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Section 11 - Heat Pumps (Heating Only and Heat Recovery)

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REPORT

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Section 11 - Heat Pumps (Heating Only and Heat Recovery)

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ABSTRACT

"Heat Pumps (Heating Only and Heat Recovery)" constitutes Section 11 in the Montreal Protocol 1994/95 Assessment, Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee.

The report presents options for a phase-out of CFC and HCFC refrigerants in residential, commercial and industrial heat pumps for heating only and heat recovery purposes, and discusses the viability of the replacement refrigerants.

The report is divided into 5 main parts:

- Executive summary
- Retrofitting of existing heat pump installations
- Refrigerant alternatives in new heat pump installations
- Developing countries considerations
- Forecast of refrigerant use in the heat pump sector

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HEAT PUMPS
(Heating Only and Heat Recovery)

EXECUTIVE SUMMARY

Heat Pumps (Heating Only and Heat Recovery)

Heating-only heat pumps are used for space and water heating in residential, commercial/-institutional and industrial buildings. In industry heat pumps are used for heating of process streams, heat recovery and hot water/steam production. They are often an integrated part of industrial processes, such as drying, evaporative concentration and distillation. Virtually all heating-only heat pumps are electric closed-cycle compression type systems.

The vast majority of heating-only heat pumps in buildings are located in Western Europe, as most heat pump installations in Japan, USA and Canada are reversible air-conditioners. It is estimated that the total number of heating-only heat pumps in these market sectors (including district heating) is roughly 1.4 million units, with a total heating capacity of about 11,000 MW and an annual heat supply of 25 TWh/year. The corresponding figures for industrial heat pumps are 7,000 units, 2,500 MW and 12 TWh/year.

HCFCs are generally accepted as a part of the solution for a rapid CFC phase-out, and HCFC-22 is the most important refrigerant in this category. Many European countries are discussing regulations on HCFCs with a view to phasing them out more rapidly than has already been agreed under the Montreal Protocol. Germany, Sweden and Italy will ban the use of HCFCs in new equipment from the year 2000. Other countries considering bringing in earlier phase-out dates include Austria, Denmark, Norway and Switzerland.

HFC-134a is currently applied for retrofitting of existing heat pumps using CFC-12 and for charging of new installations. HFC-134a heat pump technology is considered fully mature for new systems. The demand for HFC-134a is expected to increase substantially in the next years. Moreover, other HFCs as well as HFC blends are expected to be available towards the end of the decade, thus resulting in a further increase in HFC consumption.

Ammonia has recently attained a growing market share as refrigerant in large capacity heat pump systems in Europe. Halt in CFC production and further technology development, are expected to accelerate market penetration in Europe, as well as in Japan and the United States. Ammonia technology for small capacity heat pumps is expected to be available by the turn of the century.

Propane is currently used in residential heat pumps in Europe. Technology development and improved safety measures will reduce safety hazards and improve public acceptability. Hence, propane, other hydrocarbons as well as hydrocarbon blends are expected to play an increasingly important role in the next years, especially in small and medium capacity heat pumps.

Carbon dioxide is a promising long-term natural refrigerant, but is not expected to become of much commercial importance until the late 1990s.

Heat pumps for heating only purposes have a negligible impact on total refrigerant consumption volumes worldwide (<1%). The estimated refrigerant volume is approximately 11,000 tonnes, with 60% CFCs and 40% HCFCs (1993). Assessments indicate that the total annual refrigerant demand for heat pumps will be about 2,300 tonnes in the year 2000, of which 70-80% are HFCs and the rest HCFCs and natural refrigerants.

If 60% of the refrigerants in scrapped and retrofitted equipment can be recovered, approximately 2,300 tonnes of CFC and 1,150 tonnes of HCFC will be made available for reuse between the year 1995 and 2000. This is about 20% more than the expected demand for CFCs and HCFCs for servicing of existing heat pump installations.

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11 - HEAT PUMPS
(Heating Only and Heat Recovery)

11.1 Introduction

Energy conservation is one of the main strategies to meet the environmental problems arising from the continuously growing energy demand worldwide. Heat pumps, which today are a proven, reliable, cost-effective and energy saving technology, utilize environmental and waste heat and consequently reduce the demand for fossil fuels for heating, cooling and dehumidification in residential/commercial buildings and industrial applications. Because heat pumps require less primary energy than conventional heating systems, they are considered an important technology for reducing emissions of gases that harm the environment, such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x).

The vast majority of heat pumps currently in operation are electrically driven closed-cycle compression type systems. The overall environmental impact of electric heat pumps depends to a large extent on how electricity is generated. Furthermore, most refrigerants currently used in heat pumps are CFCs and HCFCs, substances now held to contribute to both the depletion of the earth's ozone layer (ODP) and the greenhouse effect (GWP). Hence, loss of these refrigerants during operation, maintenance and scrapping will partly counteract the reduction in specific CO_2 emissions.

The Total Equivalent Warming Impact (TEWI) combines the global warming effect associated with energy consumption, ie. the specific CO_2 emissions from electricity generation (indirect GWP) and with refrigerant leakages (direct GWP). The TEWI concept is useful to indicate the relative contribution to future global warming. The TEWI depends amongst others on how electricity is generated (hydro power, renewables, nuclear or coal/oil/gas-fired power stations), the Seasonal Performance Factor of the heat pump (SPF), the GWP of the refrigerant, the lifetime of the system and the leakage rate.

Section 11 discusses working fluids for heating-only and heat recovery heat pumps. Reversible air conditioners, which comprise virtually all heat pump installations in the United States, Japan and other countries with a considerable cooling demand, are presented in Section 7, "Air Conditioning & Heat Pumps (Air-Cooled Systems)".

11.2 Current Status

11.2.1 Types and Volume of Equipment

Heating-only heat pumps are used for space and water heating in residential, commercial/-institutional and industrial buildings. In industry heat pumps are used for heating of process streams, heat recovery and hot water/steam production. They are also an integrated part of industrial processes, such as drying, evaporative concentration and distillation.

Space heating heat pumps in residential and commercial/institutional buildings typically operate between 1,000 to 5,000 hours a year, depending on the climatic conditions, type and purpose of the building, etc. Industrial heat pumps have much longer operating hours, typically between 6,000 to 8,000 hours. The majority of industrial heat pumps operate in the chemical and food processing industries.

11.2.1.1 Residential and Commercial/Institutional Applications

Heating-only heat pumps in buildings are manufactured in all sizes ranging from 1 kW heating capacity for single room units, to 50-1,000 kW for commercial/institutional applications, and tens of MWs for district heating plants. Most small to medium size heat pumps in buildings are standardized, factory made units. Large heat pump installations are usually custom made and partly or totally assembled at the site.

Hot water heat pumps have captured a small fraction of water heater sales in the OECD countries. Commercial applications are more attractive relative to competitive systems than residential applications. Approximately 500,000 units are currently installed in Europe /HPC93/.

Heat sources include ambient and ventilation air, sea and lake water, sewage water, ground water, soil, rock and industrial waste water and effluent. Air and ground source heat pumps dominate the market. Evaporation temperatures typically range from -10°C to +10°C, with condensation between 40°C and 80°C, depending on the type of heat sink. Air is the most common distribution medium, except in most of the European countries and Northern parts of North America where hydronic (water) systems are predominant.

The majority of heating-only heat pumps currently in operation are electric closed-cycle compression type units, using a CFC or HCFC refrigerant. The number of engine driven systems is small but growing. Advanced gas-fired absorption heat pumps have been introduced into the market recently. The market share is negligible compared to vapour compression systems.

The vast majority of heating-only heat pumps in residential and commercial/institutional buildings are located in Western Europe. It is estimated that the total number of heating-only heat pumps in these market sectors (including district heating) is roughly 1.4 million units, with a total heating capacity of about 11,000 MW and an annual heat supply of 25 TWh/year /HPC94, GIL93/. Refrigerant charges range between 0.1 and 1.5 kg per kW thermal output, with 1.0 kg/kW as an estimated average /TOR91/. The current trend is towards compact heat pumps with small refrigerant charge.

11.2.1.2 Industrial Applications

Industrial heat pumps are generally large in thermal capacity ranging from about 100 kW to several MWs, and the systems are often custom designed. Evaporation temperatures are generally higher than with residential and commercial/institutional applications and condensation temperatures are typically in the 80°C to 150°C range.

Industrial heat pumps have a much higher Coefficient of Performance (COP) than space heating heat pumps. This is mainly due to the small temperature lifts, large size, efficient design and stable operating conditions.

The type of heat pump applied depends heavily on the process, the heat source and the operating temperatures. The most common types of industrial heat pumps are:

- Mechanical vapour recompression (MVR) systems, or open (semi-open) heat pumps, are extensively used in industrial processes where liquid is evaporated. Most systems operate with water vapour as the working fluid. In chemical industry other process vapours are used in MVRs (eg. acetone, methanol).

- Electric closed-cycle compression heat pumps are the most commonly used type of heat pumps worldwide, but also a growing number of engine driven systems are installed. Traditionally, these heat pumps have been using CFCs or HCFCs, but in recent years ammonia, HFCs and propane have been introduced. These refrigerants are used yet on a small scale. Refrigerant charges in industrial closed cycle heat pumps range from 0.5 to 2.5 kg per kW thermal output, with an estimated average roughly the same as for residential and commercial/institutional heat pumps, ie. 1.0 kg/kW /TOR91/.

- Absorption heat pumps (section 11.4.6.1) are to a small extent installed in industrial applications and in refuse incineration plants to recover heat from the flue gas cleaning process. These installations range from 5 to several ten's of MW capacity. Most absorption heat pumps use water and lithium bromide as the working pair, and are capable to deliver heat up to 100°C.

- Heat transformers (section 11.4.6.2) are used to produce useful high-temperature heat from medium-temperature industrial waste heat. Current systems use water and lithium bromide as the working pair. The maximum delivery temperature is 150°C.

The total number of industrial heat pumps worldwide is estimated at 7,000 units, with a total heating capacity of about 2,500 MW and a heat production of 12 TWh/year /HPC94, GIL93/.

11.2.2 Refrigerants

Traditionally the most common refrigerants for closed cycle compression heat pumps have been (figures in brackets indicate share of refrigerant consumption in 1990) /CAT94/:

- CFC-12 (46%)
- HCFC-22 (41%)
- R-502 (8%)
- CFC-11 (4% - heat recovery from centrifugal chillers)
- CFC-114 (1%)
- R-500 (<1%)

Refrigerants in heat pumps are primarily chosen in accordance with the temperature level of the heat sink and heat source. A typical application pattern for traditional refrigerants is given in Table 11.1.

Table 11.1 Typical application pattern of traditional refrigerants in heating-only heat pumps.

Heat Sink Temperature		
Below 55°C	55-80°C	Up to 125°C
HCFC-22 R-502	CFC-12 R-500	CFC-114

The consumption of CFCs (mainly CFC-12) and HCFCs (mainly HCFC-22) in heating-only heat pumps in 1993 is indicated in Table 11.2. These figures include charging of new heat pumps as well as recharging and retrofitting of existing installations. The data are extrapolated from the 1990 statistics /TOR91/, and later developments. The table also gives an estimate of the total refrigerant volume in existing heat pump installations in 1993. Due to many uncertainties in the calculations, all data are to be regarded indicative.

Table 11.2 Estimated annual consumption and total volume of CFCs and HCFCs in heating-only heat pumps (1993). No statistics are available for HFC-134a, ammonia and other replacement refrigerants.

Refrigerants	**Consumption, 1993 [tonnes/year]**	**Total Volume, 1993 [tonnes]**
CFCs	1,000	6,500
HCFCs	800	4,500

Several European countries have banned the use of CFCs in new heat pump installations since 1992, consequently increasing the consumption of HCFC-22, HFC-134a and other refrigerants. Ammonia has recently attained a growing market share as a refrigerant in large capacity heat pump systems in Europe, while propane is increasingly used in small systems.

11.3 Existing Heat Pump Installations

11.3.1 General

Heat pump systems have an average lifetime expectance of 15-25 years. A large number of existing installations using CFCs and HCFCs are expected to operate beyond the date of CFC and HCFC phase-out. Hence, measures have to be taken to ensure full life time operation. In practice, two options are available. Refrigerants can be *reused/recovered* or heat pumps can be *retrofitted* with alternative refrigerants.

11.3.2 Reuse and Recovery of Refrigerants

It will neither be technically feasible, nor economically justifiable to retrofit or dismantle all heating-only heat pumps using CFCs by 1995/96 . Hence, reuse or recovery of refrigerants will, in the short-run, play an important role. Provided that a proper quality of recovered refrigerants is secured, existing heat pumps may be allowed to continue operating with the refrigerant they have been designed for. Main challenges will be to seal leakages and repair existing equipment, and to ensure high quality standards for the recycling process.

An important aspect in this matter will be the *availability* of high quality recovered refrigerants for service purposes. Assuming 60% "recovery efficiency", about 2,300 tonnes of CFCs will be made available from heat pumps for reuse between 1995 and 2000, which is about 20% more than is actually needed for servicing existing installations using CFCs (section 11.6).

11.3.3 Retrofitting

The degree of plant modification depends on factors such as the alternative refrigerant chosen, system design, size, etc. Old, leaking installations in poor technical condition should preferably be scrapped and replaced with new equipment. Relatively new heat pump systems must be sealed before any retrofitting is carried out.

Technically, most equipment can be retrofitted with new refrigerants. In general retrofitting involves a thorough and systematic evaluation of safety, reliability, capacity requirements and energy efficiency. Other aspects, such as equipment, refrigerant and labour costs, as well as availability of refrigerants are taken into consideration when selecting retrofit refrigerants.

Typical modifications include change of lubricant, adjustment or change of expansion device, change of desiccant material, replacement of non-compatible sealing materials (elastomers in O-rings, gaskets, etc.), and compressor modifications/replacement. For details on retrofitting procedures for heat pumps using CFC-11, CFC-12, R-500, R-502 and HCFC-22 reference is made to /CAT94/.

Table 11.3 provides an overview of today's refrigerant alternatives for retrofitting heat pumps.

Table 11.3 Alternatives for retrofitting of heating-only heat pumps.

Refrigerant	**Alternative Refrigerants for Retrofitting**	
	Short Term	**Medium/Long Term**
CFC-11	• HCFC-123[1)]	• HCFC-123[1)]
CFC-12 and R-500	• Blends containing HCFCs	• HFC-134a • propane • HFC-152a
CFC-114	• HCFC-124 • HCFC-123	
R-502	• Blends containing HCFCs • HCFC-22	• HFC blends
HCFC-22		• HFC blends • Propane

1) Short/medium term alternative (controlled substance)

11.3.3.1 CFC-11 Alternatives

Examples of CFC-11 heat pump retrofits are not widely available.

11.3.3.2 CFC-12 and R-500 Alternatives

a) HFC-134a

When retrofitting from CFC-12 to HFC-134a, the mineral oil is replaced with a polyol ester lubricant. Proper cleaning of the heat pump system is crucial before recharging with HFC-134a, since residual mineral oil, sludge deposits and moisture may cause serious operational problems. Standardized cleaning methods have been developed, and a number of small, medium and large capacity heat pumps have already been successfully retrofitted.

b) Blends

Currently available blends for replacing CFC-12 and R-500 in heat pumps are near-azeotropic, and only minor system modifications are needed. When alkylbenzene lubricants are used, the cleaning process is much less critical compared to HFC-134a retrofitting. A common ternary blend for retrofitting heat pumps using CFC-12 and R-500 is R-401A, which consists of HCFC-22/HCFC-124/HFC-152a (52/34/13%). Volumetric refrigeration capacity and theoretical energy efficiency is approximately the same as for CFC-12.

c) Propane

CFC-12 and R-500 in heat pumps can be replaced by propane. Depending on the operating conditions, the volumetric refrigeration capacity of propane is 35-50% higher than that of CFC-12. Consequently, compressor/motor modifications are required in order to maintain the same heating capacity. Maximum achievable condensing temperature at 25 bar operating pressure will drop from 83°C to about 68°C when retrofitting from CFC-12 with propane. Due to its flammability propane should only be retrofitted into systems with low refrigerant charge. Refrigerant charges up to about 5 kg per unit is considered acceptable /CAT94/. Adequate safety precautions should be taken (section 11.4.5.2), and systems design and refrigerant charge should, as a general rule, meet regional/national codes and regulations.

d) HFC-152a

HFC-152a can replace CFC-12 and R-500 in existing heat pumps. The volumetric refrigeration capacity is about 5% lower than that of CFC-12, hence no compressor modifications are required. Since HFC-152a and CFC-12/R-500 have similar physical properties, system pressure and condensing/evaporation temperatures will remain the same. Due to the flammability of HFC-152a, the same safety precautions should be followed as when retrofitting to propane.

11.3.3.3 CFC-114 Alternatives

HCFC-124 is a possible alternative for retrofitting heat pumps using CFC-114. HCFC-124 requires higher operation pressure levels than CFC-114, and is in many cases not suitable for retrofitting heat pumps since the pressure levels will exceed design ratings. Moreover, the volumetric refrigeration capacity of HCFC-124 is 40-45% higher than that of CFC-114, and complete compressor and motor replacement is necessary in order to maintain required heating capacity.

11.3.3.4 R-502 Alternatives

Current alternatives for retrofitting heat pumps using R-502 include *HCFC-22* and *blends.*

The volumetric refrigeration capacity of *HCFC-22* is slightly higher than that of R-502, and the system pressure is almost the same. Hence, it is not necessary to replace the compressor when retrofitting from R-502 to HCFC-22, and only minor system modifications are needed. However, high discharge temperatures when operating at high temperature lifts may cause operational problems.

A number of *blends* containing HCFCs have been developed. A common near-azeotropic blend is R-402A, which consists of HFC-125/HCFC-22/propane (60/38/2%). The retrofitting procedure is simple and inexpensive.

HFC blends for retrofitting heat pumps using R-502 have been commercially available as of 1993/94, including compositions of HFC-32/125/134a, HFC-32/125/143a and HFC-125/143a/-134a. The retrofitting procedure for HFC-blends is similar to HFC-134a retrofitting.

11.3.3.5 HCFC-22 Alternatives

Current alternatives for retrofitting heat pumps using HCFC-22 are *propane* and *HFC blends.*

The volumetric refrigeration capacity of *propane* is almost the same as with HCFC-22, and no compressor modifications are needed. The maximum achievable condensing temperature when using standard 25 bars equipment increases from about 61°C to 68°C. In Germany heat pumps using HCFC-22 have been successfully converted to propane /NLJ93/.

A number of *HFC blends* which can replace HCFC-22 and R-502 in existing heat pump installations have been commercially available from 1993/94, including compositions of HFC-32/125/134a, HFC-32/125/143a and HFC-134a/125/143a. The retrofitting procedure for HFC-blends is similar to HFC-134a retrofitting.

11.4 New Heat Pump Installations

11.4.1 General

As a general requirement, heat pumps using refrigerants other than CFCs and HCFCs should have at least the same reliability and be as cost effective as (H)CFC systems. Moreover, the energy efficiency of the new systems should be the same or higher. In addition to developing new and environmentally acceptable refrigerants, it is important to modify or redesign heat pumps in order to achieve these goals. In general, the energy efficiency of a heat pump depends more on the working cycle and system design than on the refrigerant used.

11.4.2 HCFC Refrigerants

Many European countries are discussing regulations on HCFCs with a view to phase out more rapidly than has already been accepted under the Montreal Protocol. Germany, Sweden and Italy will ban the use of HCFCs in new equipment from the year 2000. Other countries considering accelerated phase-out schemes include Austria, Denmark, Norway and Switzerland.

11.4.2.1 HCFC-22

HCFC-22 is currently applied both as a pure refrigerant and as a component in blends replacing CFC-12 and R-502.

11.4.2.2 HCFC-123

HCFC-123 is suggested as a short-term alternative to *CFC-114* in high temperature heat pumps (160°C at 25 bar). HCFC-123 has about 30% lower volumetric refrigeration capacity than that of CFC-114 at 100°C evaporation temperature. The major disadvantage with HCFC-123 is its *toxicity*. Hence, engine rooms for HCFC-123 heat pumps must be equipped with gas detectors, adequate ventilation systems and means to alert operators in the event of significant leakage.

11.4.2.3 HCFC-124

HCFC-124 is currently applied as a component in ternary *blends* replacing CFC-12. It is also regarded as a short- and medium term alternative to *CFC-114* in high-temperature heat pumps. HCFC-124 requires operation at higher pressure levels than CFC-114, and the condensation temperature at 25 bar pressure is limited to 105°C (130°C for CFC-114). The volumetric refrigeration capacity is about 40-45% higher relative to CFC-114.

11.4.2.4 HCFC-141b

HCFC-141b has properties similar to HCFC-123, and can be used as a replacement for *CFC-114* in the lower temperature range. HCFC-141b has low toxicity, but is flammable. A blend of HCFC-123 and HCFC-141b has also been proposed /WFL93/. The aim of this proposition is to diminish the toxicity of HCFC-123 by mixing it with HCFC-141b.

11.4.3 HFC Refrigerants

The most interesting HFC refrigerants for heat pump applications are HFC-134a used as a single refrigerant and HFC-152a, HFC-32, HFC-125 and HFC-143a applied as components in blends. All HFCs and HFC blends require polyol ester lubricants.

11.4.3.1 HFC-134a

HFC-134a is quite similar to CFC-12 and R-500 in terms of thermodynamic and physical properties, and is regarded as the main successor of CFC-12 in medium temperature heat pump systems. The condensation temperature at 25 bar is approximately 77°C. HFC-134a is used in many new heat pump installations, and initial costs of HFC-134a systems are approximately 10% higher compared to CFC-12 systems.

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

11.4.3.2 HFC-152a

HFC-152a has long been considered a promising alternative refrigerant to CFCs due to its favourable thermodynamic and physical properties and low GWP factor. However, a major problem is the availability of the refrigerant in the Western part of the world where virtually all heating only heat pumps are installed. There are, however, many examples of successful HVAC applications with HFC-152a. It has been applied in a number of small heat pump systems, domestic refrigerators and in commercial refrigeration, eg. in the United States, Scandinavia and China /NIL91, TOR91, CAT94/.

Heat pumps using HFC-152a have approximately the same COP as CFC-12 systems at the same operating conditions /REE92/. The volumetric refrigerating capacity of HFC-152a is approximately 5% lower relative to CFC-12 at operating conditions 0°C/40°C /CAT94/.

Due to its flammability HFC-152a should only be applied in small heat pump systems with low refrigerant charge. Refrigerant charges up to about 5 kg per unit is considered acceptable /NIL91, CAT94/. When designing new heat pump plants with HFC-152a, adequate safety precautions should be taken to ensure safe operation and maintenance (section 11.4.5.2).

11.4.3.3 HFC-32

HFC-32, which is a moderately flammable refrigerant with a GWP close to zero, is considered a suitable long-term component in non-flammable ternary blends replacing HCFC-22 and R-502 in heat pump, air conditioning and refrigeration systems (section 11.4.4).

11.4.3.4 HFC-125 and HFC-143a

HFC-125 and HFC-143a have properties fairly similar to R-502 and HCFC-22, and is mainly applied as components in ternary blends replacing R-502 and HCFC-22 (section 11.4.4).

11.4.3.5 Other Alternatives

HFC-227 is an alternative to CFC-114 in high temperature heat pumps. The theoretical energy efficiency of a heat pump system using HFC-227 is lower than that of CFC-114 /WFL93/.

HFC-245ca and *HFC-356* are identified as possible long-term replacements for CFC-114 in high-temperature heat pumps. At present, there is not much information available regarding stability, toxicity and GWP for these refrigerants.

In the USA, a number of partially fluorinated propanes plus two- and three-carbon ethers have been synthesized. Eleven of these compounds show potential as substitutes, and their properties suggest that as pure fluids and blends they could be applied for most heat pump applications /NLM94/.

11.4.4 Blends

Refrigerant blends represent an important option for replacement of CFC and HCFC refrigerants, both for new heat pump installations and for retrofits.

11.4.4.1 HCFC Blends

Most of the blends commercially available contain HCFC-22 and other HCFC refrigerants. All HCFC blends require alkylbenzene or polyol ester lubricants.

- Ternary blends containing HCFC-22, HCFC-124 and HFC-152a are currently available alternatives to *CFC-12* in heat pumps. A common composition is 53/34/13% (R-401A). The volumetric refrigeration capacity and theoretical energy efficiency is approximately the same as for CFC-12, and the temperature glide is approximately 4°C.

- A binary blend containing HCFC-22 and HCFC-142b is another alternative to *CFC-12*. The blend is non-flammable, as long as the HCFC-22 content is at least 30% by weight. The temperature glide is approximately 10°C.

- There has been developed a number of blends for replacing *R-502* in various applications. Two common compositions are HFC-125/HCFC-22/propane (60/38/2%, R-402A) and HCFC-22/FC-218/propane (55/39/6%, R-403A - high GWP factor).

11.4.4.2 HFC Blends

All HFC blends require polyol ester lubricants. Various compositions of HFC-125/143a/134a, HFC-32/125/134a and HFC-32/125/143a are current alternatives to *R-502*. The United States, Japan and Europe are at present carrying out considerable research efforts in order to find suitable replacements for *HCFC-22*. In the United States and Japan most attention is given to *HFC blends*, and the alternatives evaluated includes compositions of /IEA93/:

- HFC-32/125
- HFC-32/134a
- HFC-32/125/134a
- HFC-32/125/propane/134a
- HFC-32/227ea

11.4.5 Natural Refrigerants

Natural refrigerants are long-term alternatives to CFCs and HCFCs in heat pump systems. The most significant and promising refrigerants are ammonia, hydrocarbons (eg. propane and blends of propane, butane and isobutane), carbon dioxide and water.

Annex 22, "Compression Systems with Natural Working Fluids" under the IEA Implementing Agreement on Heat Pumping Technologies (1994-97), will amongst others provide state-of-the-art information on compression heat pumps with natural working fluids, and establish guidelines for design and safety recommendations for new heat pump installations.

11.4.5.1 Ammonia

Ammonia is gaining popularity in Northern Europe, and has been applied in a number of medium-size and large capacity heat pumps, mainly in Scandinavia and Germany /NLD93, NLM94, KRU93/.

Ammonia heat pumps typically achieve a 3-5% higher energy efficiency than systems using CFC-12, HCFC-22 or HFC-134a /CAT94/. However, in applications where indirect heat distribution systems are required, no net efficiency gain is expected. The volumetric refrigeration capacity is approximately the same as for HCFC-22 and about 40% higher than for CFC-12 and HFC-134a, thus reducing the compressor capacity needed. High pressure (40 bars) piston compressors are commercially available, raising the achievable condensing temperature from 55°C (25 bar) to about 78°C.

Ammonia yields high compressor discharge temperatures, and at high temperature lifts two-stage compression may be necessary to avoid operational problems. Consequently, initial costs will increase by 15-20% and energy efficiency will increase 25-30% /CAT94/. Semi-hermetic ammonia compressors as well as soluble lubricants (polyglycols) have recently been introduced, and hermetic ammonia compressors are expected to be available within a few years.

In general, system safety requires that machine rooms are designed according to prevailing standards. Safety design measures can include proper placing and/or gas tight enclosure of the heat pump, application of low-charge systems, use of indirect heat distribution systems (brine systems), fail-safe ventilation systems, gas detectors (alarm system), water spray systems, etc.

Although ammonia is an excellent high-temperature refrigerant, it has not been applied in industrial heat pumps operating above 80°C. This is mainly due to the lack of high-pressure compressors with a reasonable efficiency. A prototype ammonia heat pump for drying is under development in Norway, operating at a maximum condensing temperature of 100°C /JON94/.

11.4.5.2 Hydrocarbons

Hydrocarbons (HCs) are flammable long-term, proven refrigerants which have been used in large refrigeration plants for many years, notably in petrochemical industry. Today hydrocarbons emerge as a viable option for replacement of CFCs and HCFCs, amongst others in residential heat pumps.

The most important hydrocarbons for medium-temperature heat pump applications are propane (HC-290) and blends of propane and (iso)butane (HC-600a/HC-600). Propylene (HC-1270), which is regarded an alternative to HCFC-22, has recently been studied and tested in Germany. At present, there is no literature information about hydrocarbon replacements for CFC-114 in high-temperature heat pumps /WFL93/.

The volumetric refrigerating capacity of *propane* is approximately the same as for HCFC-22, and in a practical application propane will yield about the same energy efficiency as CFC-12 /WFL93/. Maximum condensing temperature with standard 25 bar equipment is about 68°C.

A number of prototype heat pumps with propane are installed /NLD93, NLA94/. From January 1994 water-to-water and air-to-water heat pumps for residences and swimming pools are available from a German manufacturer. A 100 kW swimming pool heat pump using 20 kg of propane has been installed in Germany /NLD93/. Other German and Austrian manufacturers of residential heat pumps have decided to use propane as well.

When designing new heat pump systems with propane or other flammable refrigerants, adequate safety precautions should be taken to ensure safe operation and maintenance. Typical safety measures include addition of tracer gases, proper placement and/or gas tight enclosure of the heat pump, application of low-charge systems, fail-safe ventilation systems and gas detector activating alarm systems.

11.4.5.3 Carbon Dioxide

Carbon dioxide (CO_2) offers a number of advantages. With regard to safety, CO_2 is at least as good as the best of halocarbons due to its non-toxicity and inflammability. CO_2 is compatible to normal lubricants and common machine construction materials.

At 0°C the volumetric refrigerating capacity of CO_2 is between five and eight times higher than for other refrigerants, consequently reducing the compressor volume. The pressure ratio is also greatly reduced compared to conventional refrigerants. The relatively low molar mass of CO_2 reduces the mass flow and the required dimensions of compressor, valves and piping. Due to the limited volume of the system, the high pressure (above 100 bar) does not constitute a large danger in the case of rupture.

The theoretical COP of a CO_2 heat pump cycle is rather poor, and the effective application of this fluid depends on the development of suitable methods to achieve a competitively low power consumption near and above the critical point /LOR93/. By adapting the standard compression cycle, high performance can be achieved. A laboratory prototype of a CO_2 car air-conditioner, based on a supercritical high-side pressure has been tested. The results prove that the COP of the CO_2 system is at least as good as the standard CFC-12 system /CAR92/.

The ability of the transcritical CO_2 process to absorb heat at constant temperature and reject heat at gliding temperature above supercritical pressure, makes it well suited for heat pump applications where natural heat is the heat source and with a considerable temperature glide (30-50°C) on the heat distribution side. Examples of such applications are heat pump water heaters and large heat pumps in district heating systems.

The transcritical CO_2 process utilized for water heating has been examined, and the conclusion is that a CO_2 heat pump is capable of reducing the energy consumption as much as 30% compared to standard heat pump water heaters using CFC-12 or HFC-134a /NEK92/.

Carbon dioxide is not expected to become of much commercial importance until the late 1990s.

11.4.5.4 Water

Water is an excellent refrigerant for high-temperature industrial heat pumps due to its favourable thermodynamic properties and the fact that it is neither flammable nor toxic. Water has mainly been applied as a working fluid in open and semi-open MVR systems in industrial evaporation processes. Operating temperatures are in the range 80 to 150°C. A closed-cycle prototype heat pump has reached an output temperature of 300°C (85 bar) /IHP89/. The major disadvantages using water as refrigerant are the low volumetric refrigeration capacity and the relatively high pressure ratio, especially at evaporating temperatures below 100°C.

11.4.6 Alternative Technologies

11.4.6.1 Absorption Heat Pumps (Type I)

Absorption heat pumps for space heating are mostly gas-fired, whereas industrial systems are typically driven by steam or waste heat. Most of the systems use water and lithium bromide as the working pair, and can achieve about 100°C output temperature. Industrial absorption heat pumps are, for economic reasons, mainly used in large sizes (MW).

Residential absorption heat pumps are still under development. In industry absorption heat pumps are applied on a negligible scale only. In Sweden and Denmark a number of installations are in operation. They recover heat from flue gas cleaning systems in refuse incineration plants or use geothermal heat as heat source (Denmark).

Absorption heat pumps with a typical primary energy ratio (PER) in the range of 1.2 to 1.5, have a higher system energy efficiency than vapour compression systems driven by electricity produced in conventional power plants. In 1993 an advanced 250 kW absorption heat pump for space heating and cooling entered the market. Ammonia-water is the working pair. The system has been installed in a Dutch institutional building, and operates with a high seasonal PER (1.4) /IEA93/.

Research is concentrating on the development of systems with high performance, high temperature lifts, high output temperatures, a wider range of application and lower cost. This includes the development of double-lift, double-effect and triple-effect units, generator/absorber heat exchanger systems (GAX) and new working fluids.

A new working fluid for high temperatures (max. 260°C) is now available on the market. This fluid makes it possible to use cheaper construction materials as the corrosion rate is negligible /HPC94/.

11.4.6.2 Heat Transformers (Type II)

Heat transformers are used in some industries to upgrade waste heat to a useful temperature level. These systems use water and lithium bromide as the working pair. Current systems have a maximum delivery temperature and temperature lift of 145°C and 50°C, respectively. Heat transformers typically achieve PERs in the range 0.45 to 0.48. Only a few systems are in operation worldwide, the majority of them in Japan /HPC94/.

11.4.6.3 Hybrid Heat Pumps

The hybrid cycle is a combination of vapour compression and absorption. Here the evaporator is replaced by a desorber and the condenser by a resorber; an extra loop is added for the absorbent-refrigerant solution. The most common working pair is ammonia and water. In Germany 3 systems are in operation and another one in Hungary. COP ranges between 4 and 9 /IEA93/.

11.5 Developing Country Considerations

Heat pumps for heating only and heat recovery are scarcely applied in developing countries (Article 5 countries). The reason is that many developing countries are located around the Equator, hence having a very limited space heating demand. Also, since capital is limited in these regions, the CFC-consuming equipment, to the degree it exists, is more likely to have a refrigeration function (food conservation). Therefore, it is assumed that the number of heat pumps and the annual CFC consumption for such purposes both are negligible.

However, this situation may start changing towards the end of the 1990s. Centrally planned economies like the former Soviet Union, China, and most of the Eastern Europe today, all have average household energy consumptions far below that of the Western World. Economic reforms end emerging democracies will eventually yield higher living standards, which in turn will result in a higher domestic energy consumption. A significant problem in these regions is environmental pollution. Therefore, a higher energy consumption, including that for heating, should preferably not be based on direct combustion of oil or coal. This could spur the demand for heat pump systems, resulting in a world growing market. All this is connected to a high degree of uncertainty and is highly dependent on political decision making and economic growth.

11.6 Forecast of Refrigerant Use

Since CFC production will halt from the end of 1994/95, future refrigerant supply for heating-only heat pumps will come from recycled/recovered CFCs from scrapped and retrofitted heat pumps, stocked CFCs by end-users, as well as HCFCs, HFCs and natural refrigerants, particularly ammonia and hydrocarbons.

Estimated CFC and HCFC demand for heating only heat pumps in 1993 was 1,000 and 800 tonnes, respectively. Total refrigerant demand is expected to grow 5% annually.

When calculating the annual CFC demand for the period 1994 to 2005, it is assumed that 10% of the heat pumps are scrapped/retrofitted in 1994 and 20% after 1994. From 1994 CFC consumption is expected to cover leakages only (no new installations). The above figures are relative to the total CFC pool (6,500 tonnes in 1993). Furthermore, it is assumed that HCFC demand declines 10% annually (scrapping only). HFCs are expected to cover 80% of the total need for alternatives, while ammonia and hydrocarbons will cover the rest.

The following refrigerant demand estimate can be made today, Table 11.4.

Table 11.4 Estimated heat pump refrigerant demand [tonnes]. Ammonia demand is to be read as HFC equivalents.

Year	Type of Refrigerant				
	CFCs	HCFCs	HFCs	Ammonia	Total
1993	1,000	800	-	-	1,800
1994	585	720	470	115	1,890
1995	470	650	690	175	1,985
1996	375	585	895	225	2,080
1997	300	525	1,090	270	2,185
1998	240	470	1,270	315	2,295
1999	190	425	1,435	360	2,410
2000	155	380	1,595	400	2,530
2005	50	220	2,370	590	3,230

The reduced CFC and HCFC refrigerant pool (20% and 10% annually) will be reused/-recovered. Due to various reasons, only a fraction of the potential for recovery can be utilized as refrigerant, and therefore it is assumed that 60% of the available CFC and HCFC volume is actually recovered. Table 11.5 indicates the potential for CFC and HCFC recovery.

Table 11.5 Estimated potential for CFC and HCFC recovery and reuse in heat pumps.

Year	CFCs		HCFCs	
	Potential for recovery	Available for reuse (60%)	Potential for recovery	Available for reuse (60%)
1994	650	390	440	265
1995	940	560	425	255
1996	850	510	400	240
1997	760	460	380	230
1998	680	410	360	215
1999	620	370	330	200
2000	560	340	310	185
2005	320	190	225	135

About 2,300 tonnes of CFCs will be made available for reuse between 1995 and 2000, which is about 20% more than the actual CFC demand for servicing existing heat pump installations.

11.7 Concluding Remarks

HCFCs are generally accepted as a part of the solution for a rapid CFC phase-out, and HCFC-22 is the most important refrigerant in this category. Many European countries are discussing regulations on HCFCs with a view to phasing them out more rapidly than has already been agreed under the Montreal Protocol. Germany, Sweden and Italy will ban the use of HCFCs in new equipment from the year 2000. Other countries considering bringing in earlier phase-out dates include Austria, Denmark, Norway and Switzerland.

HFC-134a is currently applied for retrofitting of existing heat pumps which used CFC-12 and for charging of new installations. HFC-134a heat pump technology is considered fully mature for new systems. The demand for HFC-134a is expected to increase substantially in the next years. Moreover, *HFC and HFC blends* are expected to be available towards the end of the decade, thus resulting in a further increase in HFC consumption.

Ammonia has recently attained a growing market share as refrigerant in large capacity heat pump systems in Europe. Halt in CFC production and further technology development, are expected to accelerate market penetration in Europe, as well as in Japan and the United States. Ammonia technology for small capacity heat pumps is expected to be available by the turn of the century.

Propane is currently used in small capacity heat pumps in Europe. Technology development and improved safety measures will reduce safety hazards and improve public acceptability. Hence, propane, other hydrocarbons as well as hydrocarbon blends are expected to play an increasingly important role in the next years, especially in small and medium capacity heat pumps.

Carbon dioxide is a promising long-term natural refrigerant, but is not expected to become of much commercial importance until the late 1990s.

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