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REFRIGERANTS BEYOND 1995 - AN OVERVIEW

Wafik A. Kamal
Professor of Mechanical Engineering
College of Engineering, Qatar University
Doha, Qatar.

ABSTRACT

The count down has started. Less than 400 days, that is all the time left till the complete phase-out of CFC production. No more refrigerants R-11, R-12 or R-500 will be produced worldwide. With our extreme dependence - in the Gulf area - on air conditioning and refrigeration, and with billions of Riyals invested in existing equipment (in particular central chillers, cold stores as well as domestic fridges, freezers and air conditioners), the question is: have we prepared ourselves for the disappearance of our most common refrigerants? This paper traces the story of CFCs, their effects on the environment, the protocol mandating their phasing-out and assesses their substitutes. It highlights the need of every responsible engineer to plan a refrigerant-strategy for his refrigeration and air conditioning equipment TODAY.

1. INTRODUCTION

Two important climatic issues - Stratospheric ozone depletion and greenhouse gas increase (leading to global warming) - and the apparent connection between them have been the subject of great attention over the last 20 years. Scientists have succeeded in drawing public interest to the impending double catastrophe of global climate change and the serious increase in Ultra Violet (UV) radiation reaching the earth's surface with disastrous consequences on the biosphere - i.e. on man and his environment.

One common factor between the two phenomena is that the emission into the atmosphere of chlorofluorocarbons (CFCs) and halons is the main source of one (ozone depletion) and is one of the major causes of the other (global warming). Both theory and experimental observations as well as data collected from the stratosphere confirm the relation between the increased CFC usage and the ozone holes over the south and north poles. Assessment of the global warming potentials (GWPs) of different trace gases (natural or man-made) revealed that CFCs, although being of relatively low concentrations in the atmosphere, have a global warming potential few thousand times that of CO_2 (which is regarded as the main culprit).

Recent data [1.a and 1.b] have also confirmed a second common factor, that of the strong inter-relationship of the two phenomena. The progressive increase in greenhouse gases leads to a gradual increase in tropospheric warming, and the associated stratospheric cooling (since not enough heat is reaching it) will indirectly affect ozone concentrations in the atmosphere, which in turn will affect tropospheric climate conditions.

The serious consequences of both phenomena have alarmed people of the world [2,3 and 4] and they forced their governments to act to avert the impending catastrophe. This was manifested in a number of important meetings in Montreal, Toronto and Copenhagen in which agreements on the phasing out of CFCs and controlling of greenhouse gas emissions were signed. The meetings culminated by the convening of the Earth's summit in Rio in 1992.

This paper examines the development and applications of CFCs and their detrimental effects on the earth's atmosphere as well as response measures by the world community. It then examines potential substitutes for the most common refrigerants, and evaluates their performance in refrigerating and air conditioning systems. It progresses to outline the modifications needed in new systems to match the new refrigerants as well as modifications required in existing systems to be retrofitted with the alternative refrigerants and examines design options for improving the energy efficiency of the new systems. It finally attempts to offer guidelines to the owners of existing chillers on whether to retrofit or replace their equipment.

2. CFCs AND EARTH

2.a History of CFC Use

CFCs are organic compounds which are all synthetically produced and were developed as the "Freon" family of refrigerants by Du Pont. In 1930, the first of the family, Freon-12 was developed [5]. Introduction of the Freon refrigerants provided a tremendous impetus to the refrigeration industry, as the early refrigerants developed (R-11, R-12, R-22, R-113 & R-114) were all non-toxic non-irritating and non-flammable. Since then their uses have multiplied rapidly and many other CFCs, Hydrochlorofluorocarbons (HCFCs) and Hydrofluorocarbons (HFCs) were developed. CFC-11 has been extensively used in large-capacity, centrifugal compressor-type, water chilling machines for air conditioning large buildings. R-12 is the main refrigerant in household refrigerators and air conditioning systems as well as small capacity refrigerators for stores, restaurants etc. and small capacity air conditioning systems employing reciprocating and screw compressors. R-22 is widely used in self-contained small air conditioning equipment as well as household freezers.

During the 1970s, scientists became concerned about the potential impact of CFCs on the ozone layer. Concern continued and in 1985, scientists detected unexpected seasonal losses in the ozone layer above Antarctica. In 1987, these concerns resulted in an international agreement to reduce the production and use of CFCs to 50% by 1998. By 1988 research has shown that chlorine from CFCs contributed to the early spring ozone losses. In 1990, the protocol was amended to require a total phase out by the year 2000, bringing to a close the CFC era, 70 years after it started.

2.b Applications and Production

CFCs have been major contributors to the quality of life enjoyed today. Figure (1) summarizes the ways in which they are used today.

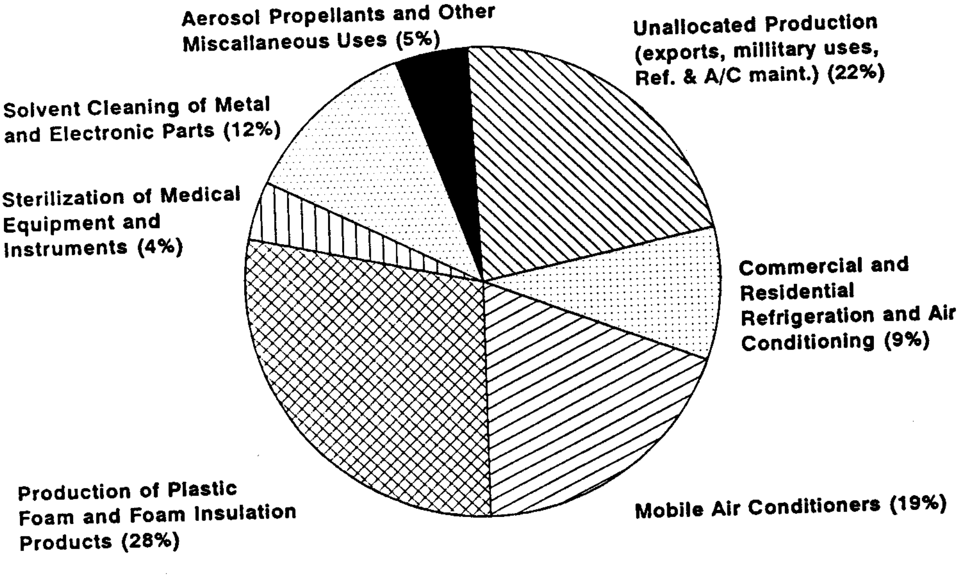

Fig. 1: Estimated uses in 1985 of fully halogenated CFCs in the United States [6]

i- Refrigeration and air conditioning:

CFCs and HCFCs are currently used extensively as the working fluids in high efficiency refrigeration and air conditioning equipment, i.e. in household refrigerators and freezers, automobile air conditioners, centrifugal chillers as well as supermarket fridges and freezers. 40-50% of all R-12 produced is used in transportation air conditioning and refrigeration. Although 85% of all centrifugal chillers use R-11, it is relatively a small portion of that produced. The USA alone has approximately 113 million refrigerators, 32 million household freezers and 74,000 centrifugal chillers.

ii- Foam blowing:

CFCs are used as the blowing agents in manufacturing high R-value foam insulations and plastic foams, e.g., polyurethane, polyisocyanurate and extruded polystyrene insulations for buildings and appliances. Foams are also used in food packaging and for cushioning appliances. 70% of all CFC-11 produced is used as a blowing agent in producing polyurethane foam (R-value $\simeq$ 8 per inch). Manufacturers of foam packaging for food service have now turned to R-22, alone and in blends.

iii- As a solvent:

Mainly for cleaning of metal parts and micro-electric circuitry and as an aerosol (spray can) propellant for insecticides, toiletries, paints etc. They are also used as a solvent in the air and space craft and computer industries. In the USA, the electronics industry accounts for one fourth of CFC demand.

iv- Other applications:

These include their uses in the sterilization of medical equipments and instruments, and military uses. They are also used as a food freezant in freezing fish, fruits and vegetables [2, 6].

Total production of the five main CFCs used today (R-11, R-12, R-113, R-114, R-115) was 1.1 million tons in 1985, distributed as follows [7]:

USA	35%	European Union	38%
Japan	15%	Eastern Europe	11%

The balance being production in developing countries such as China, India, Brazil and Mexico. More recent data suggests that these producers' share exceeds 6% now and could reach 10% by the end of the century [1.b].

Table 1 shows the most commonly used CFCs for the different applications.

Table 1: CFCs Main Applications

Application	Refrigerant
Automotive Air Conditioning	CFC-12
Retail Refrigeration and Cold Storage Systems	CFC-12 and CFC-502
Chillers for Air Conditioning in Commercial Buildings.	CFC-11, CFC-12, CFC-114 & CFC-500
Residential Air Conditioning	HCFC-22
Domestic Refrigerators and Freezers	CFC-12
Cleaning Electronic Components	CFC-113
Plastic Foams (Insulation & Packaging)	CFC-11, CFC-12, CFC-114 & HCFC-22
Sterilant (medical instruments)	CFC-12
Aerosols	CFC-11 & CFC-12

2.c Environmental Impact of the Use of CFCs

i- Ozone depletion:

The Ozone layer is ozone O_3 present at very low concentrations in the stratosphere between 12 and 50 km in altitude. O_3 is formed by the interaction of ultra-violet radiation from the sun with molecular O_2. Harmful ultra-violet radiation is absorbed during this formation process and also directly by O_3 once it is formed. The presence of chlorine in the upper atmosphere will, through a complicated series of chemical reactions, catalyze the destruction of O_3 and thus upset the balance between its continuous production and destruction. In 1974, Molina and Rowland [8] theorized that chlorine released from CFCs could migrate to the stratosphere, causing a gradual depletion of the ozone layer and allowing high energy photons (UV) to reach the surface of earth causing serious health and environmental problems. The chemical reactions for the decomposition of the two major refrigerants CFC-11 and CFC-12 can be represented as :

$$CCl_2F_2 + \text{Photon} \longrightarrow CClF_2 + Cl$$

$$CCl_3F + \text{Photon} \longrightarrow CCl_2F + Cl$$

The free chlorine then interacts with the ozone molecules, and the following reactions take place (in which chlorine is involved as a catalyst).

$$Cl + O_3 \longrightarrow ClO + O_2$$

$$ClO + O \longrightarrow Cl + O_2$$

$$O_3 + O \longrightarrow 2O_2$$

1% depletion would increase exposure to the damaging ultra-violet by 1.5-2% [9]. Since some of the CFCs have an atmospheric lifetime of 40-150 years, it would take many decades for the ozone layer to return to past concentrations. Measurements taken over both Antarctica and the Arctic (South and North poles) have confirmed that depletion, and indicated the presence of Ozone "holes" that have been growing steadily over the last two decades. The hole over the Antarctica has recently been reported [10] to be the width of the United States and the thickness of Mount Everest. In fact, data obtained shows the depletion since 1976 is five times greater than initial data analysis has indicated.

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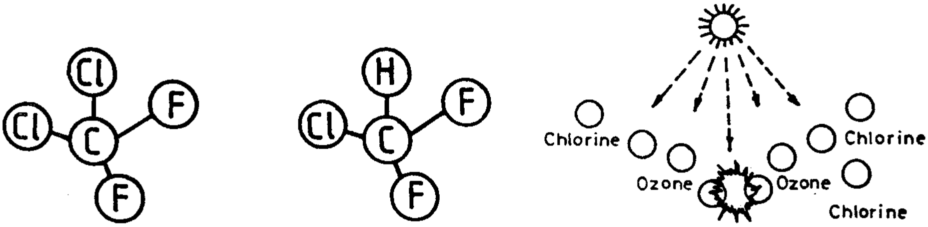
The continuous depletion of the earth-shielding ozone layer and the subsequent increased exposure to UV radiation pose the following risks:

To humans:
- Increase skin cancers and eye diseases (cataracts).
- Suppression of the human immune system responses.

To the environment:
- Damage to crops leading to decreases in agricultural production.
- Damage to marine plant (phytoplankton) productivity affecting fish productivity and further aggravating the greenhouse effect.
- Increases in the amount of ozone at ground level (a major urban air pollution factor).

Ozone Depletion Potential (ODP): Although CFCs are photochemically decomposed almost exclusively in the stratosphere, not all CFCs pose the same threat to the ozone layer. The most destructive are fully halogenated CFCs, i.e., those in which all hydrogen atoms have been replaced by either chlorine or fluorine (e.g. CFC-12, see Fig. 2). It is the chlorine, when it reaches the stratosphere, that upsets the delicate balance between ozone continuous creation and destruction. However, the ODP of a refrigerant is related not only to its chlorine content but also to its atmospheric life. Fully Halogenated CFCs have an atmospheric life of 75-120 years and so the damage continues.

On the other hand, non-fully halogenated CFCs (or HCFCs) still retain a hydrogen atom (e.g. R-22, see Fig. 2) , making them less stable. They have shorter atmospheric lifetimes and they break-down in the troposphere, i.e. at altitudes below the protective ozone layer (HCFC-22 has an atmospheric lifetime



CFC - 12

HCFC - 22

Fig. 2: CFC-12, HCFC-22 and decomposition of CFCs

of less than 20 years). A lower percentage reaches the stratosphere. The potential ozone depleting effect of common refrigerants is usually expressed as a ratio of that of CFC-11. For example if CFC-11 is assigned a value of 1, HCFC-22 has a factor of 0.05. This is why HCFC-22 may be part of the solution to the problem. Table 2 lists some common refrigerants, their Ozone Depleting Potentials as well as their Global Warming Potentials.

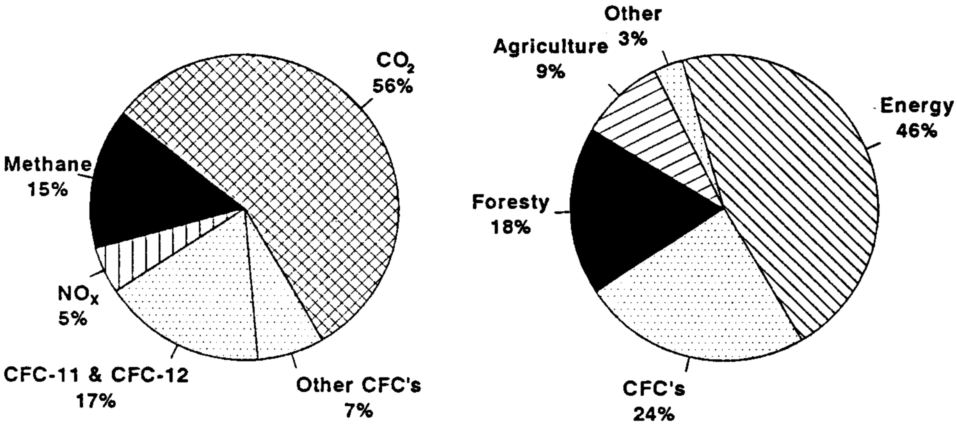
Table 2: Common Refrigerants, their ODPs and GWPs and Possible Alternatives

Name	ODP	GWP	Possible Alternatives
CFC-11	1.00	2,000	R-123, R-123a, R-152, R-141b, R-245Ca
CFC-12	1.00	6,200	R-134a, R-22, R-23
CFC-113	0.80	2,800	R-141b, R-123
CFC-114	0.70	7,900	R-124, R-142b, R-143
CFC-115	0.40	14,000	R-22
CFC-500	0.19	7,400	R-134a, R-125, R-32, R-152a
R-502 (CFC-22 + CFC-115)	0.28	13,300	HFC-125/HC-290/ HCFC-22 [near azeotrope]
HCFC-22	0.055	680	R-134a, R-32/R-125 [azeotrope]

The ultimate objective is to replace CFCs with HFCs which have no chlorine atoms and thus have an ODP of zero, e.g. HFC-134a and HFC-23.

ii- Global warming and climate change:

"Greenhouse gases" let sunlight through to the earth's surface while trapping out-bound radiation, acting in the same way as the glass panels of a greenhouse. Thus, their increased concentration in the atmosphere alters the radiative balance of the planet and results in a warming of the earth's surface. Without the naturally occurring greenhouse gases (water vapour, CO_2 and methane), the earth's average temperature would be nearly 35°C colder, and the planet would be much less suitable for human life. But the continuous rise of emissions of CO_2 & CH_4 in addition to man-made CFCs, HCFCs as well as nitrous oxides and tropospheric ozone is causing an additional warming of the global climate, with serious consequences on the biosphere. These include severe climate changes, rising sea levels (drowning many coastal areas), changes in precipitation patterns (leading to scarcities in food and freshwater), and significant changes in human settlements. Figure (3) demonstrates the contribution of CFCs to global warming in comparison to other trace gases, and to other sectors of human activities. Surprisingly the contributions of CFCs are estimated at 24% of the total in both cases. Table (3) gives a break-up of the halo-carbon global warming effect, indicating that CFCs are the worst offenders [3].



a) by Greenhouse gas

b) by Sector

Fig. 3: Estimated global contribution to radiative forcing

Table 3: Anthropogenic Sources of Atmospherically Important Halocarbons in the Late 1980s [3]

Halocarbon	Production x 10^6 kg/yr	GWP* (100 Years)	Percent of Total Effect	Uses
CFC-11 (CCl_3F)	350	3,500	17	Aerosols, refrigeration, foams.
CFC-12 (CCl_2F_2)	450	7,300	60	Aerosols, refrigeration, foams.
CFC-113	150	4,200	13	Cleaning electronic components.
HCFC-22 ($CHCl_2F$)	140	1,500	3	Refrigeration, polymers.
CH_3CCl_3	545	100	2	Industrial degreasing.
Others			5	

* GWP : Relative to that of CO_2, i.e. assuming GWP of $CO_2=1$

2.d The Montreal Protocols

Faced with growing world-wide public concern over the threat to the biosphere caused by the continuing use of CFCs, many countries signed in Montreal (1987) a protocol to restrict the availability of fully halogenated CFCs. It called for a 50% reduction of CFCs (11, 12, 113, 114 & 115) production from their 1986 levels by 1998. It was the first time that nations have acted together to address a threat to the environment before absolute scientific evidence was available. Data obtained since the agreement was signed have confirmed the serious effects of CFCs on the stratospheric ozone layer.

Accelerated Phase-Out:

In June 1990 in London, the protocol was revised with interim steps shortened and phase-out periods specified. A 20% cut from 1986 production levels was targeted for 1992, an 85% cut by 1997 and total phase-out by the year 2000. More significantly, HCFCs were considered as "Transitional Substances" that must eventually be replaced.

In February 1992, the EPA has announced that the USA would phase out production of CFCs, carbon-tetrachloride, halons and methyl chloroform by the end of 1995 [11]. In addition, it proposed the phase-out of HCFCs according to the compound specific schedule shown in table (4). As can be seen all HCFCs will be phased out (no production or consumption) between 2020 and 2030. Beginning January 1, 1996, consumption of HCFCs will be capped at the level of use recorded plus 3.1% of CFC use. On January 1, 2004 the HCFC cap is lowered to 65%, 35% by 2010, 10% by 2015, 0.5% by 2020 and a complete phase-out by 2030 [12]. Meanwhile, in order to prevent the release of CFCs or HCFCs into the atmosphere, refrigerants in existing systems must be recovered, recycled and possibly used in charging systems. These steps were adopted by Parties to the Montreal Protocol in the their meeting in Copenhagen in Nov. 1992.

Table 4: Compound-Specific HCFC Phase-out Schedule

Date	Compounds	Restriction
2003	HCFC-141b	Ban on production and consumption.
2010	HCFC-22, HCFC-142b	Production and consumption frozen at baseline levels.
	HCFC-22, HCFC-142b	Ban on use of virgin chemical unless used as a feedstock or refrigerant in appliances manufactured prior to January 1, 2010.
2015	All other HCFCs	Production and consumption frozen at baseline levels.
2020	All other HCFCs	Ban on use of virgin chemical unless used as a feedstock or refrigerant in appliances manufactured prior to January 1, 2020.
	HCFC-22 HCFC-142b	Ban on production and consumption.
2030	All other HCFCs	Ban on production and consumption.

3. FUTURE REFRIGERANTS

3.a Characteristics Considered

i- Stability: The most essential characteristic is chemical stability within the refrigeration system. The refrigerant should not decompose or react with the system components forming other compounds. It is however desirable if the refrigerant - stable in use - decomposes within a few years when released in the atmosphere, i.e. it should not be so stable that it persists indefinitely.

ii- Toxicity: It should be either totally non-toxic or of a very low order of toxicity. In domestic applications, safe refrigerants are a must, while in industrial applications low level toxicity is permitted, with safety precautions implemented and Allowable Exposure Limits (AELs) set, e.g. ammonia has always been used.

iii- Flammability: In residential and most commercial applications, a refrigerant must be non-flammable.

iv- Physical Properties (Thermodynamic and Transport): These determine the performance of the refrigerating system. Main ones are:

- Critical point and boiling point temperatures must be appropriate for the application.
- High latent heat of vaporization
- Low viscosity
- High thermal conductivity.

v- Equipment Design: These are the properties that influence the choice of the system components and their materials, such as

- Satisfactory oil solubility
- High dielectric strength of vapor
- Low freezing point
- Reasonable containment materials
- Easy leak detection
- Low cost.

3.b Criteria for Selection

The ideal refrigerant is chemically stable, non-flammable, non-toxic or low in toxicity, odourless, compatible in thermodynamic and transport properties, efficient working fluid in a refrigerating machine and inexpensive, as well as being environmentally safe. It may contain hydrogen and fluorine but be chlorine-free or as a transitional measure has a small chlorine content. Experience shows that successful candidates need to be small molecules containing one or two carbon atoms for good performance and minimum cost, and have a ratio of halogen to hydrogen atoms > 1:1 to ensure non-flammability.

The above screening criteria were applied to a wide variety of refrigerants [13,14] listed in Table 5, with the most promising HFCs marked by a ✓. As a result, potential substitutes for refrigerants commonly used today were identified and are summarized in Table 6.

Table 5: Normal Boiling Point of Selected Refrigerants

Refrigerant	(°C)	Refrigerant	(°C)
R-14	- 127.9	R-124a	-10.2
R-503	- 87.9	R-142b	- 9.7
R-23	- 82.0	R-31	- 9.1
R-13	- 81.4	R-114 X	3.7
R-13B1	- 57.7	R-143	5.0
R-32 ✓	- 52.5	R-21	8.8
R-125 ✓	- 47.8	R-160	12.4
R-143a ✓	- 47.8	R-11 X	23.6
R-502 X	- 45.4	R-123	27.9
R-22	- 40.8	R-123a	28.0
R-115 X	- 38.9	R-12/DME	28.9
R-161	- 37.2	R-152	30.7
R-500 X	- 33.5	R-141b	32.1
R-12 X	- 29.8	R-30	40.2
R-505	- 29.6	R-113a	45.8
R-134a ✓	- 26.5	R-132b	46.5
R-152a ✓	- 25.0	R-113 X	47.6
R-134	- 20.0	R-150a	57.0
R-506	- 12.0	R-132	58.5
R-124	- 12.2		

Table 6: Potential Refrigerants for Replacing CFCs in Centrifugal Chillers

Refrigerant	Substitutes	
	Non-Flammable	Slightly Flammable
CFC-11	R-123, R-123a	R-152, R-141b
CFC-12	R-134a, R-22, R-125 R-134, R-124	R-152a, R-143a
R-500	R-134a, R-22, R-125	R-32, R-143a, R-152a

3.c Potential Substitutes

i- Substitutes for R-11 (Negative pressure systems):

R-11 has been the main refrigerant used in low pressure direct drive centrifugal chillers (which have traditionally dominated the American market). HCFC-123 is an attractive substitute for R-11, since it has ODP of 0.02, and is a safe and non-toxic refrigerant [15]. It acts as a mild anaesthetic at high concentrations, so its AEL is only 10 ppm, although short term exposure to concentrations as high as 1000 ppm has no harmful effects. Replacing R-123 in existing R-11 chillers may involve replacement of seals, gaskets, bushings and diaphragms. Du Pont has constructed a $20 million plant to manufacture it. Today it costs 20-50% more than R-11. It is also slightly less efficient (between 3 and 5%) than R-11. Already, some manufacturers indicate that their R-11 centrifugal chillers are fully compatible with R-123. Due to its low AEL, it requires a refrigerant-specific detector instead of an oxygen-depletion sensor.

In general negative pressure systems require purging non-condensables to maintain efficient operation. They use breakable rupture discs as safety devices. Once these discs are broken, the refrigerant continues to be released. In view of all that, positive pressure chillers are always preferred. However, at the 1993 ASHRAE show a new centrifugal chiller was shown with an emission rate of less than 0.5% per year, a zero emission purge that causes a loss of less than 21 gm/year (an order of magnitude less than high pressure chillers) [15]. The theoretical benefits of R-123 are demonstrated in Fig. (4).

Yet, R-123 has a chlorine content and thus a low ODP, so it will eventually be phased-out by the year 2030, i.e. it is viewed as a transitional alternative. Research conducted by the EPA and EPRI suggests HFC-245ca to be a worthy far-term replacement for R-11 and R-123 [16]. Computer simulations indicate that the use of HFC-245ca in centrifugal chillers may entail an efficiency loss of

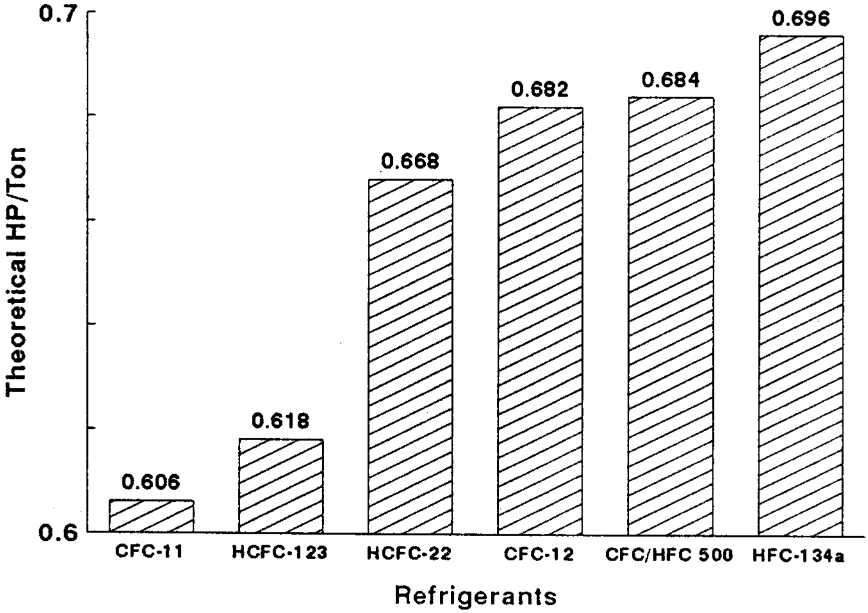


Fig. 4: Theoretical efficiency benefits of various refrigerants [15]

approximately 3-4% relative to R-11. Since the modeled volumetric capacity is within 10% of that for R-11, compressor redesign may not be required, and since delivery pressures are lower for R-245ca no pressure rating redesign of the condenser is needed. Polyester lubricants offer excellent miscibility. Unfortunately, it is flammable especially in air that has a relative humidity of 15% and above. More testing of its toxicity is needed. Generally, it can be considered a good candidate for replacement of R-123 in the long-term, but realistically one could not expect it to be available as a R-11/R-123 substitute before the year 2000 [26].

ii- Substitutes for R-12 (in positive pressure systems):

HFC-134a is an excellent substitute since it is non-flammable and has an ODP of zero and a GWP of 0.07. It is essentially non-toxic, its AEL of 1000 is the same as CFCs, and is compatible with presently available materials. It operates at a positive pressure in both the evaporator and condenser, thus eliminating the need for purge units, additional pressure valves to back-up rupture discs and vacuum prevention systems [17]. However, it is incompatible with the mineral oils presently used in chillers. As a result, new synthetic polyester and polyalkylene glycol (PAG) lubricants have been developed. Performance tests also indicated a capacity reduction of 7-8% compared to R-12. Tests on Automotive Air

Conditioning systems charged with R-134a have shown encouraging results, but found HFC-134a to be less energy efficient than R-12 by some 5%. Similar drops in efficiency were reported for centrifugal chillers using R-22.

Du Pont has developed a replacement for R-12 which is a mixture of HCFC-124, HCFC-22 and HCFC-152a that has an ODP of 0.03. It could prove to be a drop in replacement of R-12, with the efficiency being very similar to R-12 compressors. Vineyard et al. [18] reported that both efficiency and capacity for R-125 and R-124 would be substantially lower than for either R-22 or R-134a. If slightly flammable refrigerants could be used, then R-143a and R-152a would keep the capacity and efficiency unchanged.

The use of HCFC-22 in chillers is now recommended by ASHRAE, the ARI and the US-EPA as the bridging solution to the CFC problem. In the USA alone, 270,000 reciprocating water chillers and over 45 million residential heat pumps and air conditioners use R-22. Massien and Demke [19] argue that it might even be preferred to use R-134a in residential unitary equipment from a global warming view point, with the improvement in efficiency far outweighing the differences in GWP. However, bearing in mind that large tonnage chillers are 30-40 years investments and that HCFCs (including R-22) - which contain chlorine - have mandated phase-out dates, R-134a (an HFC) offers the only viable long-term choice as a large chiller refrigerant. To confirm that, it is clear now that the automotive industry has adopted R-134a, and refrigerant manufactures (ICI, Du Pont, Allied Signal, Hoechst, Daikin and Asahi Glass) are building plants for its production all over the world. Conversion from R-12 to R-134a will reduce the greenhouse impact of mobile A/C by more than 90% [4].

iii- Substitutes for R-500:

CFC-500 is a blend of CFC12 and CFC-152a. The non-flammable refrigerants HCFC-22 and HCFC-134a are also the leading candidates to substitute CFC-500, but with slight drop in both efficiency and capacity. Vineyard et al. [18] claim a substantial increase in capacity (by 50%) for R-32 over R-22 without sacrificing efficiency making it a promising replacement for R-500, but R-32 is slightly flammable and low in toxicity.

iv- Substitutes for R-114:

R-114 is used in marine refrigeration as well as a blowing agent in the foam industry. HCFC-124 with a ODP of 0.02 and GWP of 0.1 is a suitable candidate with minor modifications to the system. The only acceptable lubricant is alkylbenzene. Other possible substitutes being currently investigated are HCFC-142b and HFC-143.

v- Substitutes for R-22 and R-502 (For low temperature applications):

Introduced over 50 years ago, R-22 has been the workhorse of the air conditioning and refrigeration industry and is the predominant refrigerant in use today. A large percentage of chillers that utilize reciprocating compressors (accounting for almost one third of installed chiller capacity) use R-22, a HCFC with a low ODP of 0.05 [20]. The Montreal protocols support the use of R-22 as a viable refrigerant for new and replacement chillers through the year 2000, with adequate production of replacement refrigerant for another 20 years. However, because of the long service life of chillers the need for identification and development of chlorine-free replacement for R-22 is evident. Although table 5 shows refrigerants HFC-143a, HFC-125 and HFC-32 to be potential substitutes for HCFC-22, not one of them meets all the criteria required, and a mixture of HFCs could be the solution. The leading candidates are R-134a yielding an efficiency nearly equal to that of R-22, and an azeotropic mixture of R-32/R-125, yielding an 8-10% gain in theoretical efficiency and the possibility of bigger gains if the system is optimized for the refrigerant.

Azeotropes: These are mixtures of gases that behave as one new gas when mixed together, i.e., once they are mixed they remain mixed. One advantage is that, in certain cases, undesirable characteristics such as flammability can be eliminated. One potential azeotrope currently being investigated is R-32/R-125 (60% to 40% by weight) [20], in which the flammability of R-32 has been eliminated while thermal properties are only slightly reduced. Some studies [19] suggest that efficiencies achieved with it are even higher than current R-22 systems. Other azeotropes or near azeotropes being tested include:

R-32/R-125/R-134a (30% - 10% - 60%) , R-32/R-22, R-32/R-134,
R32/R-142b, R-143a/R-142b and R-22/R-142b.

Actually the latter is now commercially available.

vi- Ammonia - still an attractive refrigerant:

Ammonia (R-717) was the first successfully used refrigerant. It has been continuously used since last century in industrial refrigeration, in cold-storage as well as ice-making plants. Following are its major advantages [21,22]:

- **Cost:** A very cheap refrigerant which costs about one sixth of the cost of R-22.
- **Performance:** A better theoretical coefficient of performance (COP) compared to R-12, R-22 and R-502.
- **Pipe Sizes and Cost:** As the refrigerating effect of ammonia is about 6 times that of R-22 and 8 times that of R-12, the mass flow is considerably less. Coupled with its lower viscosity, the resulting cost of piping is dramatically lower. Moreover, steel and aluminum are both suitable coil materials (while copper in not) and are cheaper than copper.

- **Properties:** It has suitable thermophysical properties and a higher heat transfer coefficient than R-22 and R-12. Since ammonia is not miscible with oil, the system is much simpler to design. It does not have the pressure drop penalties associated with moving oil through it.
- **Compatibility with Moisture:** Although water is not welcome in ammonia systems, low percentage of water can be tolerated over long periods. The system does not require the moisture indicators and drier cartridges needed in CFC systems to prevent expansion valve freeze-up.
- **Environmental impact:** Ammonia has a very low atmospheric lifetime (days to weeks) giving it a GWP of zero. It has no chlorine, so its ODP is also zero.

Its biggest disadvantages are its toxicity and its flammability, making it unsuitable for domestic applications. Yet its penetrating unpleasant odour is a major safety advantage. Leaks are very easy to detect and locate.

With the advantages of using ammonia being solidly proven, the current situation regarding CFCs has revived interest in examining its use in supermarket and district cooling applications, as well as in packaged air conditioning units for commercial offices and penthouse coil units at rooftop, with piping outside food storage halls.

4. EFFECTS ON REFRIGERATION AND AIR CONDITIONING SYSTEMS

4.a Modification of Existing Systems (Retrofitting)

There is a considerable stock of existing equipment (valued at hundreds of billions of dollars) that must be maintained, despite vanishing supplies of CFCs. Increasing attention is being paid to the retrofit of this equipment, concentrating on the following issues:

(i) System performance (energy efficiency) and capacity
(ii) Lubricant transport (return to compressor)
(iii) System chemistry (reaction with non-metallic components like gaskets, O-rings, motor windage insulation, hoses, paints and coatings) [23].

HCFC-123 is a drop-in replacement of R-11 in open-drive centrifugal chillers since it meets all the selection criteria including oil compatibility. However, its substitution in existing R-11 chillers may involve replacement of seals, gaskets, bushings and diaphragms. No changes appear to be necessary in safety cut-outs, pressure transducers or the bursting disc. In hermetic motor windings, long-term testing may show R-123 to have an adverse effect on the life of motor winding insulation in existing systems and that new installation materials may be required for new systems. In the USA, over 40% of the currently installed chillers are under 10 years old. For most, retrofitting a R-11 chiller to R-123 can be a cost-effective alternative to replacement.

On the other hand, R-134a cannot be considered as a drop-in replacement for R-12 in most existing systems as it is not compatible with most lubricants. New synthetic oils have been developed, but these oils have been found to be incompatible with any trace residues of CFC refrigerants and mineral oils remaining in a chiller [23]. As a short-term solution, a non-azeotropic mixture of refrigerants with a low ODP (e.g. HCFC-22, HFC-23, HFC-152a and HCFC-142b) can be used to replace R-12 in existing system, with no (or little) modification. Two such mixtures have already been tested and proven:

(i) A R-22/R-142b mixture (60% R-22 by mass)

(ii) A blend of R-22/R-152a/R-124 (36%, 24% and 40% by mass) has been proposed for automotive A/C units [7]. It can be considered to be a drop-in replacement for R-12 in vehicle air conditioning systems.

Retrofitting R-134a in existing R-12 or R-500 centrifugal chillers can be conducted as follows:

1. Remove the mineral oil and refill with the ester oil, then flush and refill with ester oil and repeat until the level of mineral oil in the ester oil is less than 1%.
2. Remove and reclaim the CFC refrigerant by pumping out into recovery cylinders.
3. Change the expansion valve and filter-drier core to accept the new refrigerant and lubricant. You may also need to change the gear set to optimize chiller performance.
4. Test the system for leaks.
5. To enable complete evacuation, and ensure that all traces of the CFC are removed, the triple evacuation technique should be used, with the system repeatedly evacuated to 1 mm Hg absolute.
6. Charge with 134-a.

In the coming years, retrofitting equipment will be a common service practice. Conversion of the newer, more efficient R-11 and R-12 chillers to R-123 and R-134a will permit extraction of the full useful life of older but serviceable equipment. In Fig. (5) a comparison between cost and efficiency for retrofitted chillers as compared to replacement is presented. In the figure the following retrofitting categories are examined [24]:

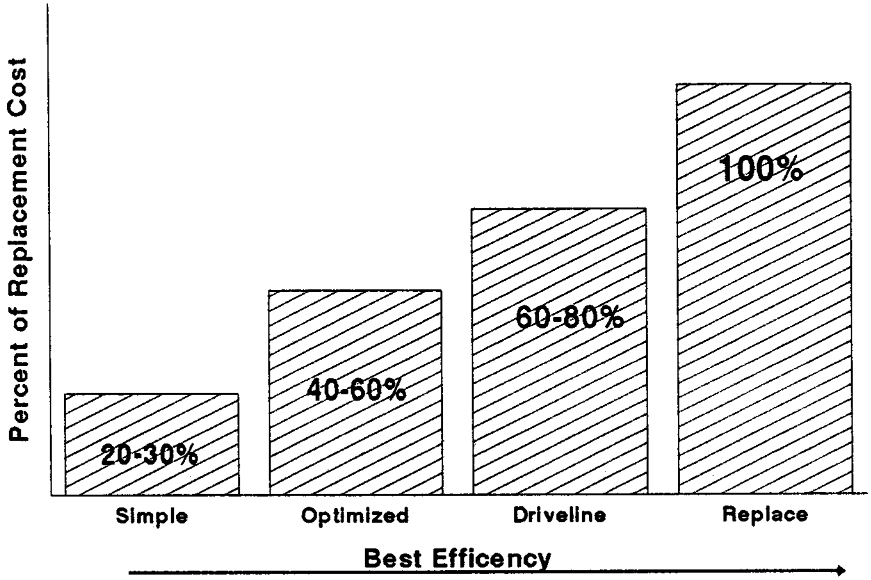


Fig. 5: Cost versus efficiency comparison for retrofitted and replacement chillers [24]

(i) **Simple conversion:** including seal and gasket changing, some control modifications and the new refrigerant charge.

(ii) **Optimized conversions:** including gear change to optimize or tune the chiller to the new refrigerant.

(iii) **Driveline retrofit:** providing an entirely new motor/compressor driveline assembly and microprocessor controllers, which eliminate the performance penalty of a refrigerant conversion.

4.b Recovery, Recycling and Reclaim (a feasible option)

Definitions: (UNEP report [27])

Recovery: means to remove refrigerant in any condition from a system and store it in an external container without necessarily testing or processing it in any way.

Recycling: means to clean up refrigerant for re-use by oil separation and single or multiple passes through moisture absorption devices, such as replaceable core filter-driers.

Reclaim: means to process refrigerant to new conditions, by means which may include distillation. This may require chemical analysis of the contaminated refrigerant to determine that appropriate process specifications are met.

Recovery and recycling of CFCs and HCFCs have significant effect on reducing demand for new production (by nearly 30%) and on reducing emissions to the atmosphere. They will help maximize the availability of these refrigerants and increase the lifetime of equipment using them. In the USA, the Mobile Air Conditioning Society, representing automotive and service equipment manufacturers is working with the EPA to examine the safety and effectiveness of recycling technology. Regulations which went into effect in July 1992, will stop the international venting of any refrigerant (including R-22). Some current water chillers have a pump-down cycle to store the refrigerant in their condensers for service. Many of these chillers also have multiple compressors that enable them to save the refrigerant even when one compressor is inoperable. In many cases, the chillers can also store the refrigerant in their evaporators allowing for the repair of condensers.

Increased conservation and recycling of CFCs and HCFCs can provide benefits to consumers, industry and the environment. USA tax legislation has more than doubled the price of CFCs since 1990. Escalating tax rates will raise the price of CFCs 5-fold in the next ten years, add to that additional increases due to production cuts, increased raw material costs and the need for revenue to invest in alternatives [4]. HFCs are also expected to cost up to 5 times as much as present CFCs.

One sector where the potential for recovery and recycling is enormous is the automobile industry, with an estimated 250 million vehicles worldwide, of which 50% could require retrofit [4, 26].

4.c New Refrigeration and A/C Systems for the New Refrigerants

Years of engineering and technical advances have made comfort cooling and process refrigeration using CFCs safe, energy-efficient and reliable. This makes the task of coming up with alternatives to CFCs quickly, a very complex one. The main modification to the new systems designed for new refrigerants are:

i. New synthetic (ester-based) oils or polyalkylene glycol (PAG) become the lubricant if the refrigerant is not compatible with the oils currently used (e.g. in replacing R-12 by R-134a). The oils used with R-134a are hygroscopic, so service engineers should check thoroughly for moisture in the system.

ii. Replacements of seals, gaskets, bushings and compressor diaphragms. Centrifugal compressor impellers should be redesigned for max efficiency.
iii. Replacement of motor winding insulation materials in hermetic compressor units, due to the aggressive solvent strength of HCFC-123.
iv. There will most likely be a change in performance, i.e. decrease in capacity and increase in power consumption. The new performance will depend on where the original operation point was located on the compressor map (in case of R-123, a drop of up to 5% in capacity and between 2 and 4% in efficiency is reported [15]).
v. Open drive motors have proven to be superior to hermetic motors from a reliability, serviceability and efficiency stand points, since the motor windings are kept out of the refrigerant atmosphere. This will become more important, since motors can be a source of contamination to the refrigerant, and as manufacturers and owners look for ways to conserve and protect their refrigerant.

Equipment manufacturers have been working with refrigerant manufacturers to develop, test and prove the next generation of packaged reciprocating and rotary screw compressors for air conditioning water chillers. Pure fluid possibilities include R-32/R-152a, R-125 and R-134a. The first two have the best thermodynamic properties but are flammable.

In general, future negative pressure systems should have the following readily available containment devices [17]:

(i) Controlled heater/pressure systems that maintain a slight positive pressure to ensure minimum air leakage.
(ii) High efficiency purge systems to minimize the exhaust of refrigerant.
(iii) Refrigerant management systems that allow its storage, recycling and cleaning during service (at least a liquid receiver for each compressor circuit).
(iv) Backup relief valves that provide self-closing backup to the breakable rupture discs.
(v) Refrigerant sensors that monitor for leaks, especially for R-123.
(vi) Oil sampling and analysis systems to lessen the need for oil changes.

In the USA, today 75,000 centrifugal chillers provide chilled water for space cooling with an average cooling capacity of 260 tons of refrigeration. The vast majority use CFC-11 (the rest use CFC-12) and typically use around 0.65 KW/ton (COP=5.41). A 10% increase in power consumption due to the use of alternative refrigerants would lead to an increase of national energy use of 30×10^{12} Btu.

Smithart and Crawford [15] have recently reported that R-123 centrifugal chillers are now available covering the range from 300 to 1,300 tons with efficiencies of 0.55 KW/ton or better, compared to values of 0.58 to 0.6 KW/ton for R-22 or R-134a chillers. As global warming emphasis grows, the efficiency advantages of R-123 will become even more important. But, the phase-out date for R-123 (the year 2030) is certainly a factor to be considered, yet it should be remembered that 35 years is longer than the life of most equipment.

4.d Foam Production

Chemical suppliers are exploring alternatives to CFCs for blown-in foam insulation. Two potential alternatives are HCFC-141b and HCFC-123, with an ODP less than 0.10 and a much lower GWP than CFC-11. However, foams produced have thermal conductivities 5-10% higher than those blown with R-11. The major draw-back though is that they chemically attack presently used plastic refrigerator liners. Yet they appear to be compatible with some plastics such as polyethylene, polypropylene and neoprene. Some refrigerator manufacturers, e.g. Hitachi [28], seem to have solved the problems with the blowing agent of the urethane foam as well as those of the lubricating oil to be used with HFC-134a and have already started commercializing high performance reliable refrigerators that do not use CFCs.

4.e Refrigerants as a Resource

In the past, refrigerants were so inexpensive that the charge was blown directly into the atmosphere during servicing. Today, the industry recognizes that they should be treated as valuable resources. The rising refrigerant costs and taxes helped in the change, together with rising environmental awareness. Design requirements were implemented which dramatically reduce leakage by minimizing unintentional venting. Regulations like the USA Clean Air Act also proscribe unintentional venting.

4.f Design Options for Improving Energy Efficiency

The average annual energy consumption per unit of the most popular type of refrigerator (an 18 ft^3 automatic defrost fridge-freezer) declined from 2000 KWH in 1972 to 1050 KWH in 1987. This improvement in energy-efficiency was achieved through two modifications.

i- The substitution of polyurethane foam insulation for fiberglass in the walls of refrigerators and freezers.

ii- More efficient compressors.

In 1990, The National Appliance Energy Conservation Act (NAECA) standards brought the maximum annual energy consumption down to 950 KWH. Currently 3/4 of the electricity is accounted for by the compressor. The other 25% are consumed by fans, anti-sweat heaters and defrost heaters.

The potential design options for reducing energy consumption fall into one of two categories: those that reduce heat gain into the food storage cabinet and those that improve the efficiency of the refrigerating system. It is widely believed in the Refrigeration Industry that the implementation of the following design options, could bring down the annual consumption of the standard unit from 950 to 700 KWH, without additional use of CFCs [6].

i- Foam insulation substitution in doors: Although foam is universally used in the side walls, fiberglass is sometimes used in doors. This should be replaced by foam to reduce heat flow (by 6% in fridges and 10% in freezers).

ii- Increased cabinet and door insulation thickness: Currently insulation thickness for doors is about 38 mm and in walls 50 mm. Adding 12.5 to 25 mm more insulation increases overall efficiency by up to 10% (in case of freezers). Investment by manufacturers is required for tooling and moulding for the thicker insulation and a decrease of the interior volume is to result if outside dimensions are maintained.

iii- Evacuated insulation panels: Several concepts have been considered by the refrigerator industry including : powder-filled panels, compact vacuum and aero-gel insulation. All give the twin advantages of lower thermal conductivity and significantly reduced ozone-depletion potential. Questions remain about their long-term vacuum integrity and how to mass produce these panels.

iv- High efficiency compressors: Advances in compressor efficiency have a significant effect on overall efficiency. Most models today have an Energy-Efficiency Ratio (EER) of 4 to 5. It is likely that an EER of 5.3 will be achieved within the next few years, through the use of variable speed compressor motors allowing a better match between heat removal loads and compressor power demand by reducing the on-and-off cycling. Theoretical estimates of the energy saving range between 10 and 20%.

v- Adaptive defrost: This makes use of "smart controls" to adjust time between defrost cycles to minimize energy use. Rather than using timers to defrost every 10-12 hrs, the new system controls defrosting according to frost build-up which is function of freezer usage and ambient conditions.

vi- Efficient fans for evaporators and condensers: Power consumption is reduced by using improved magnets and capacitor run motors, yielding a 3-5% saving of the overall energy use.

vii- Two-compressor systems: Using separate refrigeration systems for the refrigerator and freezer cabinets yields a higher overall efficiency and reduces demand for defrosting. The theoretical energy saving is 15-20% but capital cost is a major disadvantage.

Turiel and Levine [6] used a computer simulation model to examine the effects of implementing the energy-saving design options outlined above under two scenarios:

Scenario 1.	a business as usual scenario (with CFCs available)
Scenario 2.	assuming CFC-11 is not available - but either CFC-12 or an equivalent refrigerant is.

The results are reproduced in Fig. (6), in which the options are ordered so that those easiest to carry out and most effective are listed first, and are all cumulative. The figure indicates that for refrigerators the energy penalties of going to a CFC-free world are greater in the short-run than in the long-run, i.e. until evacuated panels or an equivalent CFC-free technology is available.

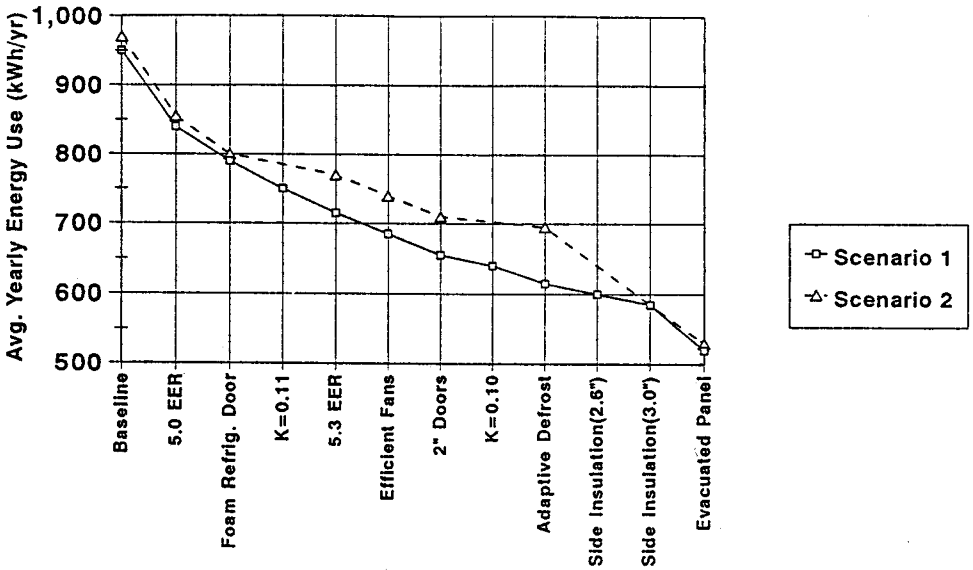


Fig. 6: Energy use for a top-mount auto-defrost refrigerator for different design conditions [6]

5. CONCLUSIONS

CFC refrigerant shortages will be a nasty surprise for the unprepared chiller owner in the not-so-distant future possibly by the end of 1994. Therefore, owners of existing chillers must develop a refrigerant phase-out plan today. Waiting for clear-cut direction from government departments or international agencies will run the risk of losing time to plan, and will possibly incur increased financial loss. The use of alternative techniques such as absorption cycles, sterling cycles and non-halogenated refrigerants like air and ammonia may provide some relief to the CFC problem. But the effective use of engineering controls, including reducing emissions, and recapturing, reusing and properly disposing of CFCs will be significant factors in meeting the environmental challenge posed.

Conversion or Replacement will depend on the following:

- Age of the chillers
- Performance of the chiller
- Safety
- Required containment
- Fit into the building (building code)
- availability of money in the near term and expense versus return on investment.

Costs for converting CFC chillers to non-CFC chillers can run into 75% of a new chiller price for negative pressure chillers (employing R-11). It also reflects the loss of efficiency resulting from the conversion. For chillers ten years or older, the significant performance loss (higher power bill) added to conversion costs might exceed the cost of a new chiller. Since new chillers have a much better performance than existing chillers, typical payback are less than five years, with the added saving of containment cost.

For positive pressure systems (employing R-12 or R-500), conversion to R-134a typically costs 26% of a new chiller price. This includes the flushing of mineral oil and recharging with synthetic oil. The 8-10% loss in capacity and 1-2% loss in efficiency can be offset by modifications of the impeller and gear/spread changes costing an additional 17% of the new chiller price.

A well studied plan must be put into operation today. The positive-pressure chillers employing reciprocating, scroll or screw compressors and R-134a as the refrigerant are the logical successors to many air conditioning plants in Qatar. There is no zero ODP replacement currently available for R-11 in negative pressure systems and it is unlikely that such a replacement could be commercially available before the turn of the century. Since chillers are capital investments for their owner there is no point in installing equipment using HCFCs such as R-22

[25], since in few years they will become obsolete. To invest a little more in R-134a today will save the owner from replacing the equipment later.

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