THE ALTERNATIVE REFRIGERANT DILEMMA FOR REFRIGERATOR-FREEZERS: TRUTH OR CONSEQUENCES

E.A. Vineyard, P.E.

ABSTRACT

In response to regulatory actions arising from the Montreal Protocol and the National Appliance Energy Conservation Act (NAECA), refrigerator-freezer manufacturers and government researchers are investigating energy-efficient replacement refrigerants for R-12. The Montreal Protocol, enacted in 1987, requires that by mid-1998, the production of R-12 be reduced by 50% relative to 1986 levels (Federal Register *1987). As a result, a replacement refrigerant must be decided upon as soon as possible to allow time for design changes, product life tests, and retooling. In an effort to select a refrigerant that has minimal impact on energy consumption and the environment, a screening analysis of potential refrigerants was performed that resulted in the selection of six candidates. The screening results show that R-134a, R-134, R-152a, R-134a/R-152a, R-22/R-152a/R-124, and R-134a/R-152a/R-124 are the most promising refrigerants for future use based on the following criteria: ozone depletion potential (ODP), greenhouse warming potential (GWP), coefficient of performance (COP), and safety. Following the screening study, energy consumption tests were performed for the three pure refrigerants in an 18 ft^3 (0.51 m^3) automatic-defrost top-mount refrigerator-freezer in accordance with the Association of Home Appliance Manufacturers (AHAM) standard for household refrigerators and household freezers (AHAM 1985). The results indicate an increased energy consumption of 6.8%, 7.3%, and 7.3%, respectively, for R-134, R-152a, and R-134a in the most efficient oil. However, when the effects of compressor efficiency are taken into account, the normalized energy consumption results in an increase of only 2.7% for R-152a and 5.5% for both R-134a and R-134.*

INTRODUCTION

The search for an R-12 replacement in refrigerator-freezers began after the 1987 ratification of the Montreal Protocol, a global agreement protecting the stratospheric ozone layer from emissions of chlorinated and brominated compounds (UNEP 1987). Before then, evidence that chlorofluorocarbons were contributing to the destruction of the ozone layer was lacking, and compelling reasons to look at substitutes were, therefore, nonexistent. In the months following the signing of the landmark agreement, initial investigations focused on drop-in replacements and transitional refrigerants in hopes that a quick cure would be found or, better still, that the Montreal Protocol would be amended to allow for a longer phaseout of R-12. It soon became apparent that it was virtually impossible to replace a refrigerant in an existing system without (1) significant changes to the design, (2) replacement of the oil, or (3) potential problems with flammability, reliability, serviceability, or toxicity. Since no easy solution was available and because the phaseout period might be shortened at a future reassessment meeting that would address new restrictions for the Montreal Protocol, the search for alternatives intensified.

In addition to the requirements of the Montreal Protocol, manufacturers also faced progressively tougher energy-efficiency standards. In 1987, the NAECA established energy-efficiency standards for several consumer appliances including refrigerator-freezers (NAECA 1987). The initial standards went into effect January 1, 1990, when the effects of the Montreal Protocol were not yet an issue because energy-efficient CFCs could still be used as refrigerants and blowing agents in foam insulation to meet energy goals. Efficiency standards for 1993 stiffen requirements by an average of 25% (*ACHR News* 1990), even though (1) long-term alternative refrigerants in some cases have been shown to be less efficient (Vineyard et al. 1989b) and (2) alternative blowing agents for foams have higher thermal conductivities that make the new foams less energy-efficient than their CFC-blown counterparts. Thus, manufacturers face an uphill battle in striving to meet the 25% reduction in energy consumption required by the 1993 standard. By 1998, the standard is expected to require an additional 25% reduction that will have to be met solely while using non-CFC insulations and refrigerants.

In a previous study to determine viable alternative refrigerants for refrigerator-freezer applications, four refrigerants were tested in an unmodified unit to determine their energy consumption compared with R-12 (Vineyard et al. 1989b). While the results provided useful information to manufacturers and suppliers, they did not fully examine all possible replacements or the effects of system modifications. Of the refrigerants tested, only R-134a and R-22/R-142b were viable possibilities as long-term replacements. Because both refrigerants resulted in a large increase in energy consumption, a more thorough investigation was necessary to (1) identify alternatives with comparable performance to R-12 and (2) test their energy consumption in a unit with minor modifications aimed at improving system performance through optimal matching of the components to the refrigerants.

SCREENING ANALYSIS

Methodology

To identify alternatives for testing, the first task was to assemble an initial list of pure refrigerant components (Table 1) from which both pure refrigerants and refrigerant mixtures could be selected. The methodology for the initial selection, similar to one used in a previous study on

Edward A. Vineyard is a Research Engineer at Oak Ridge National Laboratory, Oak Ridge, TN.

TABLE 1
List of Pure Refrigerant Components

R-32	R-134a	R-124a
R-125	R-152a	R-142b
R-143a	R-134	RC-318
R-22	R-124	R-143
R-218		

refrigerant mixtures for a heat pump application (Vineyard et al. 1989a), eliminates potential refrigerants on the basis of boiling point, chemical and thermal stability, ODP, and toxicity. Using this approach, the generated list includes many new refrigerants, such as R-134a, R-124, R-125, and R-142b, that are mentioned most often as potential solutions to the ozone problem. In addition, other refrigerants on the list, such as R-134, R-32, and R-152a, show a lot of promise but have not been seriously considered for commercial applications because of (1) insufficient property information, which prevents an accurate evaluation of the expected benefits, or (2) safety issues that must be addressed.

After refrigerant components were identified, the next step was to assemble lists of pure fluids and mixtures that would be pared down to six refrigerants for experimental testing. The initial selection criteria for each of the lists were quite different. Pure fluid selections were based on the proximity of the candidate refrigerant's calculated capacity to that of R-12. The rationale for this particular methodology is that if the capacity greatly exceeded that of R-12, the compressor size would be greatly reduced, resulting in smaller compressors that are inherently less efficient. On the other hand, refrigerants that have significantly smaller capacities would require much larger compressors, thus requiring major redesigns in the compressor compartment, having higher costs and potential noise problems. The main criterion for selecting mixtures was a small boiling point differential between the fluids to minimize the refrigerant temperature variation in the heat exchangers and the heat transfer degradation inherent with mixtures. An additional criterion was to pair a flammable component with a nonflammable component so that the percentage of the flammable component could be reduced to the point where the mixture was nonflammable. Finally, several mixture compositions were analyzed to determine the highest COP.

The final step was to devise a method for screening that would satisfy the concerns of both government and industry. This was accomplished by ranking the alternatives based on four major criteria: ODP, GWP, COP, and safety (flammability and toxicity). Values for ODP and GWP were obtained from the Environmental Protection Agency (EPA) and reflect the EPA's latest estimates using R-11 as the basis (EPA 1989). For the mixtures, the ODPs and GWPs were calculated by proportioning the values for ODP and GWP of the pure components based on the mass percentage of each component in the mixture. The ideal COPs for each refrigerant were determined by using a version of the CYCLE program that uses the Redlich-Kwong-Soave equation-of-state to determine refrigerant properties (Connon 1989). Flammability and toxicity information, some of which is based on preliminary estimates, was obtained from chemical suppliers (Bivens n.d.).

Results

The refrigerant rankings are shown in Tables 2 through 4. A high COP was considered to be desirable; thus, the rating in parentheses for COP increases as the COP decreases. On the other hand, low values for ODP, GWP, flammability, and toxicity result in low ratings. Equal weighting was given to each of the four criteria because experimentation with different weighting factors yielded no significant changes in the relative rankings among the groups. Before the final six candidates were selected, the decision was made to choose three pure fluids, two ternary fluids, and a single binary refrigerant. This decision was based mainly on preferences expressed by manufacturers that the alternative refrigerant cause as few problems as possible for manufacturing and service personnel. Pure fluids would be simpler to handle because charging problems would be minimized: unlike mixtures, pure fluids have no potential to change concentration depending on the method of charging. The reason for using two ternaries as opposed to one binary is similar. Should a leak occur in the system, the COP and capacity of a ternary could be affected less than those of a binary refrigerant, depending on the components of the mixture.

The rankings for the pure refrigerants (Table 2) shows that R-152a is the best refrigerant on the basis of its high COP, low ODP, and low GWP. These three positive attributes tend to outweigh its one major drawback—flammability. The next two refrigerants, R-134 and R-134a, both had low ODPs and relatively low GWPs. The difference between these isomers is that R-134 has a higher theoretical COP. However, less is known about its potential toxicity, a factor that lowered its safety rating. The final two refrigerants, R-124 and R-22, were not selected for experimental testing due to their overall low ratings.

Binary refrigerant rankings, shown in Table 3, indicate that the R-134a/R-152a combination is clearly the best selection, with high marks for COP, ODP, and GWP. The only concern is that the mixture, even though nonflammable in its as-charged composition, could become flammable as the result of a leak in the system, which could increase the concentration of the R-152a. The most surprising conclusion from the rankings is that the other refrigerant pairs, although not selected for experimental testing, were all ranked essentially equally, except for R-143a/R-134a and R-125/R-152a. This phenomenon occurred, with some exceptions, because the mixtures combine two high ratings with two low ratings. For example, R-152a/R-124 com-

TABLE 2
Pure Refrigerant Rankings

Refrigerant	COP	ODP	GWP	Safety	Total
R-152a	2.45 (1)	0 (1)	.026 (1)	(5)	(08)
R-134	2.39 (2)	0 (1)	.250 (3)	(4)	(10)
R-134a	2.26 (5)	0 (1)	.250 (3)	(2)	(11)
R-124	2.34 (3)	.17 (5)	.092 (2)	(3)	(13)
R-22	2.29 (4)	.05 (4)	.340 (5)	(1)	(14)

TABLE 3
Binary Refrigerant Rankings

Refrigerant	COP	ODP	GWP	Safety	Total
134a/152a (75/25)	2.34 (3)	0 (1)	.194 (2)	(6)	(12)
22/134a (25/75)	2.26 (5)	.0215 (6)	.273 (7)	(1)	(19)
134a/124 (75/25)	2.26 (5)	.0425 (8)	.211 (3)	(3)	(19)
22/124 (50/50)	2.30 (4)	.11 (9)	.216 (4)	(2)	(19)
22/152a (75/25)	2.38 (2)	.0375 (7)	.262 (6)	(5)	(20)
152a/124 (25/75)	2.39 (1)	.1275 (10)	.076 (1)	(8)	(20)
32/134a (25/75)	2.26 (5)	0 (1)	.225 (5)	(10)	(21)
125/134a (25/75)	2.20 (9)	0 (1)	.315 (8)	(4)	(22)
143a/134a (35/65)	2.22 (8)	0 (1)	.415 (10)	(6)	(25)
125/152a (75/25)	2.15 (10)	0 (1)	.389 (9)	(9)	(29)

bined two first-place ratings in COP and GWP with eighth- and tenth-place ratings in ODP and safety to yield an overall total that placed it equivalent to six other refrigerant pairs.

The ternary mixtures (Table 4) are perhaps the most interesting development among the alternatives, since they may overcome some of the drawbacks of pure fluids and binaries. One of the problems with pure fluids is that few are available in the capacity range of R-12. With ternaries, the amount of the high- and low-capacity refrigerants can be adjusted, usually with little effect on COP, to obtain the desired capacity. Nonazeotropic binaries can present a major problem if a leak in the system occurs; the possibility exists that a nonflammable mixture with a flammable component can become flammable. By "sandwiching" the flammable component between two nonflammable constituents, a nonflammable ternary can overcome the danger of a flammable mixture occurring in a system with a leak. Other possible advantages of ternaries include (1) overcoming immiscibility problems by using a large percentage of a component that is miscible with the oil and (2) opportunities for minimizing the heat transfer degradation inherent in mixtures by selecting three components that yield a mixture with a minimal temperature glide.

TEST PROCEDURE

All tests were performed on an 18 ft^3 (0.51 m^3), automatic-defrost, top-mount refrigerator-freezer with a forced-air condenser. Each series of tests with a different refrigerant used a new compressor that was sized to reflect changes in the volumetric capacity of each refrigerant. Along with each compressor change, different oils were selected based on recommendations from compressor manufacturers concerning life test results and equivalent viscosity values at operating conditions. A capillary tube manifold was also installed on the refrigerator-freezer to enable making small changes in refrigerant flow. The final capillary selection was made by performing tests to determine which capillary gave the lowest energy consumption. It should be noted that selection was somewhat limited: only one set of three capillaries was installed because of the time limitations of the project and because we wanted to modify the system as little as possible.

The tests were conducted in accordance with Section 8 of the AHAM Standard for Household Refrigerators and Household Freezers (AHAM 1985). The standard calls for four test points to be performed by running the refrigerator-freezer at two different control settings with the anti-sweat heater switch in both the "on" and "off" positions. Energy consumption results for each test point are then used to calculate a daily energy consumption based on a 5°F (−15.0°C) freezer reference temperature.

Since energy consumption is a function of the energy efficiency ratio (EER) of the compressor, some method was needed to normalize the results to take into account the fact that the compressor efficiency for the alternatives was different from that of R-12. This was accomplished by multiplying the daily energy consumption for each alternative by the following ratio: $EER_{ALTERNATIVE}/EER_{R-12}$. The

TABLE 4
Ternary Refrigerant Rankings

Refrigerant	COP	ODP	GWP	Safety	Total
22/152a/124 (35/25/40)	2.39 (1)	.0855 (4)	.1623 (1)	(2)	(8)
134a/152a/124 (60/25/15)	2.35 (3)	.0255 (2)	.1703 (2)	(3)	(10)
22/134a/152a (15/60/25)	2.36 (2)	.0075 (1)	.2075 (3)	(4)	(10)
22/134a/124 (20/60/20)	2.27 (4)	.0440 (3)	.2364 (4)	(1)	(12)

EER, a measure of the power required for a given refrigeration effect, was determined for a −10°F (−23.3°C) evaporator, a 130°F (54.4°C) condenser, and 90°F (32.2°C) subcooling and superheating entering the expansion valve and compressor, respectively. It is recognized that a better approach would be to have performance ratings from a range of evaporator and condenser temperatures in order to pinpoint the EER at the actual operating conditions. However, information of this nature was unavailable and beyond the scope of this project.

Following each compressor changeout, the unit was leak-tested and evacuated overnight to ensure that most of the moisture was removed from the system. Refrigerant was then added to the system and the unit was allowed to run until quasi-steady-state conditions were achieved. The level of charge was initially adjusted by monitoring thermocouples in the evaporator to determine the point at which enough refrigerant had been added or removed from the system so that the refrigerant was slightly superheated after it left the evaporator. Final adjustments were made to the charge by varying the levels by minimal amounts to yield the lowest energy consumption.

RESULTS

A total of four pure refrigerants including R-12 were tested. The three alternatives—R-134a, R-134, and R-152a—represent a good selection that reflects the interests of both government and industry. R-134a, the substitute mentioned most often as the leading candidate by chemical suppliers, has already been embraced both by refrigerator-freezer manufacturers in Europe and by the U.S. automotive industry. R-134, on the other hand, is a chemical with some unanswered questions. It has the same molecular weight as R-134a but differs in how the hydrogen and fluorine atoms are arranged on the two carbons. Little is known about its properties, although preliminary estimates indicate that it could be more energy efficient than R-134a (Sand et al. 1990). The best refrigerant from a theoretical viewpoint, R-152a, is the refrigerant mentioned most often as the leading alternative by the EPA because of its low ODP and GWP. Industry, however, views R-152a with great apprehension because of the issue of flammability and the accompanying possibilities for litigation.

R-134a Tests

R-134a was one of the first refrigerants tested as an alternative for R-12. Initial results were not very encouraging because energy consumption was higher than that of R-12, and accelerated-life tests revealed problems with high failure rates with some of the initial oil candidates. Discouraged by the initial results, researchers focused on other alternatives, such as R-22/R-142b, R-12/DME, and R-500, in hopes of finding a drop-in replacement that would require no changes in the present system. It soon became clear that problems existed with all of the alternatives and there could be no drop-in solution. As research in the U.S. concentrated on a range of alternatives, the European community had decided that R-134a was the refrigerant of the future and focused its efforts on finding compatible oils that would yield the best energy consumption and life test results. Initially, the oils of choice were polyglycol-based with viscosities approximately the same as those of mineral-based lubricants. Problems were experienced with these oils in the form of abnormal wear and high failure rates in accelerated-life tests (Sundaresan n.d.; Campbell n.d.). Researchers therefore began to look for other solutions. In Europe, successful tests with ester-based lubricants were reported in early 1990 (Taulbee n.d.). Samples of the ester oils later became available in the U.S., with initial tests showing positive results. Work since then has investigated the possibilities for lowering the viscosity and achieving better energy efficiencies along with performing long-term life tests.

The results for R-134a are shown in Table 5. Testing was performed with two ester-based oils of different viscosities, 90 and 100 SUS at 104°F (40°C). These oils, while considerably less viscous at the rating point than mineral oils presently used with R-12, are predicted to have approximately the same viscosity at the compressor operating temperature. Actual energy-consumption values using the two oils were 2.48 and 2.35 kWh/d for esters 100 and 90, respectively. Using the compressor energy efficiency ratios (EERs) to normalize the energy consumption yields values of 2.35 and 2.31 kWh/d, which are 7.3% and 5.5% higher than the energy consumption with R-12. It appears from these results that the oil viscosity affects not only compressor efficiency but also overall system efficiency.

TABLE 5
Refrigerator-Freezer Test Results

Refrigerant	R-12	R-134a	R-134a	R-134	R-152a
Energy Consumption (kWh/day)	2.19	2.48	2.35	2.34	2.35
Compressor EER	5.21	4.93	5.12	5.14	4.98
Energy Consumption - Normalized (kWh/day)	2.19	2.35	2.31	2.31	2.25
Oil	Mineral 150	Ester 100	Ester 90	Ester 90	AB 150
Run Time (%)	48.1	54.0	53.4	46.4	58.4
% Increase in Energy Consumption Normalized	—	7.3	5.5	5.5	2.7

This conclusion is evidenced by the fact that the normalized energy consumption is not equivalent for both cases. Refrigerant/oil miscibility data indicate that miscibility improves as the oil viscosity decreases. Thus, overall system efficiency can be improved as a result of better heat transfer in the evaporator.

Increased run times for R-134a caused a bias in the energy consumption that is not present when two refrigerants have equal run times. Energy consumption increased because of increased power to run the fans for a longer period of time and higher heat leakages, especially around the gasket area. Longer run times are an indication that at least one of the following problems is occurring: (1) the compressor capacity is not equivalent to that of the R-12 compressor, (2) the capillary is not well matched for the refrigerant being used, or (3) the oil/refrigerant combination is immiscible in the evaporator, causing fouling of the heat exchanger. Looking at the available information, it appears that all three problems contribute to the longer run times in this case. First, the compressor capacity is lower, 828 Btu/h vs. 849 Btu/h for R-12. Second, a check of the miscibility curves for R-134a with the ester oils shows a possibility for immiscibility at low temperatures. Finally, capillary selection was limited to three choices for this test fixture. The selection for R-134a was the same as that chosen for the R-12 testing. In discussions with manufacturers, we learned that R-134a usually has a more restrictive capillary than R-12. Thus, a more restrictive capillary, had one been available, might have resulted in shorter run times.

R-134 Tests

R-134 has a boiling point of −3.5°F (19.7°C), which is 12.2°F (6.8°C) higher than that of R-134a. Its capacity at operating conditions for a refrigerator-freezer is approximately 76% that of R-12; therefore, it requires a larger displacement compressor to achieve the same run times. Property data are very sparse because most research has focused on R-134a; thus, there is not as much confidence in R-134 performance estimates as for some of the other new fluids. It is also much harder to obtain research quantities of the material for experimental testing. Chemical suppliers have indicated in discussions that R-134 is more difficult to synthesize than R-134a, so it would cost more than R-134a to manufacture (Bivens n.d.). In addition, R-134 is not presently included in the Program for Alternative Fluorocarbon Toxicity (PAFT) testing to determine long-term toxicological effects of new chemical compounds. Since these tests require several years to complete, R-134 would not be available for commercial use until sometime in the late 1990s even if PAFT testing began immediately.

Testing with R-134 was performed using the same oil (ester 90) that was used for one of the R-134a tests. Results for R-134, shown in Table 5, reveal that the energy consumption, 2.34 kWh/d, is almost the same as that for R-134a. The normalized value of energy consumption is 2.31 kWh/d based on an EER of 5.14 Btu/Wh. These results are quite interesting in that there appears to be no change in compressor efficiency or energy consumption for the product as the result of using R-134 as opposed to R-134a. It is noted that the EER value for R-134 was obtained in a different manner than those for R-134a and R-152a. The compressor manufacturer was unable to perform calorimeter tests with R-134 because it was unavailable. He chose instead to perform tests with R-134a. Once we received the compressor, tests were performed with both R-134a and R-134 so that a "comparative" EER (one that accounts for the differences between the two test facilities) could be obtained. The "comparative" EER was determined by multiplying the EER obtained for R-134 at our laboratory by a ratio of the results obtained at both labs for R-134a.

R-152a Tests

Of the three replacements discussed in this paper, R-152a is the most familiar, since it is not really a new refrigerant but one that has been commercially available for a number of years as a component in the R-500 azeotrope. It is also the most efficient pure refrigerant available in the boiling point range of R-12. With a predicted capacity that is 97% that of R-12, only a small change in compressor displacement is required. Because of its low ODP and GWP, it is no wonder the EPA ranks it high on the list of replacement refrigerants. Industry, on the other hand, has expressed concerns about its flammability aspects because of the possible liability issues that could result from its use in domestic appliances. The EPA is making efforts to address the concerns of industry by working with various organizations, such as Underwriters Laboratories, to evaluate the safety issues involving the use of R-152a. If the flammability issue could be resolved, it could have the effect of moving R-152a to the forefront of the race for an acceptable R-12 alternative.

R-152a tests were performed with both an alkylbenzene oil (AB 150) and an ester-based oil (ester 90). The results were nearly identical. Only the AB 150 results are presented because compressor calorimeter data are available and because it is also the oil recommended by refrigerant suppliers. The energy consumption was 2.35 kWh/d—identical to that for R-134a and close to R-134. With a compressor EER of 4.98 Btu/Wh, the normalized energy consumption was calculated to be 2.25 kWh/d, the lowest of the three refrigerants tested. Run times, in a manner similar to those of R-134a, were noticeably higher than those for R-12. As explained earlier, longer run times contribute to higher energy consumption in several different ways.

CONCLUSIONS

The following conclusions apply only to residential refrigerator-freezers and more specifically to the particular unit tested. The results should not be construed as being applicable to other refrigeration systems, such as heat pumps or automotive air-conditioning, because those systems operate under different conditions and with different components that could affect the performance. In addition, the conclusions are based on one series of tests for determining energy consumption and are not sufficient to adequately predict the overall performance of the system under other conditions, such as pulldown and elevated ambient temperatures. Before a decision is made on the adequacy of an alternative refrigerant, further tests are in order, e.g., accelerated life, noise, and system reliability.

- R-134a performance is improved as the oil viscosity is decreased. While one would expect this result based on improvements in compressor efficiency, the reduced energy consumption goes beyond the improvement shown by the compressor. This can be seen by comparing the normalized energy consumption for the R-134a tests with different oils. As shown in Table 5, the normalized energy consumption for the ester 90 is lower than for the ester 100 test case, indicating that the energy consumption is lower because of other factors. A possible explanation is that the heat transfer is improved in the evaporator because of improved oil/refrigerant miscibility.

- R-134 performs similarly to R-134a in both the refrigerator-freezer and the compressor. Thus, there appear to be no benefits to using it for present applications. However, should future designs include an increased level of insulation so that the required capacity is greatly reduced, R-134 might be a solution to maintaining compressor efficiency by eliminating the need for compressor downsizing.

- R-152a was the best-performing refrigerant of the three tested, with a normalized energy consumption only 2.7% higher than that of R-12. From a long-term environmental standpoint, it also is the best alternative based on low ODP and GWP values. Nevertheless, flammability currently deters its acceptance by manufacturers.

A decision on an alternative refrigerant must be made soon by manufacturers in order to meet the deadlines imposed by government legislation. If a pure refrigerant is desired, it would appear that, based on the preceding results, manufacturers may choose to concentrate on either (1) improving the efficiency of R-134a or (2) defining the expected additional liabilities that would result from using R-152a and deciding on its subsequent acceptability. A third alternative is to investigate the performance of mixtures, which is the subject of future work for this project, in which the alternatives R-134a/R-152a, R-22/R-152a/R-124, and R-134a/R-152a/R-124 will be studied.

ACKNOWLEDGMENTS

This paper is an account of work performed under Research Project 614-RP, cosponsored by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the Office of Building Technology, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. The author would like to express appreciation to E.I. duPont de Nemours and Co., Americold, and ICI Chemicals and Polymers Ltd. for providing materials for this project. In addition, appreciation is extended to Don Bivens, Fletcher Campbell, and the members of ASHRAE TC 7.1 for their technical input.

REFERENCES

AHAM. 1985. *AHAM standard for household refrigerators and household freezers*. Chicago: American Home Appliance Manufacturers.

Bivens, D.B. Personal communication. E.I. du Pont de Nemours and Co.

Campbell, F. Personal communication. Americold.

Connon, H.A. 1989. "A generalized computer program for analysis of mixture refrigeration cycles." *ASHRAE Transactions*, Vol. 89, Part 1, pp. 628-639.

Federal Register. 1987. 52 FR 239, pp. 47489-47523.

NAECA. 1987. Public law 100-12, March 17.

Sand, J.R., E.A. Vineyard, and R.J. Nowak. 1990b. "Experimental performance of ozone-safe alternative refrigerants." *ASHRAE Transactions*, Vol. 96, Part 2, pp. 173-182.

Scientific Assessment of Stratospheric Ozone. 1989. Environmental Protection Agency. July 14.

Sundaresan, S. Personal communication. Copeland.

Taulbee, J.K. Personal communication. Americold.

The Air Conditioning, Heating, and Refrigeration News. 1990. January 22, p. 1.

United Nations Environmental Programme. 1987. *Montreal protocol on substances that deplete the ozone layer. Final act*. New York: United Nations.

Vineyard, E.A., J.R. Sand, and T.G. Statt. 1989a. "Selection of ozone-safe, nonazeotropic refrigerant mixtures for capacity modulation in residential heat pumps." *ASHRAE Transactions*, Vol. 95, Part 1.

Vineyard, E.A., J.R. Sand, and W.A. Miller. 1989b. "Refrigerator-freezer energy testing with alternative refrigerants." *ASHRAE Transactions*, Vol. 95, Part 2.