6. The Use of Natural Refrigerants

A Complete Solution to the CFC/HCFC-Predicament

Prof.dr.techn. Gustav Lorentzen
NTH, N-7034 TRONDHEIM, Norway

(Reprint from IIR Conference 1994 Proceedings
"New Applications of Natural Working Fluids
in Refrigeration and Air Conditioning"
May 10 - 13, 1994 Hanover, Germany)
International Institute of Refrigeration
177, Boulevard Malesherbes, F-75017 Paris (France)

---

1. Introduction

We have heard a great deal lately of the harmful effects to the environment when halocarbon refrigerants are lost to the atmosphere. This should not really have come as a surprise since similar problems have happened over and over again. Numerous cases are on record where new chemicals, believed to be a benefit to man, have turned out to be environmentally unacceptable, some times even in quite small quantities (DDT, PCB, Pb.... etc.). In the present situation, when the CFCs and in a little longer perspective the HCFCs are being banned by international agreement, it does not seem very logical to try to replace them by another family of related halocarbons, the HFCs, equally foreign to nature [1]. It has already been suggested that HFC 134a may be decomposed by sunlight in the troposphere and form acid and poisonous substances [2,3]. If this should turn out to be true, we may have to face yet another catastrophe, even worse than the CFC experience. In any case it must obviously be much preferable to use natural compounds, which are already circulating in quantity in the biosphere and are known to be harmless as I have advocated for years with only lukewarm response.

About 50 different substances have been more or less extensively used as working media over the 160 years of refrigeration history. Most of them have been discarded as unsuitable for various reasons, but a fair number of choice remains to adapt to varying conditions of application. Among them are a number of "natural" substances like, for instance, air, water, nitrogen, ammonia, hydrogen, helium, hydrocarbons and carbon dioxide, which all have possible application in the refrigeration technology of the future.

The ideal refrigeration or heat pump cycle for a given purpose is defined by the boundary conditions of the application and completely independent of the refrigerant used. The concept of the Carnot process as the ideal reference is only valid in the case of heat absorption and rejection at rigorously constant temperatures which can be closely approached by isobaric evaporation and condensation of a pure medium. In most practical cases heat will be exchanged with finite flows of liquid or gas with a more or less pronounced temperature glide. For the temperature lift and drop by compression or expansion the reversible adiabat is the natural ideal in most cases. In the common case of air cooling, using ambient air or water as a heat sink, the reference cycle may look something like the heavy drawn circuit in the T-s-diagram, Fig. 1. In order to achieve an acceptable efficiency the real cycle should approach the theoretical ideal as closely as practically possible. The possibilities are limited by the processes we are able to realise in the available types of equipment, compressors, expanders and heat exchangers, within economic limitations.

Rational compressors and expanders will operate near adiabatically since the surface area of their working space is much too small to provide any appreciable heat exchange. Considerable exergy losses occur as a result of internal friction and other irreversibility's. Philips and Vuilleumier machines differ in that they have advanced heat exchangers built into their active working volume, but even so they are far from achieving the desired near-isothermal processes. Liquid injection (or wet suction) is often proposed as a means of cooling in all types of compressors, but introduces additional losses far in excess of the theoretical gain [4]. We are by no means able to produce the arbitrary "polytropes", so popular in theoretical analysis.

Figure I - Example of the theoretical cycle for a common refrigeration application (thick lines 1-2-3-4-1) and the real cycle 1'-2'-3'-4'

Heat exchangers (evaporators, condensers etc.) require a temperature difference for functioning, depending on the surface area which has to be decided on economic criteria. The corresponding exergy loss is often increased as a result of poor matching of the temperature curves of the refrigerant and outside transport medium. Gliding temperatures can certainly be generated in gas cycles, by use of zeotropic mixtures or approached by staging, but it is rarely possible to get a perfect fit in heat absorption and discharge at the same time.

As a result of these various difficulties the real cycle will always differ very considerably from the ideal. As a typical example a normal refrigeration process is plotted in Fig. 1, using realistic performance data for the system components. The power consumption, excluding motor and transmission losses, is represented as the area 1 '-c-d-2'-3'-a-b-4'-1', and is several times larger than theoretically required. Correspondingly the true efficiency of common refrigeration and heat pump systems is very low and often in the range 10 to 30 per cent. The possibilities for further improvement are considerable.

While the thermophysical properties of the refrigerant have no influence on the theoretical cycle and affect the Evans-Perkins process (some times erroneously referred to as "reverse Rankine") only slightly through their influence on the superheat and throttling loss, their effect on the other thermodynamic losses is considerable. Most important in order to limit the heat transfer, flow resistance and compressor losses are a low molar mass and suitably high pressure at working conditions. The common halocarbons are not particularly effective in these respects. The popular comparison of refrigerants on the basis of their theoretical performance in the Evans-Perkins cycle can therefore be very misleading.

After a brief reference to the status of gas cycle systems, the following pages will discuss how a few natural refrigerants, ammonia, propane and carbon dioxide, can be used to advantage to cover the needs of most normal refrigeration and heat pump applications, using conventional compressor systems.

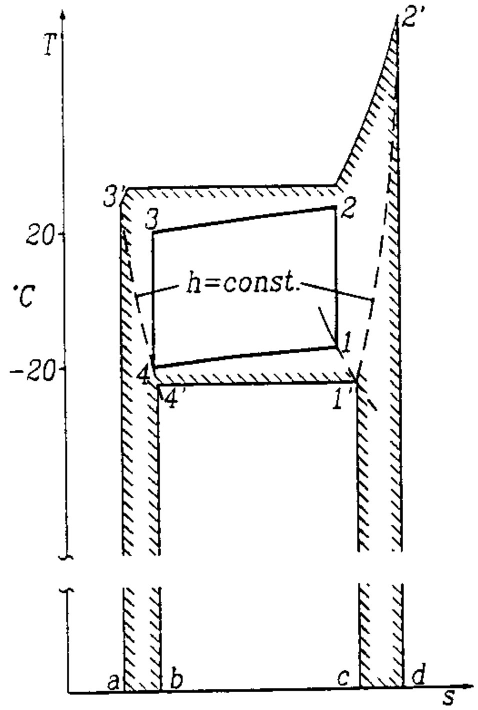

Fig. 1

2. Gas Cycle Machines

So called "cold air machines" as first introduced by Gorrie in 1844, were used extensively during the final decades of last century and well into this one, mainly for marine refrigeration. They were large, steam driven, reciprocating machinery, open on the suction side for direct cooling of the cargo holds, and the air was often cooled during and after the compression by direct water spray. The compressor cooling presumably had some effect in the large volume slow moving machines. Even so, the power consumption was excessive, the equipment was very bulky and space consuming, and there were troubles with icing up of the system, oil fumes in the air etc. The cold air machines were therefore quickly replaced by ammonia or carbon dioxide plants as they were developed to satisfactory reliability.

The open cycle cold air machine or heat pump may seem very attractive by its simplicity and environmental advantage, and numerous attempts have been made over the years to revive the idea, eliminating some of its drawbacks by using turbo or other high speed rotary machinery. The problem of excessive power consumption remains, however, Fig. 2A. The system is used some times for air conditioning in military aircraft, where compressed air is available from the jet engine and low extra weight is considered more important than fuel economy. It has been proposed for special services like cooling of deep mines by using compressed air from the surface to drive pumps or other mining machinery, or for sporadic freezing of products, using discarded aircraft turbines. None of these ideas have found any wide application.

It is clear that the open cold air system has little chance of gaining any importance for refrigeration or heat pumps in the normal temperature range unless a significant break-through should occur. This does not seem very likely at the present time.
For lower temperatures, below say 200 K, the situation is quite different.

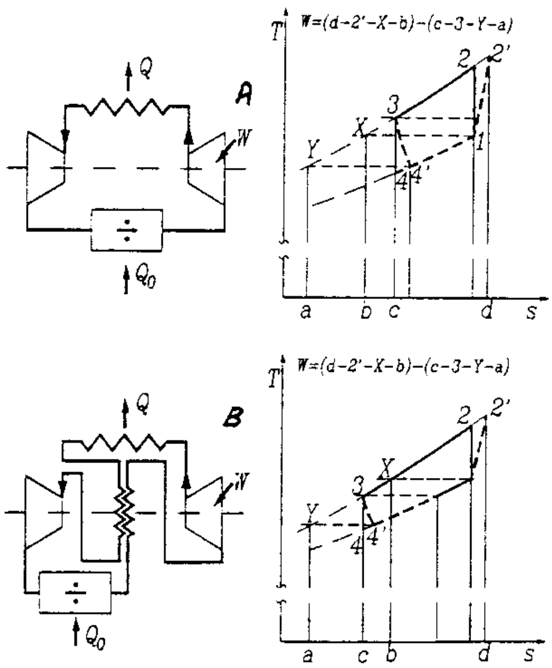

Fig. 2a and 2b

Open transcritical cycles with counterflow heat exchangers have been used to condense air and other "gases" for more than 100 years, and similar arrangements are applicable for space cooling. Fig. 2 B. More recently high pressure closed gas cycles have been developed, using hydrogen or helium very effectively (Philips etc.). At high pressures, high temperature lift, using thermal regeneration and high heat transfer gas, the problems associated with the open cold air machine are greatly reduced.

3. The Refrigerant Revolution
The first halocarbon refrigerant, R-12, was introduced in the USA in the early thirties. 20 years later the new compounds had conquered the greater part of refrigeration applications the world over, starting with the smaller equipment and air conditioning, gradually penetrating into even the large industrial area. Ammonia only has remained the preferred choice in the latter field.

One may well wonder why this revolution happened so quickly at the time, in spite of many practical difficulties in the beginning. Important factors were certainly the heavy advertising, an effective system of technical information and well organised effort by the manufacturers to solve the various problems as they occurred. But I am sure an equally powerful motive for change was the possibility to use simple and cheap construction methods, copper tubing, light screw or solder fittings, cheap automatic control equipment. hermetic motors etc. Small leaks did not matter much since they would not be noticed until refill became necessary, and this was a simple and relatively cheap operation. not without interest to the service firms and refrigerant supplier. The work could be done by people with limited qualifications, and we ended up with a contractor industry structure and lack of professionalism which contribute strongly to the problems we are facing today.

Now we have to revert to systems which must be absolutely tight and stay tight over their lifetime. We have to design for safety, even though some refrigerants may be combustible or even poisonous. We will have to rebuild the professional and responsible attitude of former days. If we manage this, we have at our disposal a series of natural, cheap and thermodynamically excellent working media.

I have no doubt that practically all normal refrigeration and heat pump needs in the future can be adequately served by three abundantly available natural refrigerants: Ammonia, Propane (or hydrocarbon mixtures) and Carbon Dioxide. This will require a concentrated effort to recover lost development during a half century of halocarbon domination. As a result we can expect a better and more energy effective technology, free of environmental problems and the monopoly of big chemical companies.

In the following we will take a brief look at some important aspects of the candidate refrigerants mentioned. Some characteristic data are compiled in Table I in comparison with common halocarbon alternatives:

4. Ammonia, the prooven Refrigerant

After 120 years of extensive usage a tremendous amount of practical experience with this refrigerant exists. There is no doubt about its excellent thermodynamic and transport properties, much superior to those of any halocarbon. It is a well known fact that an ammonia plant always has a considerably better energy efficiency in practice, when compressor speed, piping dimensions and heat transfer equipment are decided on economic criteria. Other important advantages are tolerance to normal mineral oils, low sensitivity to small amounts of water in the system, simple leak detection, unlimited availability and low price. All these factors contribute to its sustained popularity and wide application.

It is true that ammonia is poisonous and can burn with air, although these defects have often been grossly exaggerated. In reality it is 10 to 50 times less toxic than chlorine, for instance [5]. Its lower ignition limit is as high as 15,5% by volume, 3 to 7 times that of common hydrocarbons and natural gas, and the combustion heat less than half. Experience shows that accidents are extremely rare, be it by poisoning or explosion. A recent investigation indicates that fatal cases are at least as frequent with halocarbon refrigerants [6].

An invaluable asset of ammonia is its strong, penetrating and to most people unpleasant smell. Ironically enough this may be the reason for the exaggerated fear, while it is in reality a most valuable safety factor. The gas is easily detected at a concentration as low as 5 ppm in air, and it takes a 1000 times higher content before there is any real danger. The margin of safety is thus extremely generous and it takes very special circumstances for any critical situation to occur. An analysis of known cases shows that extreme negligence and violation of elementary safety precautions are invariably the cause.

It is very simple in principle to build an ammonia plant to any required level of safety. The gas is much lighter than air and easily vented away, and it is highly soluble in water. By simply placing the ammonia containing equipment in a closed and reasonably tight compartment or box and ventilate it to a safe place over the root or a built-in water reserve, any risk of external leakage dung operation can be eliminated. The ventilation can, if need be, be controlled by a gas sensor Distribution ot cold to the places of usage must. of course, be done by a safe secondary refrigerant in premises accessible to the public, except for very small capacities. Work on ammonia equipment for repair or service must be carried out by qualified personnel.
The need to use indirect cooling is the one considerable drawback of ammonia (and other combustible refrigerants) since most available brines are quite viscous at low temperatures, with high pumping power requirement and poor heat transfer. There is presently a strong development to improve on this situation, and new brands are constantly brought on the market [7].

The objection is often heard that an ammonia plant is more expensive than its halocarbon equivalent, and this is certainly true if it is a special one of a kind installation. But there is no reason it should be that way under equal conditions of production. On the contrary ammonia has a number of strong points which can actively reduce first cost:

The optimum compressor speed is inversely proportional to the square root of the molar mass of the refrigerant [4]. An ammonia machine needs less than half the swept volume of one for R-22 with the same capacity.

- The size of piping and armatures can be reduced in the same ratio

- The heat transfer area of condenser and evaporator can be reduced as a result of the excellent heat transfer efficiency of NH3.

These considerable savings should more than compensate for the extra cost of a brine pumping system and casing.
A development on the lines described is retarded by the lack of suitable small ammonia compressors and control equipment in the market and the scarcity of people with practical experience of this refrigerant. In particular cost effective small hermetics are needed, although some "canned motor" type machines are already available. More suitable evaporator designs are also required. The liquid/gas volume ratio for NH3 is very low and the problem of correct distribution and wetting of the heat transfer surface in "dry evaporators" is correspondingly even more difficult than for the halocarbons. Some type of flooding seems indicated.

The progress is now well under way, however, and we can expect a rapid growth in NH3 usage in the next few years. One exception is turbo machines, where a working medium with a somewhat hither molar mass is desirable.

5. Propane, a promising Alternative

Propane and Ethylene have been used successfully as working media in large refrigeration plants for many years, notably in the petrochemical process industry. Mixtures of hydrocarbons, adapted to the desired temperature glide, give excellent service in the enormous condensation trains for natural gas. 45 years ago propane was tried in small refrigeration systems of conventional design without any problem and with excellent performance [4].

Propane (C3H6, R-290) has excellent thermodynamic properties, similar to those of ammonia (or R-22 for that matter). The molar mass of 44 is ideal for turbo compressors and only about half to one third of that of its halocarbon competitors. Its transport properties are correspondingly better, although they do not quite match those of NH3. Propane is compatible with normal lubricating oils and machine building materials, universally available and low in price. Its physiological properties are comparable with those of the CFCs, although it has no harmful decomposition products in a fire except possibly CO at incomplete combustion.

The only important disadvantage of hydrocarbon refrigerants is that they are combustible with a very low ignition concentration limit (Table I), and this drawback has been blown up to unreasonable proportions. As a fact they are popular fuels available everywhere and used with simple precautions even in private homes, caravans and small boats. With reasonably careful design it must be even more simple to ensure safety in a hermetic closed refrigeration circuit.

Inside the working system it is physically impossible to create an explosive mixture. The amount of air required would exceed by far the limits permitting of normal operation. Any risk is therefore associated with leakage to the outside and can be eliminated by suitable enclosure and ventilation as described for ammonia. Even greater care is required in repair and service, however.
Propane is an obvious alternative to ammonia in ad kinds of refrigeration and heat pump application. Direct cooling is possible in small systems, when the charge is low enough to avoid any explosion risk in rooms where leakage may occur. One advantage is that the hardware can be very similar to CFC practice and familiar to service personnel. Propane can of course be mixed with other hydrocarbons to adjust the pressure and generate gliding temperatures.

After years of hesitation hydrocarbon refrigerant is beginning to find application in household equipment. A 50/50 mixture of propane and isobutan (R-290/R-600a) is used to approach the pressure and capacity characteristics of R-12 [8]. It is hard to see that the small charge of typically less than 50 g can represent any danger, and extensive analysis and practical testing in the USA and Germany have confirmed its safety. Also, millions of Platen/Munters refrigerators, charged with ammonia and hydrogen (!), have been used over the years without any accidents except an occasional "bad smell".
It is hard to see why hydrocarbons cannot provide a solution for other small equipment as well.

In large systems using turbo machinery propane has a particular advantage in that its molar mass is near the ideal to achieve the optimal Mach number with an impeller tip speed adjusted to the strength capabilities of modern materials and design. This favours a compact design with a minimum number of stages.

6. Carbon Dioxide, the unique Refrigerant

Carbon dioxide was a commonly used refrigerant from the late 1800's and well into our century. Due to its complete harmlessness it was the generally preferred choice for usage on board ships, while ammonia was more common in stationary applications. By the advent of the "Freons" and R-12 in the first place, the use of CO2 was rapidly interrupted. The main reason for this development was certainly the rapid loss of capacity at high cooling water temperatures in the tropics, and not less the failure of the manufacturers to follow modern trends in CO2 compressor design towards more compact and price effective high speed types. Time is now ripe for a re-assessment of this refrigerant for application with present day technology. Disregarding air and water, CO2 is certainly the refrigerant coming closest to the ideal of harmlessness to the environment [9]. With regard to personal safety, it is at least as good as the best of halocarbons. It is non-toxic and incombustible, of course. By release from the liquid form about half will evaporate while the remainder becomes solid in the form of snow and can be removed with broom and dustpan, or just left to sublimate. Most people are already familiar with the handling of "dry ice". In the case of accidental loss of a large quantity, a good ventilation system is required in order to eliminate any risk of suffocation, in particular in spaces below ground level. In this respect the situation is the same as for any large halocarbon plant.

It is some time maintained that the high pressure of CO2 could constitute a special danger in the case of accidental rupture. Actually this is not so since the volume is so small. In the same way as the product P*V is approximately the same for all systems with the same capacity, the same holds for the explosion energy, regardless of the refrigerant used.

As a fact, the high pressure and correspondingly low specific volume is perhaps the greatest advantage. The pressure level is close to the optimum for modern machine technology, as demonstrated by fields like power engineering, oil hydraulics and other processes, where it can be chosen freely. The Philips machine is another example, working at about 100 bar. In the vicinity of the critical point heat transfer is also particularly effective. All this makes for a very compact and cost effective design.

CO_2 also has a number of further advantages:
pressure close to the economically optimal level greatly reduced compression ratio compared to conventional refrigerants complete compatibility to normal lubricants and common machine construction materials easy availability everywhere, independent of any supply monopoly simple operation and service, no "recycling" required, very low Price.

One problem of this refrigerant, and in some applications an important asset, is its relatively low critical point of 31°C. With condensation well below this temperature, in a cool climate or in a low stage of a cascade system, it works with condensation like any other refrigerant. As the critical temperature is approached or even exceeded, the losses by superheat and throttling increase. It turns out, however, that in some cases this can be compensated by much improved compressor performance as a result of very low pressure ratio and small volume requirement. This has been amply demonstrated by the motorcar air conditioning system, which is fully described in reference I l01.

There is no doubt that CO_2 can be used with similar success in other small refrigeration systems as well. For larger capacities it may be worth while to take measures to reduce the losses by superheat and throttling. One obvious way is by staged compression and expansion, Fig3. Another tempting solution can be to recover expansion work in using a suitable engine, since the properties of CO_2 make this feasible.

With a conventional refrigerant like R-12 most of the theoretical expansion work comes from the flash gas and the P-v diagram becomes very thin, with a low mean pressure, Fig 4. For CO_2 the situation is quite different, with most of the work in the liquid phase, a high mean pressure and small volume requirement. An expansion aggregate becomes a cost effective element in large installations, I l ll.

In some cases the characteristics of a trans critical process are particularly well adapted to the application, when a strongly gliding temperature of heat discharge is desired. Most heat pumps extract low temperature heat from the immense reservoir of the environment (air, water, rock ...) and a process with constant temperature evaporation is therefore quite suitable rejection at essentially cons with gliding temperature 0T.

Such a process can be at Fig. 6. In order to get a sat absorbing medium (water), of 90-100 bar or higher. Tl 0°C, the discharge temperature about 70-80°C. This temper the discharge pressure and a 100 mW heat pump with identical boundary conditions for the purpose. They give off the thermal energy at a higher temperature to a finite stream of air or water with limited heat capacity, resulting in a more or less gliding temperature. The amount of temperature change can range from a few degrees in a small direct condensation air heater, 15-20 K for normal "split units", up to 30-40 K in large district heating networks and even more in some industrial applications and direct tap water heating.

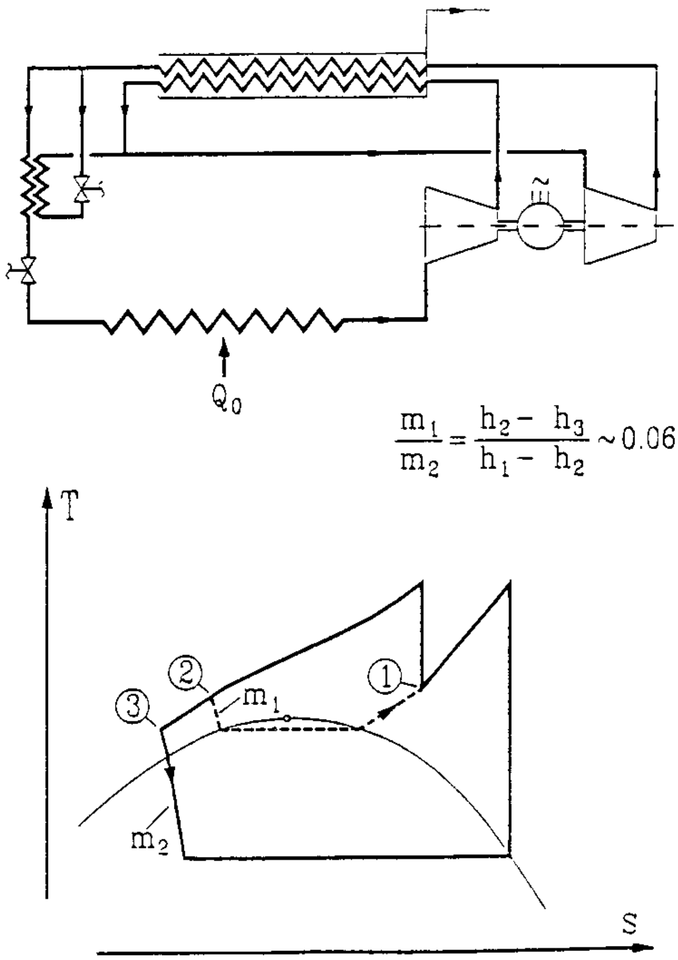

Fig. 3

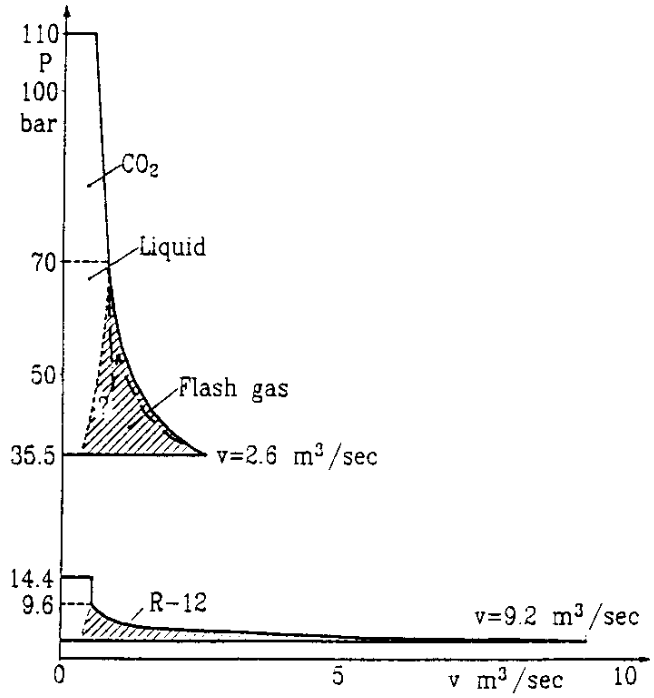

Fig. 4

This causes a very considerable excess power requirement in the normal type of cycle with condensation and heat rejection at essentially constant temperature, Fig 5A. What one should really have is a cycle with gliding temperature output as indicated schematically in Fig. 5B.

Such a process can be approached by a transcritical cycle, using CO2 as working medium, Fig. 6. In order to get a satisfactory fit to the near logarithmic temperature curve of the heat absorbing medium (water), the discharge pressure should be well above critical, in the order of 90-100 bar or higher. This means that when the evaporation temperature is for instance 0°C, the discharge temperature in single stage compression with dry saturated suction will be about 70-80°C.

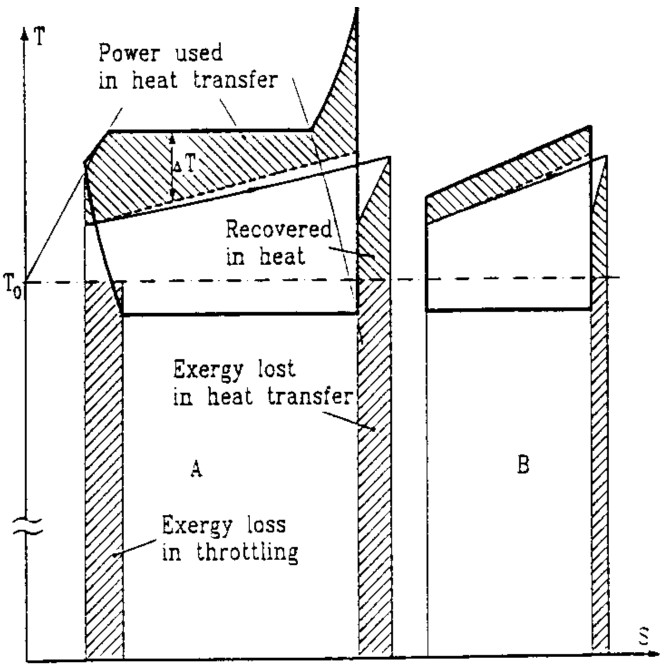

Fig 6

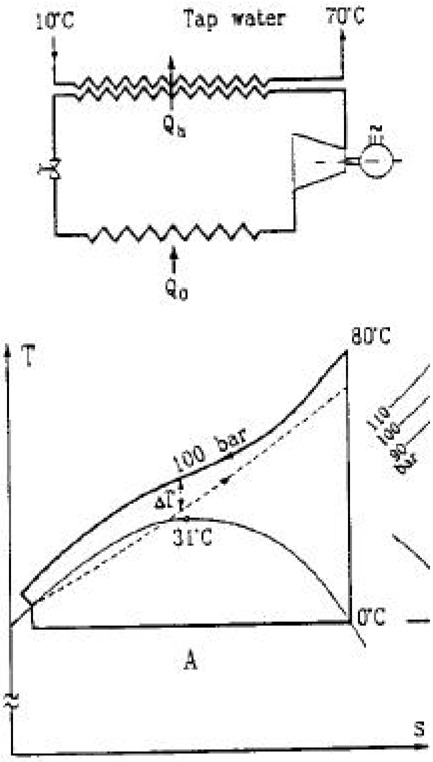

Fig 5

This temperature can be adjusted in a certain range, up or down, by varying the discharge pressure and suction gas state as illustrated schematically in Fig 6B. using a conventional suction gas heat exchanger, or, possibly, some liquid injection The flexibility in the direction of a temperature reduction is rather limited, however Lowering the pressure too much will deteriorate the temperature curve fit in heat exchange, while wet suction rapidly leads to poor compressor performance. The single stage system shown is therefore most suitable when the required temperature glide is higher than 40-50 K, depending on the heat source temperature. In such cases it may easily reduce the specific power consumption by up to 40 per cent compared to the conventional process, improving the COP correspondingly.

For most applications we need heat pumps with a smaller temperature glide. This problem is readily solved by a system of staged compression, to give a discharge temperature close to the desired level. Fig. 7 gives an example of a two stage arrangement, suitable for a modern low temperature district heating application with a heating range for instance 35-60°C. The temperature-entropy chart compares the transcritical CO2-process with a conventional R-12 system for the same capacity and temperature requirement. The power saving achieved by the better temperature fit in heat transfer is a good 20 per cent

Another good example of the efficient use of CO2 in commercial refrigeration is given in a second paper to this meeting [12].

7. Water Vapour Systems

Open cycle water vapour systems are used occasionally for direct evaporation chilling in situations with low relative time of operation, when the high power consumption is of minor importance compared to investment and labour costs. The vapour volume to be compressed is enormous, in the same order of magnitude as for an open cold air cycle of similar capacity. Steam ejectors are normally applied. The most typical example is the cooling of truckloads of lettuce in California. More recently a similar system has been introduced for the production of ice slurry [13].

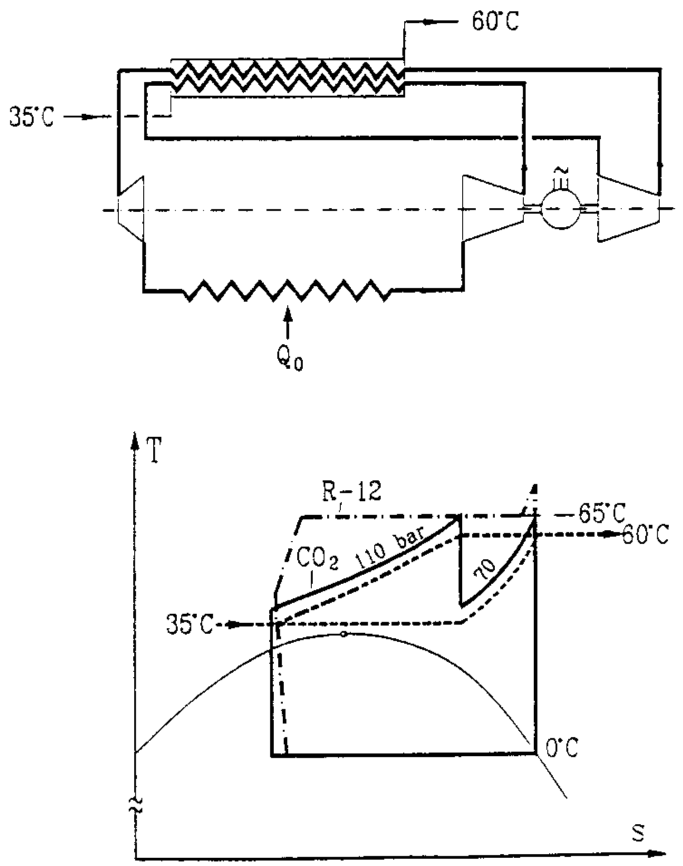

Fig. 7

Water has also been proposed as a refrigerant in regular systems using turbo- or special rotary compressors [14, Liz. The physical dimensions of these machines become very large and price must be a problem.

In the high temperature heat pump area on the other hand, water is an ideal working medium. It has been used extensively for many years in open systems for concentration of liquids by evaporation, Fig. 8. Since the temperature lift is limited to what is required for heat transfer (plus possibly some boiling point elevation) the COP becomes very high, up to 20 or more in some cases. The low lift also permits the use of simple and relatively inexpensive single stage turbo compressors.

For open or closed cycle heat pumps in a multitude of industrial applications in the temperature range upwards of 80-100°C water is the obvious choice. In this field refrigeration gradually merges with steam engineering.

8. Conclusions

Release to the atmosphere of chemicals which are foreign to nature involves a great risk, as amply demonstrated by the CFC experience and many other similar cases in recent years. It is clearly desirable to choose as refrigerants "natural compounds", which are already present in quantity in our biosphere and known to be harmless.

Suitable such compounds exist to satisfy our requirements for all common applications of refrigeration and heat pumps. Some changes in current design and practice will certainly be required, but are immediately possible on the basis of existing knowledge. In the conventional refrigeration and heat pump domain three refrigerants will be sufficient to satisfy normal requirements: Ammonia, Propane and Carbon Dioxide. More often than not they can do the job better than the present halocarbons; cheaper and with less power consumption.

Most people regard the present ban on the CFC/HCFCs as a tremendous problem. True, it is going to cost the society billions of dollars, nobody knows how many. But for the refrigeration industry it opens immense opportunities; an opportunity to improve technology, more development work, more production, more business.

Problems are the root of progress and are bread and butter to the engineer.

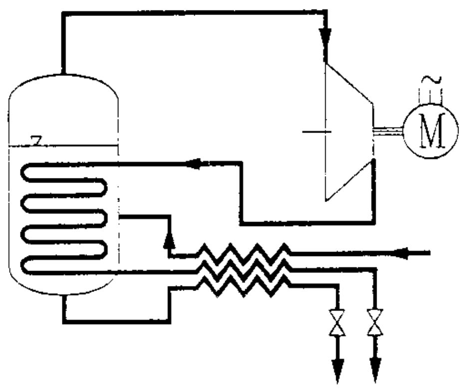

Fig. 8

9. References

1. Lorentzen, G.: "Application of Natural Refrigerants" IIR Annex 1993, Gent, p. 55-64.
2. Banks, R.E.: "Scepticism about R- 134a justified" Refrig. Air. Condit., Sept. 1993, p. 16.
3. Rosin, H.: Hygiene - Inst. Dortmund, Speech at IKK 93, Essen, referred to in Scan Ref. 1993, No. 6, p. 4-5.
4. Lorentzen, G.: "Leveringsgrad og virkningsgrad for kj01ekompressorer (Volume and energy efficiency of refrigeration compressors)", Fiskeridirekt0ren, Bergen, 1940.
5. Anon.:"Ammonia Toxicity Monograph" The Inst. of Chem. Engrs., 1988.
6. Lunde, H. and Lorentzen, G.: "Accidents and critical situations due to unintentional escape of refrigerants." Paper to appear in Int. J. Refrig., June 1994.
7. Granryd, E. and Melinder, A.: "Koldbarare tBr indirekta kyl- och varmepumpsystem (Refrigerants for indirect refrigeration and heat pump systems)" Scan Ref. 1993, No. 6, p. 29-34.
8. Meyer, A.:"Der FCKW-freie Kuhlschrank der Foron Hausgerate GmbH" Luft u. Kaltetechn.. 1993, No. 1, p. 3-4.
9. Lorentzen, G.: "Revival of CO2 as a refrigerant" Refrigeration beyond the crisis, Inst. of Refrig., London, 1993.
10. Lorentzen, G. and Pettersen, J.: "A new, efficient and environmentally benign system for car air conditioning". Int. J. Refrig., 1993, No. 1, p. 4-12.
11. Lorentzen, G.: "Large heat pumps using CO2 refrigerant" IIR Com. B 1/2. Gent 1993, p. 191-97.
12. Lorentzen, G.: "Use of CO2 in commercial refrigeration" IIR Com. B2, Hannover, May 1994.
13. Paul, J.: "Binary ice-technologies for the production of pumpable ice-slurries"
The Inst. of Refrig., London 1993.
14. Mads H. and Minds, G.: "Energy saving in process cooling by use of water as a refrigerant" IIR Com. 1/2, Gent 1993, p. 75-85.
15. Nyvad, J. and Elefsen, F.: "Energy efficient cooling by use of cycloid water vapour compressor" IIR Com. 1/2, Gent, 1993, p. 67-74.

7. History of HC Refrigerants

Greenpeace report “Back to the Future”

A Survey of Essential Information Regarding Hydrocarbons vs. HCFC-141b and HFC-134a in Domestic Refrigerators

Prepared for Greenpeace
By : John Maté
September, 1994

Acknowledgements: ‘Back To The Future’ was commissioned by Greenpeace USA and Greenpeace International Ozone Campaign.

The document was peer reviewed, with invaluable changes and information added by Tracy Heslop, Melanie Duchin, Steve Kretzmann.

Introduction

The decision regarding which alternative refrigerants and insulation blowing agents are most suitable for replacing ozone depleting CFCs in domestic refrigeration, should be based on such criteria as: environmental compatibility; safety requirements; energy efficiency; technological compatibility with existing equipment; appliance service considerations; cost factors; availability; recovery considerations; and short and long term global market prospects. Ultimately, such decisions must be based on what is best for the ozone layer and the atmosphere.

During 1993/94 the natural refrigerants, hydrocarbons R290 (propane) and R600a (isobutan), or blends of R290/R600a, have emerged as the major contenders against the synthetic compound HFC 134a for market acceptance as refrigerant substitutes to CFC 12. Similarly, another hydrocarbon, cyclopentan, is successfully competing for market share against HCFC-141b in insulation foam blowing.

Greenpeace, along with an increasing number of engineers and scientists, maintains that the future of environmentally safer refrigeration lies with natural substances, such as hydrocarbons, CO2, ammonia, water, air.[1] (see Appendix B) Among these natural substances, hydrocarbon technologies are the most readily available at the present time for commercial production of domestic refrigerators.

Hydrocarbons are flammable, a risk factor which is over emphasised by the proponents of HFCs and HCFCs. The flammability of hydrocarbons can be easily mitigated through adequate safety measures in production and product design. This has been demonstrated both in engineering research, and in the marketplace, through the rapid spread of the hydrocarbon based Greenfreeze technology in Europe, and in Asia. (Appendix A) Indeed, as one looks at the range of products and appliances that utilise flammable materials, such as electricity, natural gas, oil and gasoline, it is clear that society has chosen to mitigate and accept the risks posed by these flammable materials in exchange for the goods and services they provide. (Appendix D)

However, the negative environmental impact of both HFCs and HCFCs, that is, significant contributions to global warming, and in the case of HCFCs, significant contributions to ozone depletion, cannot be adequately mitigated. Considering all of the above criteria, with the exception of their flammability, hydrocarbons are superior to their synthetic counterparts-- HFCs and HCFCs.

The use of hydrocarbons in domestic refrigeration predates the invention of the "miracle" compounds --CFCs--in the early '30s. In the United States, in the mid '30s, out of 60 different refrigerator brands, 11 used isobutan as refrigerant. The refrigerant charge in those refrigerators is estimated to

---

[1] (a)Lorentzen, Gustav (Prof. dr.techn. ,Trondheim, Norway) : "The Use of Natural Refrigerants, A Complete Solution to the CFC/HCFC Predicament": Paper reprinted in the pre-print copy of the "Proceedings of the International Conference: New Applications of Natural Working Fluids in Refrigeration and Air Conditioning: A Contribution to Reduced Global Warming and Energy Consumption" (May 10-13, 1994, Hannover, Germany) : International Institute of Refrigeration, Commission B2 : Commission of the European Communities, Directorate-General for Energy (DG XVII)

(b)Paul, Joachim (Integral Technologie GmbH, Flensburg/Germany), "Water as Alternative Refrigerant": Paper reprinted in the pre-print copy of the "Proceedings of the International Conference: New Applications of Natural Working Fluids in Refrigeration and Air Conditioning: A Contribution to Reduced Global Warming and Energy Consumption" (May 10-13, 1994, Hannover, Germany) : International Institute of Refrigeration, Commission B2 : Commission of the European Communities, Directorate-General for Energy (DG XVII) have been approximately 1.5 kg (3.3 lbs), of isobutan. [2] In comparison, today's hydrocarbon refrigerators, with hermetically sealed compressor systems, use between 30 to 70 grams (1-2.5 oz.) of refrigerant, depending on the size of the refrigerator. (Appendix C) That is 20-50 times less refrigerant used under much safer conditions.

The recent advent of hydrocarbon technology in domestic refrigeration represents a positive technological reach "back to the future". A reach to the past in order to secure the future.

All of the major European companies will have switched their full line of domestic refrigerators to hydrocarbon "Greenfreeze" technology by the end of 1994. Unfortunately, the American refrigeration industry, suffering from environmental and economic myopia, is resistant to making the inevitable conversion. Consequently, the American industry --by clutching on to obsolete, polluting transitional technologies-- is in danger of losing its competitive edge, and the American consumer is denied the right of access to an environmentally safer appliance. Furthermore, American industry risks technological isolation and loss of export markets, as the rest of the world switches to HCFC and HFC free refrigerators.

American industry's reluctance to embrace the new Greenfreeze technology seems to be driven by short term investment/profit considerations rather than long term industrial strategy or environmental concerns. "On December 1, 1992 the London Financial Times reported that Du Pont had invested $450 million in HCFC and HFC production, and expects to hit the $1 billion mark in 1995, with an expected recovery period for the investment of no less than ten years. The company claims to require another ten to twenty years of HCFC and HFC production to profit above and beyond recouping their investment. Consequently, the production and phase out dates for HCFCs and HFCs are not based on the availability of safer technologies or substances, and therefore the needs of the ozone layer."[3]

---

[2] Granryd, Eric; Tengblad, Niklas; Nowacki, Jan-Erik, "Propane as Refrigerant in a Small Heat Pump: Safety Considerations and Performance Comparisons", Paper presented at the International Conference - New Applications of Natural Working Fluids in Refrigeration and Airconditioning, 10-13 May, 1994, Hannover, Germany.

[3] Greenpeace International, "HCFC's and HFC's: The Bad Gamble" , January, 1993:Paper reprinted in the "Proceedings of the Ozone Safe Cooling 1993 Conference": published by Greenpeace USA (1994): p.30

The present study, "Back to the Future", compiles some of the essential information regarding cyclopentan and isobutan in comparison to HCFC-141b and HFC-134a. The scope of the study does not include other alternative technologies for domestic refrigeration, for example, Stirling cycle refrigeration or vacuum panel insulation, which certainly merit extensive consideration. In the long term, these may prove to be cleaner for the environment, and more efficient, than hydrocarbon based technologies.

The study is based on the premise that for the present, in contrast to HCFCs and HFCs, conversion to hydrocarbon technology in domestic refrigeration not only makes sense from an environmental but also from a long term business perspective.

Part I : Comparison of Cyclopentan and HCFC-141b as Blowing Agents for PUR Foam Insulation in Domestic Refrigeration

"*In the past two years cyclopentan has emerged as the most promising zero Ozone Depleting Potential (ODP) alternative to CFC-11 as a blowing agent for rigid insulation foam.*" [4] (UNEP)
"The Montreal Protocol stipulates that each Party shall endeavour to ensure that HCFC's use is limited to those applications where other environmentally suitable alternative substances or technologies are not available." [5] (UNEP)

---

[4] United Nations Environment Programme (UNEP), Industry and the Environment: "Cyclopentan : A Blowing Agent for Polyurethane Foams for Insulation in Domestic Refrigerator-Freezers": Information Paper, OzonAction Information Clearinghouse, OzonAction Programme, July 1994: p.1

[5] UNEP, "Elimination of CFCs from Domestic Refrigeration Manufacture": Op.cit., Part 2, p.4

A. Environmental Compatibility of Cyclopentan and HCFC-141b

1. Ozone safe blowing agents for insulation in domestic refrigeration are essential for the protection of the ozone layer as "blowing agents are released into the atmosphere during the lifetime of an appliance" .[6] Japanese appliance manufacturers estimate that 25% of the foaming agent escape in 10 years as the polyurethane insulation deteriorates.[7]

2. The global CFC consumption in the foam sector in 1990 was 174,000 metric tonnes. The global usage of CFCs in appliance foams in 1990 was 38,000 metric tonnes [approximately 21% of the total CFC used in the foam sector]. [8]

3. In 1991, the Technology and Economic Assessment Panel of the Montreal Protocol, estimated that "...150,000 tonnes of HCFCs a year would be required to achieve a CFC phase out in foam plastics in the developed countries in 1995".[9] The importance of making the right choice for the foam blowing agents in domestic refrigeration is further amplified when we add the projected growth in domestic refrigerator/ freezer production in developing and industrialised countries. The December 1991, Technical Options Committee of the Montreal Protocol, projected "an annual production growth rate of refrigerating capacity (arising from both more and from bigger cabinets) of 15% for developing countries and 7% for developed countries ." [10]

---

[6] Ballhause, Herr. Dr. (Liebherr-Hausgerate BmbH), "Hydrocarbons Provide Zero ODP and Zero GWP Insulation for Household Refrigeration": article presented by Herr. Dr. Ballhaus at the October 12, 1993, Technology Transfer, Weltbank Montreal Fund OORG-Meeting, as reprinted in "Proceedings of the Ozone Safe Cooling 1993 Conference" (October 18-19,1993, Washington, D.C.), published by Greenpeace USA (1994), p.471.

[7] Greenpeace Japan, "CFC Substitutes Will Not Save the Earth: The Environmental Impacts of Refrigerants and Insulation Foaming Agents for Household Refrigerators in the Developing Countries", October 1993: p.9

[8] UNEP, "Cyclopentan", Op. cit. p. 2

[9] TEAP Report 1991: Montreal Protocol On Substances that Deplete the Ozone Layer: "1991 Assessment: Report of the Technology and Economic Assessment Panel (TEAP)", December, 1991: Section 8, p.11

[10] TOC Report 1991: Montreal Protocol: "1991 Assessment: Refrigeration, Air Conditioning and Heat Pumps: Technical Options Committee": December, 1991: p.86

4. PUR foam: “Mainly CFC-11 has been used to produce foams for insulation in domestic refrigerator freezers...Rigid polyurethane foams continue to be the dominant insulation used in domestic refrigerator-freezers...It is estimated that approximately 75-80% is used in refrigerator-freezers and the remaining 20-25% is used in other appliances such as display cabinets, water heaters, portable coolers, commercial appliances and vending machines....”[11]
“The total amount of CFC-11 used [for the manufacture of polyurethane insulating foam in the refrigerator and freezer industry is projected to be] 16,000 tonnes in 1994.”[12]

5. “The domestic refrigerator-freezers manufacturing industry expects to complete transition from CFCs (in industrialised countries) in 1995”.[13] Thus, making the right choice for an alternative blowing agent is all the more pressing as “today there are only two serious contenders being considered by those moving to CFC-free foam blowing: HCFC-141b and (cyclo)pentane...” [14]

6. Ozone Destroying Potential (ODP) and Global Warming Potential (GWP) of HCFC-141b:

a. ODP of HCFC-141b: HCFC-141b is an ozone destroyer, with an ozone depleting potential (ODP) of 0.11, one of the highest among HCFCs.[15] The acceptance of HCFCs as "transitional substances" in general, has been a measurement of their ozone depletion potential (ODP). ODP measures a particular chemical's capacity to destroy ozone over a 200- to 500-year time period. Using this measurement, HCFCs appear to

---

11 UNEP, “Cyclopentan”, Op.cit, p.2

12 UNEP, “Proposed Three-Year plan and Budget of the Multilateral Fund (1994-1996)”, Submitted by the Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol at the Open-Ended Working Group of the Parties to the Montreal Protocol: August, 1993, Geneva, p. 11

13 Ibid. p.1

14 United Nations Environment Programme (UNEP), Industry and the Environment: “Elimination of CFC from Domestic Refrigeration Manufacture : Refrigerant, Foam Blowing Agent”:

15 Ibid. , Part 2 : 1.2

have only 1-11% of the destructive capability of CFCs, or stated another way, “to be 89-99% better for the ozone layer than CFCs".

However, as the eminent American atmospheric scientists, Susan Solomon and Daniel Albritton concluded in 1992, "long-term ODPs were not appropriate for making short-term (decade scale) forecasts [of HCFC impacts on ozone losses]" [16]. Since the greatest degree of ozone depletion is expected within the next ten years, it is a mistake to use the long-term ODPs of HCFCs for crafting policies to protect the ozone layer in the short- to mid-term.

A more accurate measure of a chemical's capacity to destroy ozone is chlorine loading potential, or CLP, which is not based on long-term models as ODPs are, but on more straight forward calculations and observations of how much chlorine pollution actually gets into the lower and upper atmosphere in the short- to medium-term.

When CLPs are used as the measurement, HCFCs prove to be significantly more damaging than their ODPs make them appear. For example, The United Kingdom's Stratospheric Ozone Review Group reported that the relative impact, in terms of chlorine loading, of emissions of HCFC-141b after 10 years would be over half that of a similar emission of CFC-11, yet its long-term ODP is only [.11]. [17] Mr. Kajiwara, Senior Managing Director of the large Japanese Matsushita Refrigeration Company cited the ODP of HCFC-141b for the company’s 1994 decision to switch to cyclopentan, stating "its ODP is not zero... [and] to protect the ozone layer, ODP should be decreased to zero, first of all". [18]

b. GWP of HCFC-141b: HCFC-141b has a global warming potential (GWP) 1800 times of CO_2 (20 year time scale).

---

16 Solomon, S. and D. Albritton, "Time Dependent OzoneDepletion Potentials for Short- and Long-Term Forecasts", Nature, 1992, 357:33-37).

17 UNEP, Scientific Assessment of Ozone Depletion (1991 update):Stratospheric Ozone Depletion. Chapter 6 - Evaluation of Ozone Depletion and Chlorine Loading Potentials (ODPs and CLPs).

18 Kajiwara Mr., Senior Managing Director of Matsushita Refrigeration Company: Letter to Greenpeace Japan: May 9, 1994

7. Direct Global Warming Potential of CO2, CFC-11, CFC-12, HCFC-141b, HFC-134a and the Hydrocarbons Cyclopentan, Propane, and Isobutan: [19] (Table 1) * "GWP of the hydrocarbons is due entirely to GWP of the CO_2 resulting from decomposition."[20]

Gas	Lifetime (years)	20 year	50 year	100 year	200 year	500 year
CO_2		1	1	1	1	1
CFC-11	55	4400	4300	3400	2400	1400
CFC-12	116	7000	7600	7100	6200	4100
HCFC-141b	11.4	1800	1100	610	370	210
HFC-134a	15.6	3200	2000	1200	730	400
Cyclo-pentan	weeks	<3*	<3*	<3*	<3*	<3*
Isobutan	weeks	<3*	<3*	<3*	<3*	<3*
Propane	months	<3*	<3*	<3*	<3*	<3*

8. ODP & GWP of cyclopentan: Cyclopentan has zero ozone depleting potential (ODP), and very low global warming potential (GWP).

9. Summary: Clearly, cyclopentan is environmentally more compatible than HCFC-141b in terms of its ODP and GWP.

B. Safety Considerations: Cyclopentan and Flammability

1. Flammability of cyclopentan: Cyclopentan is a highly flammable gas, with a lower flammability limit of 1.4-7.8%. The lower flammability limit of HCFC-141b is 7.3-16.0%. Flammability limits designate the percentage of gas vapour in air-gas mixture that is combustible so that higher percentages

---

[19] Sources

(a) "Scientific Assessment of Ozone Depletion 1991":(Sponsored by: World Meteorological Organization, UNEP, NASA, National Oceanic and Atmospheric Administration, U.K. Department of the Environment), p. 7-18. ; and

(b) 3rd. Report by Inquiry Commission of the German Parliament: "Protection of the atmosphere",1990: from Table reprinted in the "Proceedings of the Ozone Safe Cooling 1993 Conference", Op.cit., p.41; and

(c) TOC Report 1991, Op. cit. p.65

[20] TOC REPORT 1991, OP. cit. p.66

represent lower flammability. Fortunately, the technology and the expertise in working with flammable substances is readily available in most parts of the world. The safety precautions required during the cyclopentan foaming production process are common knowledge and easily achievable through adequate safety measures.

2. Safety of c-pentane foam: Although various flammability tests bring varying results, the overall conclusion is that cyclopentan foam is safe for use in domestic refrigeration.

(a) Lematic Engineering writes: "[A] very important aspect in the household is if c-pentane in the foam insulation can explode or burn faster than the CFC or HCFC substitutes. After finishing the foaming process, c-pentane is capsuled in the polyurethane [PUR] cell matrix and no explosion is possible anymore. Even the velocity of burning of PUR foam blowed with c-pentane is not different from the ones blowed with CFC and HCFC and practically depends only on the PUR matrix and not on the blowing agent." [21]

(b) Results of flammability test from Liebherr: Dr. Ballhaus of Liebherr writes: "A standardised flammability test carried out on cubic foam samples shows that burning time after ignition of cyclopentan blown foam is only 10% longer than that of CFC11 blown".[22]

(c) Results of flammability test: Heinrich performed combustibility tests on PUR foam blown with c-pentane, and found that: "Combustibility tests have shown the PUR which was foamed with c-pentane [burns] normally. There are no deflagrations or explosions. In this regard [c-pentane] is a problemless agent." [23]

(d) Mitigating possibilities: "Matsushita evaluated flammability of c-pentane with oxygen index testing, flash point testing, gross calorific value testing, melting point measurement and other tests. Oxygen index testing confirmed the pentane insulation is 0.5 to 1 lower than CFC-11 insulation,

---

[21] Lematic Engineering (Thermotechnik Handels GmbH), Dusseldorf, "Survey About CFC Free Refrigerator Production: Part 2: Foam Insulation", 1994: p.20

[22] Ballhause, Op.cit., p. 462

[23] Greenpeace Japan, Op. cit., p.20

meaning the former burns more easily. For this reason Matsushita added flame retardant resin to the polyurethane, and when blowing the foam, increased the proportion of carbon dioxide mixed with the pentane, which raised the oxygen index to about the same as that of CFC 11."[24]

3. Safety measures to be considered: The UNEP Report writes: "Cyclopentan is a flammable blowing agent. The explosion limits are 1.1-8.7 percent by volume in air. Therefore, it is necessary to follow strictly the safety rules. Safety at the following steps is required to be considered: (a) storage of cyclopentan; (b) mixing of cyclopentan and polyol; (c) storage and metering of the mixture; and (d) foaming process." [25]

4. Developing Countries: "The technology can be mastered even in a developing country with lower working responsibilities and education, if some safety measures are made and regularly controlled. Many companies in developing countries [have for years been] using pentane as blowing agent in the expanded polystyrol sector (styropor) without any problems; and [much greater risks] are mastered in these countries in refineries, gas depots and gas filling stations." [26]

C. Energy Efficiency: Cyclopentan and HCFC-141b

1. Introduction: "The most important question -besides the ecological one- is the thermal conductivity of PUR blown with the different substitutes in comparison to CFC-11 and CFC-50% reduced. Any increase of this value will either increase the energy consumption, or will oblige the [refrigerator manufacturer] to increase the insulation thickness and reduce the ratio of net volume to gross volume. Such increase strongly increases [the] costs of a refrigerator per useable net volume. Furthermore, it is important to know how this value will change after days and years because of any reaction

---

[24] Nikkei Material, Refrigeration Industry Magazine, Japan: June 1994, No. 142: "Consumer Appliances and CFCs: Matsushita Refrigeration Co. and Sharp Corporation Adopt Hydrocarbons for Insulation"

[25] UNEP, "Cyclopentan", Op.cit., p.10

[26] Lematic Engineering, Op. cit., p.6

inside the materials, condensation, solution, evaporation of the blowing agent and diffusion with air.” [27]

2. Efficiency concerns: While many of the major German manufacturers began to switch to cyclopentan blown foam in 1993, the October 1993 OORG Report wrote: "The conversion to cyclopentan is assumed to not take place in the US and Japan, mainly for efficiency reasons, because the difference in energy consumption of an appliance blown with "100% CFC-11 and with cyclopentan lies between 6 and 12%; for this reason the manufacturers in the US and Japan prefer HCFC-141b as a temporary solution."[28] However, in 1994 the Japanese manufacturers Matsushita and Sharp began to convert their insulation production to c-pentane. This has left the US manufacturers as the last major holdout against conversion.

The efficiency concerns of the US manufacturers can be addressed by the fact that overall cyclopentan foam has better insulation value than HCFC-141b blown foam, and comparable values to CFC-11 blown foam. The manufacturers of HCFC-141b foam put forth that the efficiency penalty of HCFC-141b foam is mitigated by the special inner liner HCFC-141b requires. However, that is a fatuous point, since it accepts that HCFC-141b blown foam, in and of itself, is not as efficient as c-pentane or CFC-11 foam.

3. C-pentane foam’s superior efficiency: Test results by various manufacturers, and independent engineering firms, show that overall, the efficiency of c-pentane blown PUR-foams compare favourably with CFC-11, 50% reduced CFC-11 and HCFC 141b blown foams. Of course, test results do vary.

a. Comparison of CFC-11 foam and cyclopentan foam: Lematic Engineering, in “Survey of CFC Free Refrigerator Production “ states: "The technical data show that with pentane same thermal conductivity values, with the variation between -2% and +5%, can be reached in comparison to CFC-11, but in any case, better values than [with] HCFC and HFC

---

27 Ibid. p. 12

28 Ozone Operations Resource Group (OORG), The World Bank Global Environment Coordination Division, Environment Department, Report Number 5, October 1993: “The Status of Hydrocarbon and Other Flammable Alternatives Use in Domestic Refrigeration”: p. 7

blowed PUR. ....”[29] Furthermore, Lematic maintains that there is still room for optimising the polyurethane formula used with cyclopentan, so that even lower values can be reached in the future. [30] The October, 1993 OORG Report agrees: "The cyclopentan solution still has some way to go (status mid 1993) with regard to optimisation; a further development has the promise of a decrease of the conductivity values...the promise for the future will stimulate a conversion to cyclopentan. [31]

b. Even at the present state of optimisation cyclopentan blown foams show better values at lower temperatures than CFC-11 foam. “If the thermal conductivity is measured on refrigerators and freezers [with] operating temperatures between -30^0 C and 8^0 C, the cyclopentan foam reaches...better values...directly after foaming than the ones foamed with CFC-11: Thermal Conductivity (TC) of C-Pentane Foam Compared to CFC-11 Foam Between Operating Temperatures of -40^0 to +20^0 C [32] (Table 2)

Temperature	-40	-20	0	20
TC : CFC-11	21.6	20.6	19.3	19.9
TC : C-pentane	17.0	19.0	18.6	19.8

c. Cyclopentan foam performs better upon ageing than CFC-11 foam: “Interesting is that the increase of thermal conductivity of c-pentane driven foams are slower than the ones with CFC-11, so that after time ... the c-pentane foam reaches lower thermal conductivity values than the one made with CFC-11. These experiential results can be explained by the fact that CFC-11 can be easier solved inside the PUR matrix than c-pentane.”[33]

---

29 Lematic Engineering, Op. cit., p.6

30 Ibid. p. 12

31 OORG 1993, Op. cit. p.7

32 Lematic Engineering, Op. Cit., p. 13

33 Ibid. p. 14

d. Simulating the ageing process: The following results were reached in a test that simulates the long term diffusion and solution processes in various foams: [34] (Table 3)

PUR Foam With	% Agent	Thermal Conductivity Initial (mW/mK)	After 3 Months at 70^0 C	Used Gross Density Kg/m^3
CFC-11	12	18	27-28	32
CFC-11 50% Red.	6	19	27	33
HCFC-141b	7	19.8	27-28	36
Cyclopentan	6	19.5-19.8	25-26	36

e. Citing test results from Dow Chemicals (2/1994) Lematic Engineering offers the following data : [35] (Table 4)

Blowing Agent	Applied Foam	Thermal Conductivity	
	Density (kg/m^3)	Initial	(mW/mK) 120 days
CFC 11	30-32	17.0	23.0
HCFC 141b	34-36	19.0	25.0
Cyclopentan	38-40	19.5	24.4

f. Lematic states that "BASF and BAYER values for c-pentane blowed PUR are much better [than Dow]..and the refrigerator producers who use BASF or BAYER PUR materials are working with 10% lower densities." 36

g. In a study entitled "Light Hydrocarbons as Refrigerants and Blowing Agents for Insulation's in Household Appliances", H. Lotz presents the following conclusions: " Polyurethane blown foam has initial value of

34 Ibid. p. 15

35 Ibid. p.23

36 Ibid. p.12

thermal conductivity of the order of 20mW/mK but on ageing thermal conductivity of cyclopentan foams becomes lower than that of CFC-11 foam because of slower rate of diffusion. Thus the conductivity over the life time of PUR cyclopentan foam is even lower than that with PUR-CFC-11 foams." [37]

h. U. Schilling, in a paper entitled "Cyclopentan, the New Generation of Blowing Agents for Appliances" concludes: "The thermal conductivity values of PUR with cyclopentan in combination with special tailor-made polyol formulations are almost as good as those of CFC-11 reduced foams. On ageing the thermal conductivity of cyclopentan containing foam is lower than that of CFC-11. The mechanical properties of the foam, such as its compressive strength are retained."[38]

i. In Australia Fisher & Paykel found that c-pentane foam performed better than 50% reduced CFC11-PU foam. According to Lindsey Roke, Chief Engineer, Refrigeration Division "HC foams gave a better overall insulation by being less inferior at the edges...." and at -20 C ambient, "the cyclopentan system is a clear winner". [39]

j. Insulation thickness with c-pentane foam remains the same: "Many European and Far East producers...[using their actual refrigerator models]...compared c-pentane, HCFC-141b and HCFC-142b/22 (60/40) with CFC-11 and CFC-11 reduced, and found...that after foaming and weeks later...the c-pentane solution [does] not oblige them to change the thickness of insulation." [40] According to Lematic: "Refrigerator (foam) blowed with

---

37 Lotz, H., "Light Hydrocarbons as Refrigerant and Blowing Agents for Insulations", Paper presented at the International Conference - New Applications of Natural Working Fluids in Refrigeration and Airconditioning, 10-13 May, 1994, Hannover, Germany. pp1-13

38 Schilling, U., "Cyclopentan, the New Generation of Blowing Agents for Appliances":Paper presented at the short course, "Hydrocarbons the Environmentally Friendly Alternatives", Hannover, Germany, 9-13 May, 1994

39 Roke, Lindsey (Chief Engineer, Refrigeration Division, Fisher & Paykel): March 29, 1994, letter to Greenpeace Australia.

40 Lematic Engineering, Op.cit., p. 4

HCFC-141b or HCFC-142b/22 needs an increase of the PUR insulation thickness of 7-10%..."[41]

k. The 1994 UNEP Study on the "Elimination of CFC from Domestic Refrigeration Manufacture" states: "Insulating properties are enhanced by using blowing agents with low gas-phase thermal conductivity's. Heavy molecule blowing agents are better than light ones. In a refrigerator the cyclopentan foam can out-perform the reduced CFC-11 version... Insulating properties of cyclopentan do not deteriorate with time as fast as do those of CFC-11 blown foam. In a standard test cyclopentan foam and CFC-11 foam may both have initial values of 19 mW/mK. With a few days or weeks of ageing cut samples at 60^{o}C or 70^{o}C, the CFC-11 foam will have deteriorated to be worse than the cyclopentan foam. Its final value may be 2 or 3 mW/mK worse than the cyclopentan version."[42]

4. Mitigating for energy penalty: As noted, efficiency tests have brought varying results. In April, 1994, Matsushita (biggest refrigerator manufacturer in Japan) began selling their 410 litre (14.48 cu. ft.) & 350 litre (12.36 cu. ft.) models using c-pentane (C5H10) for insulation. At the time, on a thermo-conductivity index, where CFC-11 is 100, Matsushita estimated c-pentane at 115 and HCFC-141b at 103. To mitigate for the insulation efficiency loss in c-pentane foam (15-20% loss compared to CFC-11 foam), Matsushita reduced the diameter of the closed cells in the foam by 25%, and made the insulation 5 mm thicker (formerly 33 mm-thick refrigerator compartment and 40 mm-thick freezer compartment walls). Increase in thickness of the walls reduced usable volume by about 10 litres. [43] Sharp Corporation began marketing their 395 litre (13.94 cu. ft.) and 365 litre (12.89 cu. ft.) models with pentane-blown insulation in February, 1994. Sharp did not need to thicken the insulation. "Because our conventional models were designed with comparatively thick walls, the new wall thickness is about the same." [44]

---

41 Adler, Dirk, Lematic Engineering, "Letter to Greenpeace", March 15. 94.

42 UNEP, Op. cit., Part 2, p.3

43 Nikei Material, Op. Cit.

44 Ibid.

D. Technological Compatibility with existing Equipment of Cyclopentan and HCFC-141b

1. Impact on refrigerator inner lining: Whereas “most manufacturers have found that cyclopentan works well with standard liners”,[45] HCFC 141b “has the disadvantage that it is likely to attack conventional HIPS (High Impact Polystyrene) or ABS (Acrylonitrile Butadiene Styrene) used for interior liners. These will have to be replaced either by multilayer sheet with a resistant surface layer or by a single layer sheet with higher resistance all through.” [46]

2. Impact on polyols and MDI components: “The cyclopentan does not have uncontrolled reaction during the hot PUR foaming reaction which can increase the temperature in the core area
to 140-185^{0} C. While HCFCs at this temperature already starts reacting uncontrolled so that the received chloric and flouric products of polyols and MDI components can be toxic”. [47]

3. The adhesion of cyclopentan blown PUR is the same as with CFC-11 on HIPS, ABS and steel so there are no stability changes. [48]

E. Cost factors: Cyclopentan and HCFC-141b

1. OORG 1994 writes: “Cyclopentan technology is commercially proven and is the most cost effective of the zero ODS technologies.” [49]

2.. The current cost of cyclopentan is between .77 cents and $3.30 (US) per kg., depending on levels of purity and location and volume of purchase, with UNEP estimates being based on cyclopentan costing $1.76/kg.[50] It is expected that the prices of cyclopentan ”... will continue to drop as the

---

[45] OORG, Refrigeration Working Group, “Major Recommendations and Outcome of Recent (May 9, 1994) OORG Working Group Meetings”, p. 4

[46] UNEP, “Elimination of CFC's” , Op.cit. , Part 2, p.3

[47] UNEP, “Cyclopentan” , Op cit. p.15 (quoting Lematic Engineering)

[48] Ibid., p.15

[49] OORG 1994, Op cit. p. 8

[50] UNEP, “Cyclopentan”, Op.cit. p.13

material is extracted in greater quantities (the economies of scale). Increased demand may also encourage regional refineries to put in the equipment to extract the chemical. Specified purity levels also affect the price. It is likely that requirements will become less stringent as foam suppliers build up their experience."[51]

3. The current cost of HCFC-141b is approximately $2.93 (US) per kg., depending on location and volume of purchase. [52] [$920.00 Can., approximately US $666.00, per 500 lbs drum]

4. Prices of Insulation Foaming Agents CFC-11, HCFC-141b & Cyclopentan: Japan 1993[53]
(Table 5)

SUBSTANCE	PRICE ¥/kg (Approx.)	$US	CHARGE (g/refrigerator)
CFC-11	600	$6.00	600
HCFC-141b	800	$8.00	600
Cyclopentan	100	$1.00	700

5. Costs due to liner changes:

(a) OORG (1994) reports, that "manufacturers confirmed the finding that HCFC-141b technology tended to be relatively more expensive and hence less cost-effective in terms of unit abatement cost (UAC) due to the fact that relatively sophisticated liner systems are necessary in order to combat HCFC 141b's tendency to cause blistering of the liner and cracking under stress with standard liners. Some manufacturers also report slower production speed when using HCFC-141b." [54]

(b) UNEP writes: "Addition of multilayer extrusion capacity will cost in the order of US $70,000 per layer. A new die and associated equipment

---

[51] UNEP, "Elimination of CFC's", Op. Cit., Part 2, p.8

[52] Source: Allied-Signal Canada: August/94

[53] Greenpeace Japan, Op.cit. p.13

[54] OORG 1994, Op.cit., p.4

may also be required at US $50,000 to US $100,000 depending on what is required."[55]

(c) UNIDO: UNIDO requested US $16,950 to develop a new strategy for ODS phase-out in 4 small refrigerator companies in Egypt. UNIDO recalls that ".. it was [at first] thought that the most cost effective way of eliminating the use of CFCs would be to use HCFC-141b. This was therefore proposed in spite of the fact that both the companies and the Egyptian authorities, the EEAA, preferred the use of cyclopentan as a blowing agent. It has since been determined that because of the high cost of making inner liners which are resistant to HCFC 141b, the use of this product is no longer considered to be the most cost effective. Therefore, the projects should be reformulated to consider foam manufacturer using cyclopentan" [56]

6. Availability costs: Under the terms of the Montreal Protocol, HCFC 141b is scheduled to be phased out along with other HCFCs. European countries and developing nations are already opting for cyclopentan, resulting in a shrinking market for HCFC-141b. Consequently, "from the manufacturer's point of view, [HCFC-141b] has another disadvantage that it may be in short supply",[57] which will inevitably result in increased prices. US Clean Air Act mandates that the production of HCFC-141b be phased out by the year 2002. Again, reduced supply tends to result in increased prices.

7. Production costs: Lematic Engineering estimates that, "On the first view the comparison of investments in the polyurethane section seem to favour HCFC-141b [over c-pentane], because PUR lines do not have to be changed [when CFC-11 is replaced with HCFC-141b]. PUR lines for c-pentane PUR processing require a [one-off funding] investment in the range of 360,000 to 1.5 million DM (for very large plants)... (approximately $850,000 US).[58]

---

55 UNEP, "Elimination of CFC's, OP. Cit. Part 2, p.10

56 UNEP, Document #: /OzL.Pro/ExCom/13/15 - UNIDO Work Programme Amendments, 13th ExCom. , July 1994

57 Ibid., Part 2, p.3

58 Lohbeck, Wolo, Memo of April 14, 94, "Summary of Lematic Engineering'sEstimates".

On second view, the economic comparison does not favour the HCFC solution because of higher material costs:

(a) C-pentane is already cheaper than CFCs or HCFCs (saving of 10.000 - 12.000 DM per 100.000 units per year) (US $6,000-$7,000) and the price of c-pentane will be reduced with increased demand.

(b) HCFC-141b needs special inner liner materials - the price of this material is 10% higher than the standard material (extra cost of 45.000 to 50.000 DM per 100.000 units per year)(US $26,000-$29,500). This cost may prove to be considerably more with a cost difference of 44 to 53% (for a 100.000 annual production that means 150.000 - 175.000 DM)(US $88,000-$103,000).

(c) To achieve the same thermal conductivity level with HCFC-141b as with c-pentane, the insulation with HCFC must be 5-10% thicker, needing more PUR material (extra cost of 94.000 to 121.000 DM per 100.000 per year, at a price of 3 DM per Kilo PUR) (US $55,000-$71,000).

"Refrigerator (foam) blowed with HCFC-141b or HCFC-142b/22 needs an increase of the PUR insulation thickness of 7-10%...[This way there is] an increase not only of PUR material of 7-9%, but also a lower net volume by 5-10%, so that 'per cooled volume' the total price increase of the refrigerator is 5% of all used raw materials and components."[59]

(d) To thicken the insulation requires a change in the production line (investment cost of $250.000 to $500.000 US per refrigerator model). [60]

8. UNEP provides the following figures for the "one-off funding costs" of conversion from CFC-11 to cyclopentan, with a model based on "(a) annual production of refrigerator freezers of 200,000 units; (b) average polyurethane chemical used 4 kg/unit; (c) current CFC-11 contents, 13% W/W on total foam systems; and (d) two production lines, one for cabinets and for doors both equipped with hp dispensing machines":

-Laboratory testing equipment	$ 100,000
-Production equipment modification	$ 170,000
-Production equipment's safety modification	$ 350,000
-Cyclopentan storage	$ 200,000
-Training	$ 50,000
-Materials for trials	$ 20,000
Sub Total	$890,000

59 Adler, Dirk, Lematic Engineering, "Letter to Greenpeace", March 15. 94.

60 Lohbeck, Wolo, Memo of April 14, 94, "Summary of Lematic Engineering's Estimates".

(Estimated at cyclopentan costs at 3 DM/kg with a conversion 1.7 DM =US$) 61

9. The Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol submitted the following costs of a three phase approach, using HCFCs as transitional substitutes that is being adopted in some developing countries to eliminate CFC-11 in foam production:

a. "Phase 1 achieves 50% CFC reduction by using new polyol/water formulations [and] replacement of low pressure foam injection equipment by the high pressure variety..." [with] "the estimated average cost for a typical Phase 1 conversion project in a developing country [being] about US $300,000.

b. "Phase 2 will replace 100% of the CFCs with a HCFC-based blowing agent or blend...(either HCFC-141b or a binary blend of HCFC-142b and HCFC-22)...as is being implemented in developed countries...[at an additional cost of] US $200,000."

c. "Phase 3 is based on the introduction of non-ODS as blowing agents; however, this technology has still not been adequately tested."[62]

Since this third and most crucial phase of the process is yet to be finalised, no costs are projected. This should give an added "buyer beware" warning to developing countries that are considering the three phase approach to eliminating CFC-11. Basically, at this point, they don't know what they are buying as the final product, or what costs may be incurred.

10. HCFC-141b flammability costs: Since HCFC-141b is a flammable substance "Local costing will be needed for meeting any local requirements imposed as a consequence of the flammability of HCFC-141b. In any event foam plant costs will be very much less than those for pentane."[63]

11. Recovery costs: The cost of recovery and destruction of HCFC-141b is presently externalised from the overall cost estimates of the product and the technology. These costs should be internalised into the unit price of HCFC-

---

[61] UNEP, "Cyclopentan", Op. Cit. p. 12

[62] UNEP, "Proposed Three-Year plan and Budget of the Multilateral Fund (1994-1996)", Op.cit., p.12

[63] UNEP, "Elimination of CFCs", Part 2, p.10

141b to reflect the true cost of the substance. Cyclopentan does not need to be recovered, so no similar costs are incurred.

F. Recovery Considerations for HCFC-141b and Cyclopentan

Due to its ODP and GWP, HCFC-141b in insulation foam will have to be recovered and eventually safely destroyed, just as CFCs need to be presently recaptured.

1. In Sweden alone, it is estimated that 440,000 refrigeration appliances are discarded annually, which contain approximately 275 tonnes of CFC-11 in their insulation and about 62 tonnes of CFC-12 as refrigerant. Between 1995 and 2010, Sweden estimates that it would be possible to recover 70% of the 6,000 tonnes of CFCs that will be contained in discarded refrigeration appliances. [64]

2. In 1991, it was estimated that there were 120,000 tonnes of banked CFC's in existing domestic refrigerators/freezers world-wide.[65]

3. CFC recovery in the US: At this time there is only one company in the US, Appliance Recycling Centers of America, in Los Angeles, that deals with CFC recovery from refrigerator foams. The company uses German technology, (manufactured by Adelmann Co. in Carlsted Germany) that grinds up the insulation and extracts the CFC with 'negative pressure'. There are 18 similar plants in operation in Europe. Such recovery is not mandated in the US. The annual domestic refrigerator/freezer production is approximately 7 million units. Presently 30 to 50% of the refrigerators that the company receives for recycling contain CFCs. The company expects a great increase in these numbers as the 1970's generation of refrigerators come due for recycling.[66]

---

[64] Swedish Environmental Protection Agency, Information Department: Publisher, Ingvar Bingman:1990: "How Should We Dispose Of Old Refrigerators", p2

[65] TEAP Report 1991, Op. cit. p.2-5

[66] Source: Glynnis Joyce, Appliance Recycling Centres of America, Los Angeles, Tel. 612-930-1750

G. The Cyclopentane Revolution Market Prospects of Cyclopentane and HCFC-141b

1. UNEP: “In most parts of the world (other than USA whose present interest is in HCFC-141b) cyclopentan now has the major share of all new conversions to alternatives. All polyurethane being used for appliance insulation in Germany will be pentane-blown by the end of 1994. By far the most used pentane isomer will be cyclopentan.”[67]

2. OORG: “Europe is expected to be virtually entirely converted to cylopentane in order to achieve a zero-ODS solution in the earliest possible time frame. Meanwhile, the US market, driven predominantly by energy efficiency concerns and associated regulatory taxes, has opted primarily for HCFC-141b technology, a clearly transitional solution. Japan is pursuing both of these options...and at least one Japanese manufacturer is planning on introducing cyclopentan technology in developing countries within the Asia region....[Current] prospects are for continuing expansion as experience grows and opportunities are identified in developing as well as developed countries.” [68]

3. UNEP: HCFC-141b: Bad Investment: "HCFC-141b is an ozone depleting compound with ODP of 0.11. It is one of the highest among HCFCs. Its phase out in developed countries would need to begin quite soon- as early as 1996 in some countries. In many European countries HCFCs will not be allowed in appliance insulation. HCFC-141b also has a global warming potential two powers of ten higher than do the hydrocarbons. Using HCFC-141b would be a marketing disadvantage in coming years.” [69]

4. UNEP: “The HCFCs are only an interim solution because of the reasons that they also have to be phased out in near future. As per the Copenhagen Amendments, HCFCs will be controlled as follows:[70]

-Freeze in 1996 at 3.1% of calculated level of CFCs consumption plus calculated level of HCFCs in 1989

---

[67] UNEP, “Elimination of CFCs”, Op. cit., Part 2, p.2

[68] OORG 1994, Op. cit. , p.3

[69] UNEP, “Elimination of CFCs”, Part 2. p.3

[70] UNEP, “Cyclopentan”, Op. cit., p. 6

-35% reduction by 2004
-65% reduction by 2010
-90% reduction by 2015
-99,5% reduction by 2020; and
-100% reduction by 2030 "

These controls are for industrialised countries only. Presently, developing countries are exempt from HCFC controls.

5. Earlier HCFC phase out in Europe: August 20, 1994 article in Chemical Business News Base reports: "A decision has been made by environmental ministers of the 12 EU nations to impose more stringent control on CFC imports into the EU....The use of partially halogenated CFCs will be restricted to 2.6% of the 1989 level between 1 Jan 1995 and 31 Dec 2002. ...[The] use of HCFCs will be gradually phased out from 1994 until their complete elimination by 2014 at the latest."[71]

6. Lematic Engineering writes: By the end of 1994, "nearly all European and Far East producers, but also from other areas (e.g. Egypt) who have started, or will start now, to produce CFC free refrigerators will use c-pentane instead of the so called soft CFC (HCFC-141b, 142b/22).... [Because UNEP has] already decided to revise the limitation of HCFC use in 1994-- in case technical alternatives are available-- no one wants to...enter into a temporary [HCFC] solution...and face the problem of [investing] again....Inspite of the safety measures which have to be taken into consideration, technical values, like low thermal conductivity, lower increase of this value after time than of HCFC and CFC blowed PUR, and last but not least, lower pricing have [led to the] pentane decisions." [72]

7. In April, 1994, Matsushita (biggest refrigerator manufacturer in Japan) began selling their 410 & 350 liter models using c-pentane for insulation. In May, 1994, Sharp began selling its 395 liter (13.94 cu.ft.) and 365 liter (12.89 cu.ft) models using only c-pentane in its insulation foam. In February, 1994 Sharp put out a deluxe model with vacuum panel insulation, reinforced by pentane blown u-foam. [73]

---

71 Chemicals Business News Base, "Rubber and Plastics News", July 4, 1994

72 Lematic, Op.cit., p.5

73 Nikei Material, Op. cit.

8. India: The Swiss/German ECOFRIG project with Indian companies has moved forward to pilot plant stage following a seminar in India during the last week of August, 1994. Godrej-GE and Voltas Ltd. will receive cyclopentan foaming units by the end of the year enabling them to produce over 10,000 units a year each initially. [74]

9. USA: Cyclopentan based foam production has yet to penetrate the US market, although, according to Mr. Don Grob, Managing Engineer at Underwriters Laboratory (UL), "there is considerable interest in hydrocarbon refrigeration, at the research level, in the U.S., and the cyclopentan technology has been approved by Underwriter's Laboratory. "[75].

10. US Clean Air Act calls for early phase out of HCFC-141b : Under the jurisdiction of the EPA, the provisions of the US Clean Air Act stipulates that HCFC-141b, because of its high ODP value, will have to be phased out by the year 2002. This leaves manufacturers with a window of opportunity of maximum eight years, in practical terms five to six years, to switch over to an environmentally safer foaming agent. Of course, this represents a major obstacle to the market prospects of HCFC-141b.

11. The introduction of cyclopentan blown foam into the market influences and precedes the use of hydrocarbons for refrigerants. The October, 1993 Ozone Operations Resource Group (OORG) Report writes: "This conversion to cyclopentan has big impacts on the introduction of hydrocarbons in the refrigeration circuit....The introduction of hydrocarbons as refrigerants on the market does only make sense when a totally "green" no HFC containing appliance can be offered. This implies that only those firms that have accelerated the conversion to cyclopentan in the foam (or use XPS) are applying or will apply hydrocarbons in the refrigeration circuit in the short to mid-term. "[76]

---

[74] Heslop, Tracy "Greenpeace Ozone Campaign Newsletter": September, 1994: Internal Greenpeace document.

[75] Source: Mr. Don Grob, Managing Engineer, Underwriters Laboratory, Northbrook, Illinois: June 28 and August 28, 1994 telephone conversations with John Mate, Greenpeace researcher.

[76] OORG 1993, Op.cit., p.7

Part II: Comparison of Isobutan and HFC-134a as Refrigerants in Domestic Refrigeration

A. Environmental Compatibility of Isobutan and HFC-134a

1. Introduction: The competition for zero-ODP substitute refrigerants is today narrowed down to two candidates: hydrocarbons and HFC-134a. Hydrocarbons are relatively benign environmentally, with zero ODP and very low GWP. HFC-134a is a partly halogenated fluorocarbon (HFC) that contains no chlorine. It is therefore not directly involved in the destruction of stratospheric ozone. However, it does have known and suspected negative environmental impacts, especially its contribution to global warming. The prudent course of action, and the precautionary principle, would dictate its immediate ban.

2. HFC="HEADED FOR CATASTROPHE"
Professor Gustav Lorentzen (Norway), in a paper entitled "The Use of Natural Refrigerants, A Complete Solution to the CFC/HCFC Predicament" writes: "It has already been suggested that HFC-134a may be decomposed by sunlight in the troposphere and form acid and poisonous substances. If this should turn out to be true, we may have to face yet another catastrophe, even worse than the CFC experience...The present situation, when CFCs and in a little longer perspective the HCFCs are being banned by international agreement, it does not seem very logical to try to replace them by another family of related halocarbons, the HFCs, equally foreign to nature. In any case it must obviously be much preferable to use natural compounds, which are already circulating in quantity in the biosphere and are known to be harmless." [77]

3. HFC-134a and Global Warming: "The relative greenhouse relevance of HFC-134a is estimated to be 45 % of CFC-12. Its Global Warming Potential (GWP) is estimated to be 3,200 times that of carbon dioxide (over a time span of 20 years).... In discussions about CFC substitutes, their contribution to the greenhouse effect is often calculated on the basis of periods of 100 to 500 years. Since HFC-134a has an average life span of 16 years, and since the next 20 years is deemed to be decisive for the further

---

[77] Lorentzen, Op. Cit., [paper references : Banks, R.E. "Skepticism about R-134a justified" Refrig. Air. Condit., Sept. 1993, p.16])

development of the earth's atmosphere in terms of global warming, it makes sense to calculate the GWP of HFC 134-a on a 20 year time span."[78]

4. 1990 World Production of Refrigerators /Freezers Corresponding R-12 Consumption[79]
(Table 6)

AREA	No. of Units Produced	R12 Usage /Metric Tonnes
Western Europe	15,812,000	2368
Eastern Europe	10,857,000	2171
North America	10,911,000	1940
South America	3,000,000	535
Asia	13,750,000	2184
Africa	1,400,000	238
Australasia	650,000	90
WORLD	56,330,000	9526

"An annual production growth rate of refrigerating capacity (arising from both more and from
bigger cabinets) of 15% for developing countries and 7% for developed countries [is projected]." (See footnote #9)

5. "The domestic refrigeration industry is a rapid growth industry, particularly in developing countries. In 1994, it is estimated that about 4,000 tonnes of CFC-12 will be consumed in the production of refrigeration appliances ."[80]

6. As CFCs are phased out, the total HFCs refrigerant usage globally is projected to rise correspondingly:

Projected Refrigerant Usage (Metric Tonnes) by Years 1990, 1995, 1997, 2000, 2005 including industrialized and developing (Article 5) countries

78 Belazzi, Thomas (Dr.), "A Position Paper of Austrian Scientists and Environmentalists' Groups on the Problems Posed by Alternatives to Ozone-Depleting Substances,", Vienna, March 1993.

79 TOC Report 1991, Op.cit., p.79

80 UNEP, "Proposed Three-Year plan and Budget of the Multilateral Fund (1994-1996)", Op. cit., p. 15

(excluding the use of alternatives, e.g. hydrocarbons): 1991 calculations: [81] (Table 7)

Refrigerant	1990	1995	1997	2000	2005
CFC's	9084	4770	2930	890	0
HCFC's	0	300	500	300	100
HFC's	0	5920	12480	19400	32000

7. Projected HFC-134a production levels threaten the climate: "HFC-134a...is projected to be used at a level that poses significant risk to the climate system. The 1992 Intergovernmental Panel on Climate Change (IPPC) emission scenarios indicate, based on industry market projections, that this gas will be emitted in large volumes in the future unless controlled. By 2025 emission of HFC-134a is projected to approach 500,000 tonnes per year, whose global impact is equivalent to 10% of 1990 emissions of CO_2 from fossil fuels (when compared using a 100 year GWP). IPC projections for 2050 have HFC-134a emissions close to 1 million tonnes per year (more than the 1989 emission of the major CFCs) or nearly 20% of 1990 CO_2 emissions."[82]

"The global warming impact of the worldwide annual production of at least 200,000 tonnes of R134a equals roughly the CO2 emissions of an industrialized nation the size of France or the UK.
In the longer term, the Intergovernmental Panel on Climate Change (IPCC) has estimated that HFC emissions, if unregulated, could reach over thirteen times this level or 2,764,000 tonnes per year in the next century." [83]

8. The utilisation of HFC-134a for refrigeration/air conditioning takes on monumental environmental repercussions when the total amount of HFCs requirement is projected. "The consumption (and emission) of HFCs' (mainly HFC-134a) is estimated to grow to 230,000 tonnes in the year 2005, of which amount 20% will be used in present Article 5 countries. Half of the

[81] TOC Report 1991, Op.cit., p.87

[82] Greenpeace International, "HCFC's and HFC's: The Bad Gamble" , Op.cit., p.30

[83] Lohbeck, Wolo "Greenfreeze: The World's First CFC and HCFC Free Household Refrigerators: And A Worldwide Success for Natural Gas": Paper reprinted in the "Proceedings of the Ozone Safe Cooling 1993 Conference": published by Greenpeace USA (1994)

amount (120,000 tonnes) will be used for automotive air conditioning. About 15% (33,000 tonnes) is estimated to be used in domestic refrigeration, 50% of this in developed, and the other 50% in Article 5 countries.” [84]

9. Environmental impact of HFC-134a production: “The production of HFC-134a, requires the very same fully halogenated CFCs which are to be banned shortly. Fully and partly halogenated CFCs are by-products of the process and are to some extent sold as marketable commodities. It has to be assumed that considerable amounts of these ozone-depleting substances are released into the atmosphere, "closed production cycles" notwithstanding. (e.g., through leaks, diffuse emissions, and accidents)”. [85]

“In addition, HFC-134a production gives rise to considerable amounts of highly toxic wastes (approximately 10% of the total HFC-134a production weight) and substantially increases the need for dangerous chlorine gas and hydrogen fluoride (HF) transports.” [86]

10. Global warming and ozone depletion characteristics of isobutan: Isobutan has zero ODP, and very low GWP. “The GWP of hydrocarbons is due almost entirely to GWP of the CO_2 resulting from decomposition.”[87] Clearly, from this perspective, isobutan is far more desirable than HFC-134a.

---

84 TOC Report 1991, Op.cit., p.21

85 Ibid.

86 Ibid.

87 TOC Report 1991, Op. cit., p.66

B. Safety Considerations: Isobutan and Flammability

"Compared to the dangers of global warming, the risk of flammability from the use of hydrocarbons as refrigerants is very minor. It is a local, limited problem, and is easy to control." [88] --Manfred Dohlinger

1. Introduction: Isobutan is a highly flammable substance with a lower flammability limit of 1.7. It is in the A3 (ANSI/ASHRAE Standard 34)[89] safety group category. For test purposes it is comparable to propane. The flammability of isobutan is mitigated by adequate safety measures, and by the low refrigerant charge required. Safe technology is not a problem. As the researchers at the Institute of Thermal Engineering at Graz University of Engineering in Austria stated: "changing from CFCs and HCFCs to flammable refrigerants like propane is in fact not a problem of technology, it is mainly a problem of regulations". [90]

2. Kitchen fires: There exist relatively low safety risks associated with flammable refrigerants. For instance, "studies predict an increase of the risk of kitchen fires by only 0.04%, when using the flammable refrigerant R-152a."[91]

3. The large German refrigerator manufacturer Bosch has been mass producing hydrocarbon refrigerators since 1993. According to Bosch the possibility of a hydrocarbon-charged refrigerator exploding is one in 5

---

88 Dohlinger, Manfred "Comparative Energy Efficiency of Hydrocarbon Refrigerants", Paper reprinted in the "Proceedings of the Ozone Safe Cooling 1993 Conference": published by Greenpeace USA (1994)

89 European Committee for Electrotechnical Standardization (CENELEC), "Safety of household and similar electrical appliances: Part 2, Particular requirements for refrigerators, food freezers and ice-makers.": Section, 2.2.114

90 H. Halozan, T. Ebner, H. Lawatsch: Institute of Thermal Engineering, Graz University of Technology, Austria: "Propane-A Realistic Alternative", Paper presented at the International Conference - New Applications of Natural Working Fluids in Refrigeration and Airconditioning, 10-13 May, 1994, Hannover, Germany.

91 Liu, B.Y., Tomasek, M.L., Radermacher R., Center for Environmental Energy Engineering (CEEE), University of Maryland, "Tests with R290/R600 Mixtures in a Domestic Refrigerator/Freezer" , Paper presented at the International Conference - New Applications of Natural Working Fluids in Refrigeration and Airconditioning, 10-13 May, 1994, Hannover, Germany.

million. This probability is not especially high when compared to conventional refrigerators. [92]

4. The content of propane or butane in a European domestic refrigerator equals roughly the content of two cigarette lighters. The risk of explosion is minimal: it takes between 17 g/cubic meter and 39 g/cubic meter to create an explosive mixture. Therefore, if the refrigerant were to leak outside the refrigerator, an explosion would be “nearly impossible”.[93]

5. Marek Zgliczynski and Piero Sansalvadore (Aspera Engineering Dpt., Italy) summarise the testing of isobutan in their paper, "Contribution to Safety Aspect Discussion On Isobutan Compressors for Domestic Refrigeration": [94]
"Basic study on isobutan/air flammability behaviour have been conducted . The effect of use of flammable refrigerants in present hermetic compressors for domestic refrigeration has been experimented. Complete failure mode and effect analysis on product and compressor manufacturing have been done. Some safety aspects also on complete refrigeration system has been conducted in particular on compressor electrical safety behaviour.... Summarising the elements for risk assessment in use of hydrocarbon compressors are the following:

* Creation of explosive mixtures inside the shell
* Creation of explosive mixture around the shell
* Ignition potential of internal electrical parts
* Ignition potential of external electrical parts
* Severity of internal explosion
* Severity of flame or explosion outside the compressor shell

In summary we can conclude that compressor shell have enough strength to withstand the internal explosion and extremely low leakage probability. Small modification in electrical components can eliminate the possibility of spark generation around the compressor shell. Further investigations are in progress on starting device and electrical connection board. Final purpose

92 Greenpeace Japan, Op.cit., p. 20

93 Lohbeck, Wolo, “Greenfreeze”, Op. cit.

94 Zgliczynski,Marek & Sansalvadore, Piero: Aspera Engineering Dpt., TO Italy: "Contribution to Safety Aspect Discussion On Isobutan Compressors for Domestic Refrigeration", Paper presented at the International Conference - New Applications of Natural Working Fluids in Refrigeration and Airconditioning, 10-13 May, 1994, Hannover, Germany.

of this research is to assess the risk and compare it with the other risks already present in the normal life. Considering the present knowledge we can conclude that the risk coming from isobutan compressor seems to be reasonably low."

6. J F Missenden, M Eftekhari, and R W James (UK: South Bank Polytechnic) write in their 1991 paper: "The Use of Propane in Refrigeration Systems": "The refrigerant quantity when using propane is about half that which is required with R12 by mass [i.e. about one third of the hydrocarbons contained in the average cigarette lighter refill cartridge].

With propane, which is a petroleum product, the solubility of the refrigerant into the oil is higher than with R 12 and the refrigerant charge is smaller. The combined effect is that a much larger proportion of the propane migrates to the compressor oil than with R12. Consequently, less of the refrigerant would be immediately leaked to the atmosphere in case of a major discharge.

From a total loss of charge mass at atmospheric pressure, the propane vapour available from a 5 ft^3 domestic refrigerator would occupy about 0.014 m^3, less than the amount of natural gas trapped between the gas meter and appliances in many houses. One way of assessing the risk associated with using propane as a refrigerant is to consider what quantity of propane would need to be released in order to create a combustible mixture with air in a small kitchen. A very small kitchen would have a volume of 20 m^3. At the lower inflammable limit (2.3% propane) this would require the release of 650 g of propane. Typically a 5 ft3 domestic refrigerator would contain only 40 g of propane and would lose only 14 g of this to the atmosphere; an order of magnitude below the ignition point. In addition a large proportion of this propane will not be released by the compressor oil in the short term." [95]

7. E. Bodio, M. Chorowski, M. Wilczek (Technical University, Wroclaw, Poland) write in their paper, "Propane-Butane - An Environmentally Friendly Refrigerant": "New refrigerants should be characterised by zero or close to zero values of ODP and GWP coefficiencies....The alternative refrigerants should also be compatible with existing refrigerators and lubricants...[and] they should be non-toxic and non-flammable.

---

[95] Missenden, J.F.; Eftekhari, M; & James, R.W., South Bank Polytechnic, U.K., "The Use of Propane in Refrigeration Systems"

[In] domestic refrigerators...the condition of non-flammability is not a crucial one [because] (a) modern hermetic compressors are highly reliable, (b) amount of refrigerant filling the domestic refrigerator is small and does not cause the danger of explosion.

Theoretical considerations and experimental results enable us to state that a propane-butane mixture can be a substitute refrigerant for R12. The mixture is especially suitable for small domestic units where flammability can be neglected." [96]

8. Minimal change in product engineering required: The 1993 OORG Report writes: "Virtually all compressor manufacturers state that ... marginal product engineering would be needed to convert production lines to hydrocarbon based compressors. In order to cope with flammability, minimal product changes would be required, mainly in the field of electrical connections and feed through." [97]

9. Toxicity and flammability: "The products of combustion from propane are much less dangerous than those of R12 leaking in the vicinity of a flame where intensely toxic products such as carbonyl chloride (phosgene) or $COCl_2$ could be produced. If a kitchen fire was sufficiently fierce to raise the refrigerant to the pressure at which rupture occurred then an additional 40 g of propane would be insignificant. Indeed the toxic fumes from the cabinet and its insulation would be a much greater hazard and would include cyanides and choking smoke. By contrast propane burns cleanly and completely with a minimum of toxic products. It should also be noted that most fire injuries are due to smoke inhalation, not to burns or explosions. " 98

10. Study of Norwegian Refrigerant Accidents: "A study of the case histories of refrigeration accidents in Norway over the last decades leads to the following conclusions: The fatal accidents recorded are equally divided

---

[96] Bodio, E.; Chorowski, M; Wilczek, M: Technical University, Wroclaw, Poland: "Propane-Butane - An Environmentally Friendly Refrigerant", Paper presented at the International Conference - New Applications of Natural Working Fluids in Refrigeration and Airconditioning, 10-13 May, 1994, Hannover, Germany.

[97] OORG 1993, Op.cit. p12

[98] Missenden, J.F., Op. cit.. p.6

on ammonia and halocarbon plants. Taking into consideration that by far greater number of large refrigeration systems in the country, and all the older ones, are of ammonia type, this implies that this refrigerant is probably the safer choice with present technical standards. The fact that the majority of the near fatal cases were caused by halocarbons points in the same direction. The strong warning smell of ammonia is an invaluable asset, but at the same time may cause undue alarm and often leads to evacuation of a large area. This is very different from a halocarbon release, which is sneaky in nature and often gives no warning before somebody is rendered unconscious or killed. Most near fatal accidents are hardly published at all. As a result the public gets a completely distorted impression of the relative danger of the two types of refrigerant." [99]

11. Liability concerns in the U.S.: Greenpeace held a series of meetings with refrigerator manufacturers in the United States in 1993. One of the concerns repeatedly raised was liability. However, the solution to the liability issue seems to be at hand. Bill Walsh, one of the Greenpeace representatives at these meetings writes: “At first it appeared that it will be very hard to overcome the liability issue. However, Whirlpool and Wood make a good case that liability is not the real issue (at a mere $10 cost per fridge the industry could establish an annual $60 million liability fund, for example). Rather a loss of reputation or forced recall of the product is of greater concern." [100]

12. “No-frost” technological challenge solved for hydrocarbon refrigerators:

(a) The “no-frost” technology, which is a standard feature with 80-90% of domestic refrigerators sold in the North American and Japanese markets, has been seen as a major obstacle to hydrocarbon refrigeration. The 1993, OORG Report writes that no-frost appliances will face the greatest engineering challenge to "achieve solutions with acceptable flammability/explosion risks...Risk studies for this kind of appliances (based on actual construction features) end up with hazards some hundred times higher than [for smaller units], which can certainly not be tolerated (1 per

---

[99] Lorentzen, Gustav & Lunde, Helge: "Accidents and Critical Situations Due to Unintentional Escape of Refrigerants: A Survey of Cases in Norway over the Last Decades", Paper presented at the International Conference - New Applications of Natural Working Fluids in Refrigeration and Airconditioning, 10-13 May, 1994, Hannover, Germany.

[100] Walsh, Bill , “Report on US Fridge Manufacturers Meetings”, May 24, 1993, internal Greenpeace memo.

100-300 thousand)."[101] Similarly, the March/May 1994 World Bank Report's summary of the Second OORG Refrigeration Working Group Meeting in Hannover, writes that the use of "...isobutan for...certain applications such as no-frost refrigerators may never be possible due to possibly unavoidable safety risks".[102]

(b) "No-frost" refrigerator to be on the market in 1995: Dr. Ballhaus, Technical Director for Liebherr, announced on September 12, 1994 that the company plans to convert its latest "no-frost" model refrigerator to 'Greenfreeze' hydrocarbon technology within the first half of 1995. It is expected that other German manufacturers will follow suit.[103]

13. Hydrocarbon refrigerants in mobile air conditioning: The safety of hydrocarbon refrigeration results from the relative low charge required to accomplish similar or better values then is needed by CFC-12. This factor is taken into account not only in domestic refrigeration, but also in mobile air conditioning, which by its nature represents a greater risk. A study to "Measure the Insurance Risk of Hydrocarbon Refrigerants in Motor Cars" found that "only 40% of the mass [of hydrocarbons] is required compared to R12 or R134a....[For] a medium sized Australian car the charge of hydrocarbon is about 300g (10.6 oz.) the same as a large aerosol can." Furthermore, the study concludes that "changing from R12 to saturated [hydrocarbon] refrigerant increases the fire insurance risk [slightly] but reduces the refrigerant loss and recovery risk...[so that] ...hydrocarbons reduce the insurance risk by $2.30 /year."[104]

C. Regulatory Recommendations for use of Hydrocarbon Refrigerants in Domestic Refrigerator/Freezers

---

101 OORG 1993, Op. Cit., p.26

102 World Bank Report, "Facing the Global", March-May, 1994, Section: Portfolio Review, Ozone Layer Protection.

103 Wolfgang, Wolo, "Greenfreeze: No Frost Technology", internal Greenpeace memo, reporting on conversation with Dr. Ballhaus, September 12, 1994

104 Maclaine-cross, I.L.: School of Mechanical and Manufacturing Engineering: University of New South Wales, Australia: " Fireball, A Brief report on Pilot Experiments to Measure the Insurance Risk of Hydrocarbon Refrigerants in Motor Cars" ,January, 1993

1. U.S. Recommended Standards: Underwriters Laboratory: Proposed Safety Requirements for Refrigerators that Employ a Flammable Refrigerant (Annex DD: UL): [105]

(a) (DD2.2) Refrigerants are Classified for flammability (in accordance with the Standard for Number Designation of Refrigerants, ANSI/ASHRAE 34-1992 into "Group 1-no flame propagation", "Group 2-lower flammability", and "Group 3-higher flammability".

(b) (DD2.3) The charge size for refrigerators or freezers that employ a "lower flammability" refrigerant shall not exceed 1 lb. The charge size for refrigerators or freezers that employ a "higher flammability" refrigerant shall not exceed 1/4 lb (4oz= 113.4 g). *

(c) Proposed safety requirements (UL Bulletin 250, March 17, 1993): based on flammability studies, risk analysis and practical application; objective is to reduce the possibility of a leak, keep a leak from causing the lower flammable limit (2.15% propane vapour in air-gas mixture) to be reached, and avoid the risk of ignition. The recommendation of 1/4 lb “higher flammability” refrigerant charge has been tested and approved by Underwriters Laboratory.[106]

2. European Community Recommended Standards: The final recommendations for European standards are yet to be approved by International Electrotechnical Commission (IEC) and European Committee for Electrotechnical Standardization (CENELEC). This approval is due in the Fall of 1994.

(a) “The Technischer Ueberwachungsverein (TUEV), the German Safety and Standards Institution has approved the [hydrocarbon based] 'Greenfreeze' Models as "safe and tested" and states that as a result of their investigations "there are no dangers in the use, transport and storage of this refrigerator due to the use of the liquid gas as a cooling agent" and that "appearance and explosion of propane butane inside the refrigerator can be practically excluded". Its safety-sign is valid for the entire European Community market.

---

105 Underwriters Laboratory, “Annex DD: Proposed Safety Requirements for Refrigerators that Employ a Flammable Refrigerant”, August, 1993, Section DD2

106 Source: Don Grob, Op.cit.

Upcoming European legislation will allow up to one kilogram (1.0 Kg.) of inflammable refrigerant without restriction. The standards body co-ordinating the work has told Greenpeace that the EN 378 European Refrigeration Standard "does provide for propane as an-alternative refrigerant in small hermetically sealed systems".

Technical standards for testing of hydrocarbon-refrigerators are underway under the authority of the International Electrotechnical Committee (IEC) and its European body (CENELEC). After their publication as a European standard (autumn 94) and world-wide (mid 95), the last barriers against trade in several countries will have fallen." [107]

(b) UK Department of the Environment: "It should be noted that a domestic system would contain only about 100g of propane in a hermetically sealed refrigeration circuit. This may represent no more risk than other domestically used quantities of propane and far less risk than the large quantities of natural gas that could escape from a cooker or boiler. A draft European Standard on Refrigeration Safety is proposing that systems with less than 1 kg of propane charge can be used without restriction." [108]

(c) Missenden et.al. write: "It is proposed that group 3 refrigerant [i.e. with flammable and explosive characteristics] should be allowed to be used in domestic appliances providing the maximum refrigerant charge does not exceed 300 grams and the system has been designed for intrinsic safety."[109]

3. The July, 1994 CENELEC draft amendment to the draft European Standard EN 60335-2-24:1994 includes the following safety measures among its recommendations for compression-type appliances using flammable refrigerants:

(a) " [The appliance shall...be marked with [a clearly visible] symbol "Caution, risk of fire";

---

107 Lohbeck, Wolo , "Greenfreeze", Op. cit. p.39

108 UK Department of the Environment, Global Atmosphere Division: March Consulting Group (October 1992)

109 Missenden, Op. cit.

(b) Instruction sheet shall include: i. information for handling, installation, cleaning, servicing and disposal; ii. for appliances using more than 105 g of flammable refrigerants the minimum volume of the room in which the appliance can be installed...(a uniform gas concentration of 144 g of isobutan in a 3mm^3 volume is approximately equal to the lower explosive limit); iii. a warning to keep ventilation openings clear of obstruction.

(c) Compression-type appliances using flammable refrigerants shall be constructed so that leaked refrigerant will not stagnate so as to cause a fire or explosion hazard in areas outside the food storage compartments where the appliance electrical components are fitted -- Separate components such as thermostats which contain less than 0.5 g of flammable refrigerants are not considered to cause a fire or explosion hazard in the event of a leakage.

(d) The cooling system...shall be protected against corrosion due to electrochemical action or oxidation."[110]

D: Quantity of Hydrocarbon Charge Needed in a Domestic Refrigerator

1. The amount of refrigerant charge needed in a domestic refrigerator will vary according to refrigerator size and type of technology.

1991 Estimates of Average Size of Refrigerators and Average Charge of Refrigerant Used by Regions/Countries [111] (Table 8)

Area / Country	Average Size (in liters)	Average Charge (CFC-12)
Western Europe	200	140 g.
Eastern Europe	180	200 g.
North America	440	180 g.
Japan	300	160 g
India	165	140 g
Brazil	175	180 g

(Metric Conversions : Refrigerator Sizes & Refrigerants:(a) To convert from liters to cu. ft.
multiply by: .03531566 (b) To convert from cu. ft. to liters multiply by: 28.31605

110 CENELEC, Op. cit.

111 TOC Report 1991, Op. cit., p.79

(c) To convert from grams to ounces divide by 28.3.)

2. Centre for Environmental Energy Engineering (CEEE), University of Maryland: "The refrigerant mixture R290/R600 was tested as a drop-in substitute in a domestic 20 cu. ft. [automatic defrost, top mounted] refrigerator/freezer unit. To find the best performance, tests were conducted for several lengths of capillary tube and varying mixture concentration and charge. The highest [energy] savings of 6.5% were achieved with a blend of 70% R290 and 30% R600....The charge was 70g, which is 71% less than the R-12 charge [240g]."[112]

3. Missenden writes: "A small system with an R12 charge or 100 grams would by ratio of liquid density have an R22 charge of 92 grams, or an R290 charge of 38 grams. For systems with hermetic compressors there would be an additional small quantity of refrigerant in the shell, some of which would be dissolved in the compressor's oil." [113]

4. According to Dr. H. Preisendanz (Refrigeration Engineer) the amount of charge required to replace R-12 is 90% with HFC-134a, and 30-40% with R290 and R600.

E. Efficiency of Hydrocarbon Refrigerants compared with HFC-134a & CFC-12

"There is a consensus of informed opinion that if energy efficiency is an important goal, then hydrocarbons such as propane are the right way to go for small scale refrigeration." [114]

--John Missenden, South Bank University, UK

1. The UNEP Information Paper (July, 1994) "Elimination of CFC from Domestic Refrigeration Manufacture" writes: "Testing to date shows that refrigerators with HC-600a [isobutan] systems are nearly always more

112 Liu et. al., Op.cit.

113 Missenden, Op. cit.

114 Waide, Paul & Herring Horace, "Refrigerators, Energy, & Climate: Mandatory Energy Efficiency Standards for Domestic Refrigeration Units in the European Union: Analysis of the Draft EU Directive and Alternative Proposals for a Standard",
Report commissioned by Greenpeace International, December 1993, p.56

efficient than equivalent ones using HFC-134a and often more efficient than those using CFC-12. Because there are other factors that make rigorous comparisons difficult (such as variations in compressor and system optimisation) it is not surprising that minor variations are found between cabinet types. Advantage with HC-600a increases by several percent when the ambient test temperature moves up from 10^0 C to 32^0 C." [115]

2. Thermodynamic Capacities of HFC-134a and Isobutan:

(a) "The thermodynamic capacity of HFC-134a is 12% below CFC-12 at the standard refrigerant rating conditions (-100F evaporator, 1300F condenser) used by compressor manufacturers for performance measurements on calorimeters." [116]

(b) "In preliminary calorimeter testing of R-600a compressors with mineral oil, results showed a 6% improvement in efficiency over CFC-12 at standard rating conditions. In systems operating at cooler condensing temperatures (115^0F), the efficiency gain is projected to be approximately 13%." [117]

3. HFC-134a A Dubious Substitute: Albrecht Meyer (Engineer at DKK Scharfenstein writes: "Today's trend is to substitute R-12 by R-134a. But if R-134a performance data is compared to R-12 its poor energy efficiency becomes evident- especially with the low evaporation temperatures (-15^0 to -40^0C) and operation in small domestic hermetic compressors. These facts, and the high portion of fluorine in R-134a, make the use of R-134a as a substitute dubious....Despite the poor thermodynamic properties of R-134a compared to R-12 a lot of brain power and effort has gone into achieving similar efficiencies. With hydrocarbons however, used in those newly optimised compressors, it will be easily possible to come up with still better energy consumption....[With] properly adjusted blends of hydrocarbons it is possible to achieve very low power consumption."[118]

---

115 UNEP, "Elimination of CFCs", Part 1, Section 2.2.1, p.4

116 TOC Report 1994: Montreal Protocol: "1994 Assessment: Refrigeration, Air Conditioning and Heat Pumps: Technical Options Committee":Draft: May 1994, Section 3.2

117 Ibid., Section 3.2.2.1

118 Meyer, Albrecht (Engineer M.D. Scharfenstein), "The Success Of Hydrocarbons In Domestic Refrigeration: Energy Efficient And Environmentally Friendly"

4. GREENFREEZE ENERGY SAVING UP TO 50%: The following statement is from the Bosch-Siemens 1993 Annual Report: "A new line of refrigerators/(freezers) are distinguishing themselves with the thick 'super-insulation' as well as with a specially designed refrigeration cycle and compressor. With this (technology) an energy saving of up to 50% has been realised. The most energy efficient unit, with a capacity of 360 liters (12.7 cu. ft) unit is complete CFC and HFC free and has an energy consumption of .10kWh/100 liters. This is the equivalent of the energy consumption of a 15 Watt light bulb." [119]

F. Cost Factors: Hydrocarbon and HFC-134a Refrigerants

1. The price of HFC-134a varies according to volume and place of purchase. Global Survey Summary (March, 1994) : Costs of HFC-134a in $US per Kg. [120] (Table 9)

Price/Kg	Australia	Canada	Japan	Malaysia	Taiwan	U.S.	EC
Whole-sale	$19.04	$30.75 *	N/A	$15.54	$11.10	$12.76	$15.00
Retail	$45.87	$47.25	$28.80	$26.90	$74.10	$39.80	$60.00

* Allied-Signal Canada quoted a lesser wholesale price of $13.86 - $15.40/kg Canadian
(plus tax) depending on volume.

119 Source: Memo from Wolo Lohbeck: August 26, 1994

120 TOC Report 1994, Op.cit., Chapter 10, p.10

2. The price of Hydrocarbon Refrigerants in Germany (1994)[121] (Table 10)

Purity Level	Cost DM/Kg	
99.95%	30-35	($16.85-19.66 US)
99.9%	22-25	($12.35-14.04 US)
97%	10	($ 5.61 US)

3. Comparative prices of CFC-12, HFC-134a and HC-290 (propane) in Japan: 1993[122] (Table 11)

SUBSTANCE	PRICE (approx.) (¥/kg)	$US	CHARGE (g/refrigerator)
CFC-12	300	$3.00	180
HFC-134a	800	$8.00	150
HC-290 (propane)	300	$3.00	40

4. Purity levels influence costs: "The purity requirements of "natural" refrigerants are still being established. Synthesised refrigerants (CFCs, HCFCs and HFCs) can be produced with a very high purity. It has been easy for their manufacturing processes to meet the tight specification of existing refrigerant standards such as EN 378. Such purity levels are difficult to meet in case of hydrocarbons produced with fractional distillation processes involving stripping HC-600a from a gas field or refinery hydrocarbon stream....It is likely that in the future purity level specified will be modified so that suitable refrigerant can be obtained by distillation. Thus a specification may emerge for HC-600a to have (for example) a minimum purity of 97% with no more than 2.5% N butane, no more than 1% propane, no more than 0.2% of any other hydrocarbon and with very tight limits on water, non condensables and such carcinogens as benzene.”[123] [Such specification should have a decreasing impact on the volume cost of isobutan.]

121 Source: Dr. H. Preisendanz

122 Greenpeace Japan, Op. cit. p.9

123 UNEP, “Elimination of CFCs”, Op. cit., Part 1, Section 2.2.2., p.4

5. The refrigerant charge with hydrocarbons requires smaller amounts (30-40% of CFC-12 charge) than with HFC-134a (90% of CFC-12 charge), resulting in further savings.

6. Costs of Conversion of Production Lines:

(a) 1993 OORG Report writes: "Different opinions exist concerning the costs for conversion. Some [manufacturers] state that the conversion costs [with hydrocarbons] would be much lower than the costs for converting from CFC-12 to HFC-134a (two specific manufacturers mention that the costs for conversion are 20-25% of the costs of converting to HCFC-134a ...However, others (manufacturers with a total production volume of 17 million compressors) state that the conversion costs will be comparable to the ones for HFC-134a." [124]

(b) In Article 5 developing countries “the cost of conversion from CFC-12 to HFC-134a technology for refrigerator manufacturers is estimated to be around US $1 million per plant.

This cost includes capital cost of equipment for assembly line related to the new lubricant and refrigerant and technical assistance.”[125]

(c) OORG states: "Very substantial modifications will be necessary for converting the whole production range of manufacturer to hydrocarbons...[i.e.] huge investments in production to handle flammable/explosive material and to meet stringent safety requirements [these costs are estimated at] $7 million US for a typical production of one million appliances per year... part of this money is [for converting] to the flammable blowing agent cyclopentan. “[126]

(d) “CFC-12 test facilities do not have to be completely rebuilt [with hydrocarbons] as with HFC-134a “[127] “[The] manufacturing of compressors and appliances based on HFC-134a technology implies much higher stringency in the requirements for the quality of the production environment ...[than with CFC-12]...It is recommended that conversion from CFC-12 to HFC-134a technology should be accomplished in two phases. The first phase should involve testing of the HFC-134a technology in the

---

124 OORG 1993, Op.cit. p.12

125 UNEP, “Proposed Three-Year plan and Budget of the Multilateral Fund (1994-1996)”, Op,cit. p. 15

126 Ibid. p.7

127 Ibid. p11

manufacturing process through a pilot project, and the second phase is a full-scale conversion."[128]

7. Costs due to technical problems with HFC-134a: "Compared to other refrigerants (both CFC 12 and hydrocarbons such as propane/butane), HFC-134a is a highly unstable substance that causes serious problems in the refrigerating cycle if only small amounts of water, chlorinated hydrocarbons or CFC-12 - the refrigerant used up to now -- are present. As a consequence, virtually water-free conditions are required during the initial filling of an HFC-134a refrigerating cycle, but also for its entire operation (which may last up to several decades). "On-site" refilling, repairs, etc. are therefore expensive and difficult to carry out when HFC-134a is used (due to atmospheric humidity)."

"The possibility can therefore not be ruled out that HFC-134a refrigerating systems (e.g., in fridges) may have a shorter life span than traditional or environmentally sound systems using, for example, various hydrocarbon mixes. At lower temperatures, miscibility gaps between HFC-134a, ester oil and water may occur, causing increased compressor wear and reducing the life span of the refrigerating equipment. For the same reasons already cited, HFC-134a is entirely unsuitable as a drop-in (substitute for fully and partly halogenated CFCs) in existing systems." [129]

8. Cost of Lubricants: "Because conventional refrigerator lubricants will not dissolve in HFCs...HFC-134a needs ester oil. Ester oil is subject to hydrolysis and other problems, needing special care, which would tend to raise production and refrigerator costs (Sunami 1993). Ester oil is patented, and its price is several times higher than conventional lubricants " [130] UNEP concurs that "synthetic ester oils used with HFC-134a will always be several dollars per litre more expensive than the mineral oils commonly used in CFC-12 compressors."[131]

---

128 UNEP, "Proposed Three-Year plan and Budget of the Multilateral Fund (1994-1996)", Op. Cit. p 15

129 Belazzi, Op. Cit.

130 Greenpeace Japan, Op.cit., p.22

131 UNEP, "Elimination of CFCs", Op. Cit., Part 1, p.12

9. Compressor costs:

a. "HFC-134a compressors were introduced to the market in 1991 at some 15% to 20% price premium [over CFC-12 compressors]... [Since '91 the prices have reduced to] 3% to 8% higher....[Isobutan compressors in Europe] are being purchased for price equivalent to that using HFC-134a...[with] prices yet to stabilise in other parts of the world."[132]

b. "The cost of conversion from CFC-12 to HFC-134a technology for compressor manufacturers [in Article 5 countries] is estimated to be US $1.5 million per plant."[133]

c. "Refrigerator manufacturers in Article 5 countries which do not produce HFC-134a compressors will incur an incremental cost of about US $10 per imported new compressor."[134]

10. HFC-134a patented technology costs more: HFC-134a and its required lubricant oils are patented substances. Isobutan, is a non-patentable, widely available natural substance, that is compatible with natural mineral oils.

11. Recovery Costs: The cost of recovery and destruction of HFC-134a is presently externalised from the overall cost estimates of the product and the technology. These costs should be internalised into the unit price of HFC-134a to reflect the true cost of the substance. Hydrocarbons do not need to be recovered, so no similar costs are incurred.

G. Drop-In Possibilities: HFC-134a and Hydrocarbons

1. HFC-134a not practical for drop-in: "The option of using HFC-134a as a service retrofit of existing CFC-12 charged refrigerator-freezers is not practical. There is concern that the time required, the flushing routine, and the compatibility with previous system mixtures prevents satisfactory performance." [135] HFC-134a is therefore only applicable in new systems.

---

132 Ibid., p.12

133 UNEP, "Proposed Three-Year plan and Budget of the Multilateral Fund (1994-1996)", Op. Cit. p 15

134 Ibid. p.16

135 TOC 1994, Op.cit., Section 3.3.2.3

2. Leakage Problems: “HFCs are more prone to leak than CFCs, and the annual rate of CFC leakage, [for example], in the UK refrigeration and air conditioning industry is about 20% of the total charge - thousands of tonnes. According to the Government Building Research Establishment (BRE : a UK Government Body)”[136]: “Leakage can also be a consequence of conversion to a new refrigerant. For example, when CFC-12 or CFC-502 machine is converted to HFC-134a, leakage is more likely to occur because the HFC-134a molecule is smaller and can permeate through openings more easily. HFC-134a also has powerful solvent properties and could, for example, cause a sealing film of oil between a flange face and its mating gasket to be flushed away, creating a route for refrigerant leakage. Another problem is that the new refrigerant may react with, and cause dimensional changes in, certain elastomeric materials in seals and gaskets.”[137]

3. In 1994 there have been two announcements regarding hydrocarbon drop-in refrigerants: (a) U.K.: Calor Gas “Care.30” and (b) USA: Intervest Environmental Inc. “ES-12”. The appearance of these products on the market is further indication of the direction the technology is headed. In its promotion of “Care 30” Calor Gas states:
“In replacing R-12, which was one of the most widely used CFC refrigerants most of the alternatives have had two things in common: they are costly and not easy to install. One of the main contenders is R-134a, which involves expensive changes to existing equipment and the use of new types of oil, which can usually only be purchased from the refrigerant manufacturers. The cost to users in making the change has been high, and the efficacy of the product far from established....’CARE 30’ provides the solution. Not only can it be fitted without making changes to equipment, but it is cheaper and more efficient. The main constituents of ‘CARE 30’ have been on the planet since time began: the hydrocarbons propane and butane....’CARE 30’ has an atmospheric lifetime of <1 years, GWP of 24 (20 years), and zero ODP.”[138]

---

136 Greenpeace International, “Tehnology Update”, July, 1992 : Distributed at the Tenth Open-Ended Working Group of the Parties to the Montreal Protocol, Nairobi, 5-8 July 1994

137 Butler, David, “Refrigerant Leakage and Detection”, Building Research Establishment, September 1993: as quoted in Greenpeace International, “Tehnology Update”, July, 1992

138 Calor Gas Refrigeration, Millbrook Trading Estate, Millbrook, Southhampton, SO9 1WE, (Freephone- 0800-373-796: Fax-0703-789-228): Promotional materials. 1994

As the commentary regarding Calor's announcement stated in the Refrigeration and Air Conditioning Journal (June, 1994):

"The news that Calor Gas is moving into the refrigerants business, with a new family of hydrocarbon-based gasses, is likely to send some shivers of foreboding through some quarters of the industry. Not least, perhaps, among suppliers of 'traditional' alternative refrigerants, who have pinned their hopes, and a few million pounds in development costs, on the new generation of non-flammable fluorinated refrigerants now coming on-stream....[Calor] has practical field trials to back its claims, and some heavyweight research names supporting the case for hydrocarbon based refrigerants."

4. The Dutch organisation ECOZONE has been working with the Pakistan Holland Metal Project (PHMP) in Peshawar on a training course for fridge technicians in the use of hydrocarbon technology. A local refrigerator repair workshop charged 10 refrigerators with Fongas (a local name for LPG) and monitored the results over 10 months. No complaints were received from customers and the fridges are still working well. The company "Quite Cool Engineering" lists costs as (one twentieth compared to CFCs) and the fact that no technical changes are necessary, as major advantages of Fongas. The owner, Mr Qureshi, added that with 134a ~....we [would] have to replace the compressor and the lubricant. That would mean I can close my business, because no customer will be willing to pay me the cost of repairs of that kind. They would be better of buying a new fridge."[139]

5. Africa: Climate Action Network (CAN) Africa is working together with the National Environment Secretariat and the National Refrigeration Demonstration Centre of the Kenyan Polytechnic on a proposal to demonstrate hydrocarbon technology in Kenya. Despite receiving training from the World Bank in HFC-134a conversion, the National Refrigeration

---

139 'gate' No. 2/94, June 1994, p. 29 "Ecozone: Ozone Safe Cooling in Developing Countries", Publisher: GATE Deutsche Gesellschaft für Zusammenarbeit (GTZ), GmbH (German Agency for Technical Cooperation), Post Box 5180, D-65726 Eschborn, Germany, Tel: 49 61 9679-0

ECOZONE is a group of companies and consultants covering a range of expertise in refrigeration technology, R&D, legal knowledge on the climate issue, international treaties and small enterprise development in developing countries. Address: ECOZONE c/o Ecotec Resource BV, Kleverparkweg, 17A, NL-2023 AC Haarlem, The Netherlands. Fax: 31 23 278045.

Workers Association of Ghana are reluctant to switch to this expensive chemical. Together with Friends of the Earth Ghana, a training course is now planned in the conversion of existing refrigerators to run with hydrocarbons. 80% of the country's domestic market are second-hand refrigerators from Europe. Two years ago, the Netherlands who ship 200,000 of these fridges a year to West Africa decided to convert them to propane in order not to be accused of chemical dumping later on. The project aims to develop capacity for retrofitting in Ghana itself. [140]

H. Recovery Considerations: HFC-134a and Hydrocarbon Refrigerants

1. Due to its potent global warming potential (GWP) HFC-134a will have to be recovered and eventually destroyed. "HFC 134a would have to be recycled with the aid of vacuum pumps at great outlay and costs. This makes recovery of these greenhouse gases most unlikely. Even in Germany no more than 5 per cent of annual CFC-production is recovered today. As a result, anyone who chooses R134a will cause themselves non-ending environmental discussions as well as technical and economic problems." [141]

2. Due to their low GWP hydrocarbon refrigerants do not need to be recovered.

I. Market Prospects for Hydrocarbon and HFC-134a Refrigerants

1. Hydrocarbon refrigerants have taken over the domestic refrigerator market in Europe . All the major European manufacturers have converted, or are in the process of converting to hydrocarbon based Greenfreeze technology . The Greenfreeze technology is spreading to other parts of the world, including developing countries.

2. Hydrocarbon technology and developing countries: Developing countries can ill afford the two step phase out from CFCs currently pursued in the US. As Dr. Sukumar Devotta (Engineering Services, National Chemical Laboratory, India), who is recognised as "the most knowledgeable specialist

140 Ibid.

141 Lohbeck, Wolo, "Greenfreeze", Op. cit., p.37

on CFCs and CFCs substitutes in India" [142] states: "There are some developing countries, e.g. India and China, which are self reliant in the manufacture of both refrigerants and related hardware with a substantial domestic market. The developing countries cannot afford double changes. They would prefer to assess the merits and demerits of the possible alternatives before making a final choice so as to continue to maintain their current technological independence...." [143]

3. Hydrocarbon technology has greater promise for India and other developing countries:

(a) Mr. Burzin J. Wadia (Vice President-Manufacturing, Godrej-GE Appliances, Vikhroli, Bombay) states: "Hydrocarbon [refrigerant] is interesting for us, because it requires only minor changes in the production line. Whereas HFC-134a requires a much more stringent manufacturing process, especially difficult for us to achieve in a very humid place like Bombay. But with hydrocarbons, there is the problem of flammability. We want to see the results of the European experience. The fact that European manufacturers are now largely using hydrocarbons is of great help to us if we were to choose hydrocarbons."[144]

(b) Dr. Devotta states: "We think that hydrocarbons are attractive for India, because this technology imply minimum changes of the compressor and the manufacturing process. India already has all the technology to produce and manage hydrocarbons, which are cheap, and we have the appropriate lubricants. So, with hydrocarbons we would not be constrained by technological dependence. The situation would be totally the opposite with 134a..."[145] [With HFC-134a]"there is a significant change in the compressor and system component design e.g. heat exchangers, lubricant, filter dryer etc. The use of HFC-134a demands a very stringent quality control during manufacture and service. There is still some uncertainty on

---

[142] Erkman, Suren, "Excerpts from an interview with Dr. Sukumar Devotta (Head, Engineering Services, National Chemical Laboratory, Pune, India), March 30, 1994:
as faxed to Ravi Sharma, Down To Earth, April 12, 1994.

[143] Devotta, Op. Cit.

[144] Erkman, Suren, "Excerpts from an interview with Mr. Burzin J. Wadia (Vice President-Manufacturing, Godrej-GE Appliances, Vikhroli, Bombay), April 9, 1994:
as faxed to Ravi Sharma, Down To Earth, April 12, 1994.

[145] Erkman, Suren, "Devotta interview", Op. cit.

the long term acceptance of HFCs, particularly in Europe, with respect to the greenhouse effect as HFC-134a has a relatively high GWP....

"Hydrocarbons are naturally occurring, readily available, much cheaper and thermodynamically attractive. Most adverse impressions on the safety are based on the past data when safer design features were not incorporated....Currently, the general impression is that with the current technological advances, the safety requirements should be surmountable...In general, there is a sufficient prospect for the introduction of hydrocarbon based green refrigerators in India." [146]

4. Western and Japanese products serve as role models for markets in developing countries. This places another level of responsibility upon decision makers who determine the future of technological development. As Dr. Devotta states: "There is a marketing problem in India: people want the US, Japanese or European label. Companies are worried that competitors might begin to sell HFC-134a cooled fridges, advertising the fact that they use the same technology as General Electric. etc.. The investors also feel happy when there are such alliances with well known Western companies..."[147]

5. Future of HFC-134a in question: Because of the negative environmental impact of HCFCs and HFCs "...pressures are being applied by some parties to the Montreal Protocol for acceleration of the HCFC phase out and similar pressures to set an HFC phase out schedule are being applied in the working groups leading up to the first meeting of the Committee of the parties to the Rio Convention....In the Intergovernmental Negotiating Committee (INC) meetings leading up to the first meeting of the committee of the parties (COP) to the Rio Convention, March 1995, there is pressure to establish a climate change protocol restricting the use of selected greenhouse gases, particularly the per fluorocarbons (PFCs) and the hydrofluorocarbon (HFCs)...."[148]

---

146 Devotta, Op. Cit.

147 Erkman, Suren, "Devotta interview", Op.cit.

148 TOC Report 1994, Op.cit., Section 8. p.17-18

"The Climate Convention signed at the Earth Summit in Rio (June 1992) states that emissions of greenhouse gases should be returned to their 1990 levels, by the year 2000 and since HFCs were not produced or used in significant quantities in 1990, their future is now in serious doubt....Article 4.2b of the Framework Climate Convention states: 'Each of the Parties shall communicate [...] detailed information on its policies and measures [...] with the aim of returning individually or jointly to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases not controlled by the Montreal Protocol."[149]

6. US Government's 'Climate Change Action Plan' targets HFCs: The US Administration announced in October, 1993 its concerns regarding the global warming potentials of HFCs.
"Due to high global warming potentials, high atmospheric lifetimes, and increasing emissions, hydrofluorocarbons (HFCs) are a growing contributors to the climate change problem...[President Clinton] "is directing the EPA to use its authority under the Clean Air Act to narrow the scope of uses allowed for HFCs with high global warming potentials where better alternatives exist."[150]

7. UK government's 'UK Climate Change Program' targets HFCs: The UK government announced intentions to control HFC emissions, by stating: "They [HFCs] are greenhouse gases, and the UK is committed under the [Climate Convention signed at the Earth Summit in Rio, June 1992] to take measures aimed at returning emissions of HFCs to 1990 levels by 2000...[In particular, the Government will be] exploring the scope of voluntary agreements to ensure that, where HFCs are used, emissions are minimised and that HFCs are not used where emissions are unavoidable if safe, practical and more environmentally acceptable alternatives are available."[151]

8. The Dutch government circulates draft proposals for international ban on HFCs: At the 10th session of the International Negotiating Committee (INC10) to the Framework Convention on Climate Change (FCCC), which ended in Geneva on September 2nd, 1994, the Dutch government issued a

---

149 Greenpeace International, "Tehnology Update", July, 1992 : Op.Cit.

150 US Climate Change Action Plan, 19 October, 1993

151 UK Climate Change Program, 25 January, 1994

report entitled "Potential Effect Of HFC Policy On Global Greenhouse Gas Emissions In 2035":[152] (The FCCC was signed at the Earth Summit in Rio de Janeiro in 1992 by over 160 countries. It entered into force on March 21 1994 following ratification by 50 countries.)

(a) The report calls for: (i) No use if HFCs are not "essential"; (ii) Avoidance of HFCs having relatively high Global Warming Potentials ; (iii) Avoidance of relatively leaky applications. This is in effect a ban on the use of HFCs on all three criteria. The Dutch Government believes that the first option is the most effective way of dealing with HFC emissions.

(b) Alternatives: The report states that "Alternatives are known for most applications... It is concluded that for most applications many non-halocarbon alternatives are available." "Industries already invested considerably in alternatives for CFCs. Although not investigated, the costs of above mentioned options do however not seem problematic. Moreover, early implementation of the options could avoid extra costs in switching from HFCs to non-HFCs"

(c) Low GWP HFCs : The only HFC that meets the report's criteria of relatively low GWP (less than 600) is HFC-152a, a flammable gas. This gas has extremely limited applications.

(d) Leaky applications: Virtually all cooling applications leak; there are no "completely closed systems". The report states that "about 65% of the cooling agent in mobile air conditioning leaks away unavoidably." and "considerable amounts of HFCs leak from these [all other cooling] systems over the relatively long lifetime of the equipment".

(e) Environmental impact of HFCs: Concerns around HFCs are due to their huge global warming impact and that widespread use of HFCs will lead to a "significant greenhouse problem". The Netherlands Government's stance on the necessary policies and measures to deal with this problem is that "early action prevents big problems in the future" ..."If HFCs are to be used to replace CFCs without restriction, global HFC emissions may increase to 1931 Mtonnes CO2 equivalent per year by 2035. If HFCs are also used as substitutes for HCFCs, emissions could double to 4665 Mton CO2 equivalent per year in 2035. These HFC emissions equal 7% and 17% respectively of present CO2 emissions. "

---

152 Millais, Corin, September 1, 1994 memo summarizing a draft report by the National Institute of Public Health and Environmental Protection of the Netherlands, entitled "Potential Effect Of HFC Policy On Global Greenhouse Gas Emissions In 2035",

authored by C. Kroeze, September 1994, (report # 773001002) as released at the 10th session of the International Negotiating Committee (INC10) to the Framework Convention on Climate Change (FCCC).

Conclusion

The world has limited resources, and as the United Nations Environment Program (UNEP) 1992 Technology and Economic Assessment Panel stated, "the development of technologies which do not use either controlled or transitional substances can be inhibited because the prospect of technology using transitional substances discourages investment in technology that would only be profitable if transitional substances were not acceptable."[153] Simply stated, this means that the production and promotion of HCFCs and HFCs hinders the transition to safer alternatives.

In every category, the hydrocarbon technology is proving itself to be superior to the synthetic substances. As Missenden and James aptly put it: "Although there are risks in using flammable refrigerants in domestic refrigerators, the advantages of these refrigerants are manifest."[154] Given the environmental imperative to protect the ozone layer and to reduce greenhouse warming, the economic and moral imperative to provide the most affordable technologies available to developing countries, and the business logic of not investing in obsolete technologies, it is obvious that the hydrocarbon technologies provide the optimum answers in domestic refrigeration.

---

153 TEAP Report 1992: Montreal Protocol On Substances that Deplete the Ozone Layer: "1991 Assessment: Report of the Technology and Economic Assessment Panel (TEAP)",

154 Missenden, J.F. and James, R.W., "The use of Propane in Domestic Refrigerators", Institute of Environmental Engineering, South Bank Polytechnic, London, revised Oct. 1991.

Appendix A : “Greenfreeze - A Revolution in Technology”

In the spring of 1992 Greenpeace brought together scientists who had extensively researched the use of propane and butane as refrigerants, with an East German company DKK Scharfenstein. The company had been producing refrigerators for 50 years and was the leading household appliance manufacturer in the former East Germany. After reunification, however, it faced severe economic problems and was due to be closed down.

The meeting between the scientists and DKK Scharfenstein resulted in the birth of ‘Greenfreeze’ technology for domestic refrigeration. Greenfreeze refrigerators use hydrocarbons for both the blowing of the insulation foam and the refrigerant and they are entirely free of ozone destroying and global warming chemicals.

When DKK Scharfenstein announced their intention to mass produce "Greenfreeze", Greenpeace successfully campaigned to gather tens of thousands of pre-orders for the yet-to-be-produced new refrigerator from environmentally conscious consumers in Germany. This overwhelming support from the public secured the capital investment needed for the new ‘Greenfreeze’ product, and at the same time, salvaged the company and saved the jobs of its workers.

The major household appliance manufacturers, who had already invested in HFC-134a refrigeration technology as the substitute for CFCs, at first claimed that the 'Greenfreeze' concept would not work. However, upon realising that the first completely -CFC, HCFC and HFC-free refrigerator was about to come on the market, and recognising the market appeal of a truly environmentally friendly refrigerator, the four biggest producers, Bosch, Siemens, Liebherr and Miele gave up their resistance to the hydrocarbon technology, and introduced their own line of ‘Greenfreeze’ models in the spring of 1993.

Within a year and a half the Greenfreeze technology has spread like wild-fire throughout Europe, and to other parts of the world. Many models of 'Greenfreeze' refrigerators are now on sale in Germany, Austria, Denmark, France, Italy, Netherlands, Switzerland, and Britain. All of the major European companies, Bosch, Siemens, Electrolux, Liebherr, Miele, Quelle, Vestfrost , Whirlpool, Bauknecht, Foron, AEG are marketing Greenfreeze-technology based refrigerators. Even the Environmental Ministers of Britain, Denmark and the Netherlands have lent their support by buying a Greenfreeze refrigerator.

Hydrocarbon technology has also spread to other continents. Greenfreeze is about to be produced in Argentina. Companies in India are expressing great interest in converting to the hydrocarbons. Godrej-GE and Voltas Ltd. are currently moving ahead to a pilot plant stage to convert to cyclopentan foam blowing, in cooperation with the Swiss/German ECOFRIG project. The Dutch organisation ECOZONE has been working with the Pakistan Holland Metal Project (PHMP) in Peshawar on a training course for refrigerator technicians in the use of hydrocarbon technology.

As a result of Greenpeace's initiatives in China, Qingdao company plans to have its Greenfreeze models on the market by February, 1995. Other Chinese companies are expected to follow suit, with the assistance of bilateral arrangements with the German government, under the provisions of the Montreal Protocol. A Greenpeace exhibition in Tokyo in April 1993 attracted over 600 representatives from Japanese and South Korean companies.

In Kenya, the Climate Action Network (CAN) Africa is working together with the National Environment Secretariat and the National Refrigeration Demonstration Centre of the Kenyan Polytechnic on a proposal to demonstrate hydrocarbon technology in Kenya.

In Ghana, despite receiving training from the World Bank in HFC-134a conversion, the National Refrigeration Workers Association of Ghana are reluctant to switch to this expensive chemical. Together with Friends of the Earth Ghana, a training course is now planned in the conversion of existing refrigerators to run with hydrocarbons. 80% of the country’s domestic market are second-hand refrigerators from Europe. Two years ago, the Netherlands who ship 200,000 of these fridges a year to West Africa decided to convert them to propane in order not to be accused of chemical dumping later on. The project aims to develop capacity for retrofitting in Ghana itself.

Meanwhile, companies like Matsushita and Sharp in Japan, have gone half-way by converting to pentane blown insulation foam. Similarly, in Australia, Fisher & Paykel and E-Mail are blowing foam with cyclopentan, and E-Mail plans to have a Greenfreeze, bar refrigerator on the market by 1995.

Some of the manufacturers that market Greenfreeze in Europe have so far declined to do so in the American market. Their rationale has been that the hydrocarbon technology is not compatible with the large size and the automatic defrost features of American refrigerators. However, these concerns are easily addressed. Tests have shown that not more than 70g of hydrocarbon refrigerants are needed to efficiently cool a large American style refrigerator/freezer unit. That is well within the 113g hydrocarbon refrigerant limit recommended by Underwriters Laboratory.

The technological challenges posed by automatic defrost have also been resolved, as evidenced by the Liebherr Company's recently (09/94) announced plans to have a 'no-frost' refrigerator/freezer model on the market in 1995. Furthermore, American manufacturers could easily take the first step towards an environmentally safer refrigerator by immediately switching to blowing the insulation foam with cyclopentan, instead of continuing to use HCFC-141b.

Despite the U.S. industry's current resistance to switching to 'Greenfreeze' technology, Greenpeace is confident that 'Greenfreeze' has a bright future in the American market. This optimism is based on the inherent environmental and technological advantages of hydrocarbon refrigeration over HCFC and HFC based technologies. These substances have a time-limited market potential because of their negative impact on the environment, and they are more expensive and less efficient than hydrocarbons.

Furthermore, indications are that despite vested interests promoting the HCFC and HFC technologies, there is considerable interest on the research level in Greenfreeze technology among American manufacturers. Greenpeace believes that it is only matter of time before the technology penetrates the North American continent, and that the company that makes the first move will gain the greatest commercial benefits. The future of 'Greenfreeze' in North America will ultimately be decided by the consumers. North American consumers are just as sophisticated and environmentally conscious as their European counterparts. Soon the major manufacturers will realise that a domestic 'Greenfreeze' refrigerator offers huge market potentials.

Appendix B: Natural Refrigerants

1. Prof. Dr. Techn. Gustav Lorentzen (Trondheim, Norway) : "The Use of Natural Refrigerants, A Complete Solution to the CFC/HCFC Predicament"[155]

"We have heard a great deal lately of the harmful effects to the environment when halocarbon refrigerants are lost to the atmosphere. This should not really have come as a surprise since similar problems have happened over and over again. Numerous cases are on record where new chemicals, believed to be a benefit to man, have turned out to be environmentally unacceptable, some times even in quite small quantities (DDT, PCB, Pb...etc.). The present situation, when CFCs and in a little longer perspective the HCFCs are being banned by international agreement, it does not seem very logical to try to replace them by another family of related halocarbons, the HFCs, equally foreign to nature. It has been already been suggested that HFC 134a may be decomposed by sunlight in the troposphere and form acid and poisonous substances. [Banks, R.E. "Skepticism about R-134a justified" Refrig. Air. Condit., Sept. 1993, p.16] If this should turn out to be true, we may have to face yet another catastrophe, even worse than the CFC experience. In any case it must obviously be much preferable to use natural compounds, which are already circulating in quantity in the biosphere and are known to be harmless."

2. Joachim Paul, Integral Technologie GmbH, Flensburg/Germany, "Water as Alternative Refrigerant" [156]

"Any decision for the one or the other refrigeration system and refrigerant bears...a dimension pointing into the future. It may well happen that one "falls out of the frying pan into the fire" making the wrong decision now or later. ...The German "Umweltbundesamt" (German Federal Authority of the Environment) UBA presented already some years ago a list of desirable and less or undesirable refrigerants. This list is still valid and if the industry would have read --and understood-- this list, many developments to come would have been possible already much earlier....The following refrigerants can be claimed to be both "natural" and "safe" on the long run: Water, Air, Carbon

---

155 Lorentzen, Gustav , Op.Cit. (footnote #1a)

156 Paul, Joachim, Op. Cit. (footnote #1b)

Dioxide, Hydrocarbons, Ammonia...'Natural' in this context can be defined as:

* Substances which are part of the natural environment and balance this planet's household and which can be accommodated in the global ecological system,

* Non-chemical substances, i.e. no retort substances in a composition and/or with effects which are "unknown" to the global ecosystem,
* Substances which are "borrowed" (temporarily) from the environment and which can be applied in refrigeration plants,

* Substances, which cause no changes and alterations in the environment if these will be emitted."

Appendix C: Hydrocarbon Refrigerant tested in a U.S. Domestic Refrigerator

B.Y. Liu, M.L. Tomasek, R. Radermacher, Center for Environmental Energy Engineering (CEEE), University of Maryland, "Tests with R290/R600 Mixtures in a Domestic Refrigerator/Freezer" [157]

"The refrigerant mixture R290/R600 was tested as a drop-in substitute in a domestic 20 cu.ft. [automatic defrost, top mounted] refrigerator/freezer unit. All hardware components are the original ones used for R12, except the capillary tube, which was lengthened to control flow rate. To find the best performance, tests were conducted for several lengths of capillary tube and varying mixture concentration and charge. The highest savings of 6.5% were achieved with a blend of 70% R290 and 30% R600, and 70g of charge...

"Until now hydrocarbons are not accepted as substitutes for refrigerants in the USA because of their flammability. However, thermodynamic properties of hydrocarbons, for example propane, are similar to those of R12 and R22. Another advantage of hydrocarbons is their solubility in mineral oil, which is traditionally used as a lubricant in the compressors. Studies predict an increase of the risk of kitchen fires by only 0.04%, when using the flammable refrigerant R152a. In Germany refrigerators using a R290/R600a

[157] Liu, B.Y., Tomasek, M.L., Radermacher R., Center for Environmental Energy Engineering (CEEE), University of Maryland, Op.Cit. (footnote #84)

blend are already on the market. After changes in the hardware, 10% savings have been achieved compared to the R12 system. The charge of the blend is only 1/3 of the R12 charge, which reduces the hazard of fires...

The test unit was a 20ft^3 automatic defrost, top mounted domestic refrigerator freezer. It was equipped with a reciprocating compressor using mineral oil as lubricant. The evaporator is a forced convection, the condenser is a natural convection cross flow heat exchanger. Since the propane/butane mixture is tested as a drop-in substitute for R12, none of the components were changed. Only the capillary tube length was optimised. To control the freezer compartment temperature an independent RTD controller is installed. This controller is replacing the thermostat commonly used in refrigerator/freezer units. With this controller the temperature and the hysteresis, which is the temperature difference between maximum and minimum compartment temperature, can be regulated independently of the charge.

"The baseline test with R12 gave an energy consumption of 2.45 kWh/day at -15.9^{0}C (3.3^{0}F) freezer compartment and 1.9 ^{0} C (35.4^{0}F) food compartment air temperature. The hysteresis was 3.9K (7^{0}F). The cycle time was 26 minutes with a run time ratio of 46% and the charge was 240g of R12.

"The 70/30 blend gave an energy consumption of 2.29 kWh/d at 3.9^{0}C food and -15^{0}C freezer compartment temperature. Those represent 6.5% savings compared to the R12 test. The hysteresis was 4K (7.2^{0}F) and the run time was 28 minutes, with an on-time ratio of 33%. The charge was 70g, which is 71% less than the R12 charge. The absolute pressures are higher for the hydrocarbon blend, however, the pressure ratio is 7.8 compared to 7.9 for R12.

Conclusion: The hydrocarbon blend R290/R600 (propane-butane) is an attractive substitute for R12. In drop-in tests savings of up to 6.5% could be achieved with a mixture concentration of 70/30 and 70g of charge. More saving are expected, when hardware is changed."

Appendix D: Public Safety and Risk Perception

Eric Granryd, Niklas Tengblad: Applied Thermodynamics and Refrigeration, The Royal Institute of Technology, Stockholm, Sweden, and Jan-Erik Nowacki, NOWAB, Lindigo, Sweden: "Propane as Refrigerant in a Small Heat Pump: Safety Considerations and Performance Comparisons"[158]

"Propane is an interesting alternative to refrigerant R22 provided that precautions due to its combustibility are taken for safe use in all conceivable situations. Tests at our laboratory the last few years have indicated that propane (in pure as well as a commercial quality) is quite beneficial from a thermodynamic point of view. Furthermore its heat transfer characteristics are good.

"Public Acceptance: The public can accept flammable refrigerants. In [Refrigerating Data Book and Catalogue 1934-1936. The American Society of Refrigerating Engineers, New York 1934] one can read the following: "Inflammability, as measured by upper and lower limits, by volume of mixtures in atmospheric air is a factor. Generally speaking, fire department regulations are such that refrigerants of high inflammability are ruled out. Ethyl chloride is in this class, as are the hydrocarbons, though any of these gases is safe enough when used in small amounts, as in the domestic refrigerator...". In the same reference (p.127) there is a list of manufacturers of "Domestic Mechanical Refrigerators". 60 different refrigerators are mentioned. Out of these, 11 use isobutan as refrigerant. In those days a filling of about 4kg (8.8 lbs) was common when using SO2 as a refrigerant (p.128). That corresponds to a filling of about 1.5 kg (3.3 lbs) isobutan. Copeland was the only manufacturer of isobutan filled refrigerators. Fairly large risks must have been accepted then for the luxury of a domestic refrigerator taking into account the hermetic compressor was not in the market and that shaft leaks must have been common.

"Public fear does however not correspond to the actual threat against life or health....The fear that can be expected from the introduction of inflammable refrigerants can be expected to be of the same character as the fear of fire induced by electricity when common electricity was introduced in the beginning of the century...[when] many people could not sleep at night due to the fear for electrically induced fires....

---

158 Granryd, Eric & Tengblad, Niklas, Op.Cit. (footnote# 2)

"If the risk of fire or explosion can be considered an "old well-known risk" it is easier to accept it. If the risk can be kept "under control" the probability of acceptance is even higher. We are all driving around with velocities exceeding 30 m/s with 40-70 kg of highly inflammable liquid (gasoline) and accept the risk mainly because we "feel in control of the situation" and are used to take this risk...

"Phasing out CFCs and HCFCs is, for many applications, in fact not a problem of technology, it is mainly a problem of regulations in force as well as time available for changing technologies. Propane is an example that can be used successfully for new equipment utilising existing components as well as a drop-in for R 22 systems...."