Synopsis of Residential Refrigerator/Freezer Alternative Refrigerants Evaluation

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ABSTRACT

The experimental testing on residential refrigerator/freezers (R/Fs) is summarized in this paper. R/F testing focused on two areas: alternative refrigerants and equipment configurations. The refrigerants evaluated consisted of single components, azeotropes, and zeotropes derived from hydrofluorocarbons (HFCs) and hydrocarbons (HCs). These refrigerants were evaluated in conventional and unconventional R/F designs. Major and minor design modifications were studied. Minor modifications consisted of various capillary tube lengths, door insulations, and compressors, while major modifications included two-evaporator and two-cycle R/F systems. Results obtained from testing the two-cycle system will be discussed in a later paper. This paper presents the experimental results of alternative technologies evaluated as replacements for ozone depleting chemicals.

INTRODUCTION

Anticipating the Montréal Protocol agenda, an international panel of experts convened and proposed possible chemical alternatives to replace chlorofluorocarbons (CFCs) and halons. Following the recommendation of this panel, a joint research program was commenced with the Electric Power Research Institute to systematically search for new chemicals to broaden the range of possible alternatives. This endeavor resulted in the synthesis of approximately 40 new chemicals; eleven of the 40 were selected for further detailed evaluation.

As a result of this endeavor, the chemical industry is proceeding to commercialize five of the eleven (hydrofluorocarbon R-236fa, CF_3I, hydrofluorocarbon R-245fa, hydrofluorocarbon R-227ea, and hydrofluorocarbon R-245ca) chemicals first identified, investigated, and recommended. Many of the proposed alternatives are hydrofluorocarbons (HFCs); their performance affects the energy efficiency of the processes in which they are utilized. Therefore, a program was implemented to evaluate the energy performance of these chemicals in refrigeration equipment. Refrigeration equipment studies included performance evaluations of supermarket freezer cases, automobile air conditioners, residential heat pumps, and refrigerator/freezers (R/Fs). This paper focuses on experimental work done by studying alternative technologies for residential R/Fs, which includes innovative R/F designs.

TESTING FACILITIES AND DATA COLLECTION

Conventional 18 ft^3 (0.51 m^3) R/F designs and a Lorenz-Meutzner (LM) design, shown in Figures 1a and 1b, were tested in an environmental chamber with the temperature and humidity controlled at 90°F (32.2°C) and 40% relative humidity, respectively. During the hydrocarbon testing, the chamber temperature was maintained at 80°F (26.7°C) because this temperature was deemed to be more realistic in actual applications. Air curtains were used to maintain a uniform temperature throughout the chamber and to regulate the air circulation around the cabinet to less than 50 ft/min (15 m/min), according to American National Standards Institute/Association of Home Appliance Manufacturers (ANSI/AHAM) R/F energy consumption testing standards. The insulated doors were tested according to an ANSI/AHAM closed-door R/F energy consumption test method with no override of a factory-supplied controller. The R/F compartments were tested with the temperature control setting in the warm and medium position, as indicated in Table 1 and required by the standard.

The advanced insulation technologies employed in the R/F doors included both vacuum-based systems and atmospheric-pressure, low-conductivity gas-based systems. Vacuum-based insulation included evacuated panels using

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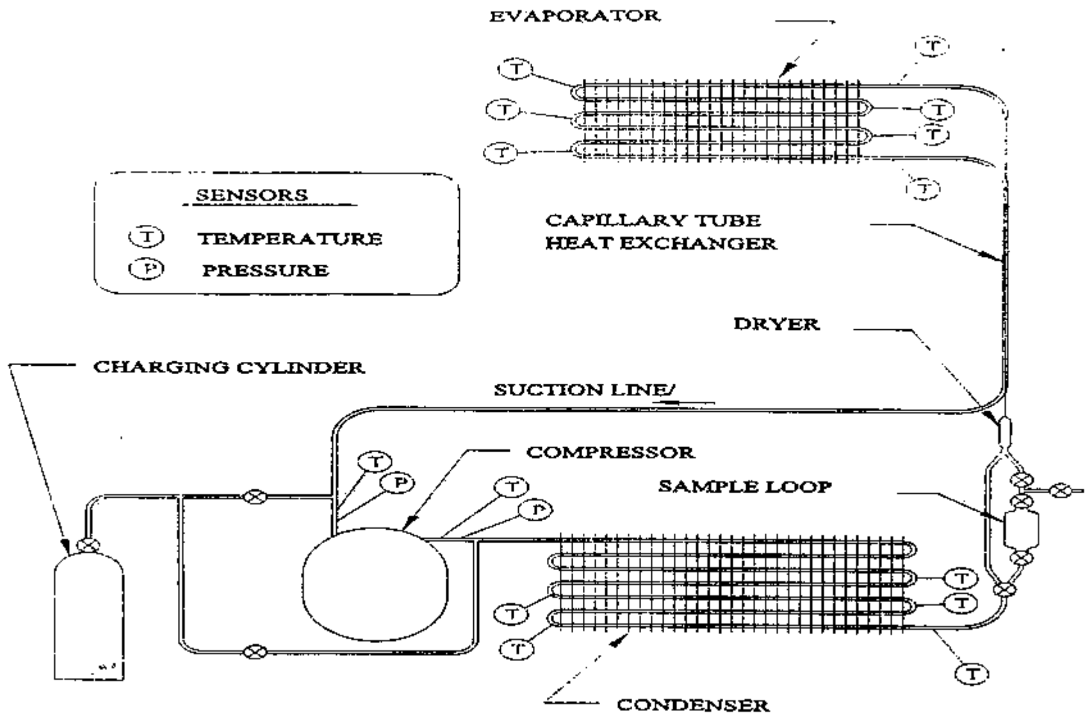

Figure 1a Conventional refrigerator/freezer.

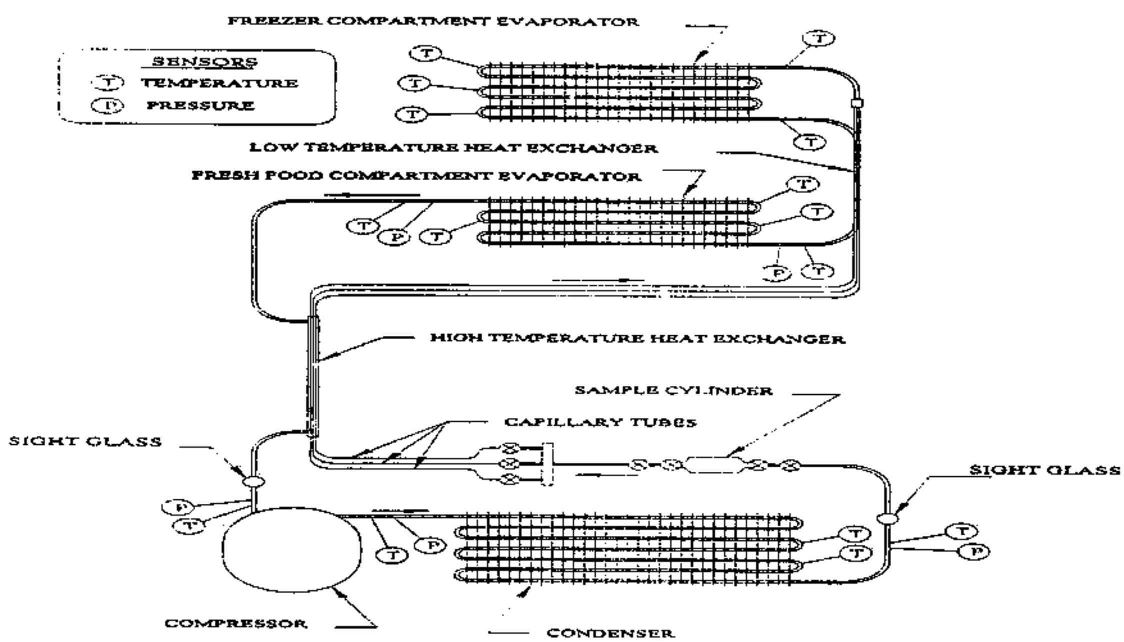

Figure 1b Lorentz-Meutzner refrigerator/freezer.

TABLE 1
AHAM Closed Door Refrigerator/Freezer Test

Door Type	Control Setting Freezer/Fresh Food	Anti-Sweat Heater	kWh	Run Time (min)	Energy (kWh/day)	Freezer (°F/°C)	Fresh Food (°F/°C)
Original	mid/mid	off	1.653	1652	1.44	2.84/−16.20	41.77/5.43
	mid/mid	on	1.785	1552	1.66	2.74/−16.26	41.75/5.42
	warm/warm	on	1.929	1914	1.45	8.85/−12.86	48.61/9.23
	warm/warm	off	1.745	2044	1.23	8.98/−12.79	48.76/9.31
Gas-Filled Panel	mid/mid	off	1.686	1754	1.38	3.08/−16.07	41.17/5.09
	mid/mid	on	1.778	1611	1.59	3.10/−16.06	40.88/4.93
	warm/warm	on	1.954	2008	1.40	8.80/−12.89	47.57/8.65
	warm/warm	off	1.756	2153	1.17	9.17/−12.68	47.87/8.82
Thick Foam (TF)	mid/mid	off	1.684	1683	1.44	3.42/−15.88	41.37/5.21
	mid/mid	on	1.831	1573	1.68	3.23/−15.98	41.06/5.03
	warm/warm	on	1.982	2032	1.40	9.84/−12.31	48.59/9.22
	warm/warm	off	1.787	2181	1.18	9.78/−12.34	49.48/9.71
Krypton-Filled	mid/mid	off	1.619	1685	1.38	3.20/−16.00	40.77/4.87
	mid/mid	on	1.801	1564	1.66	2.22/−16.54	40.03/4.46
	warm/warm	on	1.966	2010	1.41	8.60/−13.00	47.18/8.43
	warm/warm	off	1.748	2168	1.16	8.75/−12.92	48.77/9.32
Pseudo (TF)	mid/mid	off	1.633	1809	1.30	2.52/−16.38	40.31/4.62
	mid/mid	on	1.842	1672	1.59	2.02/−16.66	39.82/4.34
	warm/warm	on	1.986	2120	1.35	8.76/−12.91	46.98/8.32
	warm/warm	off	1.768	2346	1.09	9.22/−12.66	47.43/8.57

glass fibers or foams as filler material (Griffith and Arasteh 1992).

The data acquisition system consists of a 486 computer and a statistical software package. The operating parameters are scanned every 0.6 min or less, and the averages are recorded every 60 sec. R/F parameters measured and recorded include temperature, pressure, power, and time.

Weighted thermocouples were placed in the freezer and fresh food sections in accordance with the ANSI/AHAM standards (ANSI/AHAM 1988). Three identical weighted thermocouples were placed in close proximity to the ANSI/AHAM standards' weighted thermocouples in the freezer compartment. The identical thermocouples were wired parallel to an externally mounted device to control the temperature of the freezer section more precisely than the factory-supplied controller.

Type T thermocouples were attached to the evaporator, compressor, and condenser lines. The thermocouples' placement on the evaporator and the condenser are shown in Figures 1a and 1b. Accuracy of the thermocouples is ±1.0°F (0.5°C). Power measurements were monitored with a watt transducer with a range of 0 - 500 W. Accuracy of the W-h meter is ±0.2%. Pressure transducers were mounted in-line on the compressor inlet and outlet. The suction transducer has an operating range of 0 - 100 psia (0 - 689.5 kPa), and the discharge pressure transducer has an operating range of 0 - 250 psia (0 - 1,723.7 kPa). Accuracy of the transducers is ±0.1%.

The R/F was evacuated overnight to a minimum vacuum of 10 μm of mercury. Leak checks were required if the system exceeded 100 μm of mercury after 20 minutes of being isolated from the vacuum source. A predetermined amount of refrigerant was charged into the R/F as a vapor on the low side from individually prepared, 98% or greater pure refrigerant. A laboratory balance with ± 0.1 g accuracy was used to weigh refrigerants into the system to obtain the appropriate charge. Subsequent refrigerant charges to obtain optimum power efficiencies were added in the same manner.

Flammability testing was conducted in accordance with the American Society for Testing and Materials (ASTM) standard, *Concentration Limits of Flammability of Chemicals (ASTM E681-85)*. A 15 kV, 30 mA AC transformer power supply discharged over a 1/4 in. (6.35 mm) gap for 0.1 sec was the ignition source. For reproducible control of humidity, a 21.0% oxygen, 79.0% nitrogen synthetic air mixture was used in place of room air, and 96 μL of water was injected into the test vessel for each test. Tests were performed over a temperature range of 25°C to 30°C with a relative humidity variance from 58% to 76%. This testing standard has recently been modified to make it more reliable (Baskin et al. 1994).

RESULTS

Insulated R/F Doors

Four alternative insulation configured R/F doors have been developed and tested, utilizing a different R/F (Griffith et al. 1995). Gas-filled panels are insulating apparatuses containing low-conductivity, inert gas at atmospheric pressure with a reflective baffle that suppresses radiation and convection within the gas. The thick foam pseudo doors are made using flange frames, stock liners and gaskets, polyurethane foam boards, and extruded polystyrene foam strips. The flange frame is fastened to the inner liner and gasket and then set into a 4 in. (10.1 cm) thick foam board. A more detailed description of these doors is given by Griffith et al. (1995). The R/F came charged with R-134a; the conventional R/F system was not modified other than to interchange the doors. Of the four alternative configurations tested, the pseudo and gas-filled designs provided the greatest energy reduction for all four temperature control and heater settings, as seen in Table 1 and in Figures 2a and 2b. The remaining configurations (thick foam and krypton-filled) performed almost identically to the original doors. As seen in Figure 2b, the energy reductions for the pseudo door tested ranged from 4% to 11%, depending upon the control setting, and the gas-filled reductions ranged from 2.8% to 4.9%. The control setting is the position of the temperature control in each compartment. These settings are required by the testing standard for the energy consumption test.

Hydrocarbon Mixtures and Flame Suppression

The R/F energy consumption tests done in a conventional R/F revealed the following results (Baskin and Perry 1994; Baskin et al. 1994):

- The 60/40% and 70/30% (isobutane/propane) were the best overall mixtures, as seen in Table 2.

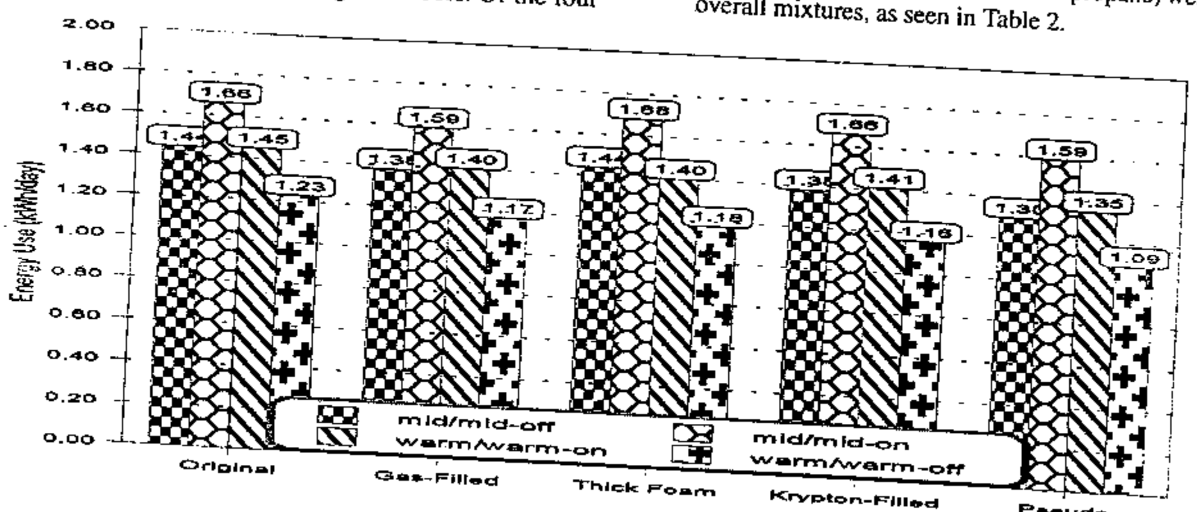

Figure 2a Energy consumption (kWh/day).

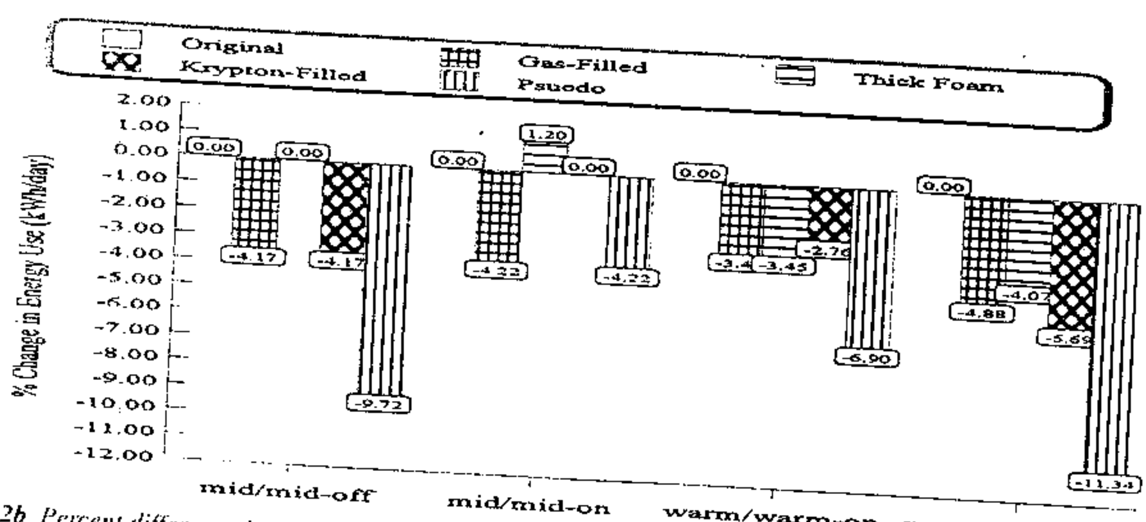

Figure 2b Percent difference in energy consumption (kWh/day).

- The trifluoroiodomethane (CF_3I)—nonflammable mixture predicted by Jon Nimitz (1994)—in the hydrocarbon mixture (70/30% isobutane/propane) causes the energy consumption to increase by 3% over that of the hydrocarbon mixture and is equal to that of R-12, for a given freezer damper setting (see Table 3).
- For a refrigeration capacity approximately equal to that of R-12, the energy consumption of the ternary refrigerant (CF_3I-86% wt, isobutane and propane-14% wt [70/30% wt isobutane/propane]) is 6.9% higher than that of R-12.
- A large concentration of CF_3I in a 70/30 mixture of isobutane/propane was necessary to ensure complete nonflammability of the refrigerant (62% volume and 86% mass, as shown in Figure 3). The area inside the curve represents flammable compositions of the mixtures, while the area outside the curve represents nonflammable compositions.

R-245cb/R-134 as R-12 Replacement

The azeotrope R-245cb/R-134 performed comparably to R-134a in a 580 Btu/h (170 W), R-134a compressor installed in a conventional R/F, as seen in Figure 4 (Baskin et al. 1996). Identical cooling capacity was obtained with no increase in the energy requirement. The reduction of the cycling losses of the R/F using R-245cb/R-134 and R-134 contributes to their performance. Yet, R-134 performed 5.9% worse than R-134a in the same equipment. These refrigerants (R-245cb/R-134 and R-134) performed slightly better than R-134a in the 970 Btu/h (284 W) compressor (Figure 5). Since R-245cb's atmospheric life is higher than originally predicted, it is no longer considered a viable alternative to R-134a.

TABLE 2
Performance of Mixture Without Flame Suppressant

Refrigerant Composition (wt %)	Energy Consumption (kWh/day)	Freezer Temperature (°C)	Charge (grams)
R-12 (100)	1.73	−14.7	159
Isobutane:Propane			
(100:0)	1.73	−10.9	72
(90:10)	1.66	−12.3	102
(80:20)	1.72	−13.7	82
(70:30)	1.68	−14.6	82
(60:40)	1.67	−14.8	72
(50:50)	1.81	−12.7	52
(40:60)	1.73	−15.3	82
(30:70)	1.75	−14.9	82
(20:80)	1.81	−15.4	72
(10:90)	1.85	−16.4	72
(0:100)	1.92	−17.1	72

TABLE 3
Performance of Mixture With and Without Flame Suppressant

Refrigerant (% wt. Composition)	Energy Consumption (kWh/day) (Freezer Temperature [°C])		Total Charge (grams)	
	Without CF_3I	With CF_3I	Without CF_3I	With CF_3I
R-12 (100)	1.73 (−14.4)	N/A	159	N/A
Isobutane:Propane (70:30)	1.68 (−14.6)	1.73 (−12.9)	82	202
		1.74 (−13.7)		222
		1.85 (−14.9)		222

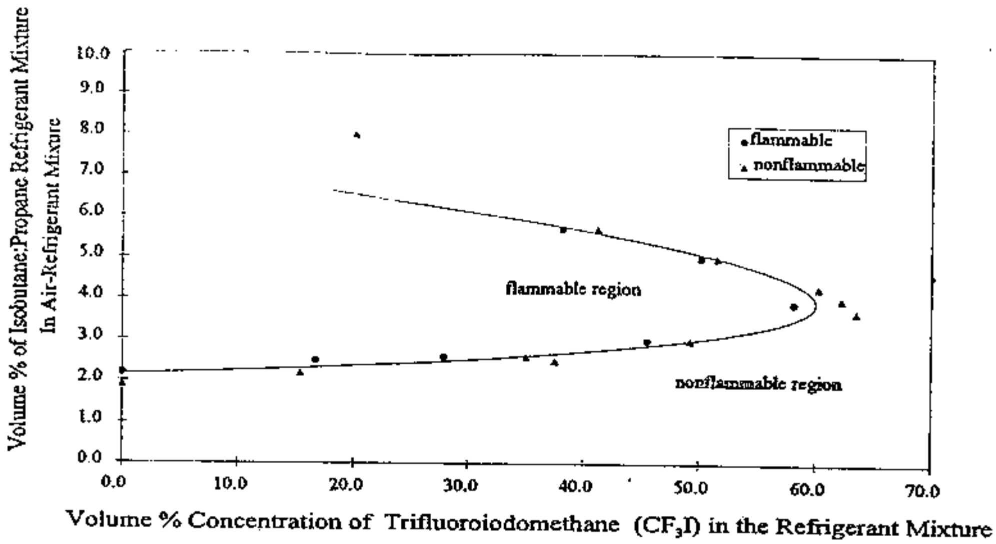

Figure 3 *Flammability suppression of trifluoroiodomethane (CF_3I) in isobutane/propane (70/30) mixture.*

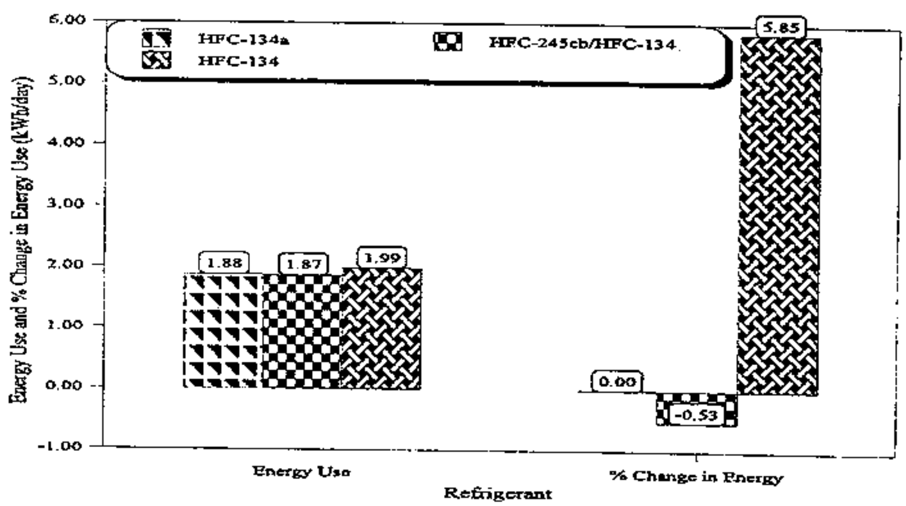

Figure 4 *Performance using 580 Btu/h compressor.*

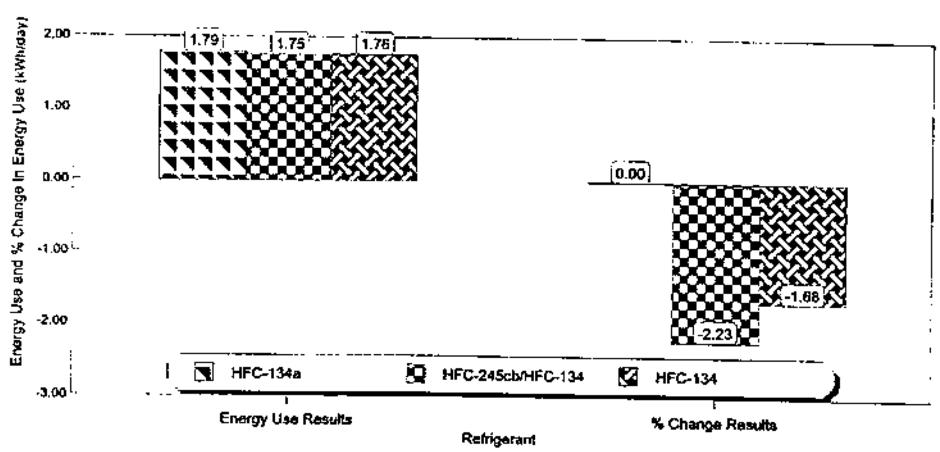

Figure 5 *Performance using 970 Btu/h compressor.*

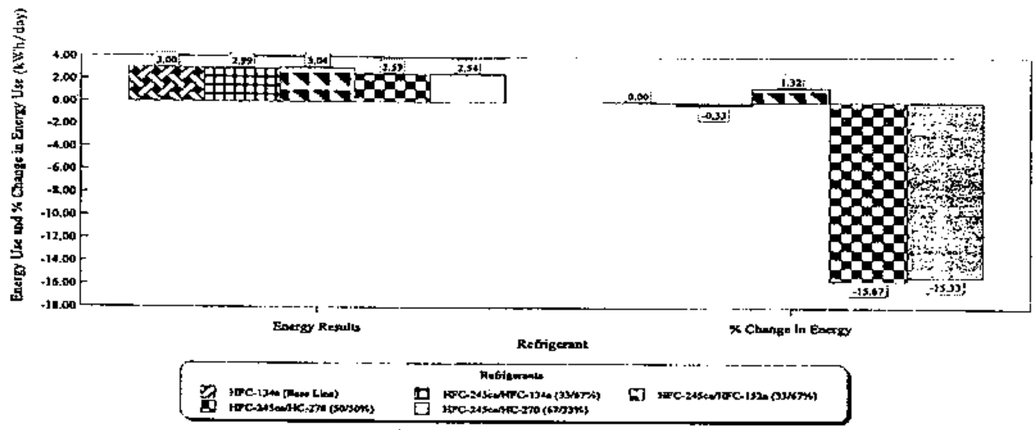

Figure 6 Better energy reduction performer of LM R/F using 750 Btu/h compressor (average freezer temperature = −14.1°C).

Zeotropic Refrigerants

A number of mixtures were evaluated—R-245ca with R-134a, R-245cb, R-227ea, R-152a, and R-270 (Baskin et al. 1997). The mixtures were tested in a R/F previously tested with zeotropes by Sand et al. (1992). Two mixtures predicted—model created by Jung and Radermacher (1991)—to outperform R-134a in the LM R/F, R-245ca/R-134a and R-245ca/HFC-152a, performed comparably to it, and a third, R-245ca/R-270, performed better as predicted. R-245ca/R-270 outperformed all zeotropic mixtures and R-134a. The mixture energy consumption reductions were approximately 16% in comparison to R-134a. R-245ca/R-152a and R-245ca/R-270 are flammable mixtures and R-245ca/R-134a may be flammable. Therefore, the flammability issue needs to be resolved and considered before utilizing these mixtures.

CONCLUSIONS

The multi-faceted approach for evaluating alternative technologies to replace environmentally harmful R/F refrigerants has revealed several legitimate alternatives. These alternatives consist of innovative refrigerants and hardware configurations. In conventional R/Fs, hydrocarbon (isobutane/propane) mixtures were shown to be the most energy-efficient and should be more cost-effective; cost-effectiveness is realized because mixtures can be drop-in replacements. No component or lubricant changes were required to obtain results presented in this report. The drawback to using hydrocarbons, i.e., flammability, can be alleviated by utilizing the flame suppressant CF_3I, which will deliver slightly reduced refrigeration capacity with comparable energy consumption. In a leak scenario, the flammable component, propane, would leak out first due to its low boiling temperature; thereby the leaked refrigerant introduces a risk of flammability. This risk should be minute due to the hermetic seal of R/Fs.

Conventional R/F doors and walls use CFC/HCFC foam insulation; therefore, varying the insulation in the R/F door can further augment the energy-efficiency and eliminate the use of CFCs in conventional and unconventional R/Fs. The energy enhancements ranged from 3.5% to 11%, depending upon insulation type. Lastly, the top zeotropic mixture used in the LM designed R/F was R-245ca/R-270. This mixture substantially reduced the energy consumption by 16%. This R/F research has provided several environmentally friendly alternative refrigerants.

FUTURE WORK

Future research should focus on the risk assessment of using flammable refrigerants that are environmentally benign. Options should be identified and implemented to reduce risks associated with their use. An option may be to use some of the risk reduction techniques employed by European R/F manufacturers (e.g., placing electric switches in wall insulation).

Other alternative R/F configurations should be tested. Tests of a LM R/F with a minor component modification (larger compressor) and two-cycle R/F with alternative refrigerants are being conducted. The results from this work will be published at a later date.

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