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ABSTRACT

With the impending phase-outs of CFCs and HCFCs, there has been considerable industry activity in trying to find alternatives. This paper describes the work in designing alternatives to R-502 based on ternary blends of R-32/R-125/R-134a.

With a backdrop of the environmental considerations, this paper includes results of trials in which R-502 has been replaced in systems with R-32/R-125/R-134a blends in supermarket applications; in these instances, the performances with the retrofit refrigerants have been comparable with, or slightly better than the original R-502 performance.

INTRODUCTION

The Montreal Protocol was revised and considerably strengthened at a meeting of the United Nations Environment Program on November 25, 1992. The Protocol accelerated the phaseout dates for the production of CFCs to the January 1, 1996 from January 1, 2000. The European Community (EC) will phaseout CFCs one year earlier. In addition, for the first time, HCFCs, such as R-22, are also regulated with a complete phaseout by the year 2030. Some European countries are phasing out R-22 in new equipment in the year 2000. It is not unrealistic to expect that the Montreal Protocol will also accelerate the HCFC-phaseout schedule.

R-502 contains CFC-115 and, as a result, will be phased out of production at the end of 1995. R-502 is widely used as a low-temperature refrigerant in the supermarket and transport industry. The need to replace R-502 has resulted in the production of a number of blends of HCFC and HFC refrigerants. This paper will discuss the selection criteria for developing blends of refrigerants to replace R-502 in the long term. In addition, several case studies are included to highlight considerations for retrofitting R-502 equipment.

REFRIGERANT DESIGN

There is no single fluid that matches the properties of R-502. R-502 is actually an azeotropic refrigerant blend of HCFC-22 and CFC-115. In most applications, a refrigerant must be practically non-flammable and of low toxicity, and must exhibit good thermodynamic properties. Currently, the best long term alternatives for matching the properties of R-502 is to blend hydrofluorocarbons (HFC), such as R-125 and R-134a, which do not have the potential to deplete the ozone.

ICI Klea undertook extensive theoretical modeling and practical tests using a series of refrigerant formulations. This work resulted in the development of two HFC refrigerant blends as alternatives to R-502, known as KLEA 60 and KLEA 61. They have zero ozone depletion and low direct greenhouse warming potential with good energy efficiency. These refrigerants have been designed to meet the needs of the widely differing applications previously covered by R-502. These refrigerants, based on blends of R-32/R-125/R-134a, are non-flammable and have a provisional allowable exposure limit (AEL) of 1000 ppm. At the time of this writing, ASHRAE's SSPC-34's recommendations to designate these as R-407A and R-407B, respectively, are currently under public review, as are other refrigerants such as R-507. Figure 1 highlights some of the R-502 alternatives currently available.

R-407A has the lowest global warming potential of all the alternatives. Theoretically, it is also the most energy efficient and several field trials have confirmed this. At extreme conditions, such -40°C (-40°F) evaporator temperature and 55°C (130°F) condenser temperature, R-407A exhibits reduced capacity in reciprocating compressors due to its higher pressure ratio. For new systems, this is not a concern as a system can be properly designed to take advantage of these properties. R-407B was designed to meet those needs where capacity can not be spared and where discharge temperature is of concern in a hermetic compressor.

Total Equivalent Warming Impact (TEWI)

Performance and the environmental impact must be balanced to achieve the lowest possible Total Equivalent Warming Impact (TEWI). TEWI, developed by a consortium of manufacturers, scientists, and the Department of Energy, refers to the total global warming impact of a system. First, there is the direct global warming impact of the refrigerants due to leakage. Second, there is the indirect global warming impact caused by the carbon dioxide (CO2) that is generated during the operation of the system. In most applications, energy consumption is the major contributor to global warming, so energy consumption is the major contributor to the TEWI value of a refrigerant. However, in some important applications, such as supermarkets, direct contributions to the TEWI of a system can be significant[1].

Figure 2 compares the typical TEWI values for R-502, a refrigerant with a Halon Global Warming Potential (HGWP) of 1.0, such as R-404A and R-507, and a refrigerant with an HGWP of 0.5, such as R-407A. The chart assume equivalent energy efficiency for comparison purposes[2]. This assumption reflects typical measured values for these refrigerants[3]. As a result, the impact of energy consumption is constant. These values are based on the 1991 AFEAS/DoE study and compares both the 100 and 500-year integrated time horizons (ITH) and the effects of 10% and 33% annual leakage rates.

Refrigerant Blends: Azeotropes and Zeotropes

All blended refrigerants can be classified as either azeotropes or zeotropes. Some have used a third classification, the Near-Azeotropic Refrigerant Mixture, or NARM. NARMs are better classified as zeotropes since it is very hard to distinguish between either type of fluid with absolute certainty.

The ASHRAE classification system designates azeotropic refrigerants by assigning them 500 series numbers. Zeotropic refrigerants are given 400 series numbers by ASHRAE. In fact, there is a growing realization that it is difficult to make a hard distinction between blends, azeotropic or zeotropic. Changes in pressure around a refrigeration system and differential solubility of the azeotropic components in oil can force separation of the components. The only true distinctions that can be made are between pure fluids and blends.

The industry's major initial concern was the potential for alteration of a system charge composition by selective leakage of some of the refrigeration components. Practical experience with thousands of running hours with these refrigerants has shown that this does not have a major effect on performance. Differential leakage can only occur if a single-phase leak occurs from a part of the circuit where both liquid and vapor are present, such as in a heat exchangers or an accumulator. Studies in laboratories and field trials show that the effect of leakage will be less severe than the normal effect of undercharging that would result from leaking either a zeotrope or a pure fluid. In nearly all situations, simple top-up with the standard blend will recover performance without any further servicing[4].

PERFORMANCE COMPARISONS

A theoretical study of the relative performance of refrigerant fluids is useful as a means of identifying sensitivities of performance to system parameters; and of anticipating the kind of effects that will be seen in "real" trials of the refrigerant. While such paper studies are necessarily restricted in their ability to predict system performance, they form a valuable part of the knowledge necessary to make an objective assessment of refrigerant performance in a given application.

In theory, modelling calculations predict that R-407A should outperform R-143a based blends, such as R-404A and R-507. The performance of R-407A, R-407B, R-404A, and R-502 has been compared under fixed mean evaporating and condensing temperatures. From this study it has proven possible to anticipate the behavior of these refrigerants in performance trials with some success. For simplicity, the performance has been calculated at equal volumetric refrigerant flowrate using an isentropic efficiency of 100%.

The variation in refrigeration capacity with evaporator temperature is shown in Fig. 3. In this case, R-407A provides the closest capacity match to R-502. R-407B and R-404A both fall short of R-502 and exhibit similar performance characteristics. Fig. 4 shows the corresponding variation in Coefficient of Performance (COP). Again, R-407A provides the closest match. R-407B and R-404A are similar; both show a drop in COP as condensing temperature rises. This effect is caused by the approach to the critical temperatures of R-143a and R-125.

It is found that additional subcooling benefits R-407B and R-404A to about the same extent; both benefit more from liquid subcooling in both capacity and COP than does R-502. On the other hand, R-407A shows no additional benefit relative to R-502. Figure 5 highlights these trends. One would therefore expect a liquid subcooler or liquid suction heat exchanger to be more beneficial to a system using R-407B or R-404A at high condensing temperatures. R-407A would still benefit from such a heat exchanger.

Calorimetry data in reciprocating compressors, figures 6 and 7, shows virtual parity, with opportunities for improvement at lower evaporator temperatures[5]. Figures 6 and 7 compare the performance of three R-502 alternatives at two condenser temperatures, 30°C (86°F) and 50°C (122°F), over an evaporating range from -40°F to -10°F (-40°F to 14°F). R-404A and R-407B are comparable over the entire range of conditions. R-407A exhibits lower volumetric efficiency, hence the slight capacity degradation at the 30°C (86°F) condenser condition. Field trials indicate essential parity between the various refrigerants[6].

Different types of compressors will affect the performance of a refrigerant. Most current R-502 equipment uses single-stage reciprocating compressors, in which capacity depends strongly on the pressure ratio. Refrigerant flowrate is related to the volumetric efficiency, which is related to the ratio of the condensing and evaporator pressures. Below -25°C (-13°F) the pressure ratio of R-407A, and to lesser extent the other alternative refrigerants, exceeds that of R-502. The result is increased volumetric losses and reduced capacity. The use of rotary compression technology, including screw and scroll compressors, will mitigate the volumetric losses, thereby improving capacity. In applications using these compressor technologies, R-407A is being shown to outperform both R-502 and the other HFC-alternatives, even at low temperatures.

When assessing relative performance of a refrigerant in a system, then it is often found that the refrigerants adopt differing steady states in order to satisfy the operating control requirements. That is, the evaporating temperature, condensing temperature, attained subcooling and attained superheat may all be different from one refrigerant to another. It is for this reason that calorimetry alone gives only a partial assessment of refrigerant performance.

CASE STUDIES

R-407A and R-407B can used in a wide range of supermarket and transport applications including both low and medium temperature. ICI Klea researched the performance of R-407A and R-407B both in-house and in the field. The following are several case studies where these refrigerants have been applied.

Open Top Display Food Freezer

At the ICI research laboratories, a freezer display case was retrofitted from R-502 to evaluate the alternative refrigerants. The procedure involved drilling the compressor case at its lowest accessible point and soldering in a pipe complete with a valve. Three flushes were required to bring the residual mineral down to an acceptable level.

Figure 8 shows the results comparing R-407A and R-407B to R-502. The display case was tested in a control ambient of 21°C (70°F) with humidity ranging from 50-70%. Despite longer run times, the instantaneous power consumption was substantially low enough to reduce the overall power consumption to equivalent levels with all the other alternatives.

Instrumented Cold Store

Several refrigerants, including R-407A and R-407B, were evaluated in a fully-instrument cold room employing single-stage reciprocating compressors where accurate measurements could be taken. Figure 9 highlights these results relative to R-502[7]. The test used a 32 cSt polyol ester lubricant with a residual mineral oil content of less than 1%. R-407A is the only refrigerant that showed improved energy efficiency over the entire range of conditions. All the refrigerants exhibited reduced capacity at increasing condenser temperatures.

Frozen Food Cold Room

A leading European hotel and catering company, as part of its program to evaluate R-502 alternative candidates recently retrofitted a store from R-404A to R-407A. The study involved retrofitting a twin-rack reciprocating compressor system and a rooftop mounted condenser. The units are connected from the compressor room to the evaporators by a 24 m (80 ft.) pipe including a 6 m (20 ft.) suction riser. The cold room is maintained by a single control thermostat at -22°C (-8°F). Only the refrigerant and the dryers were changed.

The system was instrumented to measure 9 key parameters. The instantaneous power consumption was 5% lower with R-407A with similar cycle rates. All the other performance parameters were comparable, however, further improvements may have been possible by optimizing the superheat.

Frozen Food Display Case

An Australian supermarket chain retrofitted a display case that is maintained at -30°C (-22°F). The compressor rack was situated 60 m (200 ft.) from the display case, thus this installation is typical of many supermarkets. A single-stage, open-drive compressor was retrofitted to R-407B and a 32 cSt polyol ester lubricant. Normal store operation was not affected during the refrigerant and lubricant changes. Three lubricant changes were necessary, each requiring one hour to complete, to bring the residual mineral oil to less than 5%. The system was operated 2 to 3 days between flushes. This helps to guarantee mineral oil return in the long refrigeration lines. With no superheat adjustment, the system is outperforming R-502. The display temperatures for both R-502 and R-407B were recorded over a 24-hour period as shown in Fig. 10. The display temperature with R-407B is slightly lower over the range. There was no change in power consumption or cycle rates.

CONCLUSIONS

Blends of HFC-32/HFC-125/HFC-134a are attractive options for replacing HCFC-22 and R-502. R-407A has exhibited good potential as an energy-efficient replacement for R-502 in new equipment including those employing rotary technology. R-407B can be used for retrofits with systems that have less spare capacity. R-407A and R-407B represents an excellent combination of minimal environmental impact with similar performance for R-502 in a wide range of applications.

The practical experience that the industry has already gained by using R-407A and R-407B demonstrates that service engineers can adapt readily to the new technology that is represented by the replacements for R-502. The case studies demonstrated in this paper show that both refrigerants offer potential as replacement to R-502.

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R-502 Alternatives

ASHRAE	Components	Wt %	HGWP
R-404A	R-125/143a/134a	44/52/4	1.03
R-407A*	R-32/125/134a	20/40/40	0.49
R-407B*	R-32/125/134a	10/70/20	0.70
R-507*	R-125/143a	50/50	1.05

*Under review as of 4/8/94
HGWP values are based on AFEAS

Figure 1

Comparison of TEWI for R-502 and Alternatives

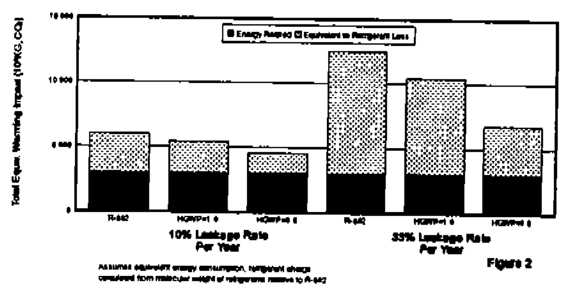


Figure 2

Theoretical Capacity

Condensing at 50°C

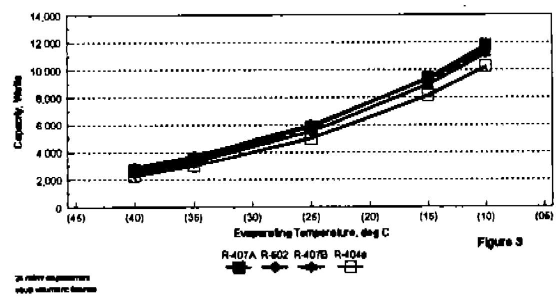


Figure 3

Coefficient of Performance

Condensing at 50°C

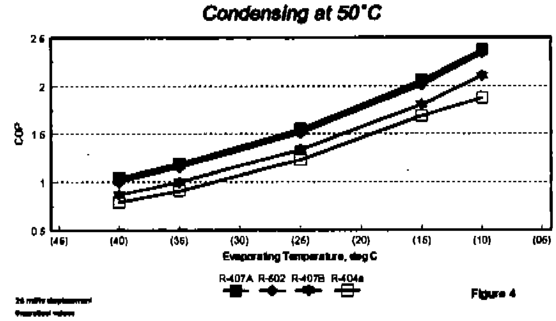


Figure 4

Effect of Subcooling

Condenser at 50 °C

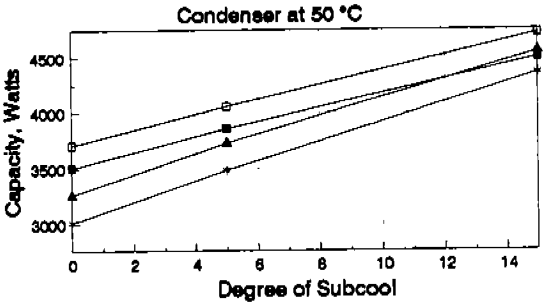
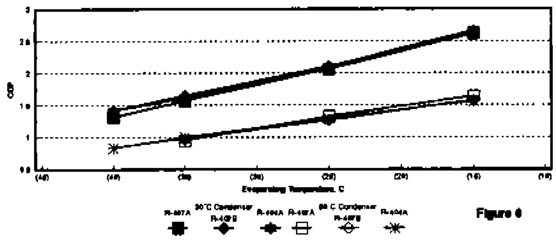


Figure 5

Coefficient of Performance

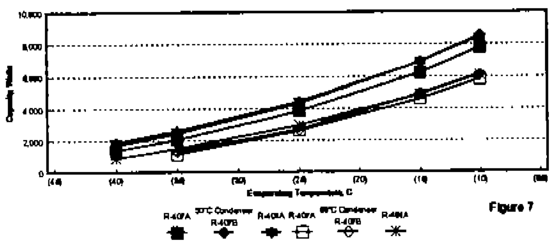
Calorimetry



Suction gas at 25 C zero subcooling

Experimental Capacities

Calorimetry



Display Food Freezer Performance

(R-502 = 1.0)

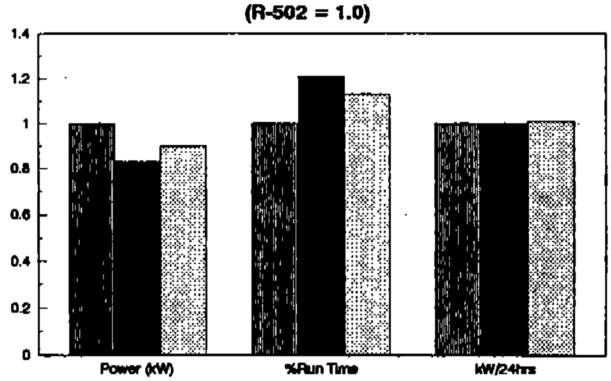


Figure 8

Instrumented Cold Storage

Condenser Temperature	R-407A Capacity	R-407B Capacity	R-407A COP	R-407B COP
37°C (99°F)	97%	103%	108%	104%
40°C (104°F)	92%	97%	103%	99%
50°C (122°F)	91%	93%	105%	98%

Room Temperature -2[illegible] °C
COPs and Capacities relative to R-502

Condenser Temperature	R-407A Capacity	R-407B Capacity	R-407A COP	R-407B COP
34°C (93°F)	94%	98%	107%	102%
40°C (104°F)	91%	92%	101%	94%
50°C (122°F)	92%	89%	108%	94%

Room Temperature -2[illegible] °C
COPs and Capacities relative to R-502

Figure 9

Cabinet Air Temperature
Frozen Food Cabinet

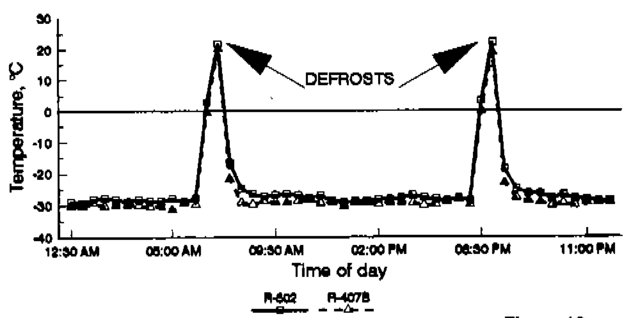


Figure 10