFC-22 or ammonia to produce the same refrigerating effect. There is limited use of HFC-134a in this subsector.

R-404A, R-407C and R-507A are currently the most used HFCs for cold storage and food processing. These blends are preferred to HFC-134a due to the higher volumetric capacity

Table 4.12. Food processing, cold storage and industrial refrigeration (2002).

	CFCs (CFC-12 and R-502)[(1)]	HCFC-22	NH_3	HFCs (HFC-134a, R-404A, R-507A, R-410A)[(1)]
Cooling Capacity	25 kW−1000 kW	25 kW−30 MW	25 kW−30 MW	25 kW−1000 kW
Emissions, t yr^{-1}	9500	23,500	17,700	1900
Refrigerant in bank, tonnes	48,500	127,500	105,300	16,200
Emissions % yr^{-1}	20%	16%	17%	12%

[(1)] See Annex V for an overview of refrigerant designations for blends of compounds.

and lower system cost (UNEP, 1998). In spite of minor temperature glides, R-404A has proven to be applicable even in flooded systems (Barreau *et al*., 1996). R-404A and R-507A are the primary replacements for R-502. The coefficients of performance are comparable to R-502 but significantly lower compared to those of NH_3 and HCFC-22, especially at high condensing temperatures. Air-cooled condensers should be avoided as far as possible. The liquid should be subcooled to achieve optimal efficiencies and high cost-effectiveness for systems with R-404A and R-507A. In chill applications it may also be necessary to add significant superheat to the suction gas in order to avoid refrigerant condensation in the oil separator (UNEP, 2003).

R-410A is also one of the HFC blends which is expected to gain a market share in food processing and cold storage applications due to the lower compressor swept volume requirements in comparison to other refrigerants (except to CO_2). The compressor efficiencies, pressure drop in suction lines and heat transfer efficiency will benefit from high system pressure (UNEP, 1998). Due to the high volumetric capacity (40% above that of HCFC-22), R-410A compressor efficiency has been reported to be higher than with HCFC-22 (Meurer and König, 1999). R-410A can have system energy efficiency similar to that of ammonia and HCFC-22 and significantly higher than that of R-404A and R-507A for evaporation temperatures down to –40°C.

4.4.4 Non-HFC technologies

Ammonia

Ammonia is one of the leading refrigerants for food processing and cold storage applications. The current market share in several European countries, especially in the north, is estimated to be up to 80% (UNEP, 1998). In the USA ammonia has approximately 90% market share in systems of 100 kW cooling capacity and above in custom-engineered process use (IIR, 1996).

Recently designed ammonia-based systems have improved quality with respect to design, use of low-temperature materials and better welding procedures. Low charge is another positive development. However, more important is that these factory made units or systems represent a new level of quality improvement. These systems are not likely to break or release their charge in another way unless there is a human error or direct physical damage. Charge reduction has been achieved by using plate-type heat exchangers or direct expansion tube and shell evaporators (UNEP, 2003).

HCFC-22

The use of HCFC-22 is declining in food processing and cold storage applications in most developed countries. In Europe some of the end-users prefer ammonia and CO_2 wherever possible, whereas HCFC-22 has become the most common refrigerant to replace CFCs in food processing and cold storage in the USA (UNEP, 2003).

In developing countries, HCFC-22 is still an important replacement refrigerant for CFCs in new systems, as from a technical point of view HCFC-22 could replace CFC-12 and CFC-502 in new systems. Another important consideration in developing countries is that HCFC-22 will be available for service for the full system lifetime.

Hydrocarbons (HCs)

A growing market for low charge hydrocarbon systems has been observed in some European countries. So far market shares are small, which may be due to the flammability of these refrigerants. Nevertheless, several manufacturers have developed a wide range of products.

Commercialized refrigerants used in food processing and cold storage applications include HC-290, HC-1270 and HC-290/600a blends, although pure substances will be preferred in flooded systems. All of these refrigerants possess vapour pressures very similar to those of HCFC-22 and R-502. System performance with regard to system efficiency is comparable to, and in some cases even superior to, that of the halocarbons. Hydrocarbons are soluble with all lubricants, and compatible with materials such as metals and elastomers that are traditionally used in refrigeration equipment. As long as safety aspects are duly considered, standard refrigeration practice for HCFCs and CFCs can be used without major system detriment to system integrity (UNEP, 1998, 2003).

Given the flammability concerns, design considerations as detailed in the relevant safety standards should be adhered to. Additional safety measures should be considered for repairing and servicing. Several national and European standards permit the use of HCs in industrial applications and lay down specific safety requirements (ACRIB, 2001; UNEP, 2003).

Carbon dioxide

Carbon dioxide technology for low temperatures such as food freezing is an attractive alternative, especially in cascade systems with CO_2 in lower stage and ammonia in the upper stage, due to its excellent thermophysical properties along with zero ODP and negligible GWP.

Further, the volumetric refrigerating capacity of CO_2 is five times higher than HFC-410A and eight times higher than for ammonia and other refrigerants. This means that the size of most of the components in the system can be reduced (Roth and König, 2001). However, application of CO_2 places a limitation on evaporating temperatures due to the triple point (the temperature and pressure at which liquid, solid and gaseous CO_2 are in equilibrium) of –56.6°C at 0.52 MPa.

CO_2 technology has been applied to food processing and cold storage, both as a conventional and as secondary refrigerant. It is expected that CO_2 market share will increase in this subsector, especially for freezing and frozen food storage.

Not-in-kind technologies

There are some not-in-kind (non-vapour compression) technologies like air cycle, vapour absorption technology and compression-absorption technology which can be used for food processing and cold storage applications. Vapour absorption technology is well-established whereas compression-absorption technology is still under development.

Vapour absorption technology
Vapour absorption is a tried and tested technology. Absorption technologies are a viable alternative to vapour compression technology wherever low cost residual thermal energy is available. The most commonly used working fluid in food processing and cold storage applications is ammonia with water as the absorbent. The use of absorption technology is often limited to sites that can utilize waste heat, such as co-generation systems.

Compression-absorption technology
Compression-absorption technology has been developed by combining features of the vapour-compression and vapour-absorption cycles. About 20 compression-absorption systems on both a laboratory and full-scale have been developed and tested successfully so far. Various analytical and experimental studies have shown that the COP of compression-absorption systems is comparable to that of vapour compression systems. However, this system suffers from the inherent disadvantage of being capital intensive in nature. The technology is still at developmental stage (Pratihar *et al*., 2001, Ferreira and Zaytsev, 2002).

4.4.5 Factors affecting emission reduction

Design aspects
The refrigeration system design plays a vital role in minimizing the refrigerant emissions. A proper system design including heat exchangers, evaporators and condensers can minimize the charge quantity and hence reduce the potential amount of emissions. Every effort should be made to design tight systems, which will not leak during the system's lifespan. The potential for leakage is first affected by the design of the system; therefore designs must also minimize the service requirements that lead to opening the system. Further, a good design and the proper manufacturing of a refrigerating system determine the containment of the refrigerant over the equipment's intended life. The use of leak tight valves is recommended to permit the removal of replaceable components from the cooling system. The design must also provide for future recovery, for instance by locating valves at the low point of the installation and at each vessel for efficient liquid refrigerant recovery (UNEP, 2003).

Minimizing charge
The goal of minimal refrigerant charge is common for all systems due to system and refrigerant costs. Normally the designer calculates the amount of charge. In large systems such as food processing and cold stores, very little attention was generally given to determining the full quantity of refrigerant charge for the equipment. Its quantity is not often known (except for small factory built units). Charging the refrigerant into the system is done on site to ensure stable running conditions.

Improved servicing practices
Servicing practices in refrigeration systems must be improved in order to reduce emissions. Topping-off cooling systems with refrigerants is a very common practice, especially for the large systems normally used in food processing and cold storage industry, which causes greater emissions of refrigerant. However in general, proper servicing has proven to be more expensive than topping-off refrigeration systems. It is therefore necessary to make end-users understand that their practice of topping-off the systems without fixing leaks must cease because of the increased emissions to the environment. The good service practices are preventive maintenance, tightness control and recovery during service and at disposal.

Installation
After proper designing of the system, installation is the main factor that leads to proper operation and containment during the useful life of the equipment. Tight joints and proper piping materials are required for this purpose. Proper cleaning of joints and evacuation to remove air and non-condensable gases will minimize the service requirements later on and results in reduced emissions. Careful system performance monitoring and leak checks should also be carried out during the first days of operation and on an ongoing basis. The initial checks also give the installer the opportunity to find manufacturing defects before the system becomes fully operational. The proper installation is critical for maximum containment over the life of the equipment (UNEP, 2003). The refrigeration system should be designed and erected according to refrigeration standards (e.g. EN378 (CEN, 2000/2001)) and current codes of good practice.

Recovery and recycling
The recovery and recycling of refrigerants is another important process that results in significant reductions in emissions. The purpose of recovery is to remove as much refrigerant as possible from a system in the shortest possible amount of time. For applications where maintenance operations require opening the circuit, the difference between deep recovery and 'normal recovery' can represent 3–5% of the initial charge (Clodic, 1997). However many countries have adopted final recovery vacuum requirements of 0.3 or 0.6 atm absolute depending on the size of the cooling system and saturation pressure of the refrigerant. This provides a recovery rate of 92–97% of the refrigerant (UNEP, 1998).

The recovered fluorocarbon refrigerants can be recycled and then reused. The process of recycling is expected to remove oil, acid, particulate, moisture and non-condensable contaminants from the used refrigerant. The quality of recycled refrigerant can be measured on contaminated refrigerant samples according to standardized test methods (ARI 700). However, recycling is not common practice in the case of large food processing and cold storage units, where the preference is to recover and re-use the refrigerant.

4.4.6 Trends in consumption

The lifetime emissions of a refrigerant are dependent on the installation losses, leakage rate during operation, irregular events such as tube break and servicing losses including recovery loss and end-of-life loss during reinstallation/reconstruction. In some European countries, HCFC systems with more than 10 kg charge (including all application areas) showed an annual emission rate of 15% of the charge in the early 1990s (Naturvardsverket, 1996). This figure dropped to 9% in 1995 (UNEP 1998). Emissions from HFC systems are reported to be less than this, and this is probably due to more leak-proof designs. On a global scale, current CFC and HCFC annual emission rates are likely to be in the range of 10–12% of the charge (UNEP, 1998). A recent study (Clodic and Palandre, 2004) has provided estimates of emissions of CFCs, HCFCs, HFCs and ammonia from the combined sector of Food Processing, Cold Storage, and Industrial Refrigeration. Table 4.12 gives the percentage annual emissions of these refrigerants.

The consumption and banks of HFCs and other fluorocarbons have been estimated for the industrial refrigeration sector as a whole. Both a top-down (UNEP, 2003) and a bottom-up approach (Clodic and Palandre, 2004) are presented here (Table 4.13). The data for 2002 and the 2015 business-as-usual projections of Clodic and Palandre (2004) are used as a basis for the refrigeration subsectors in this report, so as to ensure consistency with other refrigeration and air conditioning subsectors (see Table 4.1). However, Table 4.13 clearly illustrates the differences between both approaches, which are clearly significant for CFCs.

Food processing and cold storage are assumed to account for 75% of the combined emissions and industrial refrigeration for the remaining 25% (UNEP, 2003).

The business-as-usual projections for 2015 show a significant increase in HFC consumption.

4.4.7 Comparison of HFC and non-HFC technologies

Energy efficiency and performance

As stated above R-404A and R-507A are the proven replacements for R-502 and this also includes the application in flooded evaporators used for food processing and cold storage systems. The cycle efficiencies are comparable to R-502 but significantly lower compared to those of ammonia (non-HFC technology) especially at high condensing temperatures (UNEP, 2003).

R-410A is another important HFC refrigerant in this sector. The energy efficiency of R-410A systems can be similar to ammonia for evaporation temperatures down to −40 °C, depending on compressor efficiency and condensing temperature. The efficiency below −40 °C until its normal boiling point of −51.6 °C is slightly higher for R-410A than that of ammonia and other refrigerants. The compressor efficiencies are also reported to be higher compared to HCFC-22, due to the high volumetric capacity (40% above that of HCFC-22) of R-410A (Meurer and König, 1999).

CO_2 technology is another non-HFC technology which is gaining momentum. CO_2 as a refrigerant is being used in food processing and cold storage units in cascade systems with ammonia in higher cascade. It has been reported that the volumetric refrigerating capacity of CO_2 is five times higher than HFC 410A and eight times higher than that of ammonia and other refrigerants. Therefore the size of most components in the system can be reduced (Roth and König, 2001). The efficiency of CO_2/ammonia cascade system in the temperature range of –40 °C to –55°C is comparable to a two-stage system with R-410A. CO_2 also shows a strong cost benefit in large systems (Axima, 2002).

Life cycle climate performance LCCP

Very limited data are available for TEWI/LCCP for this refrigeration sector. A recent publication (Hwang *et al*., 2004) reports a comprehensive experimental study of system performance and LCCP for an 11 kW refrigeration system operating with R-404A, R-410A and propane (HC-290) at evaporator temperatures of −20°C to 0°C. For a comparison on an equal first cost basis, the increased cost of safety features for HC-290 was used for a larger condenser for the HFC systems. The LCCP of the R-410A system was 4% lower and the LCCP of R-404A was 2% higher than that of the HC-290 system at an annual refrigerant emission rate of 2%. The LCCP values for R-410A and HC-290 were equal at an annual refrigerant emission rate of 5%.

4.5 Industrial refrigeration

4.5.1 Introduction

One characteristic of industrial refrigeration is the temperature range it embraces. While evaporating temperatures may be as high as 15°C, the range extends down to about –70°C.

Table 4.13. Estimated consumption and banks of halocarbons refrigerants for industrial refrigeration, including food processing and cold storage for 2002. (UNEP, 2003 and Clodic and Palandre, 2004).

		Consumption ($kt\ yr^{-1}$)				Refrigerant Banks (kt)			
		CFCs	HCFCs	HFCs	NH_3	CFCs	HCFCs	HFCs	NH_3
2002	UNEP (2002)	12	28	5	-	109	165	9	-
2002	Clodic and Palandre (2004)	7	27	6	22	34	142	16	105
2015	Clodic and Palandre (2004)	4	24	18	27	21	126	85	123

Table 4.14. Major applications and refrigerants used in industrial refrigeration.

Application	Refrigerant	Other Refrigerants	CFC, HCFC Replacements
freeze drying	NH_3, HCFC-22	R-502	CO_2, R-410A
separation of gases	CFC-12, CFC-13, HCFC-22, R-503	-	PFC14, PFC-116, R-404A, R-507A, CO_2
solidification of substances	HCs, CFC-13, HCFC-22, CFC-12	-	HCs, CO_2, PFC-14, R-404A, R-507A
reaction process	Various		
humidity control of chemicals	CFC-12, CFC-13, HCFC-22, R-503		PFC-14, PFC-116, R-404A, R-507A, CO_2, NH_3, Air
industrial process air conditioning	NH_3, HCFC-22	R-502	NH_3, R-404A, HFC-134a, Water
refrigeration in manufacturing plants	Various		
refrigeration in construction	NH_3, R-502	HCFC-22	NH_3, CO_2, R-410A, R-404A, R-507A
ice rinks	NH_3, HCFC-22		NH_3, CO_2, R-404A, R-507A
wind tunnel	NH_3, R-502, HCFC-22, CFC-12	-	NH_3, R-404A, R-507A, HFC-134a
laboratories	Various		

At temperatures much lower than about –70°C the so-called ‘cryogenics’ technology comes into play. This produces and uses liquefied natural gas, liquid nitrogen, liquid oxygen and other low-temperature substances. Industrial refrigeration in this section covers refrigeration in chemical plants (separation of gases, solidification of substances, removal of reaction heat, humidity control of chemicals), process technology (industrial process air conditioning, refrigeration in manufacturing plants, refrigeration in construction), ice rinks and winter sports facilities, and laboratories where special conditions such as low temperatures, must be maintained. Some definitions of industrial refrigeration include food processing and cold storage; these are described in Section 4.4 of this chapter.

Industrial systems are generally custom-made and erected on site. A detailed description of industrial refrigeration and cold storage systems can be found in the ‘Industrial Refrigeration Handbook’ (Stoecker, 1998). Industrial refrigeration often consists of systems for special and/or large refrigerating purposes. The cooling/heating capacity of such units vary from 25 kW to 30 MW or even higher. These refrigeration systems are based on reciprocating, screw and centrifugal compressors, depending on the capacity and application.

Industrial refrigeration has mainly operated with two refrigerants: ammonia (60–70%) and HCFC-22 (15–20%). To a lesser extent CFC-502 (5–7%) has been used and other minor refrigerants complete the rest of industrial applications. Replacement refrigerants for CFCs and HCFCs, plus other non-fluorocarbon fluids are included in Table 4.14.

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

There are clear differences in how countries have developed the technology for industrial refrigeration since the starting of the CFC phase-out. In Europe, the use of HCFC-22 and HCFC-22 blends in new systems has been forbidden for all types of refrigerating equipment by European regulation 2037/00 (Official Journal, 2000) since 1 January 2001. The use of CFCs is also forbidden, that is no additional CFC shall be added for servicing. HFCs are occasionally used where ammonia or hydrocarbons are not acceptable, although they are not often preferred in Europe, as European users are expecting regulations limiting the use of GHGs in stationary refrigeration (see proposals in EU, 2004).

4.5.2 *Technical options*

Most of the industrial refrigerating systems use the vapour compression cycle. The refrigerant is often distributed with pumps to heat exchangers in the space or apparatus to be refrigerated. Indirect systems with heat transfer fluids are used to reduce the risk of direct contact with the refrigerant. Ammonia is the main refrigerant in this sector. HCFC-22, R-502 and CFC-12 are the historically used refrigerants from the group of CFCs and HCFCs. Beside the increasing share of ammonia for new systems, the current technical options to replace CFCs are HFCs, HCFC-22 and non-fluorocarbon technologies such as CO_2 and HCs.

4.5.3 *Factors affecting emission reduction*

The refrigerant charge in industrial systems varies from about 20 kg up to 10,000 kg or even more. Large ammonia refrigeration systems contain up to 60,000 kg of refrigerant. The high costs of the refrigerants, with the exception of ammonia and

CO_2, and the large refrigerant charge required for the proper operation of the plant have led to low emissions in industrial systems. In these systems annual average leakage rates of 7−10% are reported (UNEP, 2003); smallest leakage rates are observed in ammonia systems because of the pungent smell. Clodic and Palandre (2004) estimate somewhat higher annual leakage rates (17%) for the category of industrial refrigeration (which also includes food processing and cold storage). The abatement costs of refrigerant emissions from industrial refrigeration was determined to be in the range of 27−37 US$ (2002) per tonne CO_2 -eq (March, 1998). Cost data were calculated with a discount rate of 8%.

Design aspects
Industrial refrigeration systems are custom made and designs vary greatly from case to case. Due to the increasing requirements concerning safety and the quantity of refrigerant used in refrigeration systems, a design trend towards indirect systems has been observed over the past 10 years. Yet whenever possible, the majority of systems are still direct. Refrigerant piping fabrication and installation has changed from direct erection on site towards pre-assembled groups and welded connections (see Design aspects in Section 4.4.5 for additional information on design and installation practices to minimize refrigerant emissions).

Minimizing charge
There are limits on design optimization in terms of balancing low charge on the one hand against achieving high COPs or even stable conditions for liquid temperatures to be delivered to heat exchangers on the other. For example, flooded type evaporators represent the best technology available for a low temperature difference between the liquid to be cooled and distributed and the evaporating refrigerant, yet this requires large quantities of refrigerant. The increased use of plate heat exchangers, plate and shell heat exchangers, and printed circuit heat exchangers over the past 15 years has enabled the design of lower charge systems with flooded evaporators. Efforts to minimize the amount of refrigerant charge will continue with improvements in system technology.

Improved servicing practices
Trained service personnel are, according to safety standards (CEN-378, 2000/2001; ISO-5149, 1993), required for the maintenance and operation of industrial systems. Service and maintenance practices on industrial systems are updated periodically according to safety standards and service contracts, which are negotiated with the plant owner in the majority of the cases.

Recovery and recycling
Recovery of refrigerants from industrial plants is common in many countries and is sometimes also a requirement (CEN-378, 2000 and 2001). The recovery of small quantities of ammonia (less than 3 kg) through absorption in water is common practice. Larger quantities are recovered by special large recovery units and pressure vessels.

The recovery rate from industrial systems is high due to the high costs and quantity of the refrigerants, especially CFCs, HCFCs and HFCs. The recovery rate is estimated to be 92−97% of the refrigerant charge (UNEP, 2003). The recovered refrigerants are dried in the recovery systems on site and re-used.

Lifetime refrigerant emissions
As most industrial refrigeration systems are designed for specific manufacturing processes, information on lifetime emissions of refrigerants are not readily available. Even data on cooling capacities are often not official, as the production capacity of the manufactured product could be estimated from this data. However, the estimated annual leakage rates referred to in Section 4.5.3 should be noted.

4.5.4 HFC technologies

HFC refrigerants are options to replace CFC-114, CFC-12, CFC-13, R-502 and HCFC-22. The preferred HFCs are HFC-134a, HFC-23 and HFC-blends with insignificant temperature glide such as R-404A, R-410A and azeotropic blends like R-507A.

HFC-134a has completely replaced CFC-12 because of its comparable thermodynamic properties in various applications of industrial refrigeration. CFC-12 and HFC-134a are used in large systems for higher temperatures with evaporator temperatures from 15°C down to –10°C.

HFC-23 has replaced CFC-13 and to lesser extent CFC-503 for the same reasons as mentioned for CFC-12. The evaporator temperature range varies from –80°C to –55°C in the low-temperature applications of these refrigerants.

HFC-245fa, HFC-365mfc and HFC-236fa are possible replacements for CFC-114 in high-temperature heat pumps. No single fluid is ideal, especially for large industrial heat pumps, because the dew line of the fluids requires large superheat to avoid compression in the vapour region. The temperature range for condensing temperatures varies from 75°C to 100°C.

HFC-410A is not comparable to refrigerants HCFC-22 or CFC-12 in terms of thermodynamic properties because of its considerably higher vapour pressure. HFC-410A compressor efficiencies, the pressure drop in suction lines and the heat transfer efficiency will benefit from high system pressure. This HFC is used mainly in new industrial systems designed for the refrigerant, especially in terms of low condensing temperatures of 35°C to avoid pressures higher than 25 bar. In industrial refrigeration, the evaporator temperature range for HFC-410A varies from –60°C to –35°C. Due to the high volumetric capacity (40% above that of HCFC-22), compressor efficiency has been reported to be higher than with HCFC-22 (Meurer and König, 1999). R-410A has a COP similar to NH_3 and HCFC-22 and slightly higher than that of R-404A, R-507A. Further, at temperatures below –40°C and up to the to HFC-410A normal boiling point at –51.6°C, COPs are slightly higher for R-410A compared to other refrigerants (Roth *et al., 2002*).

R-404A and R-507A are the main refrigerants to replace R-502 in the temperature range from –50°C to –30°C and these have comparable cycle efficiencies (COPs) and slightly lower GWP values than R-502. For systems with R-404A and R-507A, the liquid should be subcooled to achieve optimum efficiencies and high cost-effectiveness . In chiller applications with screw compressors it may also be necessary to add significant superheat to the suction gas in order to avoid refrigerant condensation in the oil separator.

4.5.5 Non-HFC technologies

In large systems CFCs and recently introduced HFCs have a lower average share in industrial refrigeration than NH_3 and HCFC-22. For new industrial systems designers and plant owners will mainly need to decide between NH_3, HFCs and HCFC-22 (except in the EU where HCFC-22 is forbidden in new systems) (Stoecker, 1998). Non-HFC technologies described in the following subsection are sorted by refrigerant.

Ammonia

Ammonia is one of the leading refrigerants for industrial refrigeration, based on performance and safety, and is used in large quantities in locations physically separated from general public access. The current market share in several European countries, especially in Northern Europe, is estimated to be up to 80% (UNEP, 1998). In the USA, ammonia has approximately 90% market share in systems of 100 kW cooling capacity and above that use custom-engineered processes (IIR, 1996).

New ammonia systems have an improved design, use low-temperature materials and standardized welding procedures, and the systems operation and maintenance are under continuous monitoring. A human error or direct physical damage is often the reason for failure (Lindborg, 2003).

Charge reduction has been achieved through dry or direct expansion in plate type heat exchangers and shell and tube evaporators. With soluble oils, it has been possible to reduce charge by 10%. New developments showed charges of 28g ammonia per kW cooling capacity for low overall capacity down to 100 kW (Behnert and König, 2003). With these low charges, new opportunities for applications not previously considered for ammonia have been realized, such as water chillers for air conditioning (Stoecker, 1998). This new ammonia technology with high COP was regarded as being fully practical, but strong market penetration has not been achieved due to price competition with HFC-based units (UNEP, 2003).

HCFC-22

The use of HCFC-22 is declining in industrial refrigeration in Europe, as the use of HCFC-22 in new systems is forbidden by European regulations (Official Journal, 2000).

In developing countries, HCFC-22 is still an important replacement refrigerant for CFCs in new systems, as from a technical point of view HCFC-22 could replace CFC-12 and CFC-502 in new systems. Another important consideration in developing countries is that under the Montreal Protocol the production of HCFC-22 is allowed until 2040, or the full lifetimes of equipment installed in the next 15 years or so.

Hydrocarbons (HCs)

HCs can fit into any temperature range for evaporating temperatures down to –170°C. Historically, their use as working fluids has been restricted to large refrigeration plants within the oil and gas industry. A certain registered increase in hydrocarbon consumption has mainly appeared in these sectors (Stoecker, 1998).

Commercialized products used in industrial refrigeration equipment include HC-290 and HC-1270. System performance with regard to system efficiency is comparable to and, in some cases even superior to, that of the halocarbons. Hydrocarbons are soluble with mineral oils and compatible with materials such as metals and elastomers that are traditionally used in refrigeration equipment. The use of hydrocarbons in screw compressors may be problematic due to the strong dilution of mineral oil. Other less soluble lubricants such as PAG or PAO may be required. As long as safety aspects are taken into consideration, standard refrigeration practices used for HCFCs and CFCs can be used for hydrocarbon fluids without major system detriment.

Given the flammability concerns, design considerations as detailed in the relevant safety standards should be adhered to. Additional safety measures are required for repairing and servicing. Several national and European standards permit the use of HCs in industrial applications and lay down specific safety requirements. Industry guidelines for the safe use of hydrocarbon refrigerants are available (ACRIB, 2001).

Carbon dioxide (CO_2)

As well as being non-ODP and having a GWP of 1, carbon dioxide (CO_2) offers a number of other advantages:

- Excellent thermophysical properties, leading to high heat transfer;
- Efficient compression and compact system design due to high volumetric capacity;
- Non-flammable and low toxicity;
- Low system costs at evaporation temperatures below 45°C (depending on system design);
- Widely available at low cost.

CO_2 systems can be used for industrial refrigeration applications with evaporation temperatures down to –52°C and condensing temperatures up to 5°C. CO_2 is also increasingly being used in the low stage of cascade systems for industrial refrigeration. CO_2 is also commonly used as a secondary refrigerant. The design requires the same pressure of 25 bar for the secondary refrigerant systems and for the CO_2 used as the refrigerant, except for ice rinks and some other limited systems which are designed for 40 bar. Defrosting was an open issue, but the most recent developments show that several different techniques such as electrical heating, hot gas defrosting, high-pressure liquid evaporation and the distribution of hot gas have been realized in plants (Siegel and Metger, 2003).

A comparative study for low temperatures has been carried out using a typical system design with cooling capacities of 600kW at −54°C for R-410A, R-507 and ammonia used as a single fluid in two-stage systems and for NH_3/CO_2 and HFC-134a/R-410A as refrigerants in high/low stage cascade systems. The volumetric refrigerating capacity of CO_2 is five times higher than HFC-410A and eight times higher than for ammonia and other refrigerants. Therefore the size of most components in the system can be reduced. The study found the lowest cost for NH_3/CO_2 (Roth *et al., 2002*). If CO_2 is used as the refrigerant, the cost break-even point for industrial refrigeration compared to NH_3 and R-410A is approximately at an evaporating temperature of –40°C to −45°C. Below this temperature, lower costs for CO_2/NH_3 cascade systems have been achieved. It is expected that costs for screw or reciprocating units, including compressors and oil separation circuit, will be further reduced (Roth *et al., 2002*). The efficiency of CO_2 systems in this low temperature range is similar to other refrigerants such as R-410A or ammonia.

CO_2 shows strong cost benefits if the system size is increased, especially in cases where evaporators or heat exchangers are distributed and long piping systems are required. In industrial refrigeration applications, cost benefits have been achieved with total pipe runs of more than 2500 m (Siegel and Metzger, 2003).

In food processing, a trend can be observed towards CO_2 as a refrigerant at temperatures lower than –45°C and as an HTF for cooling temperatures lower than −5°C (Pirard, 2002).

Some examples are given to illustrate the use of CO_2 as refrigerant in low-temperature applications:

- In the USA, the first large CO_2 system was being erected in 2003 with cooling capacities of 6 MW (Stellar, 2003);
- In Japan a standard low-temperature cascade system has been developed with NH_3/CO_2 as refrigerants. The systems are designed for evaporating temperatures of –40 to –55°C with cooling capacities of 80−4450 kW;
- In Europe more than 30 large systems with CO_2 as the heat transfer fluid and refrigerant have been installed since 1998 and are operating with total cooling capacities of more than 25 MW (Pearson, 2004a,b);
- At least two large systems in Europe have been retrofitted from HCFC-22 (1.5 MW at −45 to −55°C) and from CFC-13B1 (2.4 MW at −35°C) to NH_3/CO_2 cascade systems (Gebhardt, 2001; König, 2002).

4.5.6 Trends in consumption

The trends in the consumption of refrigerants for industrial refrigeration as well as the food processing and cold storage subsector are discussed in Section 4.4.6.

4.5.7 Comparison of HFC and non-HFC technologies

4.5.7.1 Energy efficiency and performance

On a worldwide basis, only two refrigerants have significant market share in industrial refrigeration: ammonia and HCFC-22. Stoecker (1998) provides a comparison of both refrigerants. Compared to ammonia and HCFC-22, the market share of HFCs and non-HFC technologies is small. Nevertheless, one point of comparison is the cost of the refrigerant to be used in the system, and the lowest costs are found for ammonia (Stoecker, 1998).

The energy efficiency comparisons for HFCs 404A, 507A, and 410A with ammonia and HCFC-22 are described in Section 4.5.4. HFC410A has an energy efficiency similar to ammonia and HCFC-22, and slightly higher than R-404A and R-507A (Roth *et al*., 2002).

CO_2 technology is a non-HFC technology which is gaining momentum. The energy efficiency of CO_2 systems in the temperature range of –40ºC to –45ºC is similar to HCFC-22 and HFC refrigerants such as HFC-410A. CO_2 also shows strong cost benefit if the system size is large (Siegel and Metzger, 2003).

4.5.7.2 TEWI/LCCP/LCA

For various reasons, only limited TEWI/LCCP/LCA data are available for industrial refrigeration systems. Such systems are normally custom-designed for special requirements and are erected on site. The design differs not only in terms of cooling capacities and temperatures, but also in terms of temperature control requirements (air blast cooling systems), size of piping, distance to consumers and charge of refrigerant. There are therefore only a few references which compare TEWI and costs for the same application (Pearson , 2004a; Roth *et al*., 2002). Roth *et al*. (2002) give a comparative example for a manufacturing plant with a cooling capacity of 600 kW at −54°C (see Figures 4.1 and 4.2). In this investigation the combination of CO_2 and ammonia was more competitive than other solutions.

In addition to the above references, examples of LCCP calculations for supermarket refrigeration systems provide general guidance for selecting systems and refrigerants with a lower LCCP (see Section 4.3). Lower LCCP results from systems with low energy consumption, and in the case of fluorocarbon refrigerants, low refrigerant charge size and low refrigerant emissions. LCCP calculations should be used to optimize the choice of refrigerant and system design for the lowest environmental impact.

4.6 Transport refrigeration

4.6.1 Introduction

The transport refrigeration subsector consists of refrigeration systems for transporting chilled or frozen goods. Typically the task of a transport refrigeration system is to keep the temperature constant during transport. The technical requirements for transport refrigeration units are more severe than for many other applications of refrigeration. The equipment has to operate in a wide range of ambient temperatures and under extremely variable weather conditions (sun radiation, rain, etc.); it also has to be able to carry any one of a wide range of cargoes with

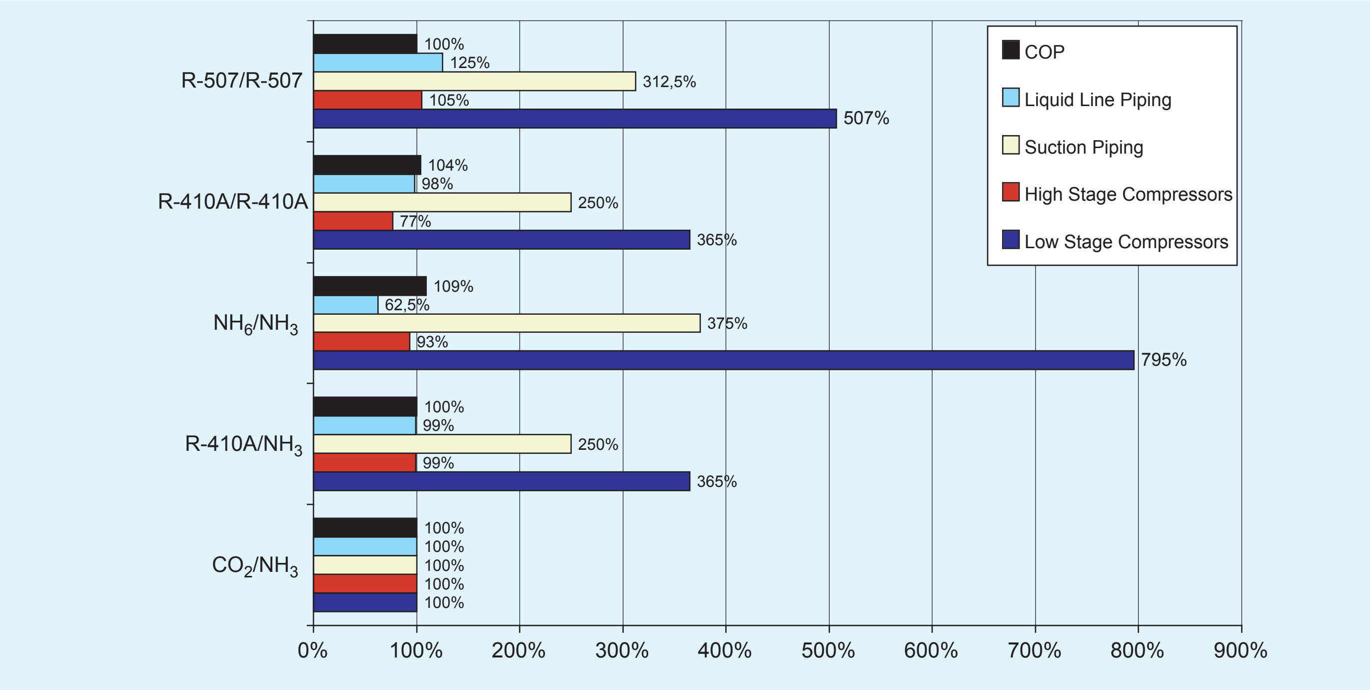

Figure 4.1. COP and size comparison of different components for different refrigerant combinations (Q_0 = 600 kW, t_C = 35°C; t_0 = −54°C; CO_2/NH_3-cascade system is equal to 100 %) (Roth and König, 2002).

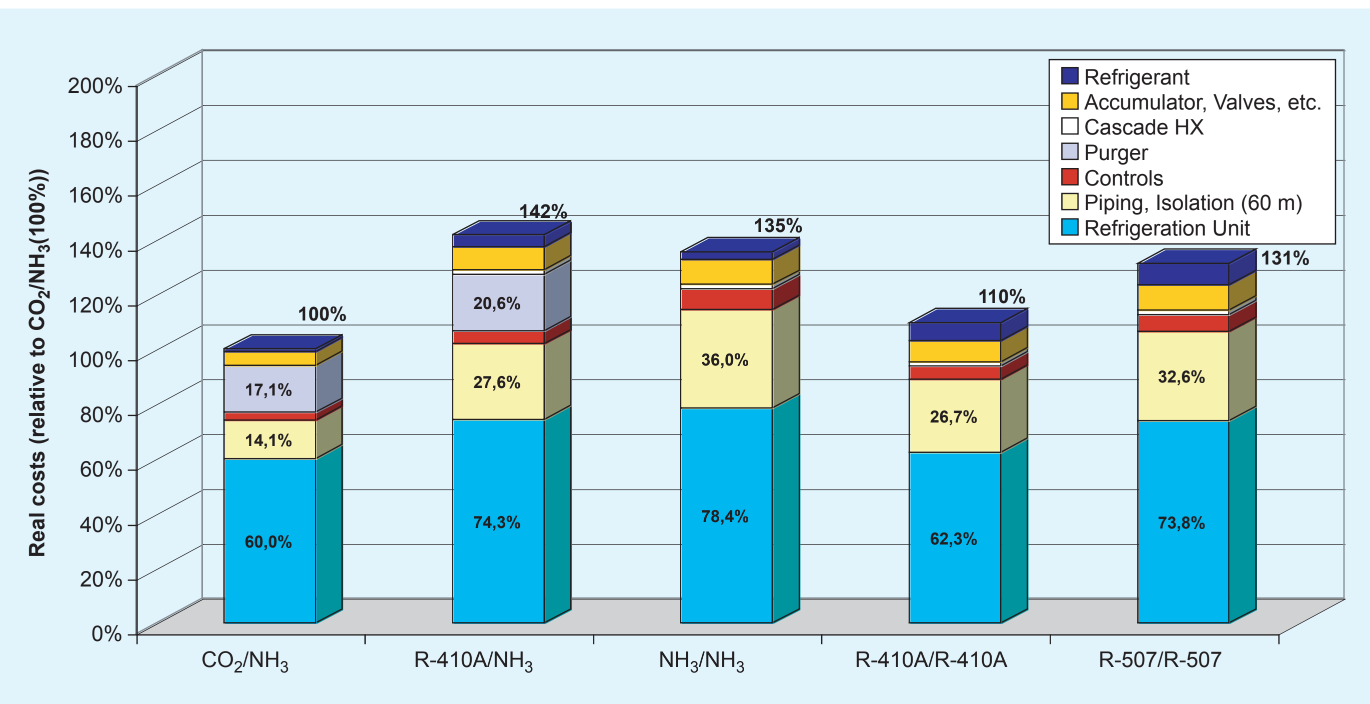

Figure 4.2. Cost comparison for different refrigerant combinations (Q_0 = 600 kW, t_C = 35°C; t_0 = −54°C; CO_2/NH_3-cascade system is equal to 100 % (Roth and König, 2002).

differing temperature requirements, and it must be robust and reliable in the often severe transport environment (IIR, 2003). Typical modes of transport are road, rail, air and sea. In addition, systems which are independent of a moving carrier are also used; such systems are generally called ‘intermodal’ and can be found as containers (combined sea-land transport) as well as swap bodies (combined road and rail transport). This section covers also the use of refrigeration in fishing vessels where the refrigeration systems are used for both food processing and storage.

The technology used in transport refrigeration is mainly the mechanically- or electrically-driven vapour compression cycle using refrigerants such as CFC, HCFC, HFC, ammonia or carbon dioxide. Due to the complete and worldwide phase-out of CFC consumption by the end of 2009, CFCs are not addressed in this chapter. In addition, a number of refrigeration systems are based on using substances in discontinuous uses. This type of equipment can be found as open uses with solid or liquid CO_2, ice, or liquid nitrogen and in these cases the refrigerant is being completely emitted and lost after removing the heat (Viegas, 2003). Closed systems such as eutectic plates (Cube *et al.*, 1997) or flow-ice, reuse the same substance (Paul, 1999). Such systems used to be very commonplace in transport refrigeration, and are still used on a significant scale. Some propose that their use should be increased in the future.

All transport refrigeration systems need to be compact and lightweight, as well as highly robust and sturdy so that they can withstand movements and accelerations during transportation. Despite these efforts, leaks within the refrigeration system occur due to vibrations, sudden shocks and so forth. The likelihood of leaks or ruptures is also greater than with stationary systems, due to a higher risk of collisions with other objects. Ensuring safe operation with all working fluids is essential, particularly in the case of ships where there are no options to evacuate a larger area (SCANVAC, 2001). The safety is either inherent in the fluids or is ensured through a number of technical measures (Stera, 1999).

4.6.2 Container transport

Refrigerated containers allow uninterrupted storage during transport on different types of mobile platforms, for example railways, road trucks and ships. The two main types of refrigerated containers are porthole containers and integral containers. Porthole containers are the older of the two concepts and are insulated containers with two front apertures and no built-in refrigeration systems. Some predict that by 2006, transport will have been completely converted to integral containers (Hochhaus, 2003; Wild, 2003).

Integral refrigerated containers are systems which have their own small refrigeration unit of about 5 kW refrigeration capacity on board. There were more than 550,000 of these in 2000, representing the transport capacity of 715,000 20-foot containers, and there numbers are set to strongly increase (UNEP, 2003; Sinclair, 1999; Stera, 1999). The electrical power needed to drive the system is supplied from an external power supply via an electrical connection. These systems typically use HFC-134a, R-404A and HCFC-22, and in some cases R-407C (Wild, 2003). Newer systems generally have a more leak-resistant design (Crombie, 1999; Stera, 1999; Yoshida *et al.,* 2003; Wild, 2003). In 1998, when older design systems were prevalent, an average annual leakage rate of 20% of the charge of about 5 kg was assumed for a lifetime of 15 years (Kauffeld and Christensen, 1998).

4.6.3 Sea transport and fishing vessels

Virtually all of the 35,000 plus merchant ships worldwide larger than 500 gross tonnes (Hochhaus, 1998) have some on-board refrigeration system. The majority of systems use HCFC-22. These refrigeration systems and options for emission abatement are referred to in Sections 4.2 and 4.3 of this report. In terms of technology and performance, chillers for air conditioning or, in case of naval vessels for electronics and weapon system cooling, are similar to stationary systems (see section 5.1 on air conditioning). The following remarks and information relate to ship-bound refrigeration systems essential to the main purpose of non-naval vessels, namely the transportation of perishable products, the chilling of fish and the like.

Refrigerated transport vessels, also called reefers, provide transportation for perishable foodstuff at temperatures between –30°C and 16°C (Cube *et al*., 1997). It is estimated that there are around 1300 to 1400 reefer vessels in operation (Hochhaus, 2002; Hochhaus, 1998), a number which has been constant for quite some time and is expected to decrease. In 2001, it was reported that more than 95% of the refrigeration installations on these vessels use HCFC-22 as a refrigerant (SCANVAC, 2001), although various HFCs such as HFC-134a, R-404A, R-507 and R-407C as well as ammonia are being used. About two-thirds of the systems are direct systems with up to 5 tonnes of refrigerant per system and the remaining are indirect systems with a charge below 1 tonne of refrigerant (UNEP, 2003). Estimates of current annual leakage rates based on known refrigerant consumption are 15−20% of the system charge (SCANVAC, 2001).

Worldwide there about 1.3 million decked and about 1.0 million undecked, powered fishing vessels. In 2001, more than 21,500 fishing vessels over 100 gross tonnes were recorded (FAO, 2002), with a slightly decreasing trend. Vessels of that size are assumed to operate internationally and to be equipped with significant refrigeration equipment. Within a wide range, the average larger fishing vessel has a refrigerant charge in the order of 2000 kg with 15−20% annual leakage rate. In 2001 more than 95% of such vessels in Europe used HCFC-22 as the refrigerant (SCANVAC, 2001). It is assumed that 15% of the fleet have full size refrigeration systems, while the remaining fleet is assumed to be equipped with small refrigeration systems that have a filling mass of approximately 100 kg.

Specialized tankers are used to transport liquefied gases, in particular liquefied petrol gas (LPG) and liquefied natural gas (LNG). Medium and large LNG tankers transport LNG at normal pressure. The refrigeration effect needed for this type of transport is provided by evaporating the LNG, which is recondensed using specialized refrigeration units. Since the number of such ships is limited (about 150 ships of above 50,000 tonnes were registered in 1996) (Cube *et al*., 1997) and the refrigeration equipment typically uses the transported, low GWP hydrocarbon gases as the refrigerant, refrigeration use in gas tankers is not further considered in this report.

4.6.4 Road transport

Road transport refrigeration units, with the exception of refrigeration containers, are van, truck or trailer mounted systems. Some trailers are equipped to be mounted or have their main bodies mounted on railroad systems; these are so-called swap-bodies. In a number of uses those systems are of the discontinuous type, using eutectic plates in closed systems (Cube *et al*., 1997) or liquid nitrogen, liquid carbon dioxide or solid carbon dioxide in open systems (UNEP, 2003). These systems are frequently used in local frozen food distribution, for example, delivery directly to the customer (Cube *et al*., 1997). Liquid nitrogen for cooling purposes is used by more than 1000 vehicles in the UK. Liquid carbon dioxide is reported to be used in 50 trucks in Sweden (UNEP, 2003). In general, the necessity for storage and filling logistics, the hazardous handling of very cold liquids and solids and the energetically unfavourable low-temperature storage reduce the widespread application of these historically frequently used technologies.

The predominant technology in road transport, covering virtually all of the remaining refrigerated road transport equipment, is the mechanical vapour compression cycle. Trailers usually have unitary equipment that consists of a diesel engine, compressor, condenser, engine radiator and evaporator with fans as well as refrigerant and controls. These systems are also used for swap bodies. Larger trucks often have similar equipment as trailers. However, as the truck size decreases an increasing proportion of systems have the compressor being driven by the drive engine (ASHRAE, 2002). Alternatively, some truck systems use a generator coupled with the truck engine to generate electricity, which is then used to drive the compressor (Cube *et al*., 1997).

In 1999, it was estimated that in North America alone 300,000 refrigerated trailers were in use (Lang, 1999). For the 15 countries of the European Union in 2000, 120,000 small trucks, vans and eutectic systems with 2 kg refrigerant charge were estimated to be in use, with 70,000 mid-size trucks of 5 kg refrigerant filling and 90,000 trailers with 7.5 kg refrigerant filling (Valentin, 1999). The worldwide numbers in 2002 were estimated to total 1,200,000 units, with 30% trailer units, 40% independent truck units and 30% smaller units. The annual amount of refrigerant needed for service is reported to be 20–25% of the refrigerant charge (UNEP, 2003). The refrigerant typically chosen is HFC-134a for applications where only cooling is needed, and predominantly R-404A and R-410A for freezing applications and general-purpose refrigeration units (UNEP, 2003).

4.6.5 Railway transport

Refrigerated railway transport is used in North America, Europe, Asia and Australia. The transport is carried out by using either refrigerated railcars, or refrigerated containers (combined sea-land transport; see Section 4.6.2) or swap bodies (combined road-land transport; see Section 4.6.4). This section concentrates on transport in refrigerated railcars.

Different technologies have been used in the past: Solid CO_2 as well as ice have been used in discontinuous emissive systems to date (CTI, 2004). Mechanically-driven refrigeration systems have also been used and are now the prime choice because of the typically long duration of trips, which makes refilling of the emitted refrigerant in discontinuous emissive systems a challenge for both logistical and cost reasons.

Mechanically driven systems are almost completely equipped with diesel engines to supply the necessary energy to the refrigeration unit. The existing fleets of railcars in Asia still seem to mostly operate on one-stage (cooling) and two-stage (freezing /combined use) CFC-12 systems (UNEP, 2003). The European railcars have been converted to HFC-134a (Cube *et al*., 1997), and this has been facilitated by European regulations phasing out the use of CFCs (EC No 2037/2000 (Official Journal, 2000)). In North America, existing older systems have been converted to HFC-134a, while newer systems utilize HFC-134a and R-404A (DuPont, 2004).

The lifetime of newer rail refrigeration systems, which are often easily replaceable units originally developed for road transport and only adapted for rail use, is believed to be 8 to 10 years with a running time of 1000 to 1200 hours per annum (refrigeratedtrans.com, 2004). Older units specifically designed for rail use have a lifetime of typically 40 years and a refrigerant filling of approximately 15 kg (UNEP, 2003). The annual leakage rate may be assumed to be at least similar to the leakage rate experienced in road transport, that is 20–25% of the refrigerant charge (UNEP, 2003).

4.6.6 Air transport

In order to provide constant low temperature during the flight, containers to be loaded upon aircraft are provided with refrigeration systems. There are some battery powered mechanical refrigeration systems (Stera, 1999), but the total number of these is believed to be small. Other, more commonly used systems are discontinuous with solid carbon dioxide (Sinclair, 1999; ASHRAE, 2002), or ice (ASHRAE, 2002). As the amount of ODS replacement during use is apparently very small, air transport will not be detailed further in this report.

4.6.7 Abatement options

4.6.7.1 General

Based on the study of Clodic and Palandre (2004), the total amount of refrigerant contained in transport refrigeration systems is estimated to be 16,000 tonnes; 6000 tonnes of this are emitted annually. It should be noted that the widespread use of R-404A as a non-ODS alternative with a relatively high GWP of 3800 kg CO_2 kg^{-1} leads to very high CO_2-equivalent emissions. Using alternatives in systems with a more moderate GWP than R-404A, such as the HFC mixture R-410A, would cut the CO_2-equivalent emissions substantially.

Current system requirements lead to a refrigerant selection which is largely limited to HFC-134a and refrigerant mixtures with a relatively high global-warming impact such as R-404A. Since the emission rates in operation are significant, improvements in energy consumption, alternative substances and not-in-kind technologies are the main options for emission abatement. R-404A is the main refrigerant in current use (IIR, 2002) and is popular because of its flexibility (medium- and low-temperature applications) and safety. Only a limited number of TEWI calculations are available in the literature; the only investigation comparing different technologies such as CFC-12, HFC-134a, R-404A, HC-600a/HC-290, ammonia and CO_2, states that R-404A systems are at least sustainable from the different options investigated for reefer ships (Meffert and Ferreira, 2003).

4.6.7.2 Containment

As there are already considerable incentives to optimize design and to minimize leakage, further containment in most uses would require a new approach not yet seen. One example might be to use fully hermetic systems for road transport (Chopko and Stumpf, 2003a, b), although the effect of this on energy consumption has yet to be determined. The development of hermetic scroll compressors for container systems with acceptable energy efficiency for both cooling and freezing applications (Yoshida *et al.,* 2003; DeVore, 1998) allows their widespread use, and leads to less service requirements and therefore less related refrigerant losses. In addition, these compressors are hermetic, which further decreases leaks (Wild, 2003). This technology has already been introduced and is penetrating the market as existing equipment is gradually replaced.

Recovery and recycling is a statutory requirement in many countries and is probably adhered to since the equipment contains a considerable, but still easy-to-handle, amount of refrigerant and due to its mobility it can easily be transported to a recovery facility (except seagoing). On the other hand due to the large emission rates in operation, the improvements through recovery and recycling, which encompass only the refrigerant losses during service and disposal, are likely to be limited.

An alternative approach to improving systems to reduce leaks might be to improve operating conditions to reduce wear, likeliness of ruptures and refrigerant losses during service. The potential of such measures compared to system-related improvements has yet to be assessed, but might be considerable.

4.6.7.3 Improvement in energy efficiency

Most refrigeration systems operate under partial load conditions for a large proportion of their useful life (Meffert and Ferreira, 1999). Different methods for partial load control have been investigated for both electrically driven compressors and open compressors (e.g. Crombie, 1999). Potential energy savings for electrical systems using frequency converters are said to reach up to 25.8% per voyage (Han and Gan, 2003). Other sources compare a range of control possibilities (Meffert and Ferreira, 1999 and 2003). These sources concluded that energy efficiency gains of more than 70% can be achieved under part-load conditions.

4.6.7.4 Discontinuous processes

The use of ice as well as solid CO_2 are both established alternatives to vapour compression systems. Besides the logistical necessities of such systems, there are also temperature limitations for the use of ice as well as handling and energy issues when using solid CO_2 (as heat absorption is energetically unfavourable at –78.4°C). These issues are even more valid for the use of liquid nitrogen, producing an unnecessarily low temperature of –195.8°C, or liquid air with –194.3°C. Nevertheless, refrigerated systems using ice and solid CO_2 systems remain abatement option for HFC in suitable cases.

The commercialization of a fully self-powered liquid CO_2 system with a moderate evaporation temperature of –51°C for the delivery of frozen product to customers was reported by Viegas (2003), and this addressed handling as well as energy efficiency issues. The system, which needs a service infrastructure, has been commercialized in Sweden (Viegas, 2003) and the UK (UNEP, 2003) and is therefore available as an abatement option, especially for local and short-haul transport.

The use of a pumpable suspension of ice crystals in water (‘binary ice’, ‘flow ice’), has been developed for certain transport uses. The suspension is pumped into the hollow walls, floors, ceilings or trays of a containment to be refrigerated. While equipment for service trolleys for passenger trains is already commercially available, the same principle is being suggested for containers (Paul, 1999). Although the remaining technical issues seem to be standard engineering tasks, the technology is not yet commercially available for cooling of full containers, trucks or vans.

4.6.7.5 Sorption processes

Sorption processes are well known, heat-driven processes using water, methanol or ammonia as a refrigerant, and solids such as activated coal, zeolite or silica gel (adsorption) as well as liquids such as lithium bromide (LiBr) and water (absorption) as sorbents in a closed circuit. The heat to drive such processes can come from a variety of sources; in the case of transport refrigeration, the waste heat from the transporter’s engine could be used. Such a use has been proposed for several years, especially for ship-bound systems (Cube *et al*., 1997).

LiBr-water systems, are frequently used in stationary applications and for the capacity range of 200 kW–600 kW, these have been reported to operate successfully and produce chilled water in certain specialized ships (Han and Zheng, 1999). Below zero refrigeration is not feasible with LiBr-water systems. As such systems have already been successfully employed on ships, their utilization might be increased at a relatively short notice.

The applicability to modes of transportation other than ships might be limited because of downscaling problems as well as design restrictions on those systems.

For truck-mounted refrigeration systems, the use of waste heat from the truck engine has been suggested to drive a water-ammonia sorption cycle (Garrabrant, 2003). For medium and small fishing vessels, adsorption ice-makers with carbon-methanol are being proposed, which utilize the exhaust heat of the ship's engine as an energy source (Wang *et al*., 2003).

4.6.7.6 Hydrocarbons

Hydrocarbon cooling systems for the recondensation of transported hydrocarbons have successfully been installed in gas tankers. International activities are underway to develop hydrocarbon systems for reefer ships (Jakobsen, 1998). In road transport refrigeration, commercially available systems have been developed in Australia, Germany and other European countries using HC-290 (propane). The systems require a leak detector in the trailer and special driver training to fulfil safety-related legal requirements (UNEP, 2003; Frigoblock, 2004).

Technically this solution could be adopted worldwide in certain road and railroad systems, especially in compact systems. Nevertheless, either certain existing regulations or present system use patterns would have to be adapted. The flammability of hydrocarbons will require additional safety measures, thus increasing the costs of the system, and in the beginning at least probably insurance rates as well. Containers might also require changes in the transporting ships.

4.6.7.7 Ammonia

Ammonia as refrigerant is being increasingly used in marine refrigeration equipment. Applications include its use in reefers (Stera, 1999), as a proposed refrigerant for sorption ice machines (Garrabrant, 2003), and the use in fishing vessels both as a single refrigerant (UNEP, 2003; Berends, 2002) and in combination with CO_2 (Nielsen and Lund, 2003). The applicability has been sufficiently proven. Ammonia as a refrigerant requires certain design considerations as well as the presence of additional safety equipment on board (SCANVAC, 2001).

4.6.7.8 Carbon Dioxide

Carbon dioxide as a refrigerant in mechanically-driven vapour compression systems, might be used as a subcritical refrigerant (critical point at 31°C) with a condensing temperature well below the critical point in cascade systems or in applications where low-temperature cooling options means are available. Alternatively, it can be used as a near-critical or, more likely, a super-critical working fluid. If the condensing temperature of CO_2 is below 15°C (border of subcritical region), this refrigerant typically offers, but not always, significant advantages in terms of efficiency and costs in comparison to other refrigerants. This advantage can only be utilized in cascade systems with other refrigerants or where low-temperature heat sinks are available. Near- or super-critical uses require a much higher pressure resistance of the equipment than is currently usual for other refrigerants, and such uses are often energetically less favourable than other refrigerants in the same temperature range.

For low-temperature uses, combinations of ammonia and CO_2 have been developed and built into ships. A comparison shows that the efficiency for a –40°C evaporation and 25°C condensing temperature is 17% higher than for a 2-stage HCFC-22 system (25% improvement at –50°C/25°C) (Nielson and Lund, 2003). The advantage of using CO_2 in such applications is that the necessary components (in particular the compressor) are commercially available or require only minor modifications, while consuming less space than other solutions.

CO_2 has also been proposed for container systems, where it would typically be used in a super-critical manner. A prototype system has yet to be reported as until recently no suitable compressor was available. A prototype CO_2 system for trucks has been developed, laboratory tested and optimized (Sonnekalb, 2000). The calculated TEWI shows a 20% decrease compared to a R-404A system.

4.6.7.9 Air

The air cycle for transport refrigeration purposes has been investigated for a number of years (e.g. Halm, 2000). A prototype system has been developed and tested, but has never been commercialized. Presently air cycle equipment for transport refrigeration does not seem to represent a suitable short- or medium-term abatement option due to the lack of suitable and reliable components.

4.6.8 Comparison of alternatives

Emissions of halocarbons in the transport refrigeration sector are related to four subsectors: Sea transport and fishing, road transport, rail transport and intermodal transport, that is containers and swap bodies. An overview can be found in Table 4.15.

There are a number of possibilities to improve those transport refrigeration systems built today to achieve a lowering of direct or energy-consumption related emissions without changing the working fluid or technology. A number of measures have been proposed and these have in part already been implemented to improve the energy efficiency, for example, the use of efficient compressors, frequency control for part load conditions, water-cooled condensers for containers on board ships, regular preventive maintenance and so forth. Measures to control direct emissions have mainly been proposed for mass-produced systems (e.g. container units) in terms of design improvements.

An alternative to improving the currently predominant halocarbon technologies is the replacement of those refrigerants by fluids or technologies with a lower GWP. Technically there are or will be low GWP replacement options available for all transport refrigeration uses where CFCs, HCFCs or HFCs are currently used. However in several cases these might increase the costs of the refrigeration system.

In case of reefer ships and fishing vessels, the most promising and already implemented non-halocarbon abatement tech-

Table 4.15. Subsectors of transport refrigeration, characteristics and alternatives.

Subsector		Sea Transport & Fishing	Road Transport	Rail Transport	Intermodal Transport
Cooling capacity	From To	5 kW 1400 kW	2 kW 30 kW	10 kW 30 kW	Approx. 5 kW
Refrigerant charge	From To	1 kg Several tonnes	1 kg 20 kg	10 kg 20 kg	Approx. 5 kg
Approximate percentage of sector refrigerant bank in subsector		52% of 15,900 tonnes	27% of 15,900 tonnes	5% of 15,900 tonnes	16% of 15,900 tonnes
Approximate percentage of sector refrigerant emissions in subsector		46% of 6000 tonnes	30% of 6000 tonnes	6% of 6000 tonnes	18% of 6000 tonnes
Predominant technology		HCFC-22	HFC-134a, HFC-404A, HFC-410A	HFC-134a, HFC-404A, HFC-410A	HFC-404A
Other commercialized technologies		Various HFCs, ammonia, ammonia, CO_2 /ammonia for low temperatures; hydrocarbon systems for gas tankers; sorption systems for part of the cooling load	Hydrocarbon, liquid CO_2; with unknown systems for liquefaction/freezing: liquid CO_2, ice slurry; with on-board HCFC/HFC refrigeration systems: Eutectic plates	Solid CO_2 (with unknown systems for freezing)	HFC-134a, HCFC-22
Low GWP technologies with fair or better than fair potential for replacement of HCFC/HFC in the markets		Ammonia, CO_2 /ammonia for low temperatures	Hydrocarbon, CO_2 compression systems; for short haul combination of stationary hydrocarbon or ammonia with liquid CO_2, ice slurry or eutectic plates	Hydrocarbon, CO_2 compression systems; for specific transports (certain fruits, ...) combination of stationary hydrocarbon or ammonia with liquid CO_2, ice slurry or eutectic plates	CO_2 compression system
Status of alternatives		Fully developed. Some cost issues related to additional safety for ammonia plants on ships. Hydrocarbon practical mainly for ships which are built according to explosion-proof standards (gas carriers, ...)	Hydrocarbon mini-series successfully field tested, lack of demand/add. requirements on utilization (driver training, parking, ...). Liquid CO_2 systems commercialized. CO_2 compression tested in proto-types, but open compressor needed for most systems in combination with leaks remains an issue	Solid CO_2 standard use, but not very energy efficient, difficult handling, high infrastructure requirements, therefore presently being phased out. Increasingly use of systems designed for trailer use with optimization for rail requirements (shock resistance, ...)	Under development – prototype testing; might be available in the near future if demanded

nology is equipment with ammonia or ammonia/CO_2 systems. These systems are likely to operate at least as energy efficiently as existing systems. One source (SCANVAC, 2001) estimates the additional costs for a ship-bound ammonia system to be 20–30% higher if retrofitted into an existing vessel and potentially lower if included in the ships planning from the start. Another source (Nielsen and Lund, 2003) assumes that small industrial ammonia/CO_2 systems might be more expensive than conventional systems, but large systems might have a more or less equivalent price for the same capacity.

In the case of container systems, CO_2 in a vapour compression cycle could develop into a promising alternative. The costs for the refrigeration system might be higher than for current conventional systems. The energy consumption will probably be higher if the containers are only air-cooled but if additional water-cooling is installed, as has already implemented on some vessels, the systems could be energetically as good as or even better than existing equipment.

Options using CO_2 and hydrocarbons exist for road transport. The hydrocarbon technology is technically implementable within a short time frame. For larger systems, CO_2 systems or hydrocarbon refrigerants are potential options, depending on the safety issues. The same alternatives could be used for new railway systems. Certain types of refrigerated road transport, such as short-range distribution trucks, might use discontinuous systems with evaporating CO_2 or nitrogen as alternative.

As transport refrigeration systems have very significant emissions and a limited runtime, which is typically far below

100%, direct emissions play a very important role in the calculation of the TEWI. The replacement options currently being considered by manufacturers do not significantly increase transport weight or volume. The data is sufficient to state that in several applications, a substantial reduction in TEWI could be achieved by introducing a low GWP technology.

References

ACRIB, 2001: Guidelines for the Use of Hydrocarbon Refrigerant in Static Refrigeration and Air-conditioning Systems. Air Conditioning and Refrigeration Industry Board, (ACRIB), Carshalton, UK.

ADL (A.D. Little, Inc), 1999: Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications. Final Report to the Alliance for Responsible Atmospheric Policy, August 23, 1999, Prepared by J. Dieckmann and H. Magid (available online at www.arap.org/adlittle-1999/toc.html), Acorn Park, Cambridge, Massachusetts, USA, 142pp.

ADL (A.D. Little, Inc.)**,** 2002: Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications. Final Report to the Alliance for Responsible Atmospheric Policy, March 21, 2002 (available online at www.arap.org/adlittle/toc.html), Acorn Park, Cambridge, Massachusetts, USA, 150pp.

AEAT (AEA Technology), 2003: Emissions and Projections of HFCs, PFCs and SF_6 for the UK and Constituent Countries. Report prepared for the Global Atmosphere Division of the UK Department for Environment, Food, and Rural Affairs, July 2003.

ANSI/ASHRAE, 2002: Standard 147-2002 Reducing the Release of Halogenated Refrigerants from Refrigeration and Air-Conditioning Equipment and Systems. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), Atlanta, GA, USA.

Arias, J. and P. Lundqvist, 1999: Innovative System Design in Supermarkets for the 21st Century. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration, (IIR/IIF), Paris, France.

Arias, J. and P. Lundqvist, 2001: Comparison of Recent Refrigeration Systems in Supermarkets. Proceedings of the 6th Ibero-American Congress of Air-Conditioning and Refrigeration, Buenos Aires, Argentina, 14-17 August, 2001.

Arias, J. and P. Lundqvist, 2002: Heat Recovery in Recent Refrigeration Systems in Supermarkets. Proceedings of the 7th International Energy Agency Heat Pump Conference 2002: Heat Pumps – Better by Nature, Beijing, China, 19-22 May 2002. IEA Heat Pump Centre, Sittard, The Netherlands.

ASHRAE, 2002: *2002 ASHRAE Handbook – Refrigeration*, (SI edition). American Society of Heating, Refrigeration and Air-Conditioning Engineers Inc., Atlanta, GA, USA.

Axima, 2002: Fish processing factory with CO_2 as brine and NH_3 as refrigerant. Axima Refrigeration GmbH, Company Information, Lindau, Germany.

Bansal, P., and R. Kruger, 1995: Test standards for household refrigerators and freezers I: Preliminary comparisons. *International Journal of Refrigeration*, **18**(1), 4-17.

Barreau, M., S. Macaudiere, P. Weiss, and M. Joubert, 1996: R-404A in Industrial Refrigeration Application for R-502 and HCFC-

22 Replacement. System with Recirculation-type Evaporator. Proceedings of the International Conference on Ozone Protection Technologies, October 21-23, 1996, Washington DC, USA.

Baxter, V.D. (ed.), 2003a: Advanced Supermarket Refrigeration / Heat Recovery Systems, Vol 1 – Executive Summary. IEA Heat Pump Centre, Sittard, The Netherlands, 73 pp (ISBN: 90-73741-48-3).

Baxter, V.D. (ed.), 2003b: Advanced Supermarket Refrigeration / Heat Recovery Systems, Vol 2 - Country Reports. IEA Heat Pump Centre, Sittard, The Netherlands (CD-ROM, ISBN: 90-73741-49-1).

Beeton, W.L. and H.M. Pham, 2003: Vapor injected scroll compressors. *ASHRAE Journal*, **45**(4), 22-27.

Behnert, T. and H. König, 2003: Entwicklung eines NH_3-Standard-Flüssigkeitskühlsatzes mit minimaler Füllmenge. *Die Kälte- und Klimatechnik*, 6/2003, 32-37 (in German).

Berends, E., 2002: Ammoniak (her)ontdekt voor scheepskoelinstallaties? (The rediscovery of ammonia as a refrigerant on new refrigerated cargo vessels?). *Koude & Luchtbehandeling*, **95**(9), 24-33 (in Dutch).

Bertoldi, P., 2003: The European End-Use Energy Efficiency Potential and the Needed Policies. European Commission, DG JRC, Presentation at Fondazione Eni Enrico Mattei, Milan, Italy, December 8, 2003 (http://www.feem.it/NR/Feem/resources/pdf/cop9/20031208/Bertoldi.pdf).

Birndt, R., R. Riedel and J. Schenk, 2000: Dichtheit von Gewerbekälteanlagen (Tightness of Commercial Refrigeration Systems. *Die Kälte- und Klimatechnik*, 9/2000, 56-63 (in German).

Bivens, D. and C. Gage, 2004: Commercial Refrigeration Systems Emissions. Proceedings of the 15th Annual Earth Technologies Forum, April 13-15, 2004, Washington, D.C., USA.

CEN, 2000/2001: Refrigerating systems and heat pumps – Safety and environmental requirements. Part 1: Basic requirements, definitions, classification and selection criteria (2001), Part 2: Design, Construction, testing, marking and documentation (2000), Part 3: Installation, site and personal protection (2000), Part 4: Operation, maintenance, repair and recovery (2000). European Standards, EN CEN 378.

Chopko, R.A. and A. Stumpf, 2003a: Advantages of All-electric Transport Refrigeration Systems. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Chopko, R.A. and A. Stumpf, A., 2003b: Survey of Multi-Temperature Transport unit refrigeration design. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Christensen, K.G., 1999: Use of CO_2 as Primary and Secondary Refrigerant in Supermarket Applications. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration (IIR/IIF), Paris, France.

Christensen, K.G., 2004: The World's First McDonalds Restaurant Using Natural Refrigerants. Proceedings of 6th IIR Gustav Lorentzen Conference – Natural Working Fluids 2004, Glasgow, Scotland, August 29 – September 1, 2004. International Institute of Refrigeration (IIR/IIF), Paris, France.

Christensen, K.G. and P. Bertilsen, 2003: Refrigeration Systems in Supermarkets With Propane and CO_2 – Energy Consumption and Economy. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Clodic, D., 1997: *Zero Leaks*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), Atlanta, GA, USA, 189 pp.

Clodic, D. and L. Palandre, 2004: Determination of Comparative HCFC and HFC Emission Profiles for the Foam and Refrigeration Sectors Until 2015. Part 1: Refrigerant Emission Profiles. Centre d'Energetique (Ecole des Mines de Paris/Armines), Report for US EPA and ADEME, 132 pp**.**

Coca Cola, 2002: Our Environmental Values – The Coca Cola Company Environmental Report 2002, The Coca Cola Company, Atlanta, GA, USA.

Coca Cola, 2004: The Coca Cola Company – Alternative Refrigeration Backgrounder. Proceedings of the Conference: Refrigerants, Naturally, 22 June 2004, Brussels, Belgium (available at http://www.refrigerantsnaturally.com).

Colbourne, D. and Suen, K. O., 2004, Appraising the flammability hazards of hydrocarbon refrigerants using quantitative risk assessment model. Part II: Model evaluation and analysis. *Int. J. Refrigeration*, **27**(2004), pp. 784-793.

Crombie, D., 1999: New Technologies Allow Radical Energy Savings in Seagoing Container Refrigeration Systems. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration (IIR/IIF), Paris, France.

CTI (Cryo-Trans, Inc.), 2004: Cryo-Trans, Inc. webpage: www.cryo-trans.com/history2.htm.

Cube, H.L. von, F. Steimle, H. Lotz and J. Kunis (eds.), 1997: *Lehrbuch der Kältetechnik – Vol. 2*, C.F. Müller Verlag, Heidelberg, Germany, 4th Edition, 850 pp.

D&T (Deloitte & Touche Consulting Group), 1996: Assessment of the Prospects for Hydrocarbon Technology in the Global Domestic Refrigeration Market, London, United Kingdom.

DeVore, T.A., 1998: Development of an Open Drive Scroll Compressor for Transport Refrigeration. Proceedings of the Purdue Compressor Conference, 1998. Purdue Printing Services, West Lafayette, IN, USA, pp. 231-236.

Dupont, 2004: Dupont website: www.dupont.com/suva/na/usa/about/success/transport1.html

EC, 2003: European Energy and Transport Trends to 2030. European Commission, Directorate-General for Energy and Transport, brussels, Belgium. http://europa.eu.int/comm/dgs/energy_transport/figures/trends_2030/index_en.htm

ECCJ (Energy Conservation Center Japan)**,** 2004: Website of the Energy Conservation Center Japan, Tokyo, Japan. http://www.eccj.or.jp/index_e.html, http://www.eccj.or.jp/summary/local0303/eng/03-01.html, http://www.eccj.or.jp/databook/2002-2003e/03_04.html, http://www.eccj.or.jp/databook/2002-2003e/03_05.html

EIA, 2004: Annual Energy Outlook 2004 with Projections to 2025

– Market Trends – Energy Demand. Energy Information Administration, US Department of Energy, Washington, DC, USA http://www.eia.doe.gov/oiaf/aeo/

Elefsen, F., J. Nyvad, A. Gerrard and R. van Gerwen, 2002: Field Test of 75 R404A and R290 Ice Cream Freezers in Australia. 5th IIR Gustav Lorentzen Conference – Natural Working Fluids 2002, September 17-20, Guangzhou, China. International Institute of Refrigeration (IIR/IIF), Paris, France.

Egolf, P. and M. Kauffeld, 2005: From physical properties to industrial ice slurry applications. *Int. J. of Refrigeration*, **20**(2005), pp. 4-12.

Enviros, 2003: Assessment of the Costs & Implication on Emissions of Potential Regulatory Frameworks for Reducing Emissions of HFCs, PFCs & SF_6. Report prepared for the European Commission (reference number EC002 5008), London, United Kingdom, pp. 39.

ERI (Energy Research Institute), 2003: China's Sustainable Energy Future – Scenarios of Energy and Carbon Emissions. Energy Research Institute of the National Devleopment and reform commission, People's Republic of China, with Lawrence Berkeley National Laboratory, USA [Sinton, J.E., J.I. lewis, M.D. levine, Z. Yuezhong (eds.)] http://china.lbl.gov/pubs/china_scenarios_summary_final.pdf

EU (European Union), 2004: Regulation of the European Parliament and of the Council on certain fluorinated greenhouse gases, Draft Regulation 2003/0189 (COD), 9 July 2004, Brussels, Belgium.

Euromonitor International Inc., 2001: Global Appliance Information System, http://www.euromonitor.com (August 2001)

FAO (Food and Agriculture Organization of the United Nations)**,** 2002: The State of the World Fisheries and Aquaculture, Rome, Italy, pp. 23.

Fernando, W.P.D. B. Palm, E. Granryd and K. Andersson, 2003: Mini-Channel Aluminium Heat Exchangers with Small Inside Volumes. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Ferreira, C.A.I. and D. Zaytsev, 2002: Experimental Compression – Resorption Heat Pump for Industrial Applications. Proceedings of the Purdue Compressor Conference, 2002. Purdue Printing Services, West Lafayette, IN, USA.

Fischer, S.K., P.J. Hughes, P.D. Fairchild, C.L. Kusik, J.T. Dieckmann, E.M. McMahon and N. Hobday, 1991: Energy and Global Warming Impacts of CFC Alternative Technologies, U.S. Department of Energy and AFEAS, Arlington, Va., USA.

Fischer, S.K., J.J. Tomlinson and P.J. Hughes, 1994: Energy and Global Warming Impacts of Not in Kind and Next Generation CFC and HCFC Alternatives, U.S. Department of Energy and AFEAS, 1200 South Hayes Street, Arlington, Va., USA.

Frigoblock, 2004: Frigoblock GmbH webpage: http://www.frigoblock.de

Garrabrant, M.A., 2003: Proof-of-concept design and experimental validation of a waste heat driven absorption transport refrigerator. *ASHRAE Transactions*, **109**(2003), pp. 1-11.

Gebhardt, H., 2001: HFCKW-Ausstieg – Umrüstung einer Industriellen Tieftemperaturkälteanlage von R22 auf CO_2/NH_3-Kaskadensystem (HCFC Phase Out – Retrofit of Industrial Low Temperature Refrigeration System from HCFC-22 to CO_2/NH_3 Cascade System). Proceedings of the Deutsche Kälte-Klima-Tagung, Ulm, 22-23 November 2001, Deutscher Kälte- und Klimatechnischer Verein DKV, Stuttgart, Germany (in German).

Gerwen, R.J.M. van, M. Verwoerd, 1998: Dutch Regulations for reduction of Refrigerant Emissions: Experiences with a Unique Approach over the period 1993-1998. ASERCOM Symposium: Refrigeration/Air conditioning and Regulations for Environment Protection – A Ten Years Outlook for Europe, 7 October 1998, Nürnberg, Germany.

Girotto, S. and P. Nekså, 2002: Commercial Refrigeration Systems with CO_2 as Refrigerant, Theoretical Considerations and Experimental Results. Proceedings of the IIR conference New Technologies in Commercial Refrigeration, July 22-23, University of Illinois, USA. International Institute of Refrigeration (IIR/IIF), Paris, France.

Girotto, S., S. Minetto and P. Nekså, 2003: Commercial Refrigeration with CO_2 as Refrigerant, Experimental Results. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Girotto, S., S. Minetto and P. Nekså, 2004: Commercial Refrigeration System Using CO_2 as the Refrigerant. *Int. J. of Refrigeration*, **27**(7), 717-723.

Godwin, D., 2004: Analysis of Costs to Abate International Ozone Depleting Substance Substitute Emissions. US EPA Report 430-R-04-006, US Environmental Protection Agency, Washington, DC, USA.

GTZ, 2002: India Servicing Sector Project Proposal, submitted September 2002 to the Multilateral Fund Secretariat, GTZ.

Haaf, S. and B. Heinbokel, 2002: Alternative Kaltemittel fur Supermarkt-Kalteanlagen (Alternative Refrigerants for Supermarket Refrigeration Installations). Proceedings of the Deutsche Kälte-Klima-Tagung, Magdeburg, 21-22 November 2002, Deutscher Kälte- und Klimatechnischer Verein DKV, Stuttgart, Germany, pp 29-42 (in German).

Haaf, S. and B. Heinbokel, 2003: Supermarkte mit alternativen Kaltemitteln. *KI Luft und Kaltetechnik* **39**(11), 508-512 (in German).

Halm, N.P., 2000: Air-Cycle Technology used for Truck Air-Conditioning. Proceedings of 4th IIR Gustav Lorentzen Conference – Natural Working Fluids 2000, West Lafayette, USA, July 25-28, 2000. International Institute of Refrigeration (IIR/IIF), Paris, France.

Han, H.D and Q.R. Zheng, 1999: Research on the Replacement for R12 and R22 used in Marine Rrefrigerating Units for Coming 21st century. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration (IIR/IIF), Paris, France.

Han, H., and W. Gan, 2003: Energy Conservation of Ocean-going refrigerated container transportation. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Harnisch, J. and C. Hendriks, 2000: Economic Evaluation of Emission Reductions of HFCs, PFCs and SF_6 in Europe. Report prepared for the European Commission DG Environment, Ecofys, Cologne/Utrecht, Germany/Netherlands, 70 pp.

Harnisch, J., N. Höhne, M. Koch, S. Wartmann, W. Schwarz, W. Jenseit, U. Rheinberger, P. Fabian and A. Jordan, 2003: Risks and Benefits of Fluorinated Greenhouse Gases in Practices and Products under Consideration of Substance. Report prepared for the German Federal Environmental Protection Agency (Umweltbundesamt) by Ecofys GmbH (Köln/Nürnberg), Öko-Recherche GmbH (Frankfurt), Öko-Institut e.V. (Darmstadt/Berlin), TU München (München), Max-Planck-Institut für Biogeochemie (Jena), Berlin, 128 pp.

Hochhaus, K.H., 1998: Reefer container ships and reefer containers. Sea Transportation. *Fruit World International*, **3**(1998), 198-204.

Hochhaus, K.H., 2002: Reefer deliveries in the doldrums. Sea Transportation. *Fruit World International*, **3**(2002), 210-216.

Hochhaus, K.H., 2003: Australia service, change in refrigerated container system. Sea Transportation, *Fruit World International*, **1**(2003), 39-46.

Hoehne, M. and P.S. Hrnjak, 2004: Charge minimisation in hydrocarbon systems. Proceedings of 6th IIR Gustav Lorentzen Conference – Natural Working Fluids 2004, Glasgow, Scotland, August 29 – September 1, 2004. International Institute of Refrigeration (IIR/IIF), Paris, France.

Hoogen, B. van den, and H. van der Ree, 2002: The Dutch Approach to Reduce Emissions of Fluorinated Greenhouse Gases. Proceedings of the IIR Conference on "Zero Leakage - Minimum Charge. Efficient Systems for Refrigeration, Air Conditioning and Heat Pumps", Stockholm, Seden, August 26-28, 2002. International Institute of Refrigeration (IIR/IIF), Paris, France.

Hundy, G.F.: Application of Scroll Compressors for Supermarket Refrigeration. Proceedings of the IMechE Seminar "Design, Selection and Operation of Refrigerator and Heat Pump Compressors", London, November 1998.

Hwang, Y., D.H. Jin and R. Radermacher, 2004: Comparison of Hydrocarbon R-290 and Two HFC Blends R-404a and R-410a for Medium Temperature Refrigeration Applications. Final Interim Report to ARI, Global Refrigerant Environmental Evaluation Network (GREEN) Program, CEEE Department of Engineering, University of Maryland, USA.

IEA, 2003: *Cool Appliances, Policy Strategies for Energy Efficient Homes*. International Energy Agency (IEA), Paris, France.

IIR (International Institute of Refrigeration), 1996: The Role of Refrigeration in Worldwide Nutrition. Informatory Note on Refrigeration and Food (November 1996). International Institute of Refrigeration (IIR/IIF), Paris, France.

IIR, 2002: Industry as a Partner for Sustainable Development – Refrigeration. International Institute of Refrigeration (IIR/IIF), Paris, France, 84 pp.

IIR, 2003: 16th Informatory Note on Refrigerating Technologies, Refrigerated Transport: Progress Achieved and Challenges to Be Met. International Institute of Refrigeration (IIR/IIF), Paris, France.

IPCC (Intergovernmental Panel on Climate Change), 1996a: *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 572 pp.

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 944 pp.

ISO (International Organization for Standardization), 1993: ISO 5149:1993 Mechanical Refrigerating Systems Used for Cooling and Heating – Safety Requirements. International Organization for Standardization, Geneva, Switzerland.

Jakobsen, A., 1998: Improving Efficiency of Trans-critical CO_2 Refrigeration Systems for Reefers. Proceedings of the IIR Conference, Commission D2/3, with D1, Cambridge, UK. International Institute of Refrigeration (IIR/IIF), Paris, France, pp. 130-138.

Kagawa, N., 2000: *Regenerative Thermal Machines (Stirling and Vuilleumier Cycle Machines) for Heating and Cooling*. International Institute of Refrigeration (IIR/IIF), Paris, France, ISBN 2-913149-05-7, 214 pp.

Kauffeld, M. and Christensen, K.G., 1998: A New Energy-efficient Reefer Container Concept Using Carbon Dioxide as Refrigerant. Proceedings of the IIR Gustav Lorentzen Conference – Natural Working Fluids, 2-5 June 1998, Oslo, Norway.

König, H., 2002: *Overview of applications with CO_2 as heat transfer fluid and as refrigerant*, Güntner Symposium Mai 2002, *Die Kälte- und Klimatechnik*, 7/2002 (in German)

Lang, D., 1999: Customer Demands Unfreeze Potential of Refrigerated Trailers. Transport Topics News from website: www.ttnews.com/members/printEdition/0002015.html.

Lindborg, A., 2000: Rätt utförda Indirekta Kylsystem förbrukar mindre Energi än Direkta, *Scandinavian Refrigeration*, **2**(2000), pp. 6-8 (in Swedish)

Lindborg, A., 2002: Mangelndes Wissen ist das grösste Hindernis für eine verbreiterte Verwendung von Ammoniak (Lack of knowledge is the main barrier for further use of ammonia). *Die Kälte- und Klimatechnik*, 1/2002, 34-39 (in German).

Lindborg, A., 2003: Sicherheit von NH_3-Anlagen, Schadensanalyse (Security of NH_3 systems – risk analysis). Proceedings of the Annual Conference of the Deutsche Kälte und Klimatechnischer Verein e.V. (DKV), Bonn, November 2003.

Lotz, H., 1993: Ermittlung des TEWI-Beitrags am Beispiel von Haushaltskuhlgeraten werksmontierter sowie feldmontierter Kalteanlagen. Proceedings of the Deutsche Kälte-Klima-Tagung, Nurnberg, 18-19 November 1993, Deutscher Kälte- und Klimatechnischer Verein DKV, Stuttgart, Germany (in German).

Lundqvist, P., 1993: *Stirling Cycle Heat Pumps and Refrigerators*. Diss. TRITA Refr. Report No 93/9, Stockholm, Sweden (ISSN 1102-0245).

Lundqvist, P., 2000: Recent refrigeration equipment trends in supermarkets: energy efficiency as leading edge. *Bulletin of the International Institute of Refrigeration*, 5/2000, 2-29.

Maidment, G.G. and R.M. Tozer, 2002: Combined cooling heat and power in supermarkets, *J. of Applied Thermal Engineeering*, **22**(2002), 653-665.

Mao, Y., W.J. Terrell and P.S. Hrnjak, 1998: Heat Exchanger Frosting Patterns with Evaporating R404A and Single Phase Secondary Refrigerants. Proceedings of the Purdue Compressor Conference, 1998. Purdue Printing Services, West Lafayette, IN, USA, pp. 277-282.

Mao, Y. and P.S. Hrnjak, 1999: Defrost Issues of Display Cabinets with DX Evaporators and Heat Exchangers with Secondary Refrigerants. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration (IIR/IIF), Paris, France.

March, 1996: UK Use and Emissions of Selected Hydrofluorocarbons – A Study for the Department of the Environment carried out by March Consulting Group. HMSO, London, United Kingdom.

March, 1998: Opportunities to Minimise Emissions of Hydrofluorocarbons from the European Union. March Consulting Group, London, United Kingdom.

March, 1999: UK Emissions of HFCs, PFCs and SF_6 and Potential Emission Reduction Options. March Consulting Group, London, United Kingdom

Meurer, C. and H. König, 1999: Effects of Accelerated HCFC Phase-Out Scenarios on Options to Replace R-22 in Heat Pumps. Proceedings of the 6th International Energy Agency Heat Pump Conference 1999: Heat Pumps – A Benefit fot the Environment, Berlin, Germany, 31 May – 2 June 1999. IEA Heat Pump Centre, Sittard, The Netherlands.

McDonalds, 2004: McDonald's Alternative Refrigeration Backgrounder, http://www.refrigerantsnaturally.com/doc/McDonalds%20backgrounder.pdf

Meffert, H., and A. Ferreira, 1999: Energy Efficiency of Transport Refrigeration Units. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration (IIR/IIF), Paris, France.

Meffert, H., and A. Ferreira**,** 2003: Part-Load Control Systems, Refrigerant Selection and Sustainability. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Meier, A., and J.E. Hill, 1997: Energy test procedures for appliances. *Energy and Buildings* **26**(1), 22-33.

Meier, A., 1998: Energy Test Procedures for the Twenty-First Century. Proceedings of the 1998 Appliance Manufacturer Conference & Expo, 13-14 October 1998, Nashville, TN, USA.

Melinder, Å., 1997: *Thermophysical Properties of Liquid Secondary Refrigerants*. International Institute of Refrigeration (IIR/IIF), Paris, France.

Naturvardsverket, 1996: Års rapporteringen for användningen av köldmedier CFC/HCFC (1995) – Sammanstallning med kommentarer (1995 Annual report regarding the use of the refrigerants CFC/HCFC – Summary and comments). Naturvardsverket (Swedish Environmental Protection Agency), Stockholm, Sweden.

Nekså, P., S. Girotto and P.A. Schiefloe, 1998: Commercial Refrigeration Using CO_2 as Refrigerant – System Design and Experimental Results. Proceedings of the IIR Gustav Lorentzen Conference – Natural Working Fluids, 2-5 June 1998, Oslo, Norway.

Nielson, P. S. and T. Lund, 2003: Introducing a New Ammonia/CO_2 Cascade Concept for Large Fishing Vessels. Proceedings of the International Institute of Ammonia Refrigeration (IIAR), 2003, Technical Paper #11.

Official Journal, 2000: Regulation (EC) No 2037/2000 of the European Parliament and of the Council of 29 June 2000 on substances that deplete the ozone layer. *Official Journal of the European Communities*, OJ L244, 29 September 2000.

Palandre, L., A. Zoughaib, D. Clodic and L. Kuijpers, 2003: Estimation of the World-wide Fleets of Refrigerating and Air-conditioning Equipment in Order to Determine Forecasts of Refrigerant Emissions. Proceedings of the 14th Annual Earth Technologies Forum, April 22-24, 2003, Washington, D.C., USA.

Palandre, L., D. Clodic, and L. Kuijpers, 2004: HCFCs and HFCs emissions from the refrigerating systems for the period 2004-2015. Proceedings of the 15th Annual Earth Technologies Forum, April 13-15, 2004, Washington, D.C., USA.

Paul, J., 1999: Novel Transport Cooling System Utilizing Liquid, Pumpable Ice. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration (IIR/IIF), Paris, France.

Pearson, A, 2004a: Carbon Dioxide in the Spotlight. c-dig meeting September 2003, Glasgow, Scotland. Carbon Dioxide Interest Group (c-dig), United Kingdom (http://www.c-dig.org/).

Pearson, A., 2004b: Case Studies with CO_2. c-dig meeting 18-19 March 2004, Dresden, Germany. Carbon Dioxide Interest Group (c-dig), United Kingdom (http://www.c-dig.org/).

Pedersen, P.H., 2003: Evaluation of the Possibilities of Substituting Potent Greenhouse Gases (HFCs, PFCs and SF_6). Environmental Project No. 771, Danish Environmental Protection Agency, Copenhagen, Denmark.

Pirard, M., 2002: CO_2/NH_3 Refrigeration in Food Processing. Güntner Symposium Mai 2002, *Die Kälte- und Klimatechnik*, 7/2002 (in German)

Poese, M., 2004: Thermoacoustic Refrigeration for Ice Cream Sales. Proceedings of 6th IIR Gustav Lorentzen Conference – Natural Working Fluids 2004, Glasgow, Scotland, August 29 – September 1, 2004. International Institute of Refrigeration (IIR/IIF), Paris, France.

Powell, L., P. Blacklock, C. Smith and D. Colbourne, 2000: The Use of Hydrocarbon Refrigerants in Relation to Draft UK Government Policy on Climate Change. Proceedings of 4th IIR Gustav Lorentzen Conference – Natural Working Fluids 2000, West Lafayette, USA, July 25-28, 2000. International Institute of Refrigeration (IIR/IIF), Paris, France.

Pratihar, A.K., S.C. Kausik and R.S. Agarwal, 2001: Thermodynamic

Modelling and Feasibility Analysis of Compression-Absorption Refrigeration System. Proceedings of the International Conference on Emerging Technologies in Air-conditioning and Refrigeration, 26-28 September 2001, New Delhi, India, pp. 207-215.

Presotto, A. and C.G. Süffert, 2001: Ammonia Refrigeration In Supermarkets. *ASHRAE Journal*, **43**(10), 25-30.

Pridasawas, W. and P. Lundqvist, 2003: Feasibility and Efficiency of Solar-driven Refrigeration Systems. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Radford, P., 1998: The Benefits of Refrigerant Inventory Control, Proceedings of the Institute of Refrigeration Conference: R22 Phase Out – Impact on End Users Today. Institute of Refrigeration, London, United Kingdom.

RefNat, 2004: Proceedings of the Conference: Refrigerants, Naturally, 22 June 2004, Brussels, Belgium (available at http://www.refrigerantsnaturally.com).

Refrigeratedtrans.com, 2004: Refrigerated Transporter website: http://refrigeratedtrans.com/mag/transportation_bnsf_buys_first/

Rolfsman, L., 1999: Plant Design Considerations for Cascade Systems Using CO_2. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration (IIR/IIF), Paris, France.

Roth, R. and H. König, 2001: Experimental Investigation and Experiences with CO_2 as Refrigerant in Cascade System. Proceedings of the Deutsche Kälte-Klima-Tagung, Ulm, 22-23 November 2001, Deutscher Kälte- und Klimatechnischer Verein DKV, Stuttgart, Germany (in German).

Roth, R. and H. König, 2002: Wirtschaftlichkeitsanalyse für Industrie-Kälteanlagen mit CO_2 als Tieftemperaturkältemittel, *KI Klima, Kälte, Heizung*, 3/2002. C.F. Müller, Karlsruhe, Germany (in German).

Sand, J.R., S.K. Fischer and V.D. Baxter, 1997: Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies, U.S. Department of Energy and AFEAS, Arlington, Va, USA.

SCANVAC, (Nordic Council)**,** 2001: Alternative to HCFC as refrigerant in shipping vessels. *SCANVAC*, 1/2001, 4-5.

Siegel, A. and A. Metzger, 2003: Modernstes Fischverarbeitungszentru m Europas in Sassnitz, Part I and II. *Die Kälte- und Klimatechnik*, Nov./Dec. 2003, (in German).

Sinclair, J., 1999: *Refrigerated Transportation*. Witherby Publishers, London, United Kingdom, 151 pp.

Sonnekalb, M., 2000: Einsatz von Kohlendioxid als Kältemittel in Busklimaanlagen und Transportkälteanlagen, Messung und Simulation. Forschungsberichte des Deutsche Kälte-und Klimatechnischen Vereins (DKV), No 67**,** 331 pp.

Stellar (The Stellar group), 2003: Stellar Report Summer 2003, Food Processing Plant at Jonesboro, Arkansas with CO_2 as refrigerant, Company Report, www.thestellargroup.com, 2003

Stera, A.C., 1999: Long Distance Refrigerated Transport into the Third Millennium. Proceedings of the 20th International Congress of Refrigeration, Sydney, Australia, 19-24 September 1999. D.J. Cleland and C. Dixon (eds.). International Institute of Refrigeration (IIR/IIF), Paris, France.

STEK, 2001: Consumption of Refrigerants in the Netherlands, Report based on the National Investigation on Refrigerant Flows, Zero measurement for 1999. Stichting Erkenningsregeling voor de Uitoefening van het Koeltechnisch Installatiebedrijf (STEK), Baarn, the Netherlands.

Stoecker, W.F., 1998: *Industrial Refrigeration Handbook*, McGraw-Hill, New York, NY, USA, ISBN: 007061623X, 782 pp.

Swatkowski, L., 1996: US Experience in Phasing Out CFC's. Proceedings of the International Conference on Ozone Protection Technologies, October 21-23, 1996, Washington DC, USA.

UNEP (United Nations Environment Programme)**,** 1994: Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (1995 Assessment). UNEP Ozone Secretariat (Secretariat to the Vienna Convention for the Protection of the Ozone Layer and the Montreal Protocol on Substances that Deplete the Ozone Layer), Nairobi, Kenya.

UNEP, 1998: 1998 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee – 1998 Assessment. [L. Kuijpers (ed.)]. UNEP Ozone Secretariat, Nairobi, Kenya.

UNEP, 2000: Report of the Thirtieth Meeting of the Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol (UNEP/OzL.Pro/ExCom/30/41), 29-31 March 2000, UNEP, Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol, Montreal, Canada.

UNEP, 2003: 2002 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee – 2002 Assessment. [L. Kuijpers (ed.)]. UNEP Ozone Secretariat, Nairobi, Kenya.

UN-ESCAP (United Nations Economic and Social Commission for Asia and the Pacific), 2002: *Guidebook on Promotion of Sustainable Energy Consumption: Consumer Organizations and Efficient Energy Use in the Residential Sector*. United Nations Economic and Social Commission for Asia and the Pacific, Bangkok, Thailand, 158 pp (available at http://www.unescap.org/esd/energy/publications/psec/, http://www.unescap.org/esd/energy/publications/psec/tables/guidelines-table-119.jpg

US DOE, 1995: Technical Support Document: Energy Efficiency Standards for Consumer Products: Refrigerators, Refrigrator-Freezers, & Freezers Including Draft Environmental Assessment Regulatory Impact Analysis. US Department of Energy, Report # DOE/EE-0064, Washington, DC, USA (available at http://www.papyrus.lb.gov/index.nsf8/0/a35eec2400d2e3c88256ced006dd732?OpenDocument&Highlight=2,011521)

US EPA, 2004: International ODS Substitute Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions. Office of Air and Radiation, US Environmental Protection Agency, Washington, DC, USA.

Valentin, B., 1999: Limitation des emissions dans les transports frigorifiques (Emission reduction in transport refrigeration). *Revue Général du Froid*, **992**, 42-45 (in French).

Viegas, H., 2003: Liquid Carbon Dioxide Transport Refrigeration System. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Wang, S., J. Wu, R. Wang and Y. Xu, 2003: Adsorption Ice-maker Driven by Exhaust Gas Medium and Small Sized Fishing Vessels. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.

Wenning, U., 1996: Three Years Experience with Hydrocarbon Technology in Domestic Refrigeration. Proceedings of the International Conference on Ozone Protection Technologies, October 21-23, 1996, Washington DC, USA.

Weston, 1997: Recycling Rate Determinant Study – Phase I Report. Roy W. Weston, Inc, Norcross, Georgia, USA.

Wild, Y., 2003: Der Einsatz von Kühlcontainern im Seetransport. Proceedings of the Annual Conference of the Deutsche Kälte und Klimatechnischer Verein e.V. (DKV), Bonn, November 2003 (in German).

World Bank, 1993: The Status of Hydrocarbon and Other Flammable Alternatives use in Domestic Refrigeration, Ozone Operations Resource Group, OORG Report No. 5.

Yang, Y., 2001: Investigation of Deep-freeze Refrigeration Systems in Supermarket Application. Diss. Royal Institute of Technology, Stockholm, Sweden.

Yoshida, Y., K. Yoshimura, R. Kato and S. Hiodoshi, 2003: Development of Scroll Compressors with the High Performance Used for Marine Container Refrigeration Unit. Proceedings of the 21st International Congress of Refrigeration, Washington, DC, USA, 17-22 August 2003. International Institute of Refrigeration (IIR/IIF), Paris, France.