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ABSTRACT

According to the results of the international testing program AREP, the most likely replacements for HCFC-22 refrigerant will be blends of HFCs. However, as concerns about their global warming potential increase, other options should also be considered. As a naturally occurring substance, propane would be an ideal refrigerant, except for its flammability. When dealing with a flammable refrigerant, the manufacturers of systems and equipment have two options: either install the necessary safety features or mix the flammable refrigerant with a non-flammable one to obtain a non-flammable mixture. This article examines both options for residential applications and compares them on a first cost basis with systems that utilize HCFC-22 and many of the leading replacements for HCFC-22.

INTRODUCTION

HCFC-22 is widely used as a refrigerant in commercial refrigeration, and in commercial and residential air-conditioners and heat pumps. HCFC-22 has favorable thermodynamic and transport properties and well known material compatibility characteristics. However, based on its ozone depletion potential of ODP = 0.055 as compared to the refrigerant CFC-11 with ODP = 1.0 [UNEP 1991, /1/], HCFC-22 will be phased out some time in the future; i.e., in the US, the current phase-out in new equipment is set for 2010, and the phase-out for production is 2020. Furthermore, the greenhouse warming potential (GWP) of HCFC-22 is 1700 times that of carbon dioxide over a 100-year time period [IPCC 1994, /2/]. As concern about global warming heightens, an earlier reduction of the availability of HCFC-22 is possible.

Most of the possible alternatives for HCFC-22 were identified within a major international testing program under the leadership of the Air Conditioning and Refrigeration Institute (ARI), referred to as the Alternative Refrigerant Evaluation Program (AREP) [Godwin 1994, /3/; ARI 1994, /4/]. Based on this program, the most likely replacements for drop-in applications will be HFC blends with thermodynamic characteristics close to HCFC-22, such as R-407C.

For new equipment, the most likely alternatives will be HFC blends with higher pressures than HCFC-22 and small or no temperature glides (azeotrope or near-azeotrope blends), such as R-410A. However, HFCs are not environmentally benign because of their global warming potential when released into the atmosphere. The GWPs of R-407C and R-410A are both 1370 times that of carbon dioxide over a 100-year time period [IPCC 1994, /2/]. In addition, the long-term environmental impact of HFCs is not known. It has already been suggested that HFC-134a may be decomposed by sunlight in the troposphere and form acid and poisonous substances [Banks 1993, /5/; Rosin 1993, /6/].

With respect to the environmental impact, the use of natural compounds, such as hydrocarbons, would seem to be preferable since they are already circulating in the biosphere and are known to be harmless to the environment. However, when using hydrocarbons in refrigeration equipment one major factor needs to be addressed: What is the impact on the safety of the product when using a flammable refrigerant?

HYDROCARBONS AS REFRIGERANTS

Hydrocarbons, propane in particular, have been used as working fluids in large refrigeration plants for many years, notably in the petrochemical processing industry. More recently, hydrocarbons have been investigated as possible replacements for CFCs and HCFCs. In many of these studies, the cycle efficiency of propane and other hydrocarbons has at least met and in most cases exceeded the efficiency of HCFC-22, while the capacity was somewhat reduced [Halozan et al. 1994, /11/; Treadwell 1994, /8/; Chen et al. 1994 /12/]. The increase in cycle efficiency of hydrocarbons is due to their excellent thermodynamic and transport properties, which result in lower pressure drops and higher heat transfer characteristics compared to CFCs, HCFCs, and also HFCs.

In addition, there are several other advantages to using hydrocarbons. In drop-in tests, propane has exhibited significantly lower compressor discharge temperatures, reducing the possibility of the breakdown of the oil and prolonging the life of the compressor. Hydrocarbons are compatible with all common machine building materials and the currently utilized mineral and alkybenzene oils. Hydrocarbons are low in cost, and readily available. Finally, due to their low density, the required refrigerant charge can be significantly less (approximately 50%) than that of HCFC-22.

One application for hydrocarbons in the immediate future is their use as replacements for halocarbons in domestic refrigerator/freezers. It is expected that hydrocarbons will take over most of the European domestic refrigerator/freezer market sometime in the future [ORNL 1993, /7/]. Currently, 90% of the German production of new refrigerators and freezers are using hydrocarbons as refrigerants. In Europe, 25% of the newly produced refrigerator/freezers are working with hydrocarbons as the refrigerant. However, the use of hydrocarbons in the US market is not likely in the near future since US manufacturers perceive many liability problems due to flammability concerns. This is leading to "two worlds" of domestic refrigeration, since global manufacturers are designing hydrocarbon systems for the European domestic refrigerator market in their European plants and HFC-134a systems for the US market in their US plants.

FLAMMABILITY AND SAFETY

The major disadvantage of hydrocarbons as refrigerants is their flammability. Although flammability is a safety concern, some safety codes still permit the use of flammable refrigerants. According to ASHRAE Standard 15-92, it is permissible to use flammable refrigerants for any application provided the total refrigerant charge does not exceed 2.72 kg and the equipment is installed according to manufacturer's specifications.

Under this standard, the responsibility of providing a safe system is transferred from the installation contractor to the manufacturer of the system. Therefore, manufacturers must design equipment which minimizes any additional risks associated with the use of a flammable refrigerant. This can be accomplished by one of two possible means: adding safety features to minimize the risks, or mixing the flammable refrigerant with other non-flammable refrigerants to obtain a non-flammable mixture.

Adding safety features

For a flammable gas to combust in air, two conditions must occur simultaneously. First, the concentration of the flammable gas must exceed the lower flammability limit (LFL). LFL is the lowest mole fraction of the flammable gas in air which will combust. Second, an ignition source must be present to ignite the flammable mixture. The purpose of any additional safety features must be to reduce the probability of either of these conditions occurring.

Due to the increasing interest in the use of flammable refrigerants, and at the request of several manufacturers, Underwriters Laboratories (U.L.) have proposed a list of safety considerations necessary to ensure the safety of systems using flammable refrigerants.

- All tubing joints should be brazed.
- Minimize the amount of refrigerant required.
- Use a pump-down cycle to store the refrigerant in the outdoor unit when idle.
- Place electrical components in an air-tight box.
- Eliminate possible locations for pools of gas to collect.
- Use and enclosed motor and place the capacitor in an electrical compartment.
- Protect coils from puncture.
- Place warning labels on the unit.
- Eliminate dissimilar metal joints.
- Determine the possibility of ignition from electric heat, motors, and electrical components and take necessary precautions.

The additional safety features required will add to the first cost of a system which contains a flammable refrigerant. Treadwell [1994, /8/] estimated that the additional cost could be up to 30% of the first cost of a typical residential unit.

Non-Flammable Mixtures

Flammable refrigerants can be mixed with non-flammable refrigerants to produce a non-flammable mixture. In fact, many of the HFC-mixtures currently under consideration as replacements for HCFC-22 are mixtures of flammable and non-flammable refrigerants. HFC-32 and HFC-152a are both moderately flammable refrigerants which are commonly used in refrigerant blends.

There are two basic means of reducing the flammability of a refrigerant mixture: dilution and chemical reaction. By mixing a small fraction of a flammable refrigerant with a non-flammable refrigerant, it is possible to dilute the concentration of the flammable refrigerant to an extent where it is not possible to reach the lower flammability limit. Many of the current HFC-blends containing HFC-32 use the dilution principle to produce a non-flammable mixture. The large fraction of non-flammable refrigerants required to dilute a highly flammable substance like propane is the primary disadvantage of this method.

Chemical manufacturers have developed substances which quench fires by chemically reacting with the constituents of the combustion process. When energy is released through combustion, these chemicals produce another reaction which absorbs the combustion energy and prevents flame propagation. This type of flame suppressant allows a much higher concentration of the flammable gas in a non-flammable mixture. R-227EA was developed as a flame suppressant to serve as a non-ozone depleting replacement for halons in fire suppression systems, but can also be used as a refrigerant. R-227EA, whose chemical name and formula is 1112333-heptafluoropropane and CF_3CHFCF_3, respectively, is non-toxic. In fact, it is used as a propellant for medical inhalants, with an LC50 value of greater than 80%. Its greenhouse warming potential is 3300 times that of carbon dioxide over a 100-year time horizon. Since the mass percentage of R-227EA in a mixture with propane must be relatively high to be considered a non-flammable mixture, such a mixture does not constitute a purely natural refrigerant and would have limited environmental benefit due to the high GWP of R-227EA.

COST-BASED EVALUATION METHOD

In general, the proper criteria for evaluating an alternative refrigerant depends on whether it is being considered for retrofits or new equipment. For new equipment, the heat exchangers, compressor, and drive motor are all design variables that can be chosen for any refrigerant to match the capacity and efficiency associated with the original system and refrigerant. The best criteria for evaluating the viability of a replacement refrigerant in new equipment is based upon economics. When designing a system for a new refrigerant, manufacturers generally try to meet two constraints: capacity and efficiency. For the residential air conditioning market, these constraints are determined based upon a marketing strategy which results in offerings that fall into various capacity and efficiency classes. Once the capacity and efficiency goals have been established, the goal of the designer is to develop the lowest cost system which will meet these constraints.

With this goal in mind, a simple method was developed at the Ray W. Herrick Laboratories at Purdue University [Douglas et al. 1995, /9/; Douglas 1995, /10/] for evaluating refrigerants based upon the cost of manufacturing systems which are optimally designed to meet specified capacity and efficiency constraints. The system with the lowest cost for a given application (i.e., efficiency and capacity) is the best choice.

Performing a design optimization on a typical air-conditioning system would be difficult, due to the large number of design variables. However, the problem can be simplified considerably by employing simple heat exchanger geometries. The simplified system is essentially a water-to-water heat pump with counterflow heat exchangers, as shown in Figure 1. The heat exchangers consist of two concentric tubes with refrigerant flowing through the center tube and water through the annulus. With this type of design, the heat exchanger can be specified with only three design parameters, namely: inner tube diameter, outer tube diameter, and length.

For the simplified system, the refrigerant loop operating conditions were chosen to be representative of an air-to-air application. The refrigerant was placed inside the inner tube to maintain flow and heat transfer characteristics similar to that of an air-to-refrigerant heat exchanger. The diameter of the outer tube and the secondary fluid flow rate were adjusted to obtain heat transfer resistances and temperature glides equal to typical air-side values.

The order of the ranking of various refrigerants that are evaluated by this optimization method applied to the simple system should be the same as it would be for a typical air-to-air system provided the following assumptions hold:

1.) The heat exchanger has enough rows to be approximated as counterflow.
2.) The optimal air-side heat transfer resistance does not change significantly between different refrigerants.
3.) The cost of the heat exchanger scales linearly with the weight of the tubing.
4.) The power consumption of the fans does not change with a change in coil design.

These assumptions will be valid provided that the air-to-refrigerant heat exchanger has four or more rows and the design changes of the heat exchanger are small.

Douglas [1995, /10/] also defined a simple cost function for optimization as

$$R(\mathbf{X}) = F_{HX}\,C_{HX} + F_{Comp}\,C_{Comp} + F_{ref,oil}\,C_{ref,oil} + F_{fix} \qquad (1)$$

where R is the system cost relative to an optimized cost for the baseline refrigerant (e.g., HCFC-22) and **X** is the vector of design variables. The cost ratio function is divided into four categories: heat exchangers (HX), compressor (Comp), refrigerant/oil (ref,oil), and fixed (fix) costs. Each cost term is expressed as the product of component cost ratio and a baseline cost fraction. The component cost ratio, C, represents the relative component cost of the new design to the component cost of the baseline. The baseline cost fraction, F, is the component's fraction of the total cost for the baseline case.

Fractional baseline costs for each component were obtained for a window air-conditioner provided by a major manufacturer. The fractional cost for the heat exchangers was $F_{HX} = 0.3$, for the compressor $F_{comp} = 0.45$, for the refrigerant/oil $F_{ref,oil} = 0.01$, and for the fixed costs $F_{fix} = 0.24$. Component costs were obtained from equipment manufacturers and used to develop correlations for costs in terms of the design variables. The heat exchanger costs were assumed to be a function of the heat exchanger material volume. The compressor costs were found to only be a function of the displacement. However, for fixed capacity and COP constraints, the motor power requirement is fixed and the dependence of cost on displacement was found to be relatively small. The refrigerant and oil costs are only a function of type of refrigerant and the mass required.

A detailed model was developed to determine the system performance and costs that could be used to evaluate the cost function of equation 1 and the constraints for cooling capacity and COP. The heat exchangers are modeled using a finite-difference method that determines variable heat transfer coefficients, pressure drops, and refrigerant inventory. The compressor is modeled using empirical coefficients determined from experimental data gathered for a single scroll compressor operating with four different mixtures. It is assumed that these empirical coefficients are also valid for other mixtures with similar thermophysical properties. In addition, the compressor can be modeled using curve-fits to measured performance data when available.

OPTIMAL COST RESULTS

The method developed by Douglas et al. [1995, /9/] was implemented within a computer program called ACOPT. The optimal cost results calculated with ACOPT are used to illustrate the trade-off between flammability and performance of hydrocarbon/flame suppressant mixtures and to compare the performance of the leading HCFC-22 replacements.

As outlined before, there are two basic means of utilizing propane safely: add safety measures, or mix propane with another refrigerant to produce a non-flammable mixture. To make comparisons between these options, the optimal costs were calculated for various mixture blends of propane (R-290) and the flame suppressant R-227EA. Figure 2 is a plot of the optimal cost relative to an optimized HCFC-22 system as a function of the mass fraction of propane. The dashed line reflects the optimal cost ratio without the additional cost of safety features. For the case of pure propane (mass fraction = 1.0), the optimal cost ratio without safety measures is 5% less than the HCFC-22 baseline.

Since a lower cost reflects a more efficient refrigerant, this trend is consistent with data presented in the literature showing up to 5% improvements in efficiency when using propane over HCFC-22. As the composition of propane is reduced by adding more R-227EA, the cost of the system increases. This increase in system cost represents the penalty of reducing the flammability of the mixture. It can be seen from Figure 1 that the optimal cost ratios between the R-290/R-227EA mixture without safety features and HCFC-22 is the same for a propane composition of 30% by weight.

For refrigerant mixtures which are flammable, the additional cost of safety features must be added to the cost ratio. As mentioned before, the cost for these safety features is estimated to add about 30% to the cost of a typical unitary air-conditioner. Although certain flammable refrigerants present greater risk than others, US industry makes no distinction between varying degrees of flammability. Once a refrigerant is labeled flammable, the same features will be required regardless of the degree of flammability.

The solid line in Figure 2 represents the system cost ratio with the 30% cost of the required safety features included if the mixture were flammable over its entire composition. The additional cost of the safety features yields an overall cost significantly greater than for HCFC-22. Therefore, a flammable mixture is not a viable alternative. However, if a non-flammable mixture with more than 30% propane could be found, the system cost ratio will be very similar to HCFC-22, and is thus a potential replacement.

Figure 3 shows results obtained with ACOPT for several of the leading HCFC-22 replacements [ARI 1994, /4/], along with propane (R-290) and mixtures of propane and flame suppressants (R-227EA). The light and dark bars represent the optimal cost ratios with and without the cost of safety features that would be required for flammable refrigerants. Clearly, the best refrigerant for this application would be propane if flammability were not an issue. However, all of these candidates perform reasonably well as compared to HCFC-22. In particular, the two leading HCFC-22 replacement candidates, R-407C and R-410A, have optimal costs that are nearly equal to those for R-22.

The assumptions associated with the simplified system and uncertainty in the modeling were evaluated by Douglas [1995, /10/] in order to determine their effect on the rank ordering of replacement refrigerants for HCFC-22. The assumptions appear to be valid for evaluating alternative refrigerants using the simplified optimization and system with one potential exception: the rank ordering for zeotrope mixtures with significant temperature glides (e.g., 10°F) can be different if the evaluations are performed based upon a pure crossflow rather than counterflow configuration. In this case, the zeotrope mixtures can benefit significantly from the use of counterflow heat exchangers.

The overall uncertainty in estimating the cost ratios due to modeling uncertainty was found to be about 3%. For the application considered in generating the results of Figure 3, the uncertainty is on the order of the differences in the cost ratios. The uncertainties could be reduced by using more accurate refrigerant-specific compressor, heat transfer, and friction loss data. Furthermore, the differences in costs depend upon the application.

The application will affect the cooling capacity and COP constraints, the secondary fluid temperatures, and the baseline cost fractions of the system components. For instance, the refrigerant cost fraction would increase significantly for a split system or for any other refrigeration application which requires long tube lengths between the condensing unit and evaporator. The results of Figure 3 were determined with a 1% refrigerant baseline cost fraction. Figure 4 shows the sensitivity of the optimal system cost ratio to various refrigerant/oil baseline cost fractions. Clearly, the differences between various refrigerants can be very sensitive to the particular application. For applications with high fractional refrigerant costs, refrigerant rankings may be relatively insensitive to performance differences and dominated by refrigerant charge requirements and costs.

The fixed costs also depend upon the application. For large chillers, the controls and other fixed costs are a smaller fraction of the total system costs. Figure 5 shows that the fixed costs do not affect the relative refrigerant rankings (50% fixed cost was used for Figure 1), but do affect the magnitude of the differences between various refrigerants. It is also expected that as the operating conditions and COP constraints change with application that the relative refrigerant rankings would change. The optimal refrigerant for refrigeration applications will certainly be different than that for air conditioning.

CONCLUSIONS

A general purpose comparison method has been developed to compare alternative refrigerants. Refrigerants are compared based upon the minimum manufacturing cost of a simplified system for specified capacity and efficiency. The refrigerant which produces the lowest cost system for the given capacity and efficiency constraints is the best choice. Using this method, propane, propane-flame suppressant mixtures, and HFC refrigerants/refrigerant mixtures were evaluated in comparison to HCFC-22. The following conclusions can be drawn.

Assuming an additional flammability cost of 30%, flammable refrigerants are not cost competitive with non-flammable refrigerants. However, the additional flammability cost of 30% is only an approximate number which has a large degree of uncertainty. The risks due to the use of a flammable refrigerant are very dependent upon application. A typical residential split system might require 2.5 kg of propane. This presents a significantly higher risk than a window air-conditioner which might only require 280 g of propane.

Until a manufacturer markets a system with a flammable refrigerant, the flammability costs are uncertain. However, the results shown here demonstrate that the optimal cost ratio of pure propane is about 5% less than that of HCFC-22. Therefore, propane would be a viable alternative if a manufacturer could design a system with a flammability cost of less than about 5%. Currently, it appears unlikely that the necessary safety features could be installed for less than 5% of the total system cost.

From the point of view of environmental impact, there is good reason to consider propane as an alternative for HCFC-22. Currently, the extra cost of safety measures severely hampers its chances of market success. However, as environmental concerns and the demands for environmentally benign refrigerants increase, people may be willing to pay more for an environmentally friendly system.

Propane and propane-flame suppressant mixtures were also compared with eight leading candidates for HCFC-22 replacements. All of the optimal costs fell within $\pm$ 5% of the HCFC-22 baseline costs and six of the refrigerants were within $\pm$ 1.5% of the baseline. The optimal costs of the two leading HCFC-22 candidates, R-407C and R-410A, were within $\pm$1%. Aside from the flammable refrigerants, only one mixture, HFC-32/HFC-134a (30%/70%), exhibited an optimal cost less than R-407C and R-410A. The small differences between the refrigerants is good news for manufacturers, since the choice of specific refrigerant will not affect the system cost significantly.

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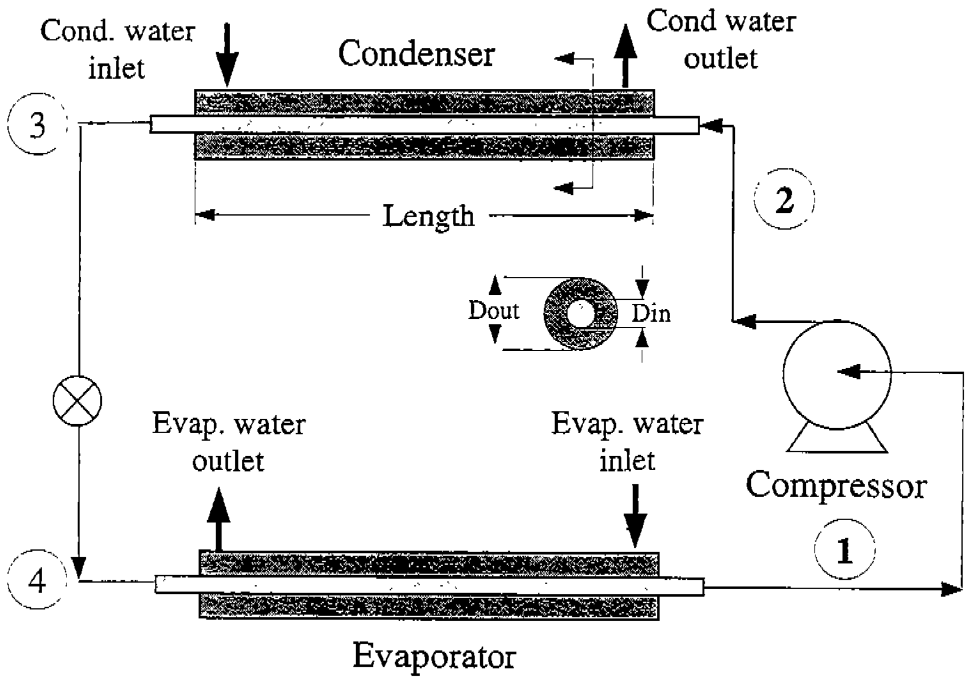

Figure 1: Schematic of the simplified system

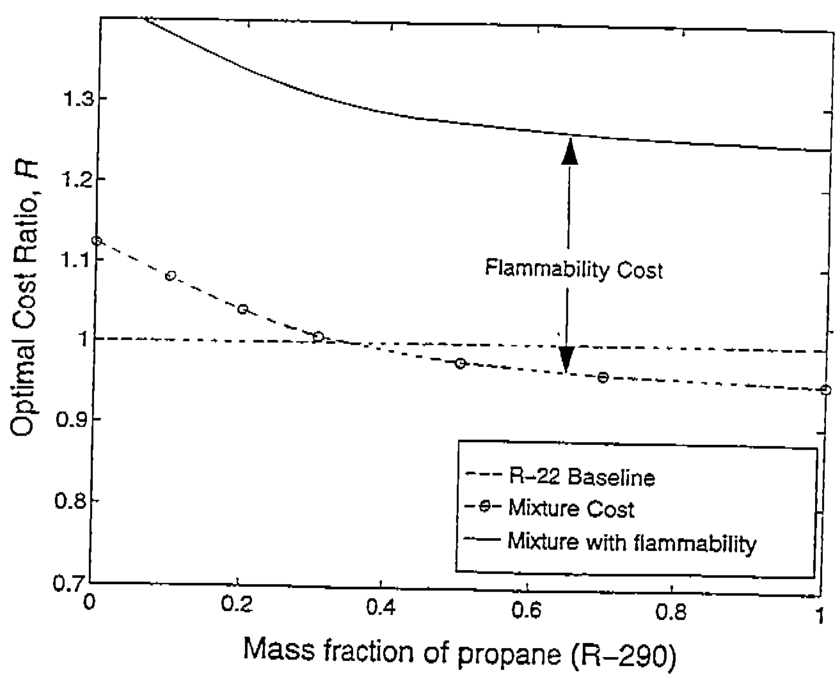

Figure 2: Optimal system cost ratio for R-227EA/R-290 mixtures with HCFC-22 as the baseline refrigerant

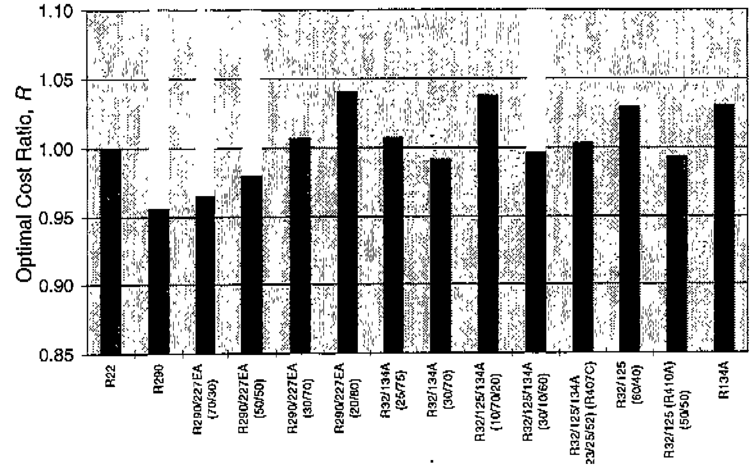

Figure 3: Optimal system cost ratios for various refrigerants with R-22 as the baseline

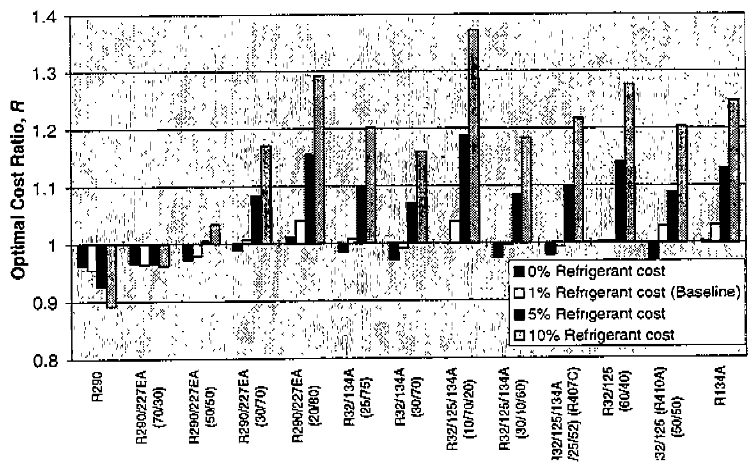

Figure 4: Sensitivity of optimal system cost fractions to refrigerant/oil baseline cost fractions

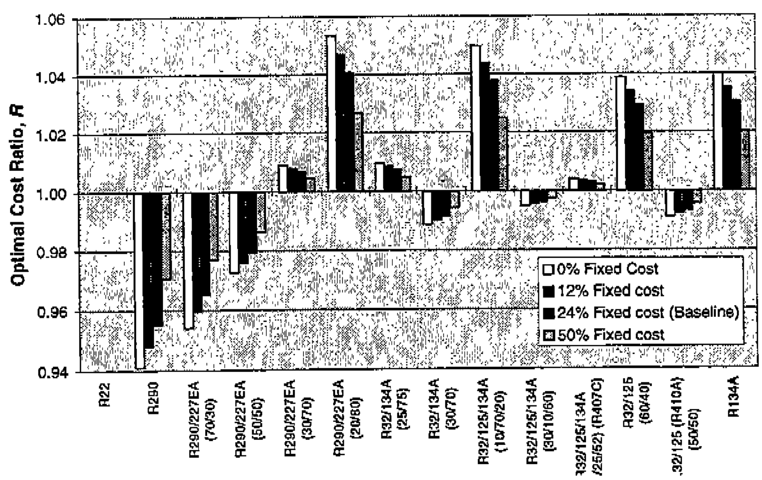

Figure 5: Sensitivity of optimal system cost fractions to the baseline cost fraction for fixed costs